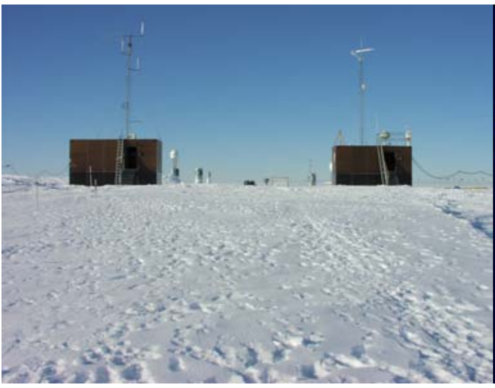
MASTER THESIS




ANALYSIS OF LIFETIME OF A TUBULAR RESEARCH STRUCTURE ON ANTARCTICA

Charlotte Saltner & Willem-Dirk Keij

June 2002

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"There is no material of engineering significance
that displays the bewildering complexities of snow."

M. Mellor, 1975

Preface

The Master of Science programme for engineering at Delft University of Technology comprises five years and ends with a thesis project. This report is the outcome of a master thesis project conducted at the faculty of Civil Engineering and Geosciences, section of Hydraulic Structures and Probabilistic Design.

The thesis project has been performed for the German Alfred-Wegener-Institute, Foundation for Polar and Marine Research (AWI). The Department of Logistics of the AWI has, in co-operation with the thesis students, set the goals for the study and given the necessary input.

This project was started in September 2001. During the last nine months of research 12 weeks were spent on Antarctica, taking part in the Antarctic expedition ANT XIX, conducted by the AWI, doing fieldwork on-site at Neumayer Station.

Acknowledgements

This thesis project would not have been possible without the support of the Department of Logistics of the AWI in Bremerhaven. Dr. H. Gernandt, head of the Logistic Department, embraced the idea of having Dutch students working on the deformations of a German polar base, which formed the starting point of our project.

We acknowledge that the good relationship between the AWI and the Netherlands Organization for Scientific Research (NWO), specifically dr. J.H. Stel, has paved the road for co-operation and joint research, in light of which the student team from Delft has been able to participate in the research programme at AWI.

As civil engineering students it took us a great effort to become familiar to the world of ice mechanics and construction under Antarctic conditions. We owe gratitude to Dipl.-Ing. D. Enß who introduced us to polar engineering and who was disposed to answer any question during the whole project.

The academic results of a thesis project are heavily dependent on the assistance received from the university. We wish to thank the thesis committee, headed by prof. drs. ir. J.K. Vrijling, for their support and guidance during the project. The freedom to

pursue our plans and work outside standard Dutch civil limits has enabled us to broaden our views on the world of civil engineering.

Being able to live and work at Neumayer Station during the Antarctic summer season 2001/2002 has, besides resulting in data for the thesis project, been a studious experience. H. Ahammer and J. Janneck gave practical assistance during this time leading to good insight on construction under Antarctic conditions.

Staying at Neumayer Station helped to understand the importance of the research conducted on site as well as the need for a safe base during the Antarctic winter. The reception by the scientific crew during the summer season as well as the close contact with the over-wintering team 2002/2003 led both to a firm foundation for our enthusiasm and to friendships across borders.

Where work on a thesis study is focused on a challenge far away one must never forgot those who are closest…

Delft, June 7th 2002

Charlotte Saltner Willem Keij

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Summary

Isolated at the centre of the Southern Hemisphere lies the world's coldest, driest and windiest continent: Antarctica. Antarctica has no aboriginal population but since the beginning of the 18th century the continent attracted many adventurers and scientists who dedicate their studies to a wide range of research fields. The wish to conduct research and other activities on such a cold and remote place has to be responded with structures that withstand the extreme polar conditions.

The German Alfred-Wegener-Institute (AWI), Foundation for Polar and Marine Research, has conducted research on Antarctica since 1981 and operates several bases on the Antarctic continent. The first German station, Georg von Neumayer (GvN), was a basis for four scientists conducting geophysical, meteorological and chemical research as well as for five personnel staff. The present study focuses on the Neumayer Station, built in 1992 after Georg von Neumayer had to be abandoned because of large deformations of the base's outer hull. Like its predecessor, Neumayer Station is a sub-surface research base erected on the Ekström Ice Shelf. Due to its location in an ice shelf the base suffers from a limited lifetime. Within the scope of this project a numerical model is developed to come to a more precise prediction of the lifetime of such a base.

FIGURE 1: Neumayer Station *(photograph: AWI)*

The snow-covered Neumayer Station is located in a 200 m thick ice shelf. The base consists of two parallel steel tubes, each of which is 8.40 m in diameter and around 90 m long, in which containers are inserted to accommodate living and working quarters. The containers rest on a steel platform structure that transfers the weight forces to the tube onto the snow. Another transverse tube of similar length contains storage, waste and tank containers, as well as space for vehicles. A tunnel links the main station with a special garage for all types of vehicles used at the station. These tubes are constructed on the snow surface but due to snow accumulation snow layers cover the base, which cause the base to disappear within 3 - 5

years. Above that the weight of the base itself and the loads resulting from inside activities cause settlements of the tubes into the snow layers below.

The time dependent increasing top loads resulting from the snow layers cause deformations of the outer steel hull, widening the horizontal dimensions and compressing the vertical dimensions.

The space above and beneath the containers is used for storage, wire infrastructure and maintenance activities. Therefore the deformations in vertical direction reach a critical value when the space falls short of 1.00 m. This value is defined by the AWI as the maximum deformation allowed to ensure safe and proper use of the tube.

A numerical model has been developed to estimate the deformations of the tubes. The deformations observed result from the widening horizontal dimensions and shortening of the vertical dimensions as well as from the (unequal) settlements of the tubes. At first these two aspects are treated separately and are combined later on using a summation of the models. The deforming ring, loaded by increasing top loads is modelled by adapting Duddeck's (1960) theory for concrete tunnels in soft soils. The behaviour of the tube as a whole in the snow/ice layer is modelled using a rheological description for a linear visco-elastic material.

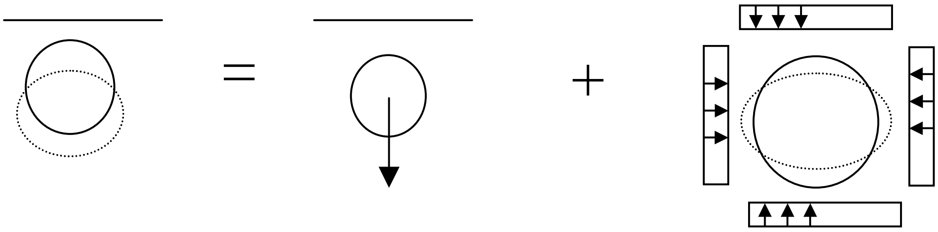

FIGURE 2: deformation of the tubular base profile divided in two phenomena *(Saltner & Keij)*

In an extensive survey programme the AWI has measured the change in horizontal and vertical dimensions of the tubes twice a year since the construction of the Neumayer Station was completed. Within this study the measurement results from the West tube averaged over the length are used to calibrate the model.

On site snow and material parameters are used as input values and the model is calibrated to the actual AWI deformation data. The calibration shows a necessary increase of the viscosity modulus of 30%, which means that the snow layers react more rigidly than the model predicts using the local data. This difference is likely to be caused by temperature effect around the circumference of the tubes.

The output of the model is calculated for the 90% probability interval of the snow accumulation, for 5, 50 and 95% probability of exceeding. This output shows that in an average (50%) accumulation case, the earliest moment of deformation larger than the acceptable maximum will be in the year 2009. Values have been given for larger acceptable deformations and other snow accumulation rates.

The use of this model is limited due to the fact that elastic modelling of the deformations is limited to small deformations. The model output is valid for deformations up to 1.30 m. The maximum limit stress for the collapse of the steel profile of the tube is not reached in that case.

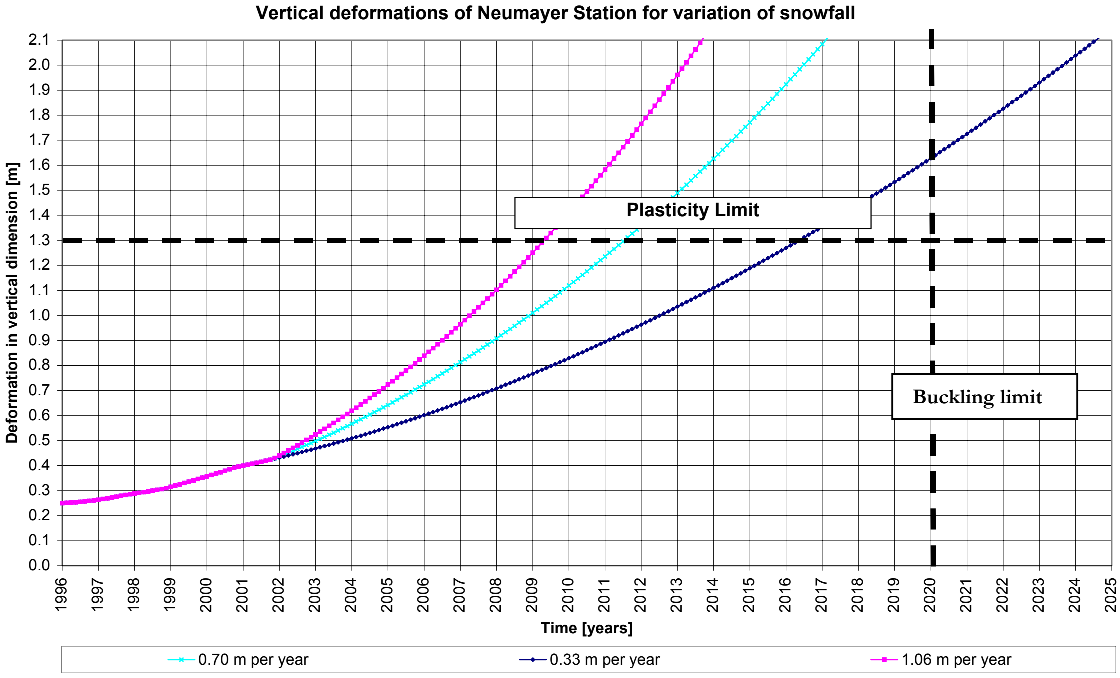

FIGURE 3: vertical deformation of Neumayer Station for variation in snowfalls *(Saltner & Keij)*

The calibrated model has been used to calculate the deformations for several different changes in base design, involving the steel profile, the radius and the snow properties directly next to the tube. Making the snow more rigid by sintering the material close to the tubes up to a depth of 10 m is an effective option.

This thesis study contributes to a design tool to assess future tubular bases. Other contributions in the discussion over a new German base will be the level of automation for a future base and the possibility of cooperation with other institutes.

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Chapter 1

Introduction

General

In February 2002 a large iceberg separated from the Antarctic continent, making world news. The accompanying rise in media attention on global warming and the rise of the sea level that are associated with the Antarctic ice sheet show that Antarctica has not lost its valued importance.

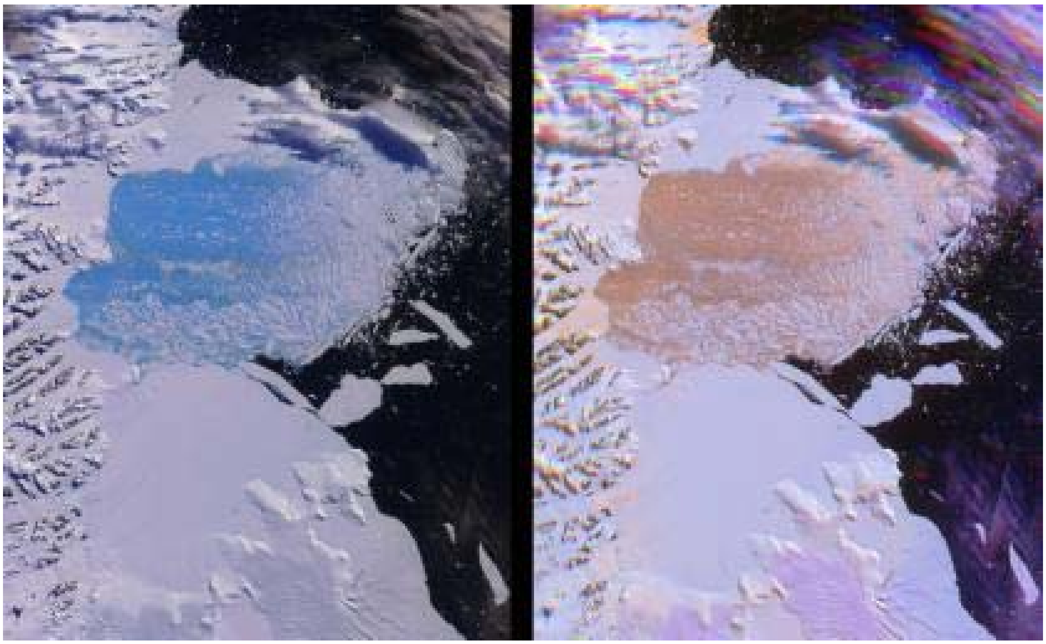


FIGURE 4: breaking-up of iceberg, picture taken Feb. 23rd 2002 *(photograph: NASA/AP Photo)*

Antarctica has been a subject of study for many generations, from the early explorers looking for a continent that was already predicted by the early Greeks and sailors looking for hunting grounds to the adventurous race to the South Pole in the early 1900’s.

After the International Geophysical Year in 1957 a total of 45 countries signed the Antarctic Treaty, limiting activities on the continent to those of environmentally sound tourism and extensive scientific research expeditions.

Understanding Antarctica and its influence on the world's climate system is equally as challenging as defining the build-up and functioning of the rich ecosystem. The research areas that touch upon the Antarctic continent are diverse and demand for research is large. Antarctic bases have been set up around the continent, on the outskirts of the thick ice sheet that covers the continent, as well as on the partly covered Antarctic Peninsula.

Some of the countries that perform research on Antarctica use permanent bases on the continent to gather data. The German Alfred-Wegener-Institute (AWI), Foundation for Polar and Marine Research has operated a base on the Ekström Ice Shelf since the early 1980s. At this location the German research effort has resulted in an extensive programme covering geophysical, meteorological and air chemical research.

The German base Neumayer Station is subject of research within the scope of this thesis project. Neumayer Station is built up of heated container units, placed inside a tubular steel hull. Due to annual snow accumulation the base, originally constructed on the snow surface, is increasingly covered by snow. Access to the station is guaranteed by annual rising of the station's entrances (ramps for vehicles and staircases for personnel). The increased snow cover, as well as the movements of the ice sheet as a whole is the reason that the lifetime of this type of base is limited.

In 1991 the deformations of the first German base, Georg von Neumayer, caused the abandonment of that base and the construction of the new base, Neumayer Station. The subsequent deformations of Neumayer Station and the implications thereof on the estimate for the lifetime of the base are the subject of this study.

The outline of this thesis report

This thesis report consists of two consecutive sections. These sections are:

1. General information: 'From Antarctica to Neumayer Station'

2. Thesis study: 'From Neumayer Station to lifetime estimation'

From Antarctica to Neumayer Station

Part 1 is an introduction to those who are not familiar with Antarctica, polar structures and/or the AWI and the German research bases.

Chapter 2 focuses specifically on Antarctica. A description of the continent and its environment is followed by the research efforts undertaken by the international community, and the role of the Antarctic Treaty therein. The German research is elaborated, as well as the institute's organisation.

The types of polar bases that are built on the Antarctic continent are sketched in Chapter 3. An analysis is made of the differences of the present types of bases and the functional requirements for living and working on the coldest continent on Earth.

Focus is put to one particular base: the Neumayer Station operated by the AWI. Chapter 4 gives an overview of the location, the layout and the logistics involved in operating the station and the relationship between the station's design and that of its predecessor.

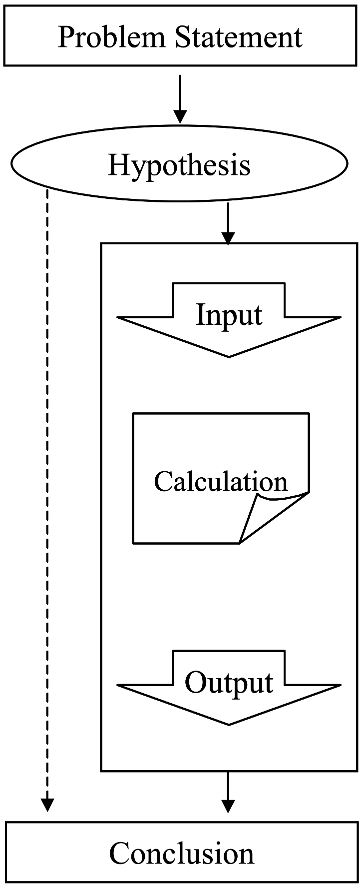


FIGURE 5: part 2: thesis study, schematic *(Saltner & Keij)*

From Neumayer Station to lifetime estimation

The second part of the report presents the actual thesis study. The thesis study is built up of four elements. These elements are generally found in each academic work pattern:

- Problem statement
- Hypothesis for solution
- Modelling of solution
- Conclusions

Firstly the problem statement has to be defined. This is described in Chapter 5. The focus of this chapter lies in an explanation as to why deformations are the subject of this study.

Secondly, after the actual problem is defined, the hypothesis, the starting point of the model can be determined, which is reported in Chapter 6. Next to different types of deformations the limit states for the structural integrity of Neumayer Station are given.

Within the scope of this project a numerical model is developed to come to a more precise prediction of the lifetime of Neumayer Station. Several steps during the model process can be distinguished. To come to a first idea on how to cope with the actual problem input on a level of model ideas and present techniques is necessary. Therefore two overviews are given that provide the reader with theoretical background: *Models Concepts for Tubular Structures* in Chapter 7 and *Physics of snow and ice* in Chapter 8.

On site loads and material parameters valid for Neumayer Station are summed up in Chapter 9. The present deformations of the base are described in measurement data that are presented in Chapter 10. By combining these data with the output of the model it is possible to perform a calibration of the model.

The developed model itself is described in Chapter 11, after which the calibration is presented in Chapter 12. Readers interested in boundary conditions and outcome regarding the model can revert to Chapter 11 and 12. At the end of Chapter 12 the calibrated model is used to come to an estimate for the lifetime of the Neumayer Station.

Taken one step further, the calibrated model can give an estimate on the effect of various design changes on the lifetime of a base. This is described in Chapter 13. The thesis study ends with several conclusions and recommendations that are given in Chapter 14.

Terms related to Antarctica and Antarctic research are given in a glossary.

PART 1

General

Chapter 2

Research on Antarctica

Antarctica

Formation of the continent

About 200 million years ago Antarctica was joined with Australia, Africa, South America, India and New Zealand in the super continent Gondwana. After the slow process of breaking into the pieces that we recognize as continents today, Antarctica settled into its present polar position and began to cool down about 40 million years ago [36].

Many scientists made suggestions about all continents once being united, but German Alfred Wegener was the first who described in 1912 a fully articulated theory - the continental drift, which envisioned a super continent he called Pangaea (‘all lands’). In the 1950’s and 1960’s exploration of the sea floor provided new data and thus new ideas, leading to the theory of Plate Tectonics, which confirmed Wegener’s theories. Also fossil evidence found in Antarctica supports the super continent theory. These species lived on Gondwana and their fossils have been found in such widely separated places as India, South America, Australia, Africa and Antarctica.

The Antarctic region

The core of the Antarctic region is the Antarctic continent. Beyond continental shores the region extends far into the surrounding ocean. There are a series of boundaries, which describe the borders of the region – ecological, geographical, and legal. In the scope of this introduction mainly the natural boundaries such as the northern limit of the pack ice, the Antarctic Convergence or limit of Antarctic surface waters are used.

The Antarctic Convergence is a temperature and salinity boundary of the Southern Ocean. This line varies, seasonally and longitudinally and the summer surface seawater temperature is around 7.8°C, whilst south of the line the temperature drops to around 2.8°C north of the Convergence and to 1.1°C south of the Convergence. The Antarctic Convergence is an area of major biological importance as the cooler southern seas meet the warmer northern waters.

Antarctica can also be divided into longitudinal sectors, e.g. the French, Norwegian, South American sectors.

The Southern Ocean

The ocean surrounding Antarctica is the Southern Ocean. It is the forth-largest ocean with an area of 35 million km^2, extending from continental Antarctica to a northern limit at the Antarctic Convergence.

In the winter more than half of the ocean surface freezes to a depth of a metre or more, forming a fast ice and pack ice. More ice enters the ocean as snow and more again as icebergs and islands that break off from the continental ice cliffs.

In September (Antarctic's late winter) the size of the continent effectively doubles with the freezing of the sea ice, which can extend more than 1000 km from the coast.

FIGURE 6: Antarctica *(source: NYSTROM Division of Herff Jones, Inc.)*

Like all other oceans, the Southern Ocean is made up of water layers. Each has a distinctive combination of salinity, temperature and density. Thus each layer flows in a different direction under the influence of wind and geostrophic forces.

Geography

Without the peninsula the continent is almost circular with a diameter of about 4500 km and an area of about 14.2 million km^2. That makes Antarctica the world's fifth largest continent, almost twice as big as Australia or Europe. The ocean basin surrounding the continent has a mean depth of 4000 m and Antarctica's coastline measures 30500 km. Antarctica is also the most arid and the highest continent with an average elevation of 2250 m. Due to its position in the Southern Ocean it is the most isolated continent as well.

Antarctica is divided by the 2900 km long Transantarctic Mountains into East Antarctica and West Antarctica with the direction deriving from 0° Longitude. Geologically East and West Antarctica are entirely different (see *Geology* below).

The two embayments into the continent, the Weddell and Ross Sea are separated by the Antarctic Peninsula.

Antarctica's continental shelf is about three times deeper than that of any other continent [39].

Geology

East and West Antarctica are entirely different as far as geology is concerned. Studies of the available exposures, together with soundings through the ice reveal East Antarctica to be a stable platform of ancient sedimentary rocks, heavily metamorphosed and overlain with younger sediments. The rocks of East Antarctica are at least 3 billion years old and thus belong to the oldest on Earth. West Antarctica by contrast is a complex of folded and metamorphosed sediments, mostly of volcanic origin. It is relatively new, only 70 million years old.

East and West Antarctica evolved in different ways, coming together only relatively recently in the world's geological history.

Climate

Height and latitude combine to make Antarctica by far the coldest continent.

Mean temperatures in the Antarctic interior range from -40°C to -70°C during the coldest month, and from -15°C to -35°C during the warmest month. Along the coastline the temperatures are considerably warmer: -15°C to -32°C during the winter, and from +5°C to -20°C during the summer. The Antarctic Peninsula experiences the highest temperatures year round.

FIGURE 7: wind speeds up to 50 kn observed at Neumayer Station in May 2002 *(photograph: S. Riedel)*

Interestingly the South Pole is not the coldest part of the continent. The lowest temperature ever measured on Earth's surface was –89.6°C at the Russian Vostok base (on Antarctica) in January 1983. In contrast, the warmest temperature ever recorded for Antarctica was +15°C in January 1974 at New Zealand's Vanda station.

The interior of Antarctica, despite its ice cap, is the world's driest desert, since the extreme cold freezes water vapour out of the air. Annual snowfall on the polar plateau is equivalent to less than 50 mm of rain.

Antarctica experiences strong winds: the katabatics caused by denser colder air rushing down off the polar plateau to the sea. These can achieve velocities of up to 300 km/h. The winds on the polar plateau, by contrast, are usually very light.

Blizzards are a quite common phenomenon on Antarctica. During an average blizzard very little, if any, snow actually falls. Instead, the snow is picked up and blown along the surface by the wind. This results in blinding conditions in which objects less than a meter away may be invisible.

Ice

The Antarctic is the ultimate icy wilderness. Only 0.6% of the continent is free of ice and the surrounding ocean provides a virtually impenetrable barrier of sea ice which in winter covers an area around one and half times the area of the continent.

In global terms 90% of the world's ice is located in the Antarctic. If melted the Antarctic ice sheet would raise sea levels around 70 m. Its purity is unmatched anywhere else in the world.

The Antarctic has not always been totally icy. When dinosaurs roamed Antarctica and hibernated through the long polar winter there was enough vegetation to sustain them. But today the ice and frigidity of the Antarctic dictate that activities will always be weather dependent and require careful planning.

Ice sheet

Like every other continent Antarctica has mountains, hills, plains, valleys and a shoreline. Unlike any other, over 98% of its area, including 96% of its shoreline is hidden under an immense layer of ice.

Antarctica's ice is formed from snow and hoar frost that has fallen, accumulated and consolidated under pressure. The flakes of snow and frost turn first to granular, air-filled névé, which at depths of 50 to 60 m compresses to solid, blue-grey ice, cloudy with air bubbles. Lower still it forms clear blue ice from which all bubbles have disappeared. This is a continuous process. Ice is constantly added to the ice sheet, and constantly lost by evaporation, melting and calving into icebergs.

Much of the thick inland ice is very old as chemical analyses of cores taken from the ice sheet show. Much of the coastal ice is by contrast relatively new, formed from heavy local snow that fell tens or hundreds of years ago, rather than thousands.

Renewed constantly by snowfall, the ice sheet slumps outward under its own weight, filling valleys, overflowing and eroding mountain chains. Much of the inner Antarctic ice sheet is relatively static but it contains within it huge rivers of ice, including both glaciers that flow between rock walls, and ice streams that flow between walls of stationary ice. Moving ice has enormous capacity for carving the underlying bedrock and carrying millions of tons of boulders, rubble and finely ground rock flour toward the sea.

The ice sheet overspreads the shore of the continent to create a coastline of ice cliffs. Grounded ice sheets make up about one-third of the coastline, slow-surging ice shelves almost half, and active ice streams and glaciers some 13 - 14%. As ice is less dense than water, the seaward edges of the ice sheet float, breaking off periodically to form ice islands and icebergs that drift out to sea.

The Weddell and Ross seas (see figure 6) have their own ice shelf: the Ronne Ice Shelf and the Ross Ice Shelf, respectively. They are extensions of the great Antarctic ice sheet.

Ice shelf

Ice is less dense than water and because near the coast ice sheets generally rest on a bed below sea level, there comes a point where it begins to float. It floats in hydrostatic equilibrium and either it stays attached to the ice sheet as an ice shelf, or breaks away as an iceberg. Being afloat, ice shelves experience no friction under them, so they tend to flow even more rapidly than ice streams, up to 3 km per year. Much of Antarctica is fringed by ice shelves. The Ross and Ronne-Filchner ice shelves each have areas greater than the British Isles.

FIGURE 8: shelf ice *(photograph: BAS)*

Across the base of ice shelves, seawater and ice come into contact. Where this seawater is warm enough, the ice shelf will melt, adding cold fresh water to the sea. This diluted seawater eventually helps to form a water mass called Antarctic Bottom Water, which is present in many of the deepest parts of the ocean. Eventually ice breaks off the ice shelves to form icebergs.

Ice stream

Although they account for only 10% of the volume of the ice sheet, ice streams are sizeable features, up to 50 km wide, 2000 m thick and hundreds of km long. Some flow at speeds of over 1000 m per year and most of the ice leaving the ice sheet passes though them.

Ice streams generally form where water is present, but other factors also control their velocity, in particular whether the ice stream rests on hard rock or soft, deformable sediments. At the edges of ice streams deformation causes ice to recrystallise making it softer and concentrating the deformation into narrow bands or shear margins. Crevasses, cracks in the ice, result from rapid deformation and are common in shear margins.

Pack-ice

In winter the sea around the Antarctic freezes, but ocean swells and wind break sea-ice, as it is known, into large pieces termed pack-ice that move under the influence of wind and currents. The extent and nature of the sea-ice plays a vital role in the earth's weather system. While open ocean reflects only 5% of incoming solar radiation, snow-covered pack-ice reflects more than 80%. Pack-ice reaches its maximum extent in

September and October when the sun's radiation over the Southern Hemisphere is increasing. The pack-ice therefore helps to keep the Antarctic cold by delaying the warming effect of the sun.

Pack-ice moves mostly under the influence of the wind and surface currents. It can change in a matter of hours from being densely packed and impassible to non ice-breaking vessels, to 'open pack' as it is known. Wide gaps in pack-ice are known as leads, sought by ship's captains trying to navigate close to the continent.

Sea-ice

The Southern Ocean develops a skin of sea-ice, surrounding continental - Antarctica and the southernmost islands for much of the year. This may be fast-ice, which grows out from the land and forms continuous sheets, or pack-ice, which is made up of floes, the broken remnants of ice sheets.

Sea-ice starts to form when air temperatures fall in March or April. Though fragmented by swell and drifted by wind, it continues to grow and thicken throughout the winter.

FIGURE 9: sea ice *(photograph: AWI)*

By August or September the Antarctic Peninsula and the rest of the continent are surrounded by semi-continuous sheets of fast-ice ringed by a wide band of pack-ice, in places over a metre thick and extending many kilometres from the coast.

Sea-ice seldom remains smooth and unbroken, winds and currents set up tensions, which open channels in the ice sheets, and pressures, which push one part of an ice field against another. These forces may double and redouble the thickness of the ice sheet.

In the early spring the sea-ice starts to disintegrate, melting and eroding under the warming influences of the returning sun.

Not all the annual sea-ice disappears completely. In much of the Weddell Sea, parts of the Ross Sea, and at several other points around the continent, sea-ice tends to accumulate in local gyres from year to year, forming thick and heavy barriers that few ships can penetrate.

Icebergs

Icebergs are huge blocks of ice afloat in the sea. They are derived from the cliffs of Antarctica's ice coastline. The largest are called ice islands and are massive sections of ice shelf several hundred kilometres long and broad that occasionally break away from the mainland ice for reasons still unknown.

Smaller tabular bergs, flat-topped, square-cut, and usually just a few kilometres long, break constantly from the ice cliffs all around Antarctica.

Lesser bergs, called bergy-bits, growlers and brash-ice, irregular in shape, break away from the glacier streams that pour slowly between the mountains.

Icebergs sometimes incorporate boulders and fragments of rock that they have picked up on their journey over the continent. Though superficially white, they are often intensely green or blue. Whiteness usually denotes the presence of air, blueness the solidity of hard, compact ice.

Glaciers

While most of Antarctica is covered by an icecap, within this system there are distinctive glaciers, the majority of which occur around the coast. The largest in the world is the Lambert Glacier in the vicinity of the Prince Charles Mountains. Some 25 miles (40 km) wide and 250 miles (400 km) long the Lambert Glacier drains a vast area. The most famous Antarctic glacier, however, is the Beardmore, which served as a pathway for early explorers such as Scott and Shackleton on their way to the South Pole.

FIGURE 10: Dry Valley Front Glacier *(photograph: NSF)*

Rock

Whereas most of Antarctica is an ice-covered wilderness, a small area (less than one percent) is free of ice and the continent contains some of the most spectacular mountain ranges anywhere in the world. The most extensive are the Antarctic Peninsula, 1700 km, and the Transantarctic Mountains, 3000 km. The highest mountain, Vinson Massif in the Ellsworth Mountains, peaks at 4897 m.

A particular feature of Antarctic rock is that, for the most part, surfaces are clean and freshly weathered. Vegetation cover is minimal, and apart from some low-lying coastal exposures, where penguin rookeries exist, they are not colonised by animals. For these reasons, geological structures and detailed relationships between rock bodies commonly are superbly displayed and easy to see in the field.

Research

Discovery of the continent

Antarctica was an undiscovered continent for a long period in human history. At the beginning of the 20th century the first humans settled on the cold continent, which was 80 years after seafarers have viewed the Antarctic Peninsula. Until that time, the presence of Antarctica had only been hinted at [I].

Prediction of existence (before 1700)

The ancient Greeks postulated the first idea of a southern land. Out of their ideas of symmetry and balance they imagined the landmasses of the northern hemisphere mirrored by a great southern continent.

FIGURE 11: early expeditions to Antarctica *(photograph: [I])*

In 1520 F. Magellan speculated that the land marking the south side of the Strait of Magellan might be the north edge of a continent. Later, in 1578, Sir Francis Drake sailed around Tierra del Fuego, proving that Magellan's assumptions were not correct.

In the following years mostly ships caught in severe weather and blown off course made more and more discoveries of new land south of previous known territories. In 1619 the Islas Diego Ramirez were discovered, which would be the most southerly recorded land until 1775.

First explorations (1700 – 1780)

The early European exploration voyages were concerned with commerce or the investigations of the newly discovered American continent. In these days any sightings of the southern continent were unplanned.

In 1699 E. Halley made the first recorded sighting of tabular icebergs at 52°S. In 1739 J. Bouvet de Lozier sighted land at about 54°S. This land later proved to be the island now called Bouvet Island. In 1771 and 1773 Y. Kergulen sailed with specific instructions to find the southern continent. He found Kergulen Island only.

In 1767 the shores of the new continent had been predicted to be between 28°S and 40°S. The English sent Captain J. Cook in search of this continent in 1768, but with no result.

Cook sailed from England again in 1772 and 1773 reaching the most southern point up until that day (71°S) and crossing the Antarctic Circle for the first time. In 1775 he discovered Willis Island and Bird islands and named South Georgia Island.

At the end of February 1775 Cook had circumnavigated Antarctica in full proving that if there was a continent, it was inhospitable and not of any use to anyone.

Antarctic hunting (1780 – 1840)

In the following years the first explorations after the discoveries of Captain Cook, concerning southern islands with large whale and seal populations, fuelled the arrival of hunters. In these years seal populations on the discovered islands were rapidly diminished.

In 1819 more seals were found south of the known territories at Livingston Island.

In 1820 the first person in history sailed into the Weddell Sea. At this time many new recordings of land were made. In 1821 the first recorded landing at Hughes Bay took place, and for the first time men over-wintered on land.

At this time new islands were discovered and the coastline of the new continent was mapped. The sealers left the exhausted sealing-grounds, and governments once again took an interest in the continent of Antarctica.

South Magnetic Pole expeditions/Return of the hunters (1840 – 1890)

The missions that were set-up in this period had two main goals: discovery of new land, and the location of the South Magnetic Pole. Dumont D'Urville, discovering Terre Adelie headed the French expedition. Lt. Wilkes was commander of the American expedition, which with 6 ships and 433 men, was the largest expedition ever dispatched to the Southern Ocean. The English expedition of J.C. Ross was specifically tasked to find the South Magnetic Pole. His new findings of land were around the Ross Ice Shelf. The conclusions from these expeditions were that the magnetic pole lay inland.

In this period the whale hunting industry developed new techniques and faster ships, which drove them further south again. The German captain Dallmann made a rather disappointing mission in 1873, which discouraged many whalers for some years. It was not until 1892 that the Dundee expedition searched for whales in the Weddell Sea again. Around 1894 a Norwegian expedition took specimens of animal and vegetation from the Antarctic continent to the mainland for the first time.

The age of exploration (1890 – 1930)

During this period the emphasis of Antarctic explorations began to shift from profit to science. The first over-wintering of a ship with crew took place during the winter of 1897, which resulted in the penetration of humans on the ice. Several parties from Britain, Germany, Sweden, France, and Norway took part in the conquest to reach the South Pole first. In 1911 the competitive atmosphere reached a climax with the explorers Scott and Amundsen battling to be the first man to reach the South Pole. The story of Scott reaching the pole only to find that Amundsen had beaten him there, and after this disappointment not making it back alive is legendary. Other major explorers from time were the German Filchner and the Australian Mawson. The British Shackleton led the last major exploration.

Mechanised exploration (1930 –1940)

Prior to this time, explorers of Antarctica were isolated from the rest of the world. The development of radio communication, aeroplanes and steam engines on steel hulled ships made it possible for expeditions to be better equipped. This era saw the first flights over the South Pole and the first motorised vehicles on Antarctica. The interest of the world shifted away from the Antarctic as the Second World War began.

Territorial claims (1940 – 1950)

From the beginning of the explorations, parties discovering new land, or islands, had claimed them to belong to their home country. The oldest permanent occupation of an island is the Laurie Island on the South Orkneys, where Argentina had a station from 1904.

Territorial claims for parts of the Antarctic continent came from Britain (1908), France (1924), Australia (1933), Norway (1939) and Chile (1940).

In the Second World War the German navy had a base from which to attack allied ships, which prompted the British to establish a base as well.

After the war the United States launched the largest Antarctic expedition ever: Operation High Jump. This operation was to establish a permanent U.S. presence on Antarctica. At the same time a Swedish-British-Norwegian scientific expedition conducted research from a temporary but continuously occupied base.

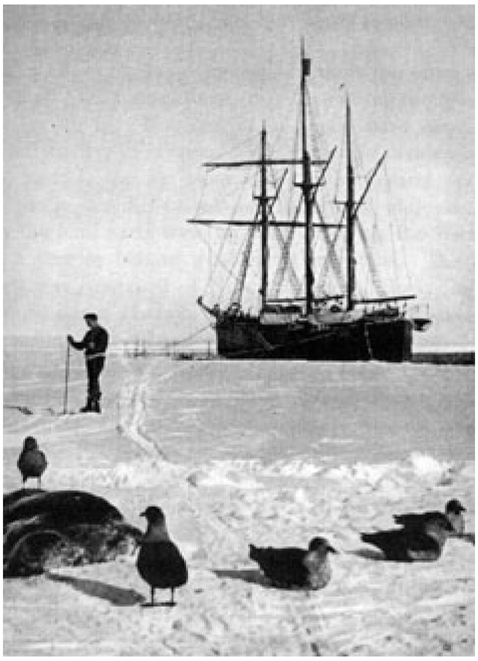


FIGURE 12: Amundsen on the Antarctic continent *(photograph: [I])*

At this time permanent bases were built to show the claims of territory. In 1945 Britain's first base was erected and in 1947 Chile and Argentina followed. In 1950 France built their first base, where d'Urville had made his first landfall. In 1954 Australia constructed its first base, Mawson station.

International Geophysical Year (1957-1958)

Already in 1882 and 1932 there had been polar research efforts, conducted through international scientific co-operation but the emphasis for these research topics had been on the Arctic. In 1950 the IGY (International Geophysical Year) was planned around the Antarctic and scheduled for 1957. Seven countries participated in the IGY with expeditions to the Antarctic: Great Britain, Chile, Argentina, France, Australia, the United States and the Soviet Union (USSR).

After the IGY the total number of stations on the Antarctic continent was 42 with 21 stations erected on the Antarctic and sub-Antarctic Islands. These stations represented the participants named above and additionally Belgium, Norway, New Zealand, Japan and South Africa.

The success of the IGY was the reason for the participating countries to form permanent research programs. These programs are still co-ordinated by the Special Committee on Antarctic Research (SCAR).

The signing of the Antarctica treaty in 1959 (see also *The Antarctic Treaty,* Appendix 1*)* was a confirmation from all parties that scientific co-operation was most important and territorial claims should be defused.

On Antarctica permanent stations have become necessary for the continuation of permanent research. It is important for scientists to live safely in an environment that seemed so inhospitable just 100 years ago.

Present research divisions

Antarctica's influence on the global climate system is significant, as is the melting of the icecap for the world's sea levels. The South Pole is a region relatively untouched by humans, which accounts for a unique ecosystem. That makes Antarctica a unique continent for several research areas. In the last 40 years Antarctica has become more and more important for scientific research.

Why science on Antarctica?

Science on Antarctica offers many advantages over anywhere else on Earth. Some examples are:

- Air quality monitoring with a reliable baseline is possible due to specifically clean air on Antarctica
- Astronomical research due to extreme dark circumstances - especially during the period of polar night
- Studying the bottom of the food chain allows scientists to better understand environmental impacts on humans
- Without any borders research findings are freely available to everyone. Furthermore many projects are internationally co-ordinated and supported without any 'home turf' issues.

The international co-ordination of results is done by SCAR, as mentioned previously.

Science on a remote place like Antarctica is expensive. This is why the research conducted is limited to:

- Subjects that cannot be researched elsewhere on Earth
- Studies that are executed with high-quality
- Studies that contribute directly to global problems

The most important aspect in conducting science on Antarctica, apart from the skills from the scientists involved, is the level of backup from logistical operations.

Research areas

On Antarctica there are numerous research projects conducted by numerous countries. An overview is presented here of several different subjects of studies [A, B, 2, 36]:

The Southern Ocean

The Southern Ocean comprises 10% of all the water in the world's ocean basins. Connecting the Atlantic, Pacific and Indian Ocean, the Southern Ocean has a major influence on the global climate. Oceanographically this ocean is of interest because of its density, its tidal features, and its influence on world sea levels.
Relevant fields of study: Climatology, Oceanography

Antarctic marine life

Cold water allows more dissolved oxygen thus creating possibilities for a rich marine life. Antarctic marine life follows a simple food chain through nutrients - algae - krill -

fish, whales, seals and birds. The marine life can be split into benthic species, living on or near the sea bottom, and pelagic species, living in the water column.

Research is conducted for warm-blooded animals as birds, seals and whales as well as for cold-blooded animals as fish, squid, krill, algae and seafloor communities.

Relevant fields of study: Biology, Ecology, Ornithology, and Geo-biology

FIGURE 13: offshore sampling
(photograph: AWI)

Antarctic terrestrial life

Life on Antarctica is not widespread as a result of the harsh environment. The life that is presently studied can be subdivided into:

- Plants and microbes

On the 0.4% of land surface not covered with ice and snow, plant life exists. Research programmes aim to establish an overview of the different species and try to find out how plant life is transported by wind.

- Invertebrates

Insects have been seen to survive at temperatures up to -28°C. The study topics range from understanding the survival of these creatures to the processes in the simple ecosystem they constitute.

- Life in lakes and streams

On the icy landscape of Antarctica several lakes exist showing a high concentration of salinity. In these lake ecosystems of bacteria and microbes occur that are isolated test subjects for researchers.

Relevant fields of study: Biology, Botany and Ecological Systems

Antarctic landmasses

Less than 1% of the rock of the Antarctic continent is accessible for studies. Nevertheless Antarctica is a perfect place to study the Earth crust movements, past climate changes and ancient rock formations:

- Minerals

Past disputes between countries have taken place concerning the possibility of major sources of minerals and fossil fuel lying beneath the landmasses. No strong evidence has been found yet to support this theory.

- Fossils

In Prehistoric times Antarctica was covered with rainforests and the climate was tropical. From the fossils of plant and animal life scientists can learn the species of that time.

- Antarctic land formations

In the Antarctic scientists can study the effect of large layers of ice on the underlying rock as well as the deposits of glaciers.

- Soils

The soils of Antarctica are composed of a dry, salty, permafrost mass, usually more than 500 years old. Study of these soils is important for better understanding of the underlying processes.

- Meteorites

Meteorites are collected to gain information concerning our solar system. Landing in the ice and slowly sublimating to the surface there have been some 1000 discovered on Antarctica.

Relevant fields of study: Geology, Geomorphology, Palaeontology, and Glaciology

Antarctic Ice

About 98% of the Antarctic continent is covered by ice masses. Scientists find, by researching the ice, solutions and data for a variety of fields:

- The ice sheet

From the thickness of the ice sheet the total volume of freshwater stored in the ice can be determined. Estimates are that this is presently 85% of the world's total volume.

- History of our climate

From ice coring and analysis, a historical record can be obtained of the atmosphere in the past.

- Global pollution

Antarctica is remote from all sources of pollution in the world. That is why the effects of pollution can be measured very well from carbon dioxide levels in ice cores and the snow.

- Floating ice shelves

From satellite monitoring of floating icebergs one can measure the amount of ice, and thus freshwater, that flows into the Southern Ocean.

- Sea-ice

The presence of sea-ice varies with the seasons and years. This ice cover stops light from entering the water, which affects the biological habitat of many species during considerable times a year. The importance of data on Antarctic sea-ice also lies in the better prediction of the Southern Ocean models.

Relevant fields of study: Geology, Glaciology, Oceanography, and Climatology

Atmosphere

Weather forecasting

The weather on Antarctica influences the weather above the surrounding countries. Due to this, precise monitoring of the weather above numerous parts of the continent takes place. Monitoring is conducted by people at research bases or by automatic weather stations.

Atmospheric science

Atmospheric science provides data for the issues of ozone layer depletion and Global Warming. On Antarctica the stratosphere is monitored for ozone concentrations and research is conducted for the process of ozone destruction. The global warming issue is studied by monitoring the 'greenhouse gases' like carbon dioxide in the atmosphere.

Geo Magnetism

Antarctica is, like the Arctic, a place on Earth where the magnetic field enters the landmasses. It is thus an ideal place to study particles from the sun entering the atmosphere.

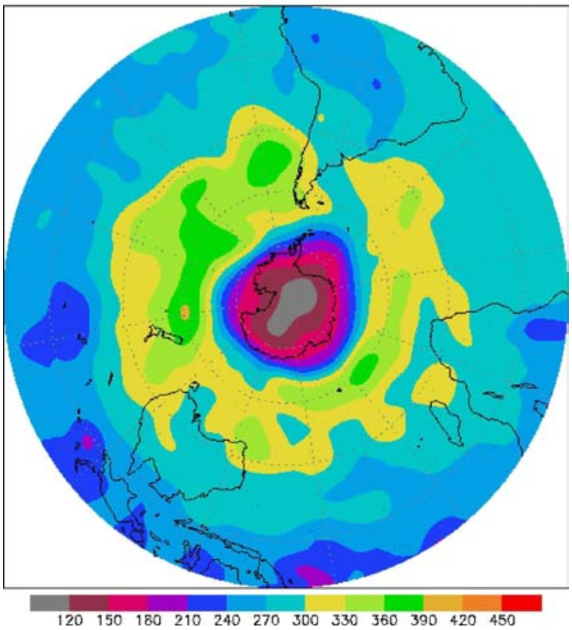


FIGURE 14: total ozone analysis
(source: Meteorological Laboratory at NM)

Astronomy

For astronomers the requirements for a good study are places with little light pollution and as little air pollution as possible. Antarctica provides such a place, which is much cheaper than mounting telescopes on satellites.

Human Presence

The main reason for scientists to study the behaviour of humans on Antarctica is to learn from the isolated living and the seasonal changes from polar day to night. Topics of interest are:

- Endocrinology

Studies into the adaptation of the human body to other daily rhythms are used to develop treatments for people with jetlag or sleep-disturbances. The life on an Antarctic base, in polar day or night gives a good background for experiments.

- Epidemiology

Due to medical checks on staff the health record at polar research bases is excellent. Whenever a new team visits the spread of viruses like colds or flu can be studied.

- Psychology

Small groups of scientists and technical support staff stay together in a small and isolated place during the Antarctic winter. The behaviour of the team as well as their individual experiences under the extreme local conditions can be fields of study.

COMNAP

To conduct research on Antarctica, the participating countries set up the ‘Council of Managers of National Antarctic Programs’ (COMNAP) in 1988. COMNAP was established to bring together those managers of national agencies responsible for the conduct of Antarctic operations in support of science.

Membership of COMNAP is open to the national organisation responsible for planning and conducting that nation's research in the Antarctic, provided the national government is a party to the Antarctic Treaty and the country is actively engaged in research in the Antarctic.

The objectives of COMNAP are:

- To review, on a regular basis, operational matters and to facilitate regular exchanges of information
- To examine, discuss and seek possible solutions to common operational problems
- To provide a forum for discussion in order to frame in a timely, efficient and harmonious manner
- Responses to common issues directed to Antarctic Operators, in particular requests from and Recommendations of the ATCM
- Appropriate input to SCAR responses to questions involving science and operations/logistics
- To provide, in conjunction with the Scientific Committee on Antarctic Research (SCAR), the appropriate forum for discussions on international collaboration in operations and logistics.

The work of COMNAP is undertaken through:

- Annual meetings of national representatives
- Biennial symposia on Antarctic and logistics and operations
- Technical workshops on topics of interest to member agencies (e.g. Antarctic Environmental Impact Assessment – Bologna 1991, Oversnow Traverse Technology – Washington DC 1994, Antarctic Air Transport Networks – Washington DC 1995)
- Working groups assigned to particular issues such as contingency planning, Antarctic tourism, environmental monitoring, air operations, etc
- Close co-operation and joint activities with SCAR

The following countries are members of COMNAP:

Argentina, Australia, Belgium, Brazil, Bulgaria, Canada, Chile, China, Ecuador, Finland, France, Germany, India, Italy, Japan, Korea, Netherlands, New Zealand, Norway, Peru, Poland, Russia, South Africa, Spain, Sweden, Ukraine, United Kingdom, the United States, Uruguay.

At present there are 80 bases on the Antarctic continent, 44 bases manned all year round and 36 summer bases.

Belgium, Canada and the Netherlands are countries that are members of COMNAP without running a permanent base. Bulgaria, Ecuador, Finland, Italy, Norway, Peru, Spain and Sweden have summer bases only.

The Antarctic Treaty

The Antarctic Treaty (see Appendix 1) is a landmark agreement through which countries active in Antarctica consult on the uses of the whole continent. The treaty applies to the area south of 60°S and in its preamble and 14 articles it:

- stipulates that Antarctica should be used exclusively for peaceful purposes and not become the scene or object of international discord
- prohibits nuclear explosions, the disposal of nuclear waste and many measures of a military nature
- guarantees freedom of science and promotes the exchange of scientists and research results
- allows on-site inspection by foreign observers to ensure the observance of the treaty
- removes the potential for sovereignty disputes between treaty parties

The treaty was negotiated by the 12 nations present in Antarctica during the International Geophysical Year (IGY) 1957 - 1958. From 1959 it was developed into what is called the Antarctic Treaty System. In this system there are consultative parties, that pursue research in Antarctica, and acceding parties, that are not active in research and thus do not have voting rights.

Currently there are 26 consultative parties, and 17 acceded parties. These parties have managed many disputes over Antarctica resulting in

- Agreed Measures for the Conservation of Antarctic Flora and Fauna (1964)
- Convention on the Conservation of Antarctic marine Living Resources (CCAMLR, 1972)
- Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMR, 1988)
- Protocol on Environmental Protection to the Antarctic Treaty (1991)

This last protocol is still used today to ensure that the treaty parties commit themselves to the comprehensive protection of the Antarctic environment and its dependent and associated ecosystems.

Alfred-Wegener-Institute, Foundation for Polar and Marine Research

General

The institute was established as a public foundation in 1980. The Alfred-Wegener-Institute in Bremerhaven, the Potsdam Research Unit (1992), the Biologische Anstalt Helgoland (BAH) and the Wadden Sea Station Sylt are part of the Foundation Alfred-Wegener-Institute for Polar and Marine Research (AWI).

Polar and marine research is conducted to improve the understanding of ocean-ice-atmosphere interactions, the animal and plant kingdoms of the Arctic and Antarctic, and the evolution of the polar continents and seas. Given the major role played by these regions within the Earth's climate system, global change is a central focus of the research effort at AWI.

Polar and marine research are central themes of global system and environmental science. The Alfred Wegener Institute conducts research in the Arctic, the Antarctic and at temperate latitudes. It co-ordinates polar research in Germany and provides both the necessary equipment and the essential logistic back-up for polar expeditions [A].

German polar research divisions

Geosystem

Geoscientists at the AWI are reconstructing the history of the polar continents and seas. They study sedimentation history, the processes of deposition and geological transformation in the oceans, marine bio-geochemical cycles, and the paleoclimate of the polar regions. Glaciologists are working on the reconstruction of climate history from ice cores, researching the mass balance and the dynamics of the large ice masses in Greenland and the Antarctic, as well as their interactions with the global climate. Seismic measurements and the identification of anomalies in the Earth's gravitational and magnetic field provide the scientists with valuable information about the structure of the Arctic and Antarctic continental shelves. Atmospheric chemists are unravelling the chemical processes in the troposphere and stratosphere that determine our environment.

Climate System

Studies in the Climate System Department of the AWI focus on the coupled ocean-ice-atmosphere system and its importance for the world climate. Researchers conduct surveys and numerical simulations related to oceanic circulation, transport of substances and energy in the polar seas and the polar atmosphere, and to the influence of these processes on the global climate system.

Oceanographic studies concentrate on the modification of water masses in the Weddell Sea and the North Polar Seas, and on the spreading of deep and bottom waters into the world ocean. Atmospheric studies focus on the investigation of climate relevant processes on different scales in space and time. In addition, variations in the concentrations of climate-forcing trace gases and aerosols, and their impact on the Earth's radiation balance are studied.

Pelagic Ecosystem

FIGURE 15: inland transport of expedition participants and material *(photograph: AWI)*

The open waters of the oceans and its enclosed seas - the pelagic realm – cover 70% of Earth's surface and are inhabited by an astronomical number of minute algal cells (phytoplankton) that grow suspended in the sunlit surface layer. Their photosynthesis provides the food (organic matter) that sustains the bacteria, the unicellular protozoa and the minute animals (mostly midge-sized crustacea) of the zooplankton. These in turn are food of the higher levels of the marine food web (fish and whales). The bacteria, protozoa and zooplankton break down organic matter thereby returning nutrients to the phytoplankton. The activity of individual organisms through the seasons adds up to cycling of essential elements, in particular carbon, nitrogen, phosphorous and silica that extend from millimetre to global scales. The study of these cycles is called biogeochemistry. Evidence is mounting that the biogeochemical cycles run by the pelagic ecosystems are essential cogwheels within the complex machinery regulating Earth's climate.

Benthic Ecosystem

Benthic Ecosystem deals with ecological, physiological and eco-toxicological topics. Shelf and coastal waters of the polar seas as well as coastal waters of the North Sea are the areas of major interest. Central themes are the reactions of cells, individuals, populations and communities towards external influences, and organisation and dynamics of populations, communities and ecosystems.

Logistic Department

The Logistics Department co-ordinates the entire institute's polar activities and advises scientists and participants on expeditions. The responsibilities of logistics include

- Provision and maintenance of the polar stations, research ships and polar aircraft. This encompasses repairs, technical modifications and new construction work, in order to ensure that the scientific requirements are met in all cases
- Co-ordinating the transport of expedition participants and materials to ships and research bases
- Procuring materials, fuel and equipment for expeditions

Special efforts are dedicated to the development of new technological solutions to ensure that polar research activities are environmentally sound and compliant with best available techniques.

Research bases

The AWI operates several polar research bases, including the Koldewey Station on Spits Bergen and the Neumayer Station on Antarctica. At the Argentinean Jubany Station on King George Island AWI owns the Dallmann Laboratory, which is only occupied during the Antarctic summer season.

Dallmann Laboratory

The Dallmann Laboratory is situated on the Antarctic Peninsula, South Shetland Islands at 62°14'S and 58°40'W.

AWI and the Instituto Antártico Argentino (IAA) jointly opened the laboratory in January 1994 at Argentina's Jubany Station on King George Island.

The Dallmann Laboratory offers living and working space for twelve scientists, and is equipped with four laboratories, workshops, storage space, an aquarium container, diving equipment and some igloo huts. Although the Jubany Station is staffed throughout the year, the Dallmann Laboratory is only open during the Antarctic summer months from October to March.

Supported by the logistics available at the Argentinean station, the laboratory offers biologists and earth scientists the facilities they need to work in ice-free areas and shallow waters close to the coast. This is possible only in the few Antarctic areas where the coastline is not covered by thick shelf ice.

Georg van Neumayer Station (GvN) and Neumayer Station (NM)

The Neumayer Station (NM) is situated on the Ekström Shelf Ice at 70°39'S and 08°15'W.

The first base 'Georg von Neumayer' (GvN) on Antarctica was established in 1981 on the Ekström Shelf Ice as a research observatory for geophysical, meteorological and air chemical measurements, as well as a logistics base for summer expeditions. Ice movements and heavy snow deposits necessitated the construction of a new station building in the early 1990's.

FIGURE 16: staircases at Neumayer Station *(photograph: M. Takata)*

In March 1992, the new Neumayer Station was completed only ten kilometres from the original site and continues the research activities. The station's research and measurement programme has steadily expanded ever since and now includes monitoring of vertical ozone distribution.

The snow-covered Neumayer Station is located on shelf ice that is 200 m thick and almost completely flat. The shelf ice margin, where supply ships moor, is about twelve metres high and ten kilometres away. The station consists of two parallel steel tubes, each of which is 8.40 m in diameter and around 90 m long, in which containers are inserted to accommodate living quarters, kitchen, mess, hospital, various laboratories, workshops, radio operator's room, sanitary facilities, two power supply stations and a snow melting plant. Another transverse tube of similar length contains storage, waste and tank containers, as well as space for vehicles. A tunnel links the main station with a special garage for all types of vehicles used at the station, which range from motor sledges to a rotary snow plough.

Nine people live and work at Neumayer Station during the Antarctic winter: one medical doctor, two geophysicists, one meteorologist, one air-chemist, one engineer, one electrician, one radio operator/electronics engineer and a cook. The team stays in Antarctica for 14 to 15 months. For nine months they are isolated from the outside world, and can only be reached via telecommunication.

When the station was being designed, the requirements laid down in the new Protocol on Environmental Protection to the Antarctic Treaty were adhered to, e.g. the use of environmentally neutral construction materials, catalytic converters for the diesel generators and oil collecting equipment for the oil tanks.

Kohnen Station

The Kohnen Station is situated in the Dronning Maud Land at 75°00’S and 00°04’E, 2892 m above sea level.

Within the framework of the European Project for Ice Coring in Antarctica (EPICA), in 2001 AWI established the Kohnen Station as a logistic base for ice drilling activities during the polar summer.

FIGURE 17: Kohnen Station *(photograph: J. Kipfstuhl)*

The base consists of eleven standard 20-ft containers sitting on a 32 m long and 8 m wide platform. The Kohnen base can accommodate up to 20 people.

The logistics for Kohnen Station are based mainly on land-transport facilities. Each field season normally lasts from December until mid-February. The distance between Neumayer Station and Kohnen base is 757 km.

Chapter 3

Structures in Snow and Ice

General

Scientists and additional personnel staying and working on Antarctica live at research bases. Distinction is made between bases manned during the whole year and summer bases. Both kinds of base are found all over the continent but most of them are located at or close to the coast. Travelling to these bases is mainly possible during Antarctic summer season, from November to April. Going to Antarctica by aircraft or ship is most common. The chosen way of transportation depends on the location of the station and the purpose of the transport. Inland transport is predominated by snow dozers, sledges and polar aircraft.

To ensure continuity in research most of the present stations are permanent bases where research is conducted every year. The following two kinds of bases are found: summer-only-bases and all-year-bases. Summer-bases are manned, depending on the location and the kind of research, approximately during the beginning of December until the end of March. Summer ploughs use all-year-bases during the months December - March while the winter plough remains on-site until November/December of the following Antarctic season.

Because of research reasons most of the active countries maintain permanent bases on the Antarctic continent. These bases are mostly operated by national Antarctic institutes, such as the B.A.S. (British Antarctic Survey) and the AWI (Alfred Wegener Institute, Foundation for Polar and Marine Research) for Great Britain and Germany respectively.

History of construction in cold regions

The need for structures that resist cold climates is very old. For hunting purposes in the Arctic and Antarctic people have always sought to found permanent residence [16 – 18, 23].

Arctic region

The Arctic region shows building efforts in northern Canada, Greenland, northern Europe and Russia. The main property of these building practices is that building takes place on soils, whether frozen or unfrozen.

For the handling of equipment and site selection a great deal can be learned for building on polar ice. There is however no base on the Arctic ices, except for the North Pole drifting bases. These are clusters of buoys afloat with the ice, to monitor ice movement, and climate data.

Antarctic region

The Antarctic region has been visited since 1900. From that time Antarctic bases have been established. From the graph below it becomes clear that a high level of construction activity was seen around the International Geophysical Year 1956/57.

Functional requirements of polar structures

Conducting research on the Antarctic continent requires a range of basic functions and conditions that have to be fulfilled to make life and work possible on site. Normally

FIGURE 18: research bases on Antarctica *(source: SANAP)*

people will stay on Antarctica for periods between three and fifteen months in secluded circumstances. This implies that the research bases people are staying at must meet these functional requirements. A distinction has to be made between research bases used for summer research programmes only and for research bases that are manned during the whole year. In the scope of this thesis project this chapter will focus on the functional requirements regarding over-wintering bases.

The general functional requirements listed below are not quantified in detail. This is mainly due to the unique site conditions found in Antarctica. Conditions at the South Pole are markedly different not only from those in cold regions such as Alaska or Canada but also from any other Antarctic station. The extent of research programmes conducted on site, as well as the available budget, influence the size of a research base. Besides this one has to consider that scientific staff always have to be backed-up by technical support personnel, especially during the winter season. Smaller populations than 8 persons are therefore unusual.

Although every country and/or institute make different demands on research programmes and thus research bases there are a number of requirements that have to be accomplished by every base to ensure a safe stay for all persons on-site. These requirements are listed below [10, 11]:

- Housing (applicable for different number of persons during winter and peak season population)
- Main station power plant (generators)
- Emergency power plant
- Fuel storage and distribution system (including main station and emergency storage)
- Food services (three to four meals a day)
- Water and sewage systems, sanitation pumping
- Airport operation (whether or not on a snow runway)
- Communication and technology requirements (science, aircraft, data, meteorology, station operations)
- Vehicle maintenance
- Medical services
- Cargo operations (receipt, inventory, storage)
- Scientific work and science support
- Station operations administration
- Morale, welfare and recreation
- Air-conditioning and ventilation system
- Alarm and fire-fighting system
- Station supply and transport of personnel
- Workshops

All requirements must be met in the scope of the Antarctic Treaty and the Madrid Protocol, which contains environmental agreements.

Economic aspects of construction in polar regions

Base structures on Antarctica are functional buildings. Architectural issues are rarely taken into consideration. Alternatives created during the design process deal ordinarily with technical and/or logistical variants. Investment and operation costs are many times higher than they would be for comparable structures in the home country. As far as the constructions costs are concerned the following estimate comparing to costs in Germany can be made [12]:

TABLE 1: cost factors in comparison to construction in Germany *(source: Enß)*

Contribution	Cost factor
Planning	1.2
Material supply	1.3
Assembly	4.0

There are a number of unfavourable factors that lead to the considerable increase in construction costs. Some examples are health checks with loss of wages, travelling (wages) and travel costs (air and ship), accommodation and board on-site, erection, maintenance and disassembly of construction camp, polar clothes, modification of equipment and tools and the longer use (travel time), overtime, extra charges due to Sundays and public holidays, severance and extra communication pay, hindering due to wind, temperatures and light, hindering due to snow drift and removal of snow drift damage.

Due to environmental conditions mentioned Madrid Protocol all polar structures have to be removed completely or as far as possible. This has to be taken into consideration when planning a new base.

Because of the long travel periods of the construction personnel and the difficult working conditions on the Antarctic construction site far-reaching pre-assembly is a major issue. The pre-production and partial assembly of units seems unreasonably expensive. However, in most cases a complete assembly on-site would be far more costly, which has been proved in comparative calculations.

Different types of polar structures

Generally the chosen base location on Antarctica determines the appropriate type of structure. Building a scientific facility on Antarctica requires different construction skills than elsewhere on Earth. The functional requirements are also very specific in Antarctic circumstances. Several construction concepts are possible but not all of them can be applied to any desired base. There are also several possibilities to differ base concepts. In this thesis project the base concepts are distinguished by making use of the different positions of the bases relative to the (snow) surface.

Besides the research bases themselves there are a number of other structures such as aircraft landing strips and masts that could also be taken into consideration. Within the scope of this project these types of structures are examined further.

The following base concepts can be distinguished [12, 33]:

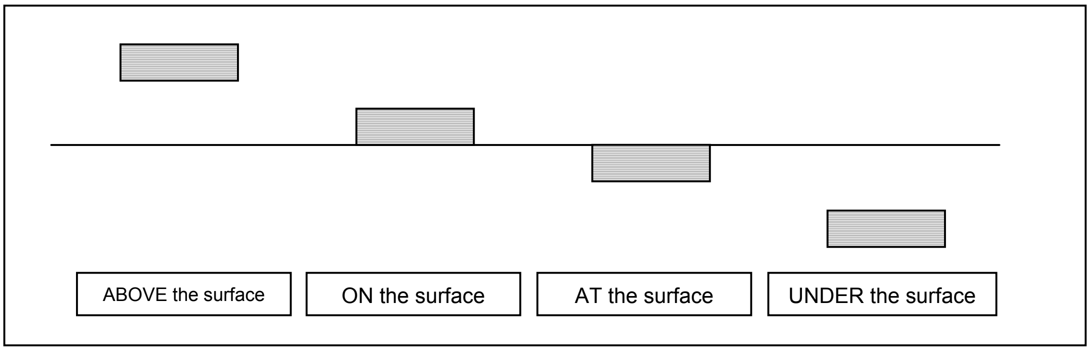


FIGURE 19: different types of polar structures *(Saltner & Keij)*

- Bases ABOVE the surface
- Bases ON the surface
- Bases AT the surface
- Bases UNDER the surface

The differences between these concepts lie mainly in the base foundation. Different foundations require different attention concerning engineering. A base founded on a rock surface does not require the same level of engineering as a foundation on ice.

At larger bases on Antarctica, e.g. Halley 5 (U.K.), structures above as well as under the surface are used.

This thesis study focuses on sub-surface bases founded on ice. Layers of Antarctic ice tend to move laterally and accumulation of snow, which turns into ice, increases the loads on the bases over the years.

Bases above the surface

Bases above the surface consist of (container) units on a platform structure that is founded on posts in the snow/ice. This structure is comparable to the platforms used in offshore gas and oil exploration. The skeleton of posts keep the platform elevated and most of the research facilities are placed in containers. There are two main possibilities for platform structures, joined containers or a base built up from separate modules. The latter is used both for summer camps and for all-year bases.

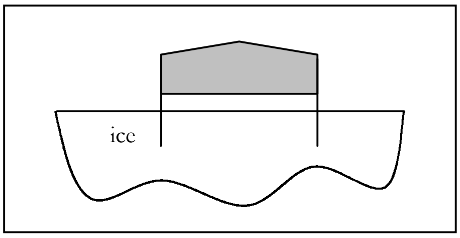


FIGURE 20: bases over the surface *(Saltner & Keij)*

Elevated structures on posts can be founded in the snow or on rock. Such structures are suitable for placement on the ice shelf and on rock surfaces found on the Antarctic continent.

FIGURE 21: Sanae 4 *(photograph: Saltner & Keij)*

The elevation of the base prevents direct snow accumulation on the weather side of the base but underneath the structure higher wind speeds will occur leading to wind scoop and drift snow will lead to sastrugi. Bases founded on ice shelves must be lifted up once every (second) year due to annual snow accumulation by varying distances depending on the location on Antarctica. Otherwise the base will disappear completely in the snow after a number of years. At elevated bases founded on rock no snow accumulation under the base is recognized. High wind speeds remove any accumulated drift snow but it is deposited at some distance from the base. These bases therefore do not have to be lifted.

Lifting a complete base is done mostly with hydraulic stamps that provide space to lengthen the posts of the base. The lifting process must be conducted with care to anticipate torque damage to the base platform but can also be used to adjust non-uniform settlements of the base.

Countries that decide to build an elevated base also need other structures to keep vehicles dry and safe as giving this function to the elevated base itself would be far too expensive. In these cases combined base structures are found.

At most of the present research bases built as a platform structure the container units used are combined and interlinked. Further a structure that consists of unit modules is possible. The modules can be replaced and/or switched in line fairly easily to establish a different use of the base.

Examples of elevated bases:

- Kohnen Station (Germany)
- Halley 5 (U.K.)
- Sanae 4 (South Africa)
- New Scott-Amundsen-Base (USA)

A brief summary of advantages and disadvantages for elevated bases is given in the table below:

FIGURE 22: Kohnen Station *(photograph: J. Kipfstuhl)*

TABLE 2: advantages and disadvantages for elevated bases

Advantages	Disadvantages
- Fast transport, assembly and disassembly due to use of standard container units	- Non-uniform settlement due to high loads on the foundation
- Full recovery (except for the posts) and recycling of the base upon abandonment is possible	- Significant wind scoop under and sastrugi next to the base due to snow drift
- Outside hull of the base is easily accessible for base maintenance	- High manpower expenditure when lifting the base
- Solar energy collectors can be used on the roof of the base	- Vibrations and sounds due to wind resonance
- Differential movements in the shelf ice can be adjusted	- Other structures necessary for vehicles e.g.
- No snow accumulation under the base when founded on rock	- Base posts not recoverable after disassembly
- View of daylight and surroundings	- Low flexibility for adding new modules to the base

Bases on the surface

There are several different structures that can be erected directly on the surface. In this case temporary and permanent bases structures have to be distinguished. Temporary bases are used for expedition purposes, construction camps and/or accommodation of summer guests staying during the Antarctic summer season. Permanent structures are used for research bases when a foundation on the surface is possible.

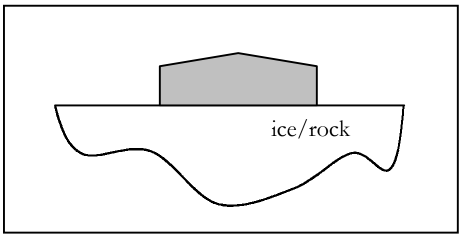


FIGURE 23: bases on the surface
(Saltner & Keij)

Permanent structures

2% of the Antarctic continent is never, or during the Antarctic winter only, covered with snow. Most of these locations are found on the Antarctic Peninsula. In this region it is possible to found bases directly on the rock surface. This results in simple building techniques and the bases look more or less like normal buildings. Bases close to the coast may suffer from strong winds that throw up rocks and from corrosion due to seawater. When the rocky location is covered with snow during the winter season snowdrift also occurs which accumulates easily at the base of the structure. Therefore most of the bases are elevated slightly and this enables snowdrift to pass the structure.

It is not possible to construct and keep permanent bases on the snow surface. Due to snow accumulation the structure will disappear only a few years after construction and become a sub-surface structure.

Examples of bases on the surface:

- Rothera (U.K.)
- Mc Murdo (USA)
- Jubany (Argentina)
- Scott Base (New Zealand)

FIGURE 24: McMurdo *(photograph: NSF)*

A brief summary of advantages and disadvantages for bases erected on the surface is given in the table below:

TABLE 3: advantages and disadvantages for bases on the surface

Advantages	Disadvantages
- Fast transport, assembly and disassembly possible due to use of standard container units	- Levelling of the construction site required
- Full recovery at abandonment - View of daylight and surroundings - Flexible container placement - Base easily accessible for maintenance and repairs due to on-surface erection	- Special solutions required concerning seawater - Re-assembly of summer-only bases every year
- Use of solar power possible - Low settlements expected	- Vibrations due to on-surface erection - Snow accumulation

Temporary structures

Several forms of temporary shelter exist. Most of them can be used everywhere on Antarctica. Temporary shelters are structures erected for short-term use such as domestic expeditions only e.g. for one summer season. Usually they are mounted or placed directly on the smoothed snow surface, less often on small hills made by snow dozers. Only foundations on the surface are applied with low surface loads so that settlement does not have to be taken into consideration.

To ensure proper insulation and to prevent loss of heat at the surface level, plywood combined with styrofoam is used. With temporary shelters a proper anchorage against lifting-up due to wind must be guaranteed, especially because many temporary shelters are relatively light e.g. tents. In such cases blocks of ice can support the tent but the structural integrity is marred.

Some time ago, moveable structures were applied for summer bases only but nowadays they are also used as permanent facilities at permanent manned bases. Size and weight of the

FIGURE 25: Scott tent *(photograph: J. Kipfstuhl)*

units (huts, containers) influence the possibility of removal of these units without any damage, from the snow and to reinstallation at another location close to the original location after a certain time period (mostly one year).

The igloo is the most well known invention of the Inuit. The term 'igloo' refers to any kind of dwelling and can be used as temporary shelter only. An experienced worker can build an igloo in about 20 minutes. Nowadays the use of electric equipment such as power saws etc. facilitates quick construction of igloos. Rectangular blocks are cut and placed around an excavated circle in a spiral that diminishes in diameter as the structure rises, finally forming a dome of maximum three metres wide. The joints are sealed with powdered snow. Without any maintenance the structure will remain in place for only a couple of months.

Bases at the surface

Cavities

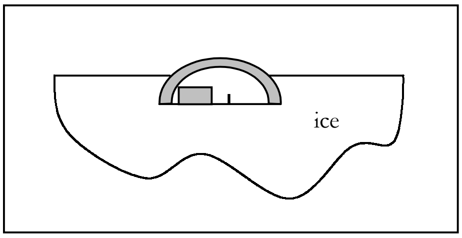


FIGURE 26: bases at the surface
(Saltner & Keij)

'Bases at the surface' refer to a type of structure with the main base under the snow surface and the roof at the surface. Within this category several different structures are possible. The most basic example is that of an unstiffed/unbraced/unlined cavity. The time-dependant stability of unstiffed cavities in snow and ice is known from inspection tunnels in glaciers. But also cavities with large span (about 10 to 20 m) do not collapse when they are dug to an adequate depth (or the covering snow layer is sufficient). All cavities however do close slowly due to a gradient in pressure through vicious creep of the snow and/or the ice. That is why the temperature of snow forms the largest influence on the speed of closure. Through static favourable digging of the cavity (arches, circular cavities, dome shape) only few improvements can be made as far as the time-dependant viscous creep is concerned. If such tunnels and cavities are used for long-term base and work purposes a well-designed removal of warmth and ventilation with cold air is recommended and necessary.

Cut-and-cover trenches

A more permanent structure can be constructed when applying cut-and-cover trenches. The trench is dug with snow excavators and covered with a roof. For this structure all desirable measures can be cut in the snow ground.

This construction idea has probably been used since people have wanted to stay for longer periods in snow regions. One of the largest appliances of this type of structure on Antarctica was the American Byrd Base built in 1960/61. The complete base consisted of trenches of 8 m in width and 3.65 m in height covered with semicircular waved steel plates. Parts of the American Amundsen-Scott-Base at the South Pole is also built following the cut and cover method.

Because the roof, at or above the snow surface, will suffer from wind and snowdrift around the structure this type of structure is not used any more for permanent structures as research bases that have to last more than 10 years. It is still used for temporary research camps, as at e.g. Kohnen Station.

Example of a base at the surface:

- Amundsen-Scott-Base (USA)

FIGURE 27: Scott-Amundsen-Base
(photograph: NSF)

Sliding cover

Smooth surfaces mostly remain free of snow when they slightly stick out of the snow surface. This knowledge is used for a structure with a sliding cover as a roof. For this structure a trench is dug in the snow ground. Elevated roof structures with a smooth, flat roof surface are kept sticked out of the snow surface by periodically lifting. Under the roof the space in the snow cavity can be used for storage purposes and/or the placement of containers or other installations.

FIGURE 28: vehicle hall at Neumayer Station
(photograph: J. Kipfstuhl)

The structure consists of flexible transoms and posts and roof cover plates with snow proof dilatation joints. The foundations of the posts have to be constructed in a way that lifting is allowed or they are lifted together with the posts.

The walls of the cavity remain made up of snow, also the ground floor, which has to be filled up when lifting the roof. This structure allows the construction of large covered facilities as the top loads due to snow remain low.

This type of structure had been developed when preliminary designs were made for NM. Due to lack of experience with this kind of base it was first used for the vehicle hall at NM. At NM the sliding cover is located in relation to the wind so that the longitudinal axis of the vehicle hall is perpendicular to the wind direction. This minimises the snow accumulation on the roof due to snowdrift.

TABLE 4: advantages and disadvantages for bases at the surface

Advantages	Disadvantages
- No vibrations and noise due to submerged position	- (Annual) lifting of the entire structure is necessary due to snow accumulation on top of the roof
- High flexibility in use	- High manpower expenditure when lifting up the base
- Creep of ice walls inside can easily be adjusted	- No daylight (when used as permanent base)

Advantages	Disadvantages
- Small settlements due to small top loads	- Cooling of the hall is necessary due to high temperatures and sun radiation during summer season
- Accessible for maintenance and repair	- Anchors needed due to wind suction forces
- Any form possible	

Bases under the surface

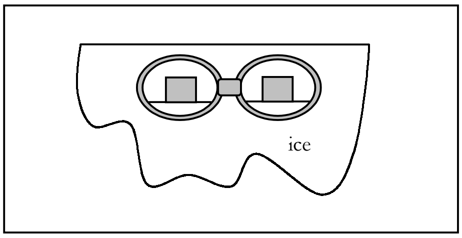


FIGURE 29: bases under the surface *(Saltner & Keii)*

Bases under the surface are normally built on the snow surface. Due to snow accumulation they 'disappear' within the first couple of years. Sub-surface structures do not suffer from high wind speed and vibrations. They are dimensioned to withstand the progressive accumulation of snow and their disappearance is planned. This makes this type of structure suitable for stations founded on the Antarctic ice shelves, where large quantities of snow accumulation are measured. This base concept is found at many locations on Antarctica and was applied quite early by the British. Most of the sub-surface bases have a circular profile that enables arching effects in the surrounding snow and/or ice when the base has disappeared. The bases consist of (circular) tubes that take over the snow and ice loads. Within the tubes the working and living quarters are placed, normally container-sized units are used.

The accumulation of snow as well as the movement of the ice shelves influence the lifetime of sub-surface research bases. The increasing loads and tensions result in deformations of the tubes, which reach a maximum depending on the material used, the quantity of snow accumulation and/or the required space in the tubes. Many different final design experiments have led to different solutions that (most of the time) improved the former design of sub-surface bases. Nevertheless this type of structure is not used often any more for the construction of a new research base. The general problem is, besides the limited lifetime, the high costs of removal. The British built Halley 1 to 4 as sub-surface bases but chose an elevated structure for Halley 5. Also the South African base Sanae 4 is constructed as an elevated structure on a rock after having worked and lived in 3 sub-surface bases many years.

FIGURE 30: Halley 4 *(photograph: BAS)*

Practical experience shows that tubes made of steel are the best solution for sub-surface bases. The British chose a wooden tube for Halley 4, which collapsed earlier than expected.

Examples of sub-surface structures:

- GvN (abandoned) and NM (Germany)
- Sanae 1-3 (abandoned) (South Africa)
- Halley 1-4 (abandoned) (U.K.)

FIGURE 31: Neumayer Station *(photograph: AWI)*

TABLE 5: advantages and disadvantages for sub-surface bases

Advantages	Disadvantages
- No vibrations and/or noise due to wind	- No access to daylight
- No lifting of base is necessary	- No extension of the base is possible
- Accumulation of snow in the vicinity of the base is not seen to be undesirable due to the sub-surface position of the base	- Outside hull deforms heavily during lifetime
	- Snow loads on the structure rise in time
	- Access must be adjusted annually
	- Removal and recycling is expensive, the outer hull will remain inside the ice

Disassembly and recycling

The Madrid Protocol as annex to the Antarctic Treaty states that all parts of structures built on Antarctica that are not used any more have to be dissembled and taken back to the home country. The disassembly of a research base is a large scale and expensive operation. Recycling of materials used in the former base are desirable and executed if it does not lead to excessively high costs. The disassembly of the former German summer base Filchner can be seen as an example that materials can indeed be used again as parts of the base were recycled and now used as Kohnen Station.

Cost analysis of different base concepts

Elevated bases and sub-surface bases are both applied successfully on Antarctica. Advantages and disadvantages of the concepts can be summarized as shown below:

TABLE 6: cost analysis between elevated and sub-surface bases *(source: Enß [12])*

	Elevated	Sub-surface
Investment costs	- higher	+ lower
Operation costs	+ lower	- higher
Lifetime	+ higher	- lower
Disassembly	+ easier	-more difficult
Wind- and weather proof protection	- less	+ more
Energy supply	- higher	+ less
Lighting supply	+ less	- higher
Access	- easier	+ more difficult
Snowdrift	- more	- less
Safety	= equal	= equal
Psychological welfare	+ better	- worse

Besides the comparison between elevated and sub-surface structures an economic study has been performed regarding all discussed possible structures. The results are shown in table 7. The permanent shelter founded on the surface is a low cost, flexible solution as the table shows. However in this study no cost effects have been included regarding the annual excavation of such a base. The sub-surface base has low annual maintenance costs due to the absence of wind loads. But, it has to be considered that the compared types of structures cannot be applied at every location on Antarctica, which makes a direct comparison difficult.

The table of the economic study will be presented on the following page:

TABLE 7: cost analysis of different base concepts *(source: Schmidt [33])*

		Base over the surface	Igloo	Base on the surface	Sliding cover	Base under the surface
Costs						
Investment (material)	%	115	0	80	110	100
Erection of a garage	%	100	100	100	40	60
Annual (general)	%/a	105	-	150	130	100
Demolishing	%	96	0	50	92	100
Removal	%	80	0	60	100	45
Technical parameters						
Energy	kW/m^2	60	0.5	90	90	80
Solar panels, horizontal	%	80	-	100	0	0
Solar panels, vertical	%	100	-	100	100	0
Wind	%	100	70	80	0	0
Weight	$tons/m^3$	0.3	0.07	0.25	0.3	0.3
Maintenance	days	75	10	250	180	55
General parameters						
Lifetime	years	17	0-0.5	20	30	15
Flexibility	%	60	-	100	90	10
Re-movability	%	80	-	100	90	0
Station/Garage	S/G	100/0	-	100/0	100/30	100/10

Chapter 4

The Neumayer Station

History of the German polar research bases

1981 – 1992: Georg von Neumayer Station (GvN)

German polar research efforts began with Germany signing the Antarctic Treaty on March 3rd 1981. Germany acquired a consultative state, which meant that the new member signed up to conduct research on Antarctica.

Conducting research on the Antarctic continent implied the need of a base for scientific research as well as a starting point for expeditions. From 1979 on possible proper locations were explored and preliminary designs were made. Two possible locations were found which were on the Ronne-/Filchner Ice Shelf and on the Ekström Ice Shelf.

The base was erected during the two polar summer seasons 1980/1981 and 1981/1982 on the Ekström Ice Shelf. Georg von Neumayer Station (GvN), as the base was called was constructed of jointed containers placed inside a hull, made of steel Armco Thyssen tubes of 7 m in diameter. All working and living quarters were located in the containers, such as laboratories, kitchen, offices and the private rooms of the over-winterers etc. The steel tubes take over the loads of the surrounding ice and snow. Experiences with the design, construction, operation and maintenance of sub-surface research bases, such as the British Halley Station and the South African Sanae, could be shared and was used in the design of GvN.

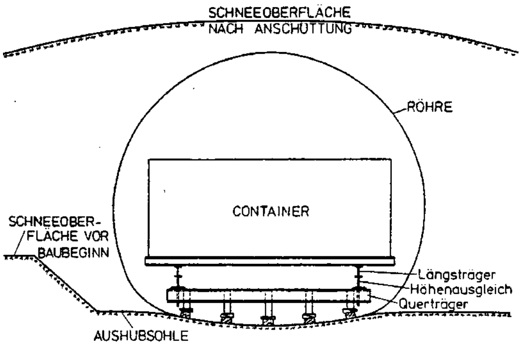


FIGURE 32: cross section GvN *(source: Polarmar)*

The cross-section shows that the containers were placed on a platform within the tubes. The loads are guided to the platform construction. Spindles in the platform construction take up local non-uniform settlements of the tubes. The base was built on the ground level and covered with snow after completion but diminished already a few years after that under the snow surface because of snow accumulation. The lifetime of sub-surface bases in the shelf ices of Antarctica is limited due to deformation in the surrounding snow and the heavy snow accumulation. After ten years of operation the station reached this limit and a new base was erected: Neumayer Station [10, 8, A].

1992 – present: Neumayer Station (NM)

Due to the limited lifetime of sub-surface research bases located in the Antarctic ice shelves new plans concerning a new base had to be made. To maintain the scientific research programmes in this area a new location had to be found in the direct neighbourhood of GvN. The successor base, Neumayer Station (NM), was built at a distance of 8 km from the old base at 79°39'S and 08°15'W. The ridge of this ice shelf, the Atka Iceport, is located at about ten kilometres distance from the base and serves as landing place for supply vessels. At the location of NM the Ekström Ice Shelf is about 200 m thick and moves towards the Southern Ocean at a rate of around 150 m/year. The differential movement of the ice shelf is an important design parameter as it influences the lifetime of a base as it flows with/in the shelf ice towards the ocean. At GvN the movement was determined perpendicular to the main direction of the base with $4*10^{-3}$ m/(m and year). More attention was paid at this feature when the location for NM was chosen. Here the differential movement was measured with $0.5*10^{-3}$ m/(m and year) and the base was erected parallel to the main movement direction.

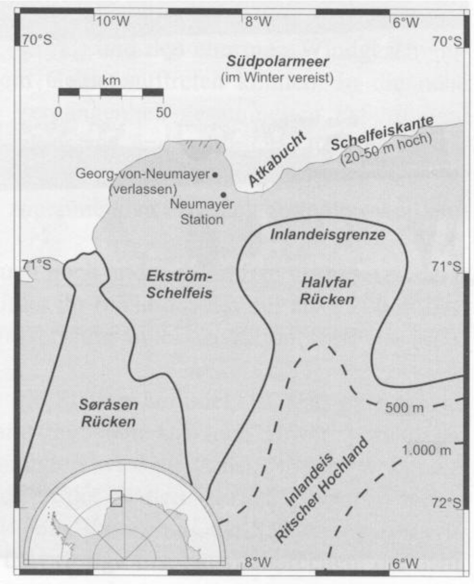


FIGURE 33: location of GvN and NM
(source: C. Tolkmit)

In 1989 the first new design ideas were examined. Besides the sub-surface tubular structures other base concepts were taken into account. The new British Halley Station was constructed as a platform above the surface, comparable to offshore platforms. Also the AWI had had the first experiences with a base above the surface. The summer station Filchner was erected as a platform base as well.

Still, the final decision led to a design for a new sub-surface base. Lack of knowledge and experience regarding the new techniques as well as budget was responsible for this conclusion.

A great deal could be learned from GvN and the experience gained during construction, operation and maintenance helped to improve the design for NM. Requirements for the successor base could be made, especially regarding more space for research operations as well as general functions as the kitchen and the hospital. These requirements lead to 125% larger internal surface area of the base compared with GvN. Other requirements concerned the maintenance and repairs of the vehicles, which led to the design of a weatherproof garage.

Neumayer Station on the Ekström Shelf Ice was designed to support 9 - 10 persons during the winter, including scientists and support personnel, who are to live in buildings within a tubular sub-surface structure. The summer population has reached a total of 65 persons, including scientists and personnel for construction and station support and maintenance.

The station total area amounts to 2001 m^2. 765 m^2 of the total station area are heated/air-conditioned and 154 m^2 used as accommodation [11, 13, A].

Structure and layout of Neumayer Station

The experiences gained during design, construction, operation and maintenance of GvN formed the basis for the plans for NM. After having considered a number of variations in base design, as platform or other sub-surface structures, the AWI decided for an improved sub-surface structure, similar to GvN.

Neumayer Station is built up of several different structural elements:

- Steel tubes and shafts
- Platform structure
- Containers
- Staircases
- Tunnels
- Sewage mains and pit
- Vehicle hall
- Wind generator
- Northern and eastern ramp
- Partition walls
- Research observations and other outside facilities

The figure below shows the base layout.

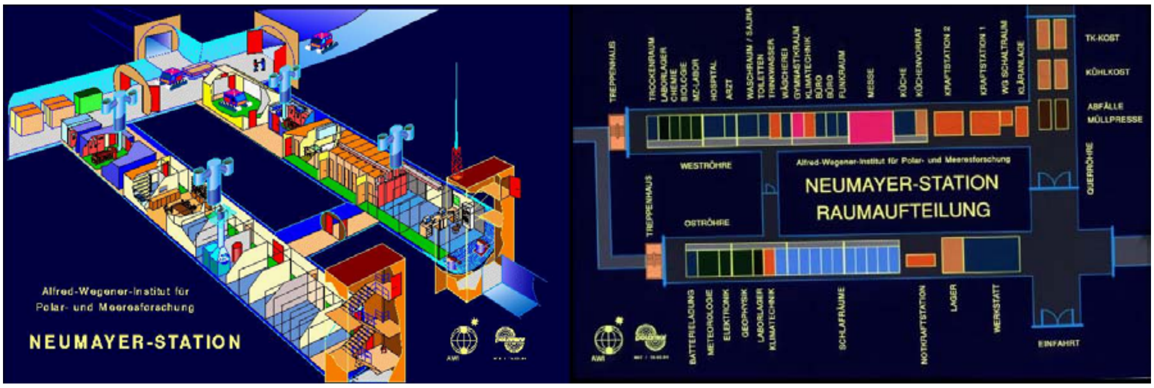


FIGURE 34: Neumayer Station, layout *(source: Polarmar)*

Steel tubes and shafts

The base consists of three steel tubes. The tubes had a diameter of 8.40 m at the time of construction and are 7 mm thick. In contrary to the slightly ellipse shaped profile with a flat bottom edge used at former sub-surface bases as Sanae, Halley 3 and GvN, a circular profile was chosen. This profile is designed to withstand the elevation of the bottom section of the tube better and longer than it was observed at GvN. More arching effect and more clear space under the containers respond better to the expected deformations. With a tube diameter of 8.40 m and a plate thickness of 7 mm a larger and thicker profile was chosen compared to GvN, which guarantees more space for deformations.

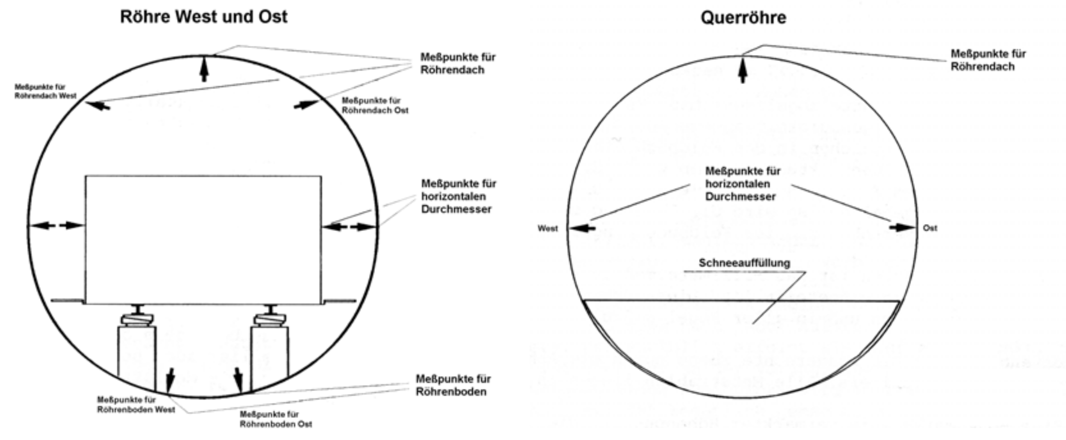


FIGURE 35: cross section of the west-/east tube and the crosswise tube *(source: Polarmar)*

The steel plates used for the tube profile are not galvanized at the bottom edge. This keeps welding simple but this was also done due to environmental requirements. In the first case the whole profile was designed un-galvanized but reflection at the inside of the tube sections would have been too low and a great deal more artificial light would have been necessary.

Two steel tubes are arranged in parallel and together with a smaller connecting tube the shape is reminiscent of a capital letter ‘H’. At one end of the tubes the base can be accessed via two staircases and at the other end the third tube connects the H-shaped structure as a cross-wise tube. For vehicles used at and around the base as well as sledges and spare parts a garage was constructed. Two ramps are constructed to exit the base with vehicles.

The base was erected on a North-South axis to keep the snowdrift as low as possible and to spread out future extensions and compressions in the surrounding snow favourably over the structure. The tubes are calculated to withstand the loads from snow top loads and differential movements in the ice shelf for up to 15 years. The envisioned end of lifetime of the tubes will thus be reached in 2007.

Nine or at most ten people live and work at Neumayer Station during the Antarctic winter: a medical doctor who also acts as the head of the station, two meteorologists, two geophysicists, an engineer, an electrician, a radio operator/electronics engineer and a cook. Each team over-wintering at the base stays there for 14 to 15 months. For nine months of that time their only link to the outside world is by radio or other telecommunications.

The partitioning of the different rooms inside NM is based on operational and technical grounds.

Accommodation and most of the other base facilities consist of 20-ft air-conditioned and isolated containers, which are placed in the West and East tube and founded on a steel grid-like platform structure. The containers in each tube are grouped together, using a connected hallway. Dilatation joints, allowing small differential settlements of each container group separate the containers. All working and living quarters are placed within these container groups.

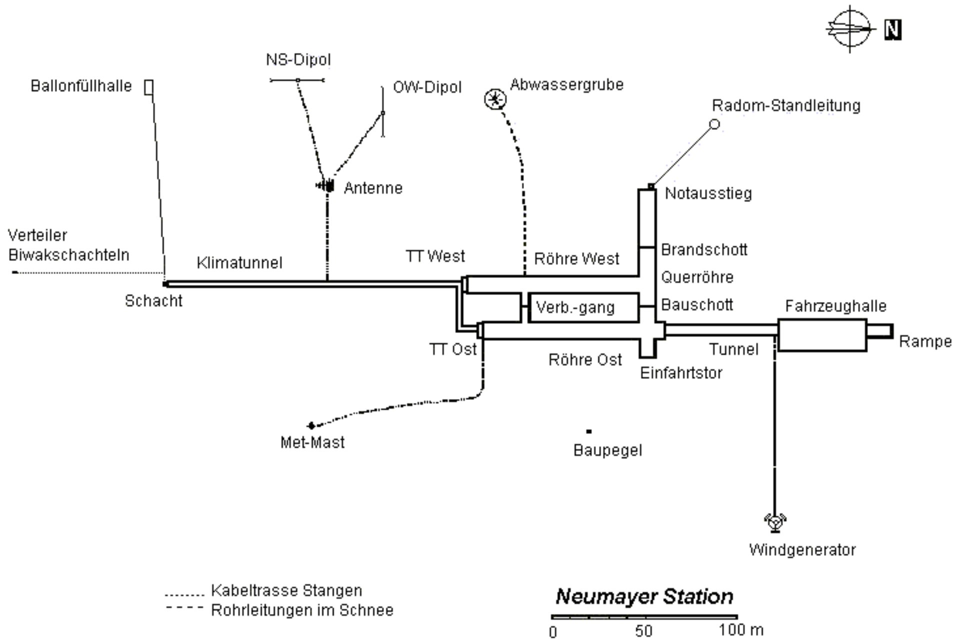


FIGURE 36: plan view Neumayer Station and outside facilities *(source: Polarmar, modified by Saltner & Keij)*

The cost advantages due to prefabrication and facilities of transport override the disadvantages in installation and fittings. Because of the stable structure of the containers for transport and taking up the inside loads they are also appropriate to take over pretensions due to possible overloading of the platform structure. Thus the containers are grouped together.

West tube

The West tube contains laboratories, sanitary facilities, offices, lounge, kitchen and power supply units.

Most of the facilities are placed in one 20-ft container. To obtain a general view of the partitioning a summary of the 25 container units placed in the West tube is given:

■ Kitchen	2 containers	■ Toilets	1 container
■ Food Store	1 container	■ Showers and sauna	2 containers
■ Lounge and mess room	4 containers	■ Surgery	1 container
■ Communication room	1 container	■ Hospital	2 containers
■ Offices	2 containers	■ Multifunctional laboratory	1 container
■ H.V.A.	1 container	■ Biology laboratory	1 container
■ Gym	1 container	■ Chemistry laboratory	1 container
■ Laundry	1 container	■ Laboratory storage	1 container

■ Snowmelter	1 container	■ Dry clothes	1 container

East tube

The East tube contains the private quarters of the over-wintering team as well as laboratories and general facilities. A workshop and workshop storage is also located in the East tube, but are not part of the air-conditioned container group.

Again, a brief summary of all units is given:

■ Sleeping rooms (1 person during winter, 2 during summer)	11 x 1 container
■ H.V.A.	1 container
■ Laboratory storage	1 container
■ Geophysics laboratory	2 containers
■ Laboratory storage	1 container
■ Meteorology laboratory	2 containers
■ Batteries	1 container

Cross-wise tube

The cross-wise tube at the end of the East and West tube consists of three sections. These secyions are separated by firewalls. The most westerly section of the tube is used as storage for fuel tanks. About 132000 litres of Arctic diesel can be stored here, which will last throughout the whole winter with a consumption of around 500 litres/day.

The middle section is used as storage for several refrigerated and garbage containers and the garbage press. On the East side of the cross-wise tube there is one of the two ramps that connect the outside with the base. The remaining space in front of the ramp opening is used for different storage purposes and for vehicles.

Platform structure

The term 'platform structure' refers, as far as sub-surface structures are concerned, to those structures that create a horizontal bearing surface that take over the loads of the containers and/or varying loads to the bottom sections of the tube. The bottom sections of the tubes can deform heavily in time and the platform structure has to compensate these deformations. Many proper solutions are possible; at Neumayer Station the following has been chosen: (see figure 37)

FIGURE 37: platform structure at Neumayer Station
(photograph: M. Takata)

The platform structure consists of beam frames that are placed on cylinders made of waved steel that are filled with sand. Pressure and loads are set on the cylinders and spread over the sand. The beam frame can be adjusted in height so that non-uniform deformations can be compensated.

Staircases

The bottom parts of the staircases are exposed to the same snow pressure as the bottom section of the tubes but do not have the same static favourable shell form. That is why the bottom parts of the staircases show heavy deformations at the end of the lifetime of the base. Although broken parts of the staircase walls have been noticed at GvN a larger dimension of the afflicted parts in the first case is not necessary. At NM the staircases are designed in a way that the walls made of plywood can be removed as soon as the snow loads and/or the deformations become too large. The snow walls can easily be controlled and cut off when they grow into the staircase.

Tunnels

At Neumayer Station two tunnels have been dug: a climate tunnel and a tunnel between the northern and eastern ramp that also connects the vehicle hall with the base. The climate tunnel was dug and covered with wood in February 1992 after the construction of the base was completed. The vehicle tunnel was constructed one year later.

Both tunnels are temporary constructions and their lifetime is much shorter than that of the base itself. In both tunnels the breaking of the wooden roof had been expected and indeed has already taken place. Enough snow covering guarantees an arching effect and the broken wooden beams can be removed. In the extremely wide vehicle tunnel the snow roof and walls have deformed quite heavily after ten years of use but the snow can easily be cut out to maintain the necessary profile.

Climate tunnel

Due to relatively high temperatures around 0°C or even higher during the summer season the tubes inside the snow warm up easily. Warm air in the non-isolated parts of the base, especially under the platform construction under the container groups causes melting of the surrounding snow. Melted water penetrates into the tube and most of the time refreezes on the inside. This is not viewed as a danger but can disturb daily base activities. For this reason a so-called climate tunnel is dug. It is a tunnel under the snow surface, about 155 m long and at present between 1.20 and 2 m high and 2 m wide. It connects the East and the West tube as shown in figure 36. Through the pores of the snow above and around the tunnel air flows from the outside to the inside of the tunnel and reaches a temperature of about -15°C. This cold air is pumped via the tunnel into the station to cool down the warmed-up air.

Garage

A 65 m and 5.50 m long tunnel connects the crosswise tube with the garage (vehicle hall). The garage is used to store the snow vehicles as well as sledges and small fuel tanks. The structure chosen for the garage is one of the concepts, which were taken into account for the whole base structure. The idea was based

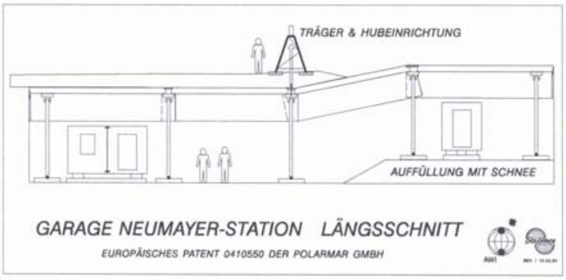


FIGURE 38: section of the garage at NM *(source: Polarmar)*

on a completely new concept and by using it for the vehicle hall the first experience with this type of structure could be gained.

The new concept implies a garage that lies in the snow with the roof at surface level. The garage is 46 m long and 16 m wide. Depending on the annual snow accumulation the roof has to be jacked up which is possible because of the flexible structure. The garage is connected with the outside also by ramp.

Research observatories and other outside facilities

Meteorology

The meteorology observatory is designed as a radiation and climate monitoring station. Measurements of radiation are carried out on a large scale as part of a global observation network to detect long-term changes in the Earth's radiation budget and their impacts on climate. Every three hours weather data is transmitted to other Antarctic stations and into the global meteorological data network (GTS), where it is used for weather forecasting, etc. Since 1992, vertical ozone profiles are included in the regular observations.

Geophysical observatory

The geophysical observatory detects earthquakes around the world and continuously registers the temporal fluctuations in the Earth's magnetic field and the tidal movements of the ice-shelf. In addition to these observations, detailed investigations of local earthquakes are carried out with the help of remote stations up to 80 km away.

Air chemistry

The air chemistry observatory measures atmospheric concentrations of trace gases, such as ozone, and minute particles of dust in the air. The isolated location makes it a valuable reference site for measuring under conditions of extreme air purity. The research program is flexibly designed so that new analytical methods and current problems in air chemistry can be swiftly integrated. In addition, the proximity to the ice margin permits the detection of substances released from the ocean to the atmosphere.

FIGURE 39: air chemistry observatory at Neumayer Station *(photograph: AWI)*

Summer and winter storage

For storage purposes two different bases are set up. The winter storage is located close to the Atka Iceport, at the shelf ice ridge. Sledges, summer huts, containers and other things not used at the base during the winter are stored here. The summer storage is located in the direct neighbourhood to NM. Freight from the supply vessel, food containers etc. is stored here.

Summer huts

FIGURE 40: movable summer hut *(photograph: J. Kipfstuhl*

During the Antarctic summer season up to 40 people live and work at Neumayer Station. The new over-wintering team, together with logistic personnel and scientists join the old team at the base to conduct maintenance and research programmes. As the base is designed to accommodate 22 persons only additional housing facilities are necessary. There are different kinds of summer huts used for this type of accommodation. Excluding tents they are all connected with electricity and heating.

Supply

The station's power supply comes from diesel generators, the waste heat from which is used for the heating system and for melting snow. There are two systems installed of 100 kW each that supply power to the base in turn. In case of emergency a 50 kW emergency power unit takes over the supply. A 20 kW wind generator, which is used at Neumayer Station, is an innovative and eco-friendly source of energy. When the station was designed, the requirements laid down in the new Protocol on Environmental Protection to the Antarctic Treaty were adhered to e.g. through the use of environmentally neutral construction materials, catalytic converters for the diesel generators and oil collecting equipment for the oil tanks. Waste is routinely collected and shipped back to Germany once a year.

The heating of the container groups inside the tubes is solely achieved with warm air. Rooms with a high heat emission due to installed equipment and rooms open to high sun radiation (vehicle hall) are cooled with air.

Fresh water needed for the base operation is gained in a 10 kW snowmelt installation. 4000 litres of snow can be dug into a vertical shaft that is connected to the snowmelt generator. The over-wintering team's water consumption is less than 2000 litres/day so that a refill once every day is sufficient. Above that two storage tanks of 2000 litres each are also installed.

Wastewater is treated in a biological treatment plant. Cleared and filtered wastewater is transported to a wastewater dump at a distance of 90 m from the base. Water contaminated with laboratory or other waste is collected and transported back to Germany.

At present there are several possibilities to communicate with the outside world. Radio communication is used to contact other Antarctic bases and ships but also telecommunication - telex, telephone, fax and Internet - is possible.

At a polar research base fire is the most dangerous accident that can occur. Damages increase rapidly because of lack of water to extinguish the fire and the fact that not enough persons are present at the base to fight the fire. Because of that attention is paid carefully to active and passive fire fighting.

At NM fire measures are taken on two fronts, by defensive (firewalls, fire sensors, fire fighting equipment, slow- or non-flammable materials, emergency exits, emergency shelter) and offensive measurer.

Logistic support

Neumayer Station is mainly supported via the research and supply vessel Polarstern, owned by the AWI. Due to ice conditions on sea and at the Atka Iceport, which is at about eight-kilometre distance to the base, Neumayer receives two ship visits per season, in December/January and in February/March.

FIGURE 41: research and supply vessel FS Polarstern at the shelf ice ridge at the Atka Ice Port *(photograph: AWI)*

During the summer season two polar aircraft are used for scientific research as well as for intra-continental cargo and transportation purposes. For these aircraft (Dornier 228-101), which normally arrive during the first weeks of December, a 60 m wide and 1000 m long airstrip has to be prepared at about 600 m distance from the base.

For field parties a range of vehicles can be used. At Neumayer eight Kässbohrer Pistenbullies suitable for traverse and field operations are available. They can be equipped with cargo sledges and/or mobile field stations. Ten small snowmobiles can be used for research and recreation activities in the neighbourhood of the base. Logistic maintenance activities can be carried out with two chieftains (cranes) and one snow excavator.

Construction of Neumayer Station

In Bremerhaven, Germany several sections of the base were pre-assembled to ensure a flawless and swift construction and easy system operation. The pre-mounting of all technical settings were done as far as possible to keep the time of mounting on-site on Antarctica as short as possible. Besides the material stock tests of all aggregates all diesel generators, air conditioning and the (waste) water treatment plant were tested.

Neumayer Station had to be constructed within one Antarctic summer season only. If weather and ice conditions are favourable about 80 days of construction work could have been expected. On average, up to a third of the time no construction is possible on any weather dependent works. For the construction of Neumayer Station 63 days were scheduled for transport and mounting. The limit conditions were defined as followed:

- Wind speed > 15 m/s or
- Air temperature < - 25°C or
- Sighting distance < 12 m

FIGURE 42: Georg von Neumayer Station (ca. 1983) *(photograph: C. Drücker)*

The construction team consisted of 49 workers and three persons as supervisory staff. They were accommodated in a camp close to GvN at a distance of about 8 km to the construction site.

The construction works started with digging trenches of 1.50 m in depths as foundation for the tubes followed directly by the mounting of the circular tube profiles. The team started with the West tube because it contains mainly technical installations that had to be set up and run before the station would have been completed.

Not only bad weather seamed to hinder the construction works. During days of sunshine the mounted tube sections heated up and melted into the snow foundation. Because of the stiffness and the size of the construction corrections were very difficult to adjust. At dilatation joints where partition walls are placed compensation in height was possible.

As soon as a complete tube was mounted the platform structure that has to carry the containers were constructed. After the placing of all heavy inside installations the tubes were closed at both ends. At the south end of West and East tube the staircases were erected. The complete base was covered with approximately 50 cm of snow, wherefore more than 60000 m^3 of snow had to be moved.

After having completed the outer structure of the base as well as the inside containers the garage was built and the team began to install technical and communication equipment. Also the outside research facilities as the geophysical and air chemistry observatories and the meteorological installations were set up.

The construction of the new Neumayer Station was finished on March 12th 1992 and it was immediately transferred to operation by the AWI. Due to extreme bad weather conditions at the end of the construction period 96% of the construction works were finished. The missing works

FIGURE 43: construction of NM 1991/1992 *(photograph: AWI)*

concerned mainly the garage and the connecting tunnel with the base [14].

The construction of Neumayer Station comprised several phases:

Phase 1

Building starts on flat terrain that has been selected.

Phase 2

A trench is made to serve as a foundation for the station. The trench is 1.50 m deep.

Phase 3

The steel tubes are built up, from corrugated iron plates.

Phase 4

When steel tubes are finished the steel cylinders with the steel beam elements are put in place. The cylinders are levelled to ensure proper container placement.

Phase 5

The containers are installed into the steel tubes by crane. When all containers are inside the tube the closing wall can be added, and the tube is sealed.

Phase 6

Between the containers general system connections are made for heating, communications and water handling. The access between containers is made with walkways.

A plastic cover around the tube, sheltering it from solar radiation to prevent warming is installed.

Phase 7

The tube is covered with snow to decrease the exposure to the elements in its first winter.

When the station was finished on March 12th 1992 it was immediately transferred to the operation of AWI.

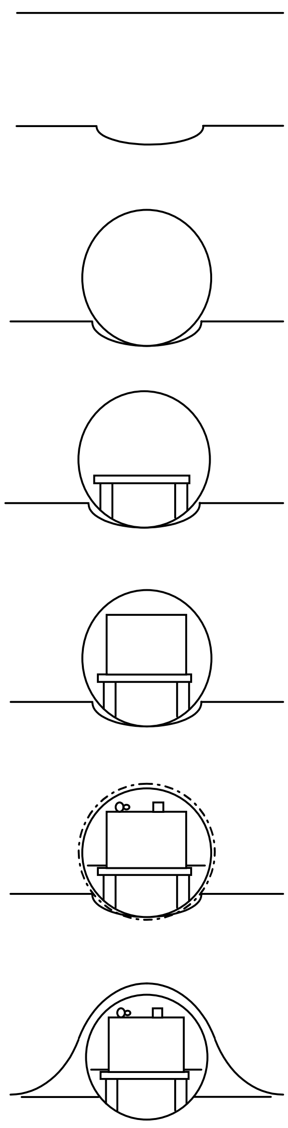


FIGURE 44: construction phases of Neumayer Station *(Saltner & Keij)*

PART 2

Thesis Study

Chapter 5

Problem Statement

General

Antarctica is subject to many research activities. Research has mainly been conducted since 1957, the International Geophysical Year (IGY), when research activities were booming and co-operation between countries began.

The Alfred-Wegener-Institute, Foundation for Polar and Marine Research (AWI) conducts research in the Arctic, the Antarctic and at temperate latitudes to improve the understanding of ocean-ice-atmosphere interactions, the Arctic and Antarctic animal and plant life and the evolution of the polar continents and the seas. Global Climate Change is also a central focus of research efforts as the polar regions play a major role within the Earth's climate system. Besides the research activities, the AWI co-ordinates polar research in Germany and provides the essential logistical backup for polar expeditions.

FIGURE 45: 3D-image of Neumayer Station (*source: Polarmar)*

Given this research effort scientists and additional personnel, who live and work on Antarctica need, depending on the kind of research conducted, temporary or permanent places to stay. Many different types of possible structures fulfil the requirements of people to stay and survive for a certain time under such extreme conditions as are found on Antarctica. Today a wide range of research bases is found all over the Antarctic continent. The problems experienced in erecting permanent structures on Antarctica are numerous.

The AWI operates several bases. Within the scope of this project the German Neumayer Station, built in 1992 on the Ekström Ice Shelf at 79°39'S and 08°15'W is the subject of research.

The Neumayer Station is a tubular sub-surface research base, which was constructed on the snow surface and was buried in the last ten years due to an annual snow accumulation of about 70 cm/year. In January 2002 the average snow cover above the station measured 3.70 m. The base consists of three main tubes and some other on- and sub-surface facilities. The steel tubes contain all main working and living quarters. The lifetime of Neumayer Station is influenced by [14]:

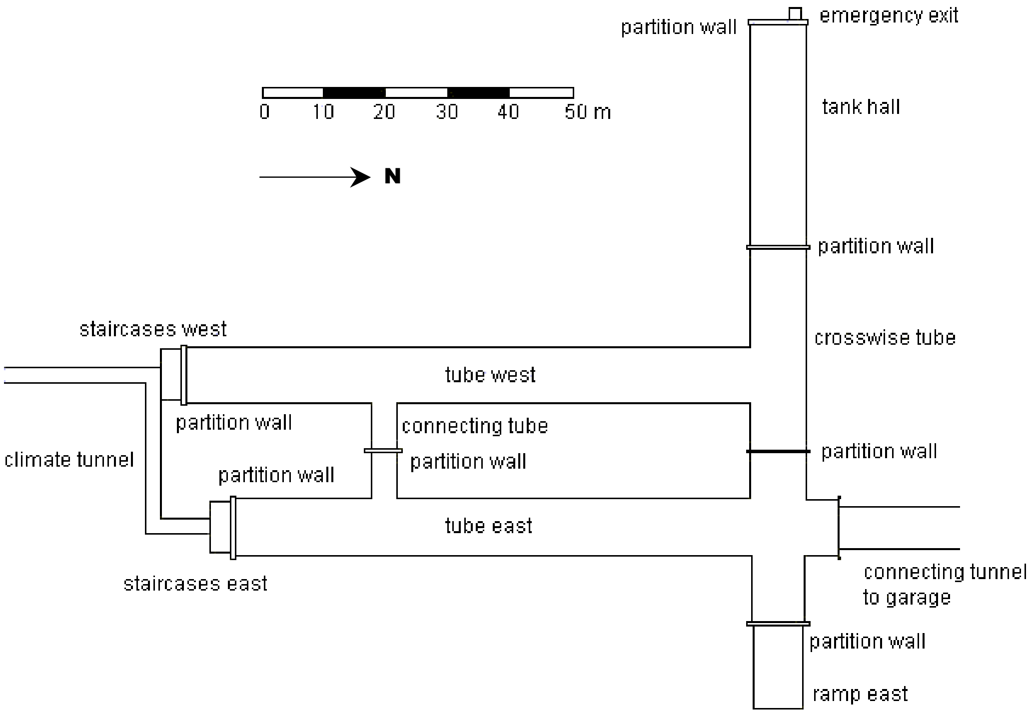


FIGURE 46: plan view Neumayer Station *(source: Polarmar, modified by Saltner & Keij)*

- Structural integrity

The structure becomes unstable, leaky and/or heavily deformed due to loads acting on the tubes so that the required safety for users can no longer be guaranteed or living conditions become unsuitable for permanent residence.

- Operation and maintenance expense

The technical operation of Neumayer Station becomes more expensive over time because of the disproportionate growth of repair, maintenance and spare-part costs. For the most part this concerns maintenance at the base’s structure and adjustment of the entries and outside facilities of the base to the changing conditions due to snow accumulation and snowdrift.

- Scientific and contract related agreements

New scientific requirements (e.g. flight logistics, storage logistics, new laboratories) as well as new treaty obligations (environmental agreements, work related agreements) can restrict the lifetime of a base because realisation of the changed needs can sometimes be obtained more economically in a new base.

- Developments in research needs and/or techniques

If scientific data can be collected automatically on-site, no conventional bases are necessary.

In principle the criteria can be reduced to the factors safety, economy and efficiency.

This thesis project focuses on the integrity of the structure. In the next section a description of the precise problem that is the subject of the research will be outlined.

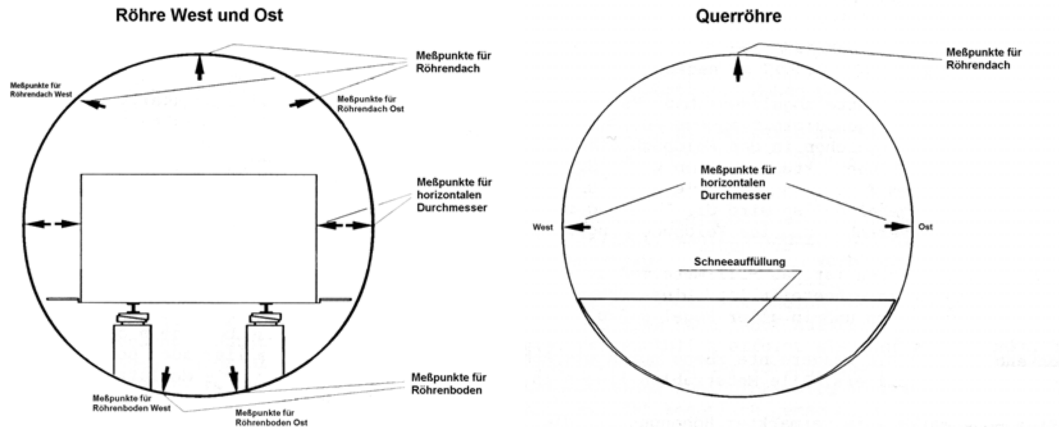


FIGURE 47: cross section of the west-/east tube *(source: Polarmar)*

Problem statement

Neumayer Station was designed for a 15-year lifetime and the base has currently (2002) been in operation for ten years. During this period the AWI has observed, among other issues regarding the use of the base, deformations of the steel tubes. Because of similar experiences gained at the former German base Georg von Neumayer, which was also a tubular sub-surface research base, the deformations were expected and have been measured since the construction of Neumayer Station was completed [1, 14].

Large deformations of the steel tubes affect the operation of the base. Since the deformations will develop in time the question arises as to when the base loses functionality due to the deformations. If working and living conditions at Neumayer Station become unsuitable the institute will have to make the decision to abandon the base.

Obtaining an accurate prediction of the time of abandonment forms an important factor within the schedules of the Logistic Department of the AWI. Ahead of the abandonment plans and preliminary designs must to be made concerning a new base concept that keeps research activities going continuously. Further disassembly of the old base must be taken into consideration. At present the deformations of the steel tubes of Neumayer Station are measured with a surveying programme established for the base. The range of measurement data shows the present state of the deformation of the deformation and its course in the past. It is observed whether the data corresponds with the estimation made during the planning of the base. Based on the measurement data and visual observation the remaining lifetime will be estimated. A (numerical) prediction model can be helpful to predict the lifetime more precisely.

The problem statement this thesis focuses on, can thus be described as:

What are the processes governing the deformations of the steel tubes?

At what point in time does Neumayer Station have to be abandoned due to deformations of the steel tubes?

What are possible (future) design changes to prolong the lifetime of the base?

Research goals

To answer the question mentioned in the problem statement two aspects are presented:

- To what extent can the steel tubes of Neumayer Station deform without hindering working activities, storage or other use of the space around the containers in the tubes? The answer to this question results in a definition of a profile of free space for different tube sections.

- At what time will the state of deformation have reached the profile of free space? A physical model will be developed to get a better understanding of the processes that lead to the deformations. This model will be extended into a prediction model that helps to estimate the deformations that have to be expected in the future. Based on the outcome of the model a prediction can be made as far as the operation period of Neumayer Station is concerned.

The deformation of the steel tubes is one issue within the problem of the integrity of the structure. Obtaining an idea of the processes that govern the deformations together with a numerical prediction can provide important information for the design of future tubular bases. The experience gained at the former base Georg von Neumayer can be supplemented with this. Other issues concerning the structural integrity as well as further influences on the lifetime mentioned above are not taken into consideration within the scope of this project. At the end of this report a wider view on the lifetime of Neumayer Station and ways to prolong the lifetime is presented.

Structure of report

To discuss the extent to which the steel tubes of Neumayer Station can deform without hindering activities, storage or other use of the space around the containers in the tubes, the general functional requirements for Antarctic (sub-surface) research bases as well as specific requirements for Neumayer Station are described. Together with the

Logistic Department of the AWI the profile of free space for various sections of Neumayer Station has been determined.

The use of Neumayer Station is affected by the deformations of the steel tubes that have occurred since the construction of the base was completed. Besides the different influences on the limited use of Neumayer Station the deformations during the operation time are determined.

Neumayer Station is a tubular sub-surface research base. The three main tubes of the base resemble a tunnel structure in soil. Several mechanical models that describe the loads on tunnels as well as stresses and deformations of these structures are presented. Besides the mechanical models also other aspects concerning tunnel construction in soil and rock are given which may be important to consider in the course of this research.

Neumayer Station is located in an ice shelf of the Antarctic continent. To obtain an idea as to what kind of materials ice and snow are and how to deal with them in an engineering model the physics of ice and snow are studied. Besides mechanical properties of ice and snow, attention is paid to the theory of visco-elastic behaviour as well as rheological modelling of snow.

With the understanding how to model tubes in soil and the necessary physics of snow and ice mechanical properties of snow and ice at Neumayer Station are presented. A range of data has been determined by the AWI concerning snow profiles, snow pressures, elasticity and viscosity of snow layers close to Neumayer Station. Also a summary is given of the different loads that act on the structure.

The last chapters of this report deals with the results of this project. At Neumayer Station measuring the present deformations is a first step. To observe the deformations a comprehensive survey programme was implemented after construction of the base. The results of the present survey together with the data obtained in the last ten years are analysed and described. The deformations as well as their probable causes are determined. Having conducted the survey programme also leads to a number of conclusions concerning the survey programme itself.

To assess the lifetime of Neumayer Station based on the deformations of the steel tubes the soil mechanical models are combined with what is known about ice and snow. The deformation data collected during the last ten years are used to calibrate the numerical model. To obtain a first impression of the future developments of the deformations in time the least square method is applied. The other mechanical models used for the analysis of lifetime are taken closely into consideration and result in a statement concerning the end of the lifetime based on the criteria of deformation.

A sensitivity analysis is conducted to obtain an impression of the sensitivity of the results for different input parameters. In the last chapters a range of structural aspects for the future as well as conclusions regarding the limits of applicability of the results presented in this thesis and recommendations concerning further research on this subject are given.

Chapter 6

Deformation of Neumayer Station

Basic factors that affect the operation time of Neumayer Station

In Chapter 5 *Problem Statement* a brief summary of factors that affect the lifetime of sub-surface research bases was given. This summary is presented again below:

- **Structural integrity**

The structure becomes unstable, leaky and/or heavily deformed due to loads acting on the tubes so that the required safety for users can no be guaranteed or living conditions become unsuitable for permanent residence.

- **Operation and maintenance expense**

The technical operation of Neumayer Station becomes more expensive over time because of the disproportionate growth of repair, maintenance and spare part costs. For the most part this concerns maintenance at the base's structure and adjustment of the entries and outside facilities of the base to the changing conditions due to snow accumulation and snowdrift.

- **Scientific and contract related agreements**

New scientific requirements (e.g. flight logistics, storage logistics, new laboratories) as well as new treaty obligations (environmental agreements, work related agreements) can restrict the lifetime of a base because realisation of the changed needs can sometimes be obtained more economically in a new base.

- **Developments in research needs and/of techniques**

If scientific data can be collected automatically on-site, no conventional bases are necessary.

In general any of these factors can be relevant for the functionality of Neumayer Station. The lifetime of Neumayer Station was estimated at 15 years counting from the construction date (1992 – 2007). This estimate was mainly based on experiences gained at the former base Georg-von-Neumayer because of the similarities in the design. At Georg-von-Neumayer the deformations of the tubes that were measured in an extensive survey during the lifetime were one of the decisive reasons underlying the decision to abandon the station after 11 years of operation. At that point in time the functionality of the base was almost completely lost. In the design of the current base Neumayer Station attention was paid to three main factors that were expected to result in a longer operational period than 11 years. These factors were [14]:

- At the location chosen for Neumayer Station less differential movement (strain) in the ice than at the location of GvN was measured. At GvN the elongation vector laid during the total time of operation perpendicular to the tubes and the heavy stretches in the snow of 4E-03/a increased the deformation of the tubes in an unfavourable manner. This resulted in an increase of the horizontal dimension of the tube of 30 mm and therefore in a decrease of the vertical dimension of the same extent. At the Neumayer Station location the elongation vector runs only during the first years perpendicular to the tubes and the deformation is equal to 0.5E-03/a.

- The cross-section of the tubes at Neumayer Station was chosen to be circular to create more stability in the bottom sections of the tubes. At GvN a slightly elliptical cross-section with a flat bottom section led to a revolved bending direction. As well as the circular profile the thickness of the steel sheets was raised from 6.25 mm to 7 mm.

- To reduce the effect of vertical compression the tubes were pre-tensioned horizontally to shape the cross-section to an upright ellipse. The pretension strings should have been removed after the base was totally covered with snow and the snow had been compressed. Due to delays during construction of Neumayer Station the pretension was not applied and it is assumed that this has a negative influence on the lifetime of the station.

Neumayer Station has been operating for ten years and currently it suffers from minor loss of structural integrity, which will be discussed in the following section. Other incidents observed at the base are: wastage of surrounding structures such as the connecting and the climate tunnel, obstructed access of the base due to increasing differences in snow level between the snow surface and the base, and an increase in maintenance and operational expenses. Changes in scientific and contract related agreements as well as matters of automation seem not to be subject of discussion at this point of time. The factors mentioned above influence the operation time of Neumayer Station but are not considered to be decisive for an estimation of the remaining operation time.

The aim of this project is to analyse the lifetime of Neumayer Station as an example of tubular sub-surface research structures on Antarctica. Within this project the analysis of lifetime will be based exclusively on the structural deformation. In a former estimation of the remaining lifetime of Neumayer Station, there were two ways to approach such an analysis [14]:

- Given the planned lifetime of 15 years the estimations made during the planning and design of Neumayer Station and probable changes that have taken place are examined. The influences of these changes are used to estimate the remaining operation time.

- The present condition of the base and the factors that have influenced this condition are examined. Based on the data the preliminary remaining operation time must be determined.

Enß combined both methods to come to a reasonable result. In this thesis the emphasis will lie on the second method and the analysis of lifetime will be based on a numerical model in order to estimate the remaining operation time.

Structural integrity

In the previous section a range of factors was mentioned that influence the operation time of Neumayer Station but that are not considered to be decisive for the end of lifetime. Due to the fact that the remaining lifetime of Neumayer Station will be analysed based on the integrity of the structure, attention will be paid to the structural elements of the base.

The steel tubes together with the partition walls form the most important parts of the structure. The staircases, entry to the garage as well as the entry to the connecting tunnel to the base, the eastern ramp and the emergency exit are all joined to the steel tubes. The garage and the connecting tunnel itself are separate structures that are not of importance for the lifetime of the base.

The development of the structural integrity of Neumayer Station is monitored by the Logistic Department of the AWI. Several phenomena are observed:

- Deformation of the steel tubes

The expression ‘deformation’ refers to a range of different kinds of changes in the original circular profile (cross-section) and the cylindrical form (longitudinal section) of the tubes.

- Leakage

Leakage is reported during the summer season only. Due to relatively high temperatures outside, heat energy penetrates into the snow layers above the structure and results in melting of snow. The structure was covered with plastic during construction but there may be parts where the plastic shows tears. The melted snow leaks through the bolted tube plates to the inside where it refreezes. Leakage is not an immediate danger to the structure and is not subject of this thesis project.

As already mentioned in Chapter 5 the deformations of the steel tubes were expected due to the experience obtained with the base GvN. An extensive survey backs up the visual monitoring of the deformations. The survey is conducted once or even twice a year.

The deformations of the tubes can be separated into:

- Longitudinal differential deformations

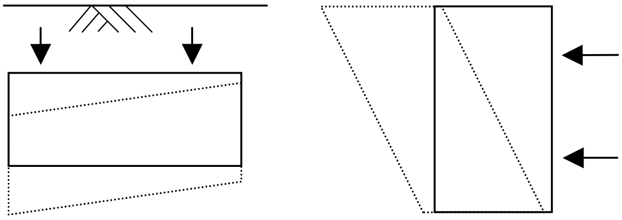


FIGURE 48: side view and top view of one of the tubes *(Saltner & Keij)*

Due to longitudinal deformations of the tubes it is possible that the containers could no longer be adjusted in vertical direction any more. This results in areas under and/or above the containers in the tubes that become inaccessible for maintenance and other work purposes.

- Deformation of the cross-section

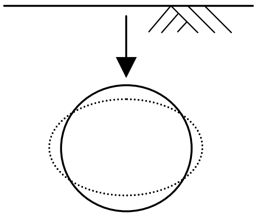


FIGURE 49: cross-section of one of the tubes *(Saltner & Keij)*

Deformations of the cross-sections are assumed to result mainly from vertical pressure on the tube section and less from differential settlements of the right and left part of a tube, which are observed as distortion [13]. These deformations also limit the proper use of the space above and under the containers.

Some factors regarding the structural integrity that are probably not relevant for the operation time of Neumayer Station [14] are given below:

- Longitudinal and crosswise inclination of the entire tubes
- Deformation of the tubes due to differential movements of the snow foundation
- Deformation of the partition walls and of the tubes at sections close to the partition walls

The deformations of the steel tubes due to settlement are rated to be decisive for the point in time at which Neumayer Station has to be abandoned. Among the deformation observed in the tubes, the sections at the southern part of the West tube, and the cross section of the crosswise tube and the crosswise tube together with tank hall are assessed as critical.

Limit states of Neumayer Station

The moment at which a tube is not fit for purpose anymore is defined by a limit state. Two types of limit states can be distinguished, respectively the Ultimate Limit State and the Serviceability Limit State:

ULS (Ultimate Limit State)

When an ultimate limit state is reached the structure is endangered by structural collapse. This limit state for a tube can be generally divided into [3]:

1. Local failure of the roof due to buckling behaviour. The stresses at a local point are so high that buckling occurs, leading to large deformations and collapse.
2. Global failure of the roof due to the occurrence of plastic bending. This is classified as a shearing failure, where the tunnel is unable to sustain the stresses in the roof.
3. Failure of the soil at the sides of the tunnel. This failure mode takes place due to compression of soil.

Usually a combination of failure types 2 and 3 takes place at once. The deformation behaviour for such a combined loading is that of horizontal ovalisation. This ovalisation leads to a stress relief above and below the tunnel, while the lateral stresses will increase due to compression of the soils on the horizontal outsides of the liner.

When the liner is flexible and the soil behaves stiffly, the lining will deform until the bending moments have vanished. The tunnel will be loaded by hoop stresses only in this case [7].

Calculating the maximum load on the tube leads to a definition of the zone in which the ULS will not be reached.

Buckling behaviour

The maximum load that can be taken in a buckling criterion can be determined by the following equation [28]:

$$q_{\max} = \frac{Et^3\left(\frac{\pi^2}{\alpha^2} - 1\right)}{12r^3(1-\nu^2)}$$

with:

E	Young's modulus of steel
t	plate thickness
2α	angle of curvature
r	initial radius of tube

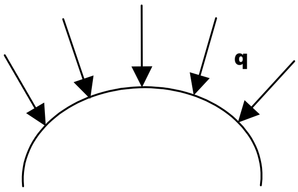


FIGURE 50: top loads on the tube *(Saltner & Keij)*

υ = Poissons ratio of steel

This calculation is a check upon the buckling behaviour that can be executed when the steel profile data (E, $t_{equivalent}$) are defined. The check will be done in the section *Limits of the model* in Chapter 11 *A Deformation Model for Neumayer Station*.

Ovalisation behaviour

Failure of the roof, combined with the failure of the soil next to the tube is ovalisation behaviour. This behaviour has its limits at the collapse of the soil, or the occurrence of a plastic hinge in the structure. Both mechanisms will cause large deformations and collapse.

The occurrence of a plastic hinge in the tube will take place when the limit stress of the steel of the outer hull is exceeded. This limit stress is defined as [7]:

$$\sigma_{\lim} = \frac{M}{I}\frac{h}{2} + \frac{N}{A}$$

with:

M	Moments in the cross section
I	Moment of inertia
h	Vertical dimension of the cross section
N	Normal forces
A	Cross section area

The limit stress must lie below the limit stress for steel as defined in the Eurocode (EC). For this study it is assumed that standard steel, S235, is used at Neumayer Station. The standard value for steel used here is deemed valid at the appropriate low temperatures:

$$\sigma_{\lim} = f_{y;rep} = 235 N / mm^2$$

Calculations made with a tube model yield the appropriate moments and forces for the tube to perform a check to this limit stress.

The two checks that have been named here are performed to test the outcome of the model. The collapse of soil will not be tested due to lack of specific ice collapse data for the Neumayer site. The collapse of ice due to deformations at other stations has not yet been observed.

SLS (Serviceability Limit State)

The Serviceability Limit State is defined as that point of loading at which the deformations are large enough to cause negative influence on the functioning of a structure. Here the functionality will be defined according to the profile of free space.

The functionality of Neumayer Station is limited by the deformations of the outer hull. Due to these deformations the space inside the tube decreases continuously in height.

FIGURE 51: West tube, profile of free space in northern direction (left) and southern direction (right) (*photograph: M. Wölk)*

To assess when the functionality of the base will be lost it is necessary to evaluate a value for the minimum space needed inside the tubes. This minimum space is defined through an analysis of the profile-of-free-space (PFS) [conversation with H. Ahammer].

The profile of free space differs for each tube of Neumayer Station, depending on the use of the containers, the use of the roof sections and the space next to the containers. The PFS is characterised by three variables:

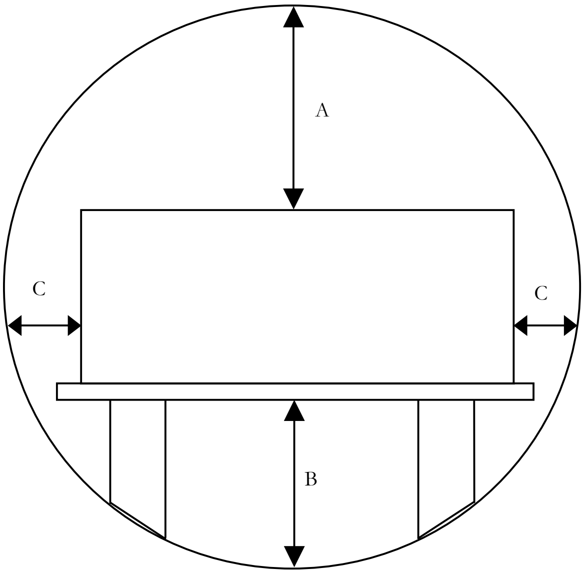


FIGURE 52: cross-section of the East and West tube *(Saltner & Keij)*

- (A) indicates the minimum space needed above the roof of a row of containers and is determined as the distance from the top of the containers to the top section of the tube.
- (B) indicates the minimum space needed under a row of containers and is determined by the distance between the bottom section of the tube and the top of the platform structure that bears the containers.
- (C) indicates the space necessary next to a row of containers and is determined by the distance between the horizontal dimension of the tube and the sidewall of the container.

To assess more effectively the space needed on top of the containers parameter A is split up into two parameters, respectively A_1 and A_2.

Parameter A_1 is determined right in the middle of the tube where the largest distance is found. Parameter A_2 indicates the smaller height at the edge of a container row.

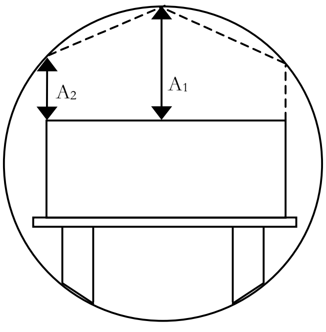


FIGURE 53: cross-section with roof section *(Saltner & Keij)*

West tube

The West tube is used for working and living quarters (0 m < x < 40 m, measured from staircases West in northern direction) and for different types of machinery, which is placed in the container units T2, T3 and T9. The station machinery is not part of the grouped air-conditioned containers and the sizes differ from those of ISO 20-ft containers.

Values A

The values for parameter A, which indicates the minimum space required above a row of containers are determined by visual observation and quantified in co-operation with staff of the Logistic Department.

The results are summarised in the table below:

TABLE 8: values A West tube

Area	Minimum height (A_1)	Maximum height (A_2)
Living/working quarters	800 mm	1600 mm
T2	1500 mm	2200 mm
T3	1500 mm	2100 mm
T9	1500 mm	2200 mm

Values B

The platform structure that bears the containers consists of steel cylinders filled with sand on which a steel frame is placed. Wooden wedges are used to make vertical adjustment of the containers possible.

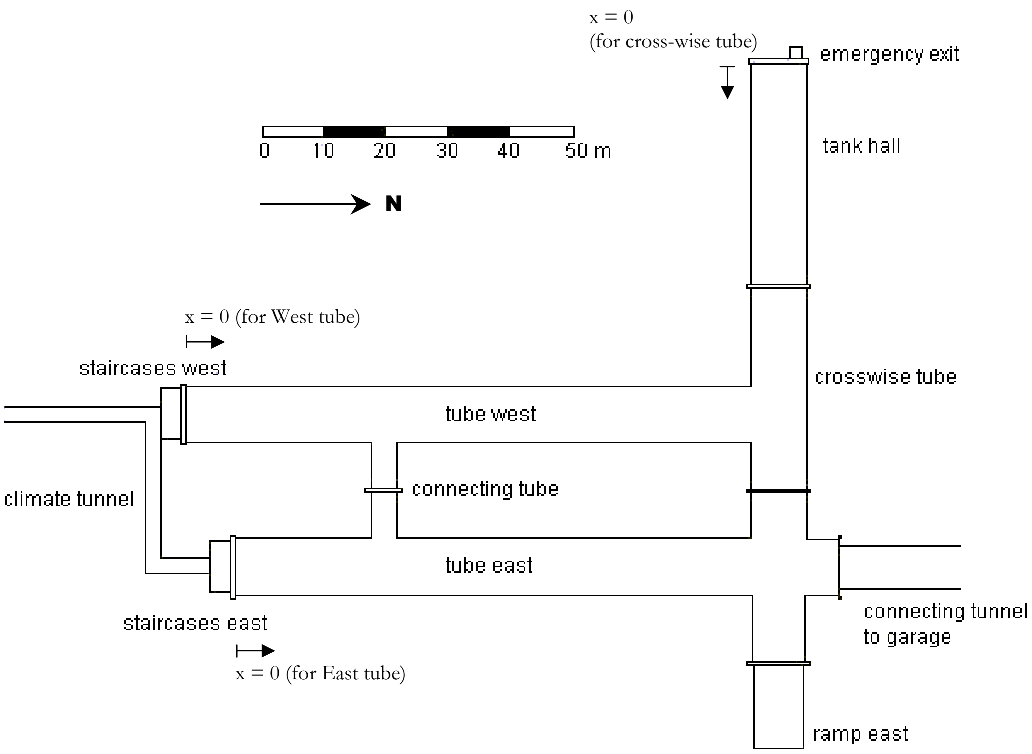


FIGURE 54: plan view Neumayer Station *(source: Polarmar, modified by Saltner & Keij)*

The containers on top of this platform structure form the living and working quarters of the base's inhabitants and must therefore be kept level. The execution of levelling requires heavy labour, such as welding, cutting and cleaning away of steel. This requires a minimum range of space.

The AWI requires the space for this kind of maintenance work to be at least 1.50 m below the wooden surface, and 1.00 m below the steel frames of the platform structure. These values refer to the distance determined exactly in the middle of the tube section, as shown in figure 52.

Values C

On both sides, outside of the containers steel gratings are placed, originally for emergency purposes only. However these grids are also used frequently to move in a tube. Unequal settlement of the bottom of a tube is observed as a distortion of the tube's cross-section and results in different dimensions at both sides of the containers in the different tubes. At Neumayer Station the gratings are fitted when necessary to follow the distortion of the tube. This means that when at one side the steel hull threatens to touch the grating it is shortened and on the other side the grating is extended in order to close the gap between the grid and the tube's sidewall. Besides the distortion the tube also deforms horizontally; the horizontal dimensions increase. In case of emergency a minimum space is needed to move safely in the tube outside the containers.

The minimum required escape route on both sides of the containers is set at 0.50 m width for the gratings. Due to the circular profile of the tube the distance has to be set to 0.75 m.

East tube

The East tube contains living and working quarters (0 m < x < 47 m, measured from staircases West in northern direction), station machinery and the T6 emergency power aggregate (47 m < x < 56 m) and a mechanical and technical workshop (56 m < x < 85 m). Due to different sizes of the container units used for the different functions, the profile of free space has to be determined for each section separately.

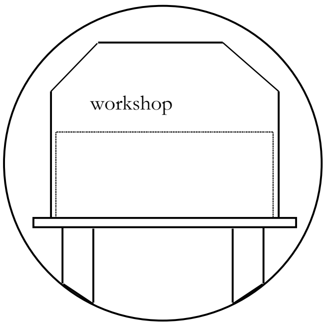


FIGURE 55: cross-section with workshop *(Saltner & Keij)*

Values A

The workshop, which is located at the northern end of the East tube differs in size and cross-section compared to an ISO container. Its height is 5.10 m maximum and 3.00 m minimum.

TABLE 9: values A East tube

Area	Minimum height (A_1)	Maximum height (A_2)
Living/working quarters	1200 mm	1500 mm
T6	1000 mm	1500 mm
Workshop	500 mm	2600 mm

Values B

In the East tube the same platform structure is used to support the containers, machinery and the workshop as in the West tube. Thus the same value as determined for the West tube can be applied here: B = 1.50 m.

Values C

The East tube uses the same gratings as the West tube and the same distortion and deformation processes take place. Values determined for the West tube can also be applied here: C = 0.75 m.

Cross-wise tube

The partition walls in the cross-wise tube separate the tube into three sections, each used differently.

- Storage of fuel in tank containers (0 m < x < 36 m)
- Storage of refrigerated and waste containers (36 m < x < 68 m)
- Manoeuvring space and possible vehicle storage (68 m < x < 95 m)

As the crosswise tube is used for storage of containers that differ in weight and that are placed inside the base by snow vehicles the base is filled up with snow up to a third of the tube's height. A platform structure that supports the containers is not necessary. This allows larger deformations than in the West and East tube. The containers stored inside are moveable and can be replaced when necessary.

PFS Summary

Given the stricter requirements for deformations of tubes containing the living and working quarters the profile of free space of the East and West tube are decisive for this analysis. Above that the spaces in these two tubes cannot be adjusted as easily as is possible in the crosswise tube.

The definite profile of free space for the use of Neumayer Station is thus determined by the dimensions evaluated for the East and West tube. No loss of functionality of the base will occur when the defined profile of free space is kept clear of deformations. This profile has the following dimensions:

TABLE 10: PFS summary

Parameter	Minimum value
Minimum height (A_1)	2500 mm
Maximum height (A_2)	1500 mm
Space under platform structure (B)	1500 mm
Space at both sides of the container (C)	750 mm

To assess the upper limit of the accepted deformations the defined minimum profile of free space has to be compared with the actual state of the tubes. A view on half a tunnel section is sufficient because of symmetry. This is done in the figure below. The PFS is marked with a xxx line.

The largest deformations are expected at the top and bottom of the circular profile. When the minima of the profile of free space are taken into account together with the dimensions of the container (H_C = 2.543 m, w_C = 6.053 m) the total acceptable deformation can be determined.

Between the PFS and the top of the tube there is a space of 1.00 m, and at the bottom a space of 0.90 m. When the deformation are a maximum of 0.90 m the inside structure will have contact with the hull.

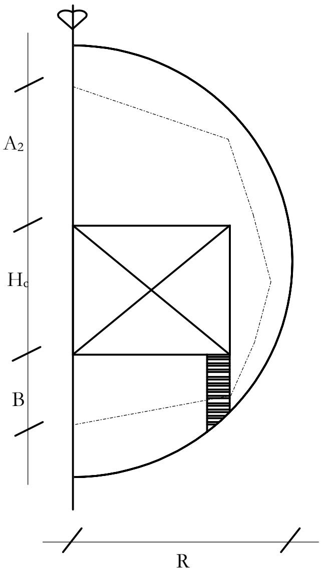


FIGURE 56: PFS
(Saltner & Keij)

A model for a tube in ice

For this thesis a model has to be developed that takes into account the deforming ring that sinks into the ice due to its own weight and increasing top loads from snow. The model that is used to describe this behaviour is based on the subdivision of a complex behaviour into two sub-models that are less complex.

The model will be based on the following hypothesis:

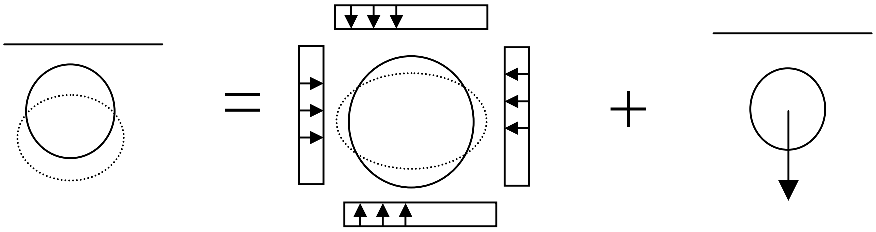


FIGURE 57: deformation of profile divided in two phenomena *(Saltner & Keij)*

'It is possible to describe the behaviour of a subsiding, deforming tube in ice by summing up the behaviour of two sub-models. One will describe the settlement of a rigid body in a viscous material based on rheological equations, the second model will describe the (elastic and viscous) deformations on the ring due to increasing top loads'

The graphic display of this hypothesis is given in figure 57.

The first sub-model shows a ring that is deformed due to top loads from the surrounding snow. The deformations are related to the soil support the ring receives at its sides. The model is a standard soil model with extensions possible for different soil models. Duddeck shows a model with elastic springs for soil. The models that are available to be used will be explained in Chapter 7.

The second sub-model is that of a rigid ring that settles into snow due to its own weight and top loads. The settlement into the snow is directed by the viscous behaviour of the ice. This viscous behaviour is added to an elastic strain that will occur in ice as in other materials. The typical behaviour of ice related to other materials and the possible rheological modelling for the viscous behaviour is treated in Chapter 8.

The model process followed within this research can be divided into three phases:

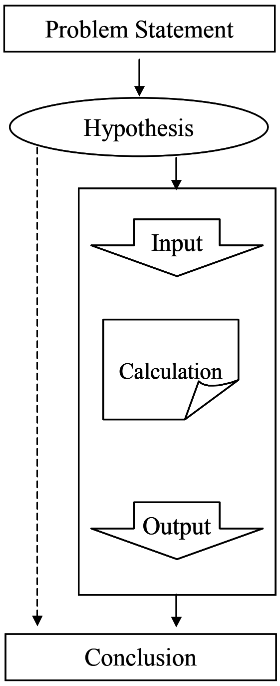


FIGURE 58: the process of modelling *(Saltner & Keij)*

Input phase:

Input parameters representing the situation at Neumayer Station are necessary to set-up the first model steps. Natural surroundings, steel parameters of the tubes and loads on the tubes from human activities and natural causes must be summed up to be used as input for the running model. (see Chapter 10)

Calculation phase

The models that have been selected from the available theory in Chapters 7 and 8 will be combined and elaborated into one model to calculate the deformations of Neumayer Station.

Output phase

The output of the model must be compared with the limit states as described in the previous section. The model can be calibrated to the data that has been gathered at Neumayer Station since 1992.

Chapter

7

Model Concepts for Tubular Structures

The first sub-model that is used to model the deformations of Neumayer Station in ice is the model of a deforming ring in ice. This model is derived from present information of modelling tunnels in soil.

Modelling a tunnel shaped structure is carried out to obtain a value for the bending forces and normal forces that will be exerted on the lining. The lining will react to these forces by deformation.

In this thesis project deformation is assumed to be the most important issue for deciding upon the end of the lifetime of NM station. This assumption is based on the observed behaviour of other sub-surface tubular polar bases (Georg von Neumayer and Sanae 3) that have reached a point of maximum deformation earlier than a strength limit state within their lifetime.

This chapter will state the use of different models that can be used to describe the behaviour of tunnels in soil.

Loads on Tubes

Sub-surface tubes will be loaded in three dimensions. In the scope of this research the deformations in the vertical plane are important. In the vertical plane, the loads that can be distinguished are [35]:

1. Distributed top loads
2. Soil loads
3. Concentrated loads due to traffic
4. Weight of tube
5. Loads inside the tube
6. Forces due to pressure inside or outside the tube
7. Forces due to temperature gradients

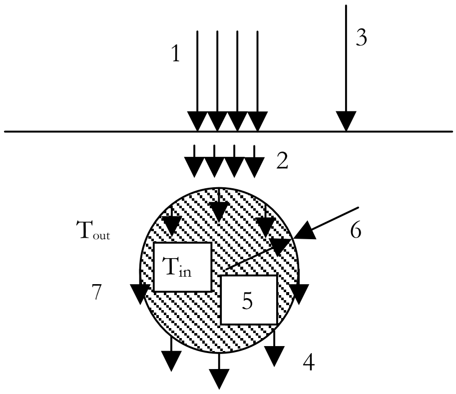


FIGURE 59: overview of types of loads on tubes *(Saltner & Keij)*

In this study a selection of the loads described above are taken into account. These loads concern the distributed top loads (1), soil loads (2), the weight of the tube (4) and the loads resulting from activities inside the tube (5).

The loads that are not taken into account are:

Point loads from traffic:

Top loads due to traffic at Neumayer Station can descend from pistenbully's with sled tugs stopping on top of the base. This is a rather unusual event within the base operation and will not be included in the basic calculations.

Pressure forces inside/outside tube

The tube is not pressurised or used as a transport medium for gas or liquids, which makes this load case obsolete.

Forces due to temperature gradients:

The temperature of the space between the hull and the heated containers is kept at the same temperature as the outside snow layers to decrease the possibility of warming effects of solar radiation reaching the tubes through the snow. Although heating of the tubes is observed during the summer seasons, the temperature gradient is excluded from the calculations.

Comparison of tubular structures in ice to structures in soil and rock

The tubular structure of Neumayer Station can be compared to a tunnel in ice. As already mentioned in Chapter 4 NM was constructed on the snow surface. Its sub-surface position has not been derived from excavation or drilling as usually applied for tunnel structures. The tunnel is covered by the snow and ice that form a firm bedding. Compared to conventional tunnel structures techniques of installation by drilling or segmental sinking do not show any similarities. Some similarities with the base structure in ice can be found when comparing tunnelling to other firm soils.

The behaviour of ice around the circumference of the tunnel will be assumed to interact with the tunnel lining in a manner comparable to soil. It is with this assumption in mind that model concepts for tubular structures are described here.

NATM

A tunnel in soil that has a reasonable standing time can be installed with the New Austrian Tunnelling Method (NATM). The standing time is a measure for the reaction of soil to the excavation of the tunnel. When the soil is rigid and the newly excavated space for new tunnel element has a standing time of more than 30 minutes, the NATM can be applied [41].

The NATM aims to gain the co-operation of tunnel elements and lining, allowing the soil to settle over some distance to create stress in the tunnel elements. The NATM is seen to be an ideal way of constructing tunnels because in good soils no extra measures are needed to ensure the safety of workers. The NATM is flexible and can be used to build tunnels in several shapes and sizes.

When soil is too loose, the tunnelling process of NATM can still be applied by freezing the soil layers around the area that need to be excavated. Frozen soil generally has a longer standing time, which allows this method to be used. Studies have been carried out into the advantages of this method with soft soils.

In the calculations applied within this study the model by Duddeck incorporates the interactions between tunnel and lining, creating smaller deformations due to stress reduction. This same principle is covered in the NATM although the installation technique used differs greatly.

Arching

When vertical pressures in soil, caused by its own weight, are measured a reduction from the expected pressure is observed [37]. This reduction is caused by the effect of grains of soil generating friction forces that decrease the pressure.

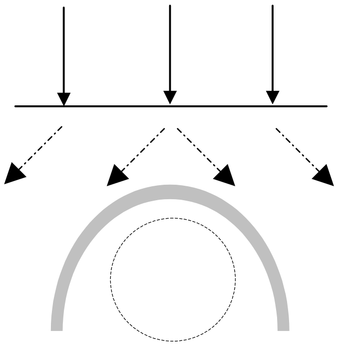


FIGURE 60: redistribution of vertical soil pressures due to arching *(Saltner & Keij)*

This effect is called arching, and can be used to reduce the dimensions of a tunnel lining. When soil has a high cohesion or high friction angle, this arching effect is visible. Arching depends mainly on the soil parameters on site and the total soil cover above a tunnel structure. For the snow and the ice that is present at Neumayer Station no data is available regarding arching effects.

Duddeck observed arching effects for deep tunnels for structures that meet the relationship (total snow cover)/(radius) > 6. Applying this relationship for Neumayer Station a comparable situation will occur when the tubes with a diameter of more than 8 m are covered with 50 m of snow and ice. Given the annual snow accumulation this situation will be met after 70 years of operation, which is far beyond the expected lifetime of the base.

Analytical solution for stresses without soil reaction

Bouma (1993) developed an analytical solution for stresses in a curved wall [4]. The model makes use of an elementary definition of a curved beam and can be used to model a cylinder in soil.

The stresses in a curved beam can be described by three equations:

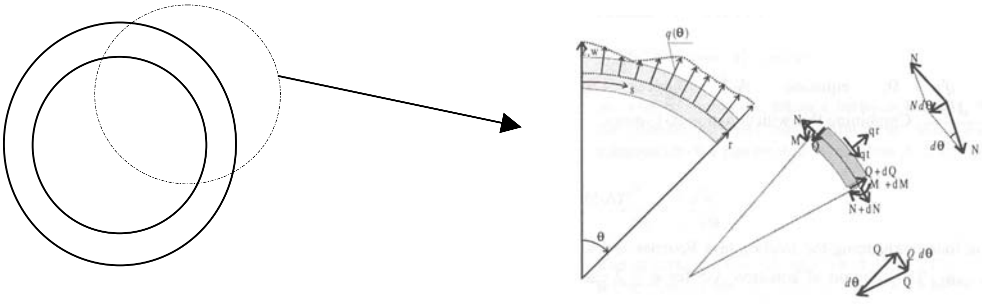


FIGURE 61: analytical solution for stresses in a curved wall according to Bouma *(source: Bakker [3])*

Radial Equilibrium

$$\frac{d^2M}{ds^2} - k_r w_r + \frac{N}{r} - q_r = 0$$

In this equation k_r is the radial sub grade reaction modulus of soil.

Tangential equilibrium

$$\frac{dN}{ds} - k_t w_s - \frac{Q}{r} + q_t = 0$$

In this equation k_t is the tangential sub grade reaction modulus.

Kinematical equilibrium

$$EI\left(\frac{d^2 w_r}{ds^2} + \frac{w_r}{r^2}\right) + M = 0$$

The variables w_r and w_t in these equations are the radial and tangential displacements measured in the radial direction. These are of interest for this study.

The equations above lead to one differential equation. For the analytical solution simplifying assumptions are made. A first simplification is to calculate the forces on a cylinder without taking soil reactions into account. For this example in soil k_r and k_t will be equal to zero. This means that the reaction of the soil to the deformations of the tube is neglected.

In soil the liner of a tunnel will be loaded by the vertical stresses originating from the weight of the overlaying soil. The horizontal stresses (σ_h) are related to these vertical stresses (σ_v) by factor λ:

$$\sigma_h = \lambda \sigma_v$$

In Bouma soil pressures σ_v are calculated at the middle of the circular profile and taken as a constant over the circular circumference in the calculation.

Due to the difference in stress from horizontal and vertical stresses bending moments are developed in the liner. The radial loading by the horizontal and vertical soil loads is rewritten as a loading situation that is a function of the angle of inclination, and a constant part:

$$q_r = q_0^r + q_2^r = -(\frac{\sigma_v + \sigma_h}{2}) - (\frac{\sigma_v - \sigma_h}{2})\cos(2\theta)$$

The occurrence of tangential loads depends on the roughness of the liners outer surface. With two assumptions, (a) the initial soil stresses act as an active load on the tunnel, and (b) the stress distribution can be approximated by a sinus, the tangential loading on the tunnel will be:

$$q_2^t = (\frac{\sigma_v - \sigma_h}{2})\sin(2\theta)$$

When the wall is assumed to be rough and the load is considered isotropic, the displacements, together with the moments and normal forces can be derived. The displacement is expressed in a combination of compressive stresses and a part related to the stress difference.

$$w = q_0^r \frac{r^2}{EA} + q_2^r \frac{r^4}{EI}\cos(2\theta) = -(\frac{\sigma_v + \sigma_h}{2})\frac{r^2}{EA} - (\frac{\sigma_v - \sigma_h}{12})\frac{r^4}{EI}\cos(2\theta)$$

Analytical model for subgrade reaction

The Bouma model given in the previous section does not take any sub grade reaction into account (k_r and k_t are both zero). The sub grade reaction causes redistribution of moments, leading to smaller deformations. Simplifying this redistribution to zero, Bouma makes an overestimate of the deformations that occur. An improved model, which does take the soil reaction into account, is the model by Duddeck [9].

Duddeck assumes a lining that is supported by an elastic foundation over an area from $\varphi = \beta$ to $\varphi = -\beta$. Analytical solutions for this load case are difficult to derive. Numerical solutions such as that derived by Duddeck (1964) are more appropriate.

Duddeck adopted a number of simplifying assumptions in his model:

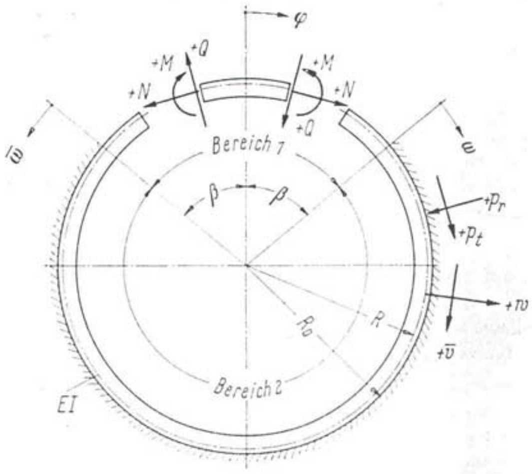


FIGURE 62: the basis for the Duddeck model
(source: Duddeck [9])

1. The tunnel profile remains unchanged in the axial direction, which means no 3 -dimensional effects take place.
2. The thickness of the liner of the tunnel is small compared to its radius.
3. In the relationship between σ_v and σ_h as mentioned earlier, the factor α is not dependent of the depth.
4. The elastic foundation is dictated by the constant of Winkler: $C_b = \gamma E_s/R$. Values for γ can be found in literature and range between 0.66 and 3.
5. The specific mass of the soil is considered constant along the tunnel diameter.

Duddeck uses the following depth dependent formula for the vertical stresses:

$$\sigma_v = \gamma (H - R_0 \cos(\theta))$$

Bouma relates the horizontal stresses to the vertical stresses by a factor λ. Because Duddeck's model incorporates two areas, one elastically founded and one unfounded, the analytical calculation tends to get elaborate quickly.

The equations that can be put together at the point of contact between the areas have their origin in five equilibriums. Among these are moment equilibrium, normal force, connection in x-y plane, bending connectiveness and tangential symmetry.

The integrals have been solved relative to a factor K, representing soil pressure and ring stiffness influences, and a factor $u_{Duddeck}$, representing soil stiffness. The analytic solution for the deformations is:

$$w_{1(unsupported)} = A_1 \cos(\phi) + A_2 \phi \sin(\phi) + a^2 B_0 - K \cos(2\phi)$$

and

$$w_2 = e^{-u\omega}(B_1 \cos(v\omega) + B_2 \sin(v\omega)) + e^{-u\bar{\omega}}(B_1 \cos(v\bar{\omega}) + B_2 \sin(v\bar{\omega})) + B_0 - \frac{9}{a^2+8} K \cos(2\phi)$$

$w_{1(unsupported)}$ is the deformation in radial direction in the unsupported area of the cross section, from $\varphi = -\beta$ to $\varphi = \beta$. The factor w_2 covers the remaining area.

The factors of A_1, A_2, B_0, B_1 and B_2 can be obtained from a graph that shows the relationship between K and $u_{Duddeck}$.

Together with the formulae and the constants derived above a deformation profile can be calculated. This profile depends on the angle φ.

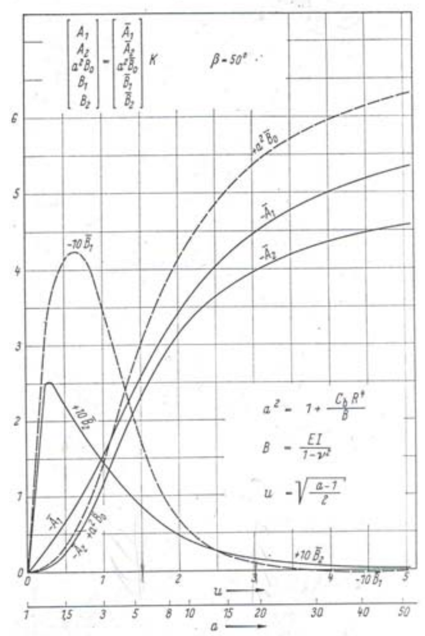


FIGURE 63: analytical solution by Duddeck for dimensionless coefficients in relation to $u_{Duddeck}$ *(source: Duddeck [9])*

Finite element models

The calculation of loads on tubular structures can also be determined by finite element models [5].

Using a finite element method a construction with a complex geometry is divided into a finite number of elements with a simple geometry. These elements are joined together in nodes, making a numerical calculation possible. In a FEM the soil layers can be modelled separately, special loads can be easily taken into account and complex shapes can be modelled, making finite element modelling a suitable alternative for analytical calculations.

In 1988 tests were performed with a culvert, modelled in DIANA. DIANA is a finite element programme developed in the Netherlands by TNO-Bouw. The outcome of the numerical calculation was tested in the full-scale structure, leading to a good agreement between model and reality.

In this study no finite element modelling will be applied, due to lack of appropriate or applicable software. Developing a finite element programme falls outside the scope and the time available for this study.

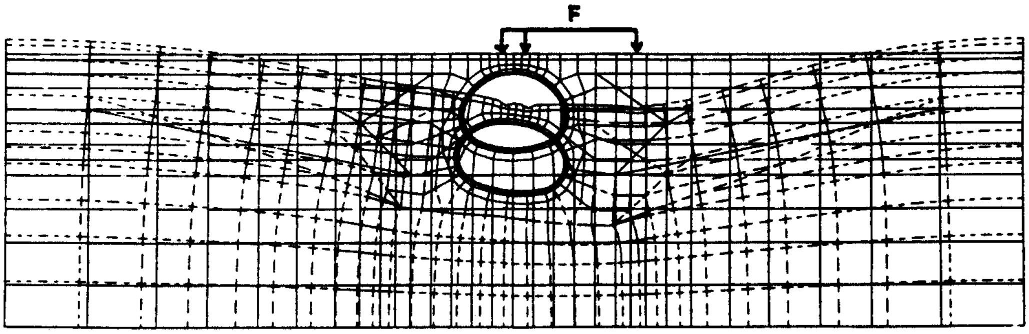


FIGURE 64: finite element model for a tunnel structure in soil *(source: [35])*

Chapter 8

Physics of Snow and Ice

Layers of ice on Antarctica are built up of snow and ice. This chapter describes the processes involved in the composition of these layers of ice, and their consequences for modelling snow as a building material.

Properties of ice

Ice, the frozen form of liquid water, is abundant on the Earth's surface, in the planetary system, and in interstellar space. If all the ice presently existing on Earth melted, sea level would rise about 70 m. In some planets and in most moons, ice is the major constituent [25, 27].

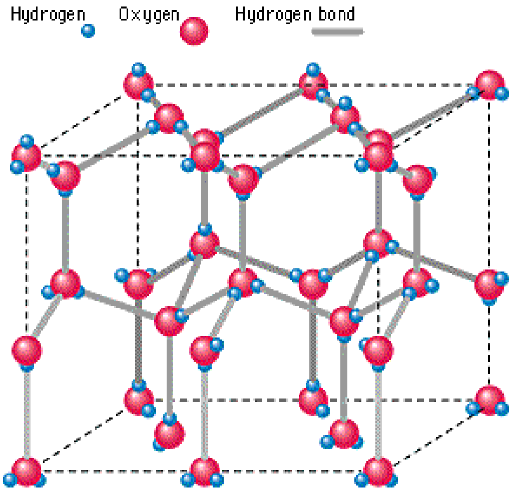


FIGURE 65: six-cornered hexagonal ice *(source: http://school.discovery.com/)*

All of the natural ice on Earth is hexagonal ice as manifested in six-cornered snow flakes (see figure 65):

At lower temperatures and at pressures above 2 kbar many other ice phases with different crystalline structures exist. No other known substance exhibits such a variety

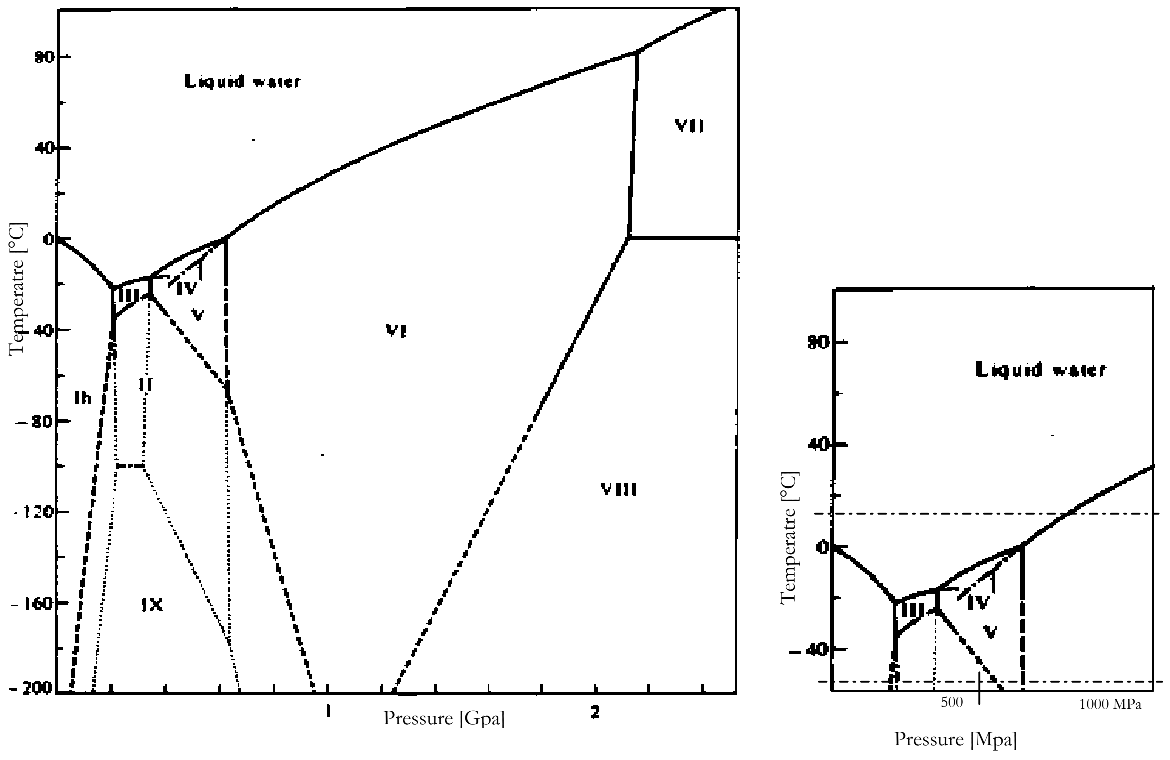


FIGURE 66: phases of water for different temperature/pressure values *(source:[P])*

of forms. The phase diagram of ice shows the conditions of stability for the ice phases for different temperatures in °C (see figure 66)

This figure shows the nine phases of ice as a function of temperature and pressure. Normal ice exists in the region marked I(h). The 'h' stands for hexagonal.

The appropriate range for Neumayer Station is given, for temperatures ranging from +10°C to -50°C.

Ice is a granular material. The individual size and shapes of the grains, the ice crystals, vary greatly. The hexagonal molecule structure of ice defines the orientation of the crystals. Four different types of ice van be distinguished:

Primary ice:

Primary ice develops when the water surface is calm and the temperature gradients are too large.

Secondary ice

Secondary ice develops when pieces of ice grain sink under the primary ice layer.

Superimposed ice

Superimposed ice is formed at the top of the ice layer, from snow of from top layers of primary ice.

Agglomerate ice

Agglomerate ice consists of individual pieces of ice that have refrozen.

General parameters for ice

From general engineering tables parameters can be found for the mechanical behaviour of ice. These parameters are valid for with T = 269K (-4°C):

Density	917	kg/m^3
Young's modulus	3E+09	Pa
Linear Expansion coefficient	50E-06	K^{-1}
Specific heat	2.2E+03	Jkg^{-1}K^{-1}
Heat conductivity	2.1	Wm^{-1}K^{-1}

Properties of snow

Layers of snow are formed when snow crystals accumulate on the snow surface. The snow crystals are formed in the atmosphere when air density conditions combined with the weather are right. If the temperature in the cloud of water particles falls beneath a certain point, the freezing point, the water droplets will form ice crystals. These ice crystals will grow into snow crystals, which fall from the clouds due to gravity [N, P, U].

The density of the snow layer on the surface that is formed by these snow crystals depends on the wind speed. Through influence of winds the crystals are rolled together and break into pieces. The layer of snow crystals that remains through this process is called the ice matrix.

Depending on the temperature in the snow layer, the ice matrix is filled with water particles and an air/water gas mixture. If the water content of the snow is more than 3% it is called wet snow, water content of less than 3% means dry snow. Dry snow is common at subzero temperatures.

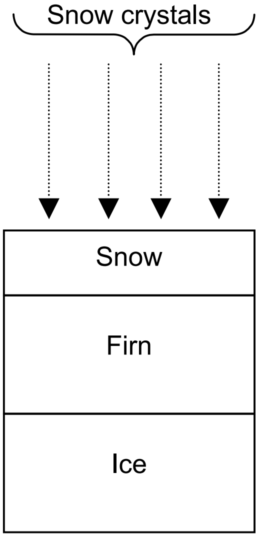


FIGURE 67: types of snow *(Saltner & Keij)*

The snow on the Antarctic continent can be typed as dry snow due to the low temperatures on the continent.

In the ice matrix, three different types material can be distinguished:

- Snow: The top layer of fresh material
- Firn: Older, settled snow that is densified though its own weight
- Ice: Polycrystalline, hexagonal ice I(h)

The transformation of snow into ice is called the metamorphosis of snow. This metamorphosis depends on outside temperature, temperature gradients in the snow cover, and the moistness of the snow, the solar radiation that is absorbed and the density of upper layers.

The metamorphosis of snow has effect on several parameters of the snow layer:

- The shape of snow crystals
- The dimensions of snow crystals
- The porosity of snow layer
- The density of the snow layer

In general increase of depth will mean bigger snow crystals, smaller pores and higher density.

The saying ‘no two snowflakes are exactly alike’ is very true indeed. There are as many forms to snowflakes as there are numbers of flakes. There is also some variety of precipitation that is called snow. These types of frozen precipitation include:

Snow crystals: Individual, single ice crystals, often with six-fold symmetrical shapes. These grow directly from condensing water vapour in the air, usually around a nucleus of dust or some other foreign material. Typical sizes range from microscopic to at most a few millimetres in diameter.

Snowflakes: Collections of snow crystals, loosely bound together into a puffball. These can grow to large sizes, up to about 10 cm across in some cases, when the snow is especially wet and sticky.

Rime: Super cooled tiny water droplets (typically in a fog) that quickly freeze onto whatever they hit. For example one often sees small droplets of rime on large snow crystals.

Graupel: Loose collections of frozen water droplets, sometimes called ‘soft hail’

Hail: Large, solid chunks of ice

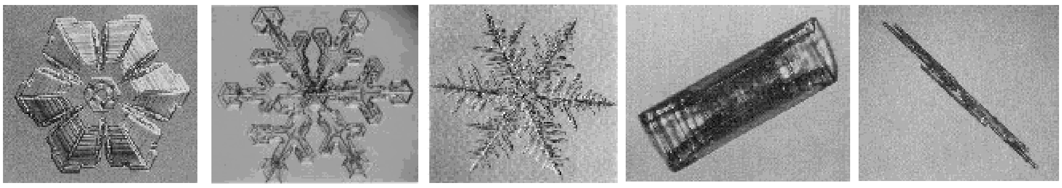


FIGURE 68: different forms of snow crystals (1-5) *(source: [P])*

A simple observation on a snowy day, with a low-power microscope or hand-magnifying lens, quickly reveals a great variety of snow crystal shapes. Some different types include basic plate-like forms, such as (1) Simple sectored plate, (2) Dendrite sectored plate, (3) Fern-like stellar dendrite or basic column-like forms as (4) Hollow column or sheath-like crystal as (5) Needle crystal.

There are other forms of ice crystals. These other forms are mostly variations and combinations of the above basic types, such as plates with dendrite extensions, capped columns, etc.

Density of snow layer

For this report a closer look at the density of snow is of interest. There are several density measurements known [12]:

Filchner Ice Shelf	5 - 55 m depth	Meussen (1998)
Brunt Ice Shelf	1 - 50 m depth	Polarmar (1993)

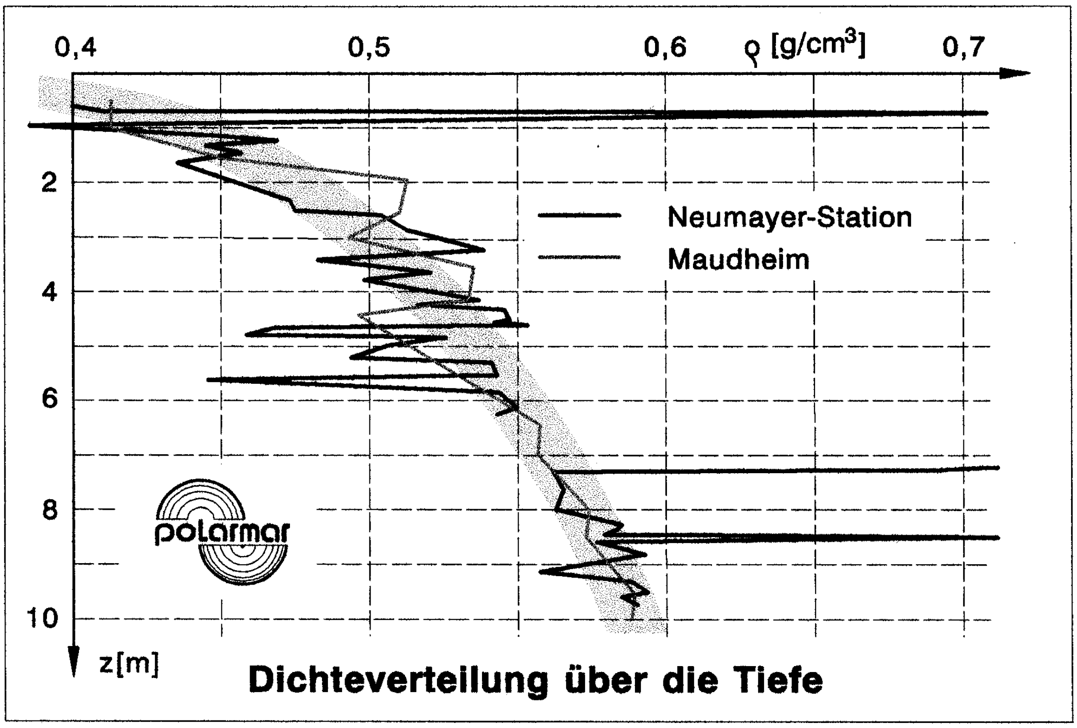


FIGURE 69: density of snow distribution as a function of depth *(source: Polarmar)*

For the German base Georg von Neumayer and for the Swedish base Maudheim the density depth relation is determined through Rammsonde measurement.

Specific for the conditions on Antarctica are the first 2 m, where the profile indicates that the measurements show large deviations from the mean. This is an indication of the non-homogeneity of the material.

When snow accumulates on the surface, the load increases on the old snow layer. Due to this increase the snow particles are compressed. Between the fallen snow, of a density of approximately 300 kg/m^3 and the homogenous ice of 917 kg/m^3 lie three phases.

$\varrho = 550\ kg/m^3$

At this point the maximum density is reached by reorganisation of the ice crystals only.

$\varrho = 730\ kg/m^3$

At this point the contact surfaces between the crystals are at a maximum.

$\varrho = 820\ kg/m^3$

At this point the material consists of the polycrystalline ice I(h) only.

The density of the shelf ice will be equal to the density of fresh snow on the surface (ϱ_0). Deeper, the snow will be more and more dense to a limit value for ice, $\varrho_{ice} = 917$ kg/m^3.

Temperature of the snow layer

The temperature of the snow layer depends on the outside air temperature at the surface [15]. The formula for this effect is given by:

$$A_z = A_0^{\left(-z\left(\pi \frac{n}{\varepsilon}\right)^{0.5}\right)}$$

with

A_z = Temperature at depth z [cm]

A_0 = Temperature at the surface

z = Depth in cm

n = Frequency of temperature changes

ε = Heat diffusion factor [cm^2/s]

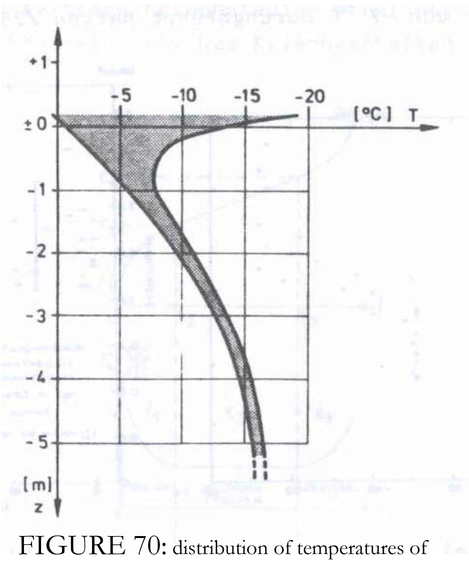


FIGURE 70: distribution of temperatures of snow layers measured at GvN *(source: Enß)*

Mechanical properties of snow and ice

Elasticity

The Young's modulus of snow depends on the density and the temperature of snow. Denser snow yields a climbing Young's modulus as do lower temperatures [22].

This behaviour is measured in several research efforts. One of which is depicted here. The Young's modulus of snow is seen to vary according to the location of the test taken.

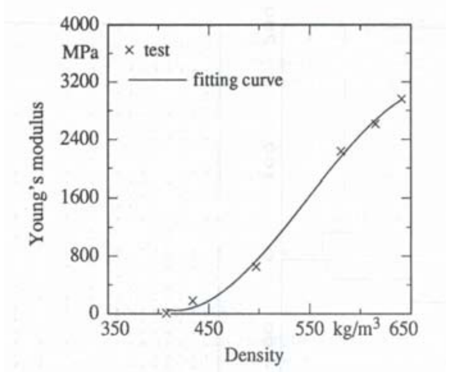


FIGURE 71: Young's modulus of snow *(source: [22])*

Viscosity

Snow deforms under loads in an elastic manner directly after loading takes place. If the load remains on the snow for some time, a slow plastic deformation will occur. This time dependent deformation is called viscous creep [43].

As seen for the example of clay, this material, after a elastic deformation of ε_0, reaches the final deformation after some time. This is called creep behaviour of an attenuating type. This means that the final creep is a limit value.

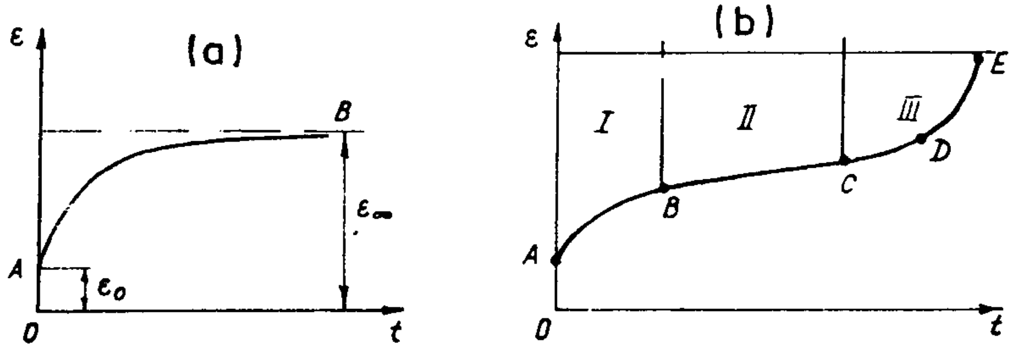


FIGURE 72: comparison of material behaviour under load for clay (a) and snow (b) *(source: Zaretskiy [43])*

For snow another behaviour has been observed. The behaviour of ice is divided into five intervals:

0 – A: Elastic deformation

A – B: Creep at decreasing rate

B – C: Constant creep

C – D: Acceleration of creep without failure

D – E: Intensive acceleration of creep leading to failure

For construction purposes the interval A – B is kept small. With viscous creep the extent of the creep deformations depends on the stress. If the stresses are small, creep deformation is proportional to these stresses, for large stresses the deformations are more than proportional.

Experiments that were meant to lead to values for the creep deformation in snow and ice have proven that viscous creep is difficult to measure, owing to in-homogeneities in the material and difficult determination of material displacements [43]

Modelling snow and ice with rheological models

Materials of varying properties can be modelled through rheological models. In general materials will react differently to stresses put upon them [26, S]. Three deformation types under loads can be distinguished:

- Elastic deformation

- Viscous deformation
- Plastic deformation

All three types of deformation are modelled by a rheological element. Combined these elements can be used to model all sorts of materials.

Hooke element

The elastic deformations are modelled with a Hooke spring. The characteristic parameter for a Hook element is the Young's modulus (modulus of elasticity), E.

When the deformations are linear end time independent then the relation between stress σ and the deformation ε is:

$$\sigma = E\varepsilon$$

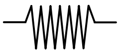


FIGURE 73:
Hooke element
(Saltner & Keij)

Newton element

The Newton dashpot is used to model the time-dependent, viscous deformation behaviour of a material.

For the deformation stress we find:

$$\sigma = \eta\varepsilon'$$

FIGURE 74:
Newton element
(Saltner & Keij)

with

$\varepsilon' = d\varepsilon/dt$

Parameter η is the Newton viscosity of a material.

St. Venant element

Plastic material behaviour is characterised with this element. The permanent deformation occurs after a certain maximum stress has been reached.

$$\varepsilon = 0 \qquad \text{if } \sigma < \sigma_v$$

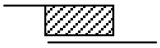


FIGURE 75:
St. Venant element
(Saltner & Keij)

and

$$\varepsilon = \varepsilon(t) \qquad \text{if } \sigma > \sigma_v$$

with:

σ_v is the critical stress.

Basic material types

The basic elements all describe idealised materials. Actual material types can be modelled by combining the basic elements. These elements can be placed in sequence or in parallel order. In sequence the separate deformations are added u, while stresses remain the same for all elements.

$$\text{Sequence}: \qquad \varepsilon = \sum \varepsilon_i \ \text{ and } \ \sigma = \sigma_i$$

When elements are placed in parallel the total stress is a summation of all stresses and the deformations are similar.

$$\text{Parallel}: \qquad \varepsilon = \varepsilon_i \ \text{ and } \ \sigma = \sum \sigma_{\mathrm{i}}$$

For time dependent behaviour both derivatives in time are similar:

$$\varepsilon^i = \sum \varepsilon_i \ \text{ and } \ \sigma^{\mathrm{i}} = \sum \sigma_i$$

Modelling visco-plastic behaviour

For a visco-plastic material the Bingham model is the usual modelling. This model has a parallel placement of a St. Venant element and a Newton dashpot.

For this model the rheological equation is:

$$\sigma = \eta^* \varepsilon' + \sigma_v$$

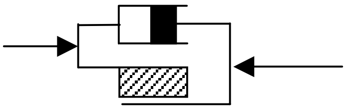


FIGURE 76: model for visco-plastic behaviour *(Saltner & Keij)*

for $\sigma > \sigma_v$

This material will only start to deform visco-elastically when the initiation stress σ_v is reached.

Modelling visco-elastic behaviour

A visco-elastic material will show deformation independent of a certain initiation stress. For this type of material the Maxwell model is used. The Maxwell model has a Hooke's spring in sequence with a Newton's dashpot.

$$\sigma + \sigma' \frac{\eta}{E} = \eta \varepsilon'$$

FIGURE 77: model for visco-elastic behaviour *(Saltner & Keij)*

For the Maxwell model the equation is given above:

Modelling viscous behaviour with friction

For materials that behave viscous, with internal friction effect, the Kelvin model has been made. The Kelvin model is built up of a dashpot and a spring element in a parallel combination.

Here the equation is:

$$\sigma = E\varepsilon + \eta\varepsilon'$$

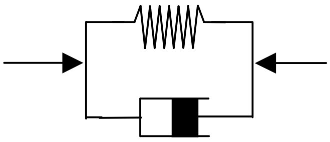


FIGURE 78: model for viscous behaviour with friction *(Saltner & Keij)*

Combined materials

Next to the above-mentioned basic material types there are many different advanced models. These will not all be explained here, but are listed below.

Jeffreys model	Visco-elastic fluids
Lethersich model	Visco-elastic fluids
Zener	Visco-elastic bodies
(two types of models, plastic and elastic)	
Bingham-Hooke model	Visco-plastic bodies
Prandtl-Newton model	Visco-plastic materials
Burgers model	Flow of bitumen
Schwedorf model	Flow of gelatine
Schofield-Scott-Blair model	Over-all model

Two rheological models have been previously used in the modelling of snow. These two will be highlighted below.

Modelling snow as a visco-elastic material

Attempts to model snow theoretically have mainly been phenomenological. Because creep tests take a great deal of time and labour and the obtained results are often scattered, simple constitutive equations are usually adopted [24].

Results from models depend greatly on the model set-up and the parameters that are needed. Three different types of models are described here. These types are described from simple modelling to an extended rheological description.

Mahrenholtz

With Mahrenholtz the total deformations are divided into elastic deformation and viscous deformation [22]:

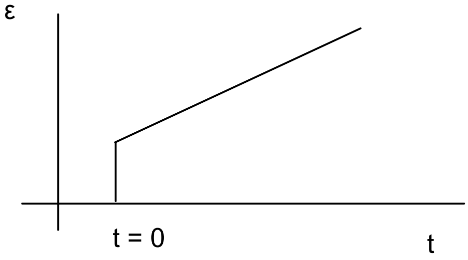


FIGURE 79: elastic and viscous deformation
(Saltner & Keij)

$$\varepsilon = \varepsilon_e + \varepsilon_v$$

with

ε_e = elastic strain

ε_v = viscous strain

Hooke's law can describe the elastic strain:

$$\varepsilon_e = \frac{\sigma}{E}$$

where σ is stress and E is the Young's modulus.

Newton's law can determine the viscous strain rate:

$$\varepsilon_v' = \frac{\sigma}{E_v}$$

where the viscosity parameter E_v is taken as a function of density ϱ. Since the density depends eventually on time t, the total deformations are:

$$\varepsilon(\sigma, t) = \frac{\sigma}{E} + \int_0^t \frac{\sigma(t)}{E_\upsilon(t)} dt$$

Burgers

The Burgers model is used to model asphalt-like materials. This model can also be used to model the time dependent deformation of the ice.

The Burgers model is built up of a Kelvin and a Maxwell element placed in sequence.

The time dependent deformation of this model is depicted in figure 80. In this creep process there are three phases when loading a sample:

A. Elastic deformation, when the load is applied at time t_0. Immediately this elastic deformation, following Hooke's law takes place. The Young's modulus for this behaviour is $E_{1.}$

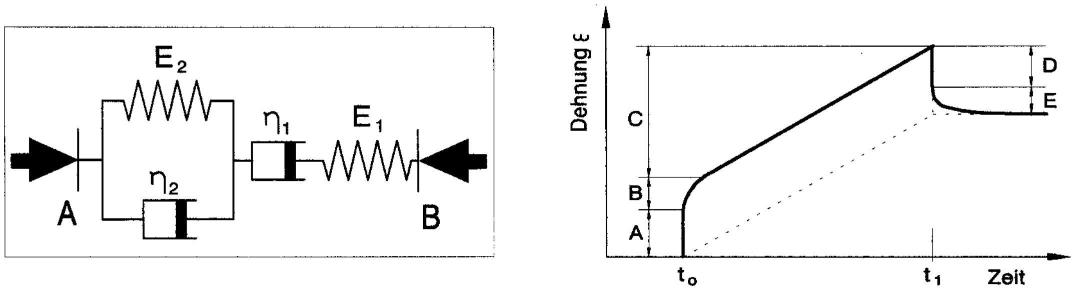


FIGURE 80: rheological depiction of the Burgers model *(source: Enß)*

B. Visco-elastic creep deformation. This behaviour is led by the value for the dashpot η_2 and the Hooke's spring E_2 and will last until the load is high enough to cause permanent deformations.

C. Viscous creep deformation, caused by the dashpot η_1.

The η used here to describe the dashpots is similar to the E_v used earlier.

Thus:

$$\varepsilon_v = \sigma \frac{t}{\eta} = t \frac{\sigma}{E_v}$$

Phase B (visco-elastic) is usually very small, making a model possible of elastic and viscous creep only.

Elasto-viscoplastic

Koiter, to model the viscoplastic hardening of ice, suggested the elasto-viscoplastic model of ice. This model includes a lagging element, for which the stress equation is:

$$\sigma = \sigma - r$$

with r = internal stress

Adding this element will extend a normal Kelvin element, to model hardening effect of snow.

The model that will be used in the scope of this study is that described by Mahrenholtz for the deformations of the snow layers.

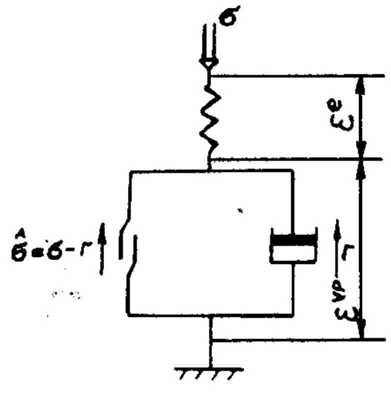


FIGURE 81: elasto-viscoplastic model for ice *(source: Zaretski [43])*

Chapter

9

Construction Parameters at Neumayer Station

The model developed for the deformations of Neumayer Station over time will be calibrated to the actual station. Therefore data is needed on a number of variables. The local temperature profile together with snow parameters is essential for the calibration of the model. The density, elasticity and viscosity of the local snow layers are given as well as information regarding the differential movement of the ice shelf as a whole. At the end, steel parameters of the tubes and the different loads that act on the base are given.

The temperature profile at Neumayer Station

The outside temperature influences the temperature of the snow. This effect is depth dependent because the snow acts as an insulating medium. This means that during the summer season temperatures within the snow layers are generally lower whilst during the winter season higher temperatures are measured in the snow than outside.

The temperatures of the snow layers vary during the day following the changes in external temperature. This effect was measured in 1983 at GvN.

The two graphs depict the temperature of the snow during daytime and at night. The graph shows that due to the insulation of snow, a change in temperature will not influence the temperature of the snow below 2 m in depth.

The temperature of the snow below 5 m in depth does not deviate significantly from the average annual temperature on site, which is –17.8°C.

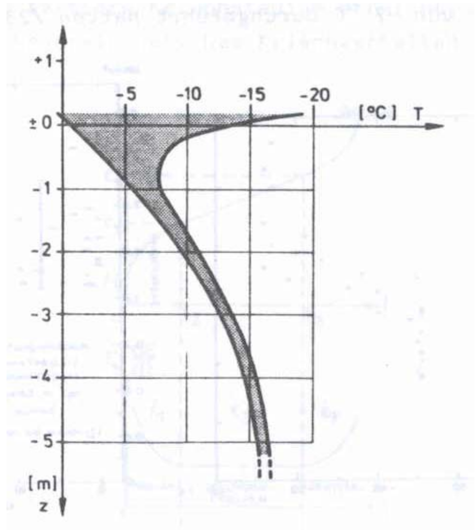


FIGURE 82: distribution of temperatures of snow layers measured at GvN *(source: Enß)*

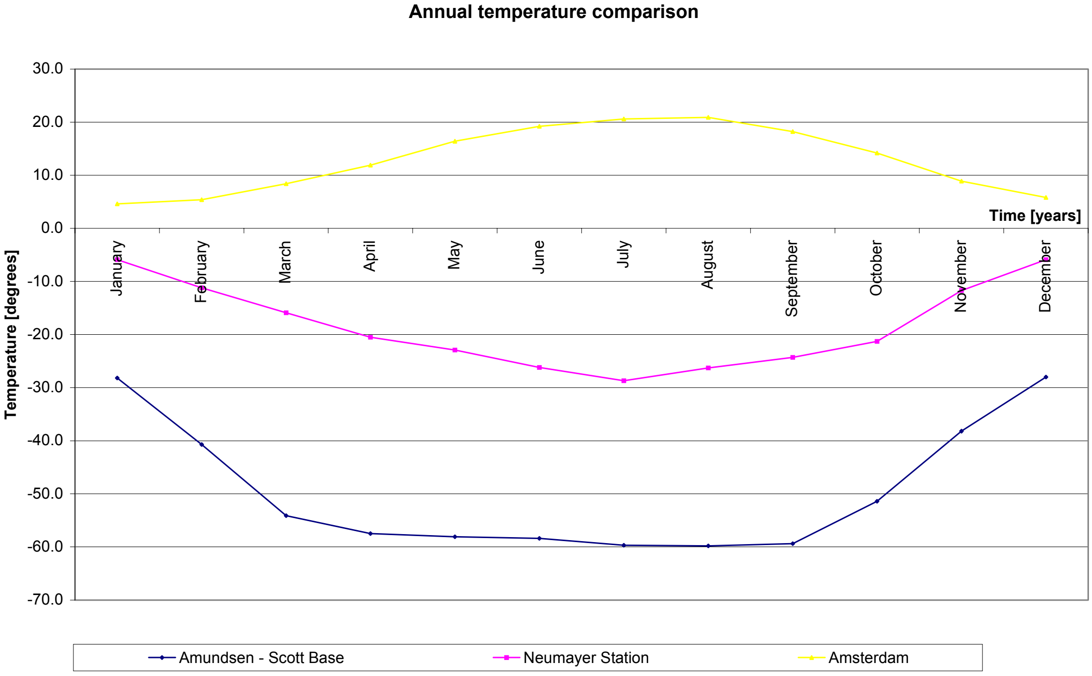


FIGURE 83: annual temperature profile for Neumayer Station compared to Amsterdam and Amundsen-Scott-Base *(Saltner & Keij [G])*

Properties of snow

The snow parameters used for this research are derived from literature. Snow parameters that are of interest for this study are:

- The density of the snow layer relative to depth
- Elasticity of the snow layer relative to depth
- Viscosity of the snow layer relative to depth

Density of snow layer

For this research a closer look at the density of snow is of interest. There are several density measurements known:

Filchner Ice Shelf	5 - 55 m depth	Meussen (1998)
Brunt Ice Shelf	1 - 50 m depth	Polarmar (1993)

For GvN and for the Swedish base Maudheim the relationship between density and depth was determined through a 'Rammsonde' measurement.

The measurements presented in the graph above show large deviations from the mean of the snow density within the first 2 m of snow. It indicates the non-homogeneity of the material and the randomness with which the snow layers are formed and compressed over time.

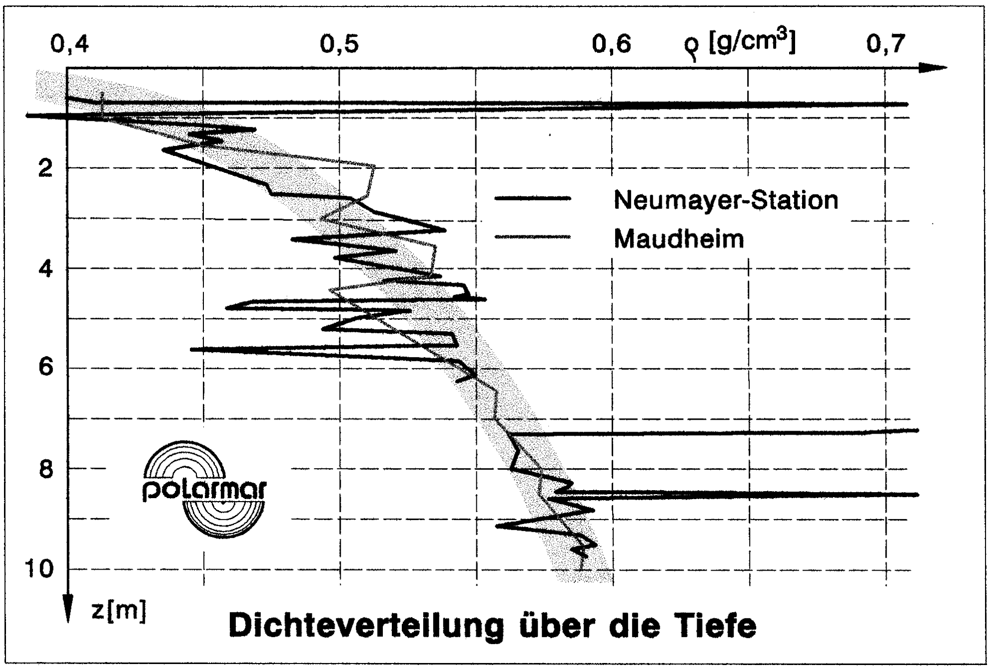


FIGURE 84: density of snow measured at GvN and Maudheim *(source: Polarmar)*

The density of snow increases in depth due to the pressure of new snow accumulation on the surface. At the location of the former AWI summer base Filchner an accumulation rate of 154 - 204 kg/m^2 per year was measured. This accumulation causes a vertical pressure on the underlying layers.

On the basis of observations the following empirical relations can be given to obtain an impression of the depth dependent density of snow:

$$\rho(z) = \rho(0) + Cd^{0.5}$$

with:

$\varrho(0) = 385.5$ kg/m^3

C = 60.1 kg/m^{3}m$^{-0,5}$

d = depth in metres

Elasticity of the snow layer

The Young's modulus of snow depends on the density and the temperature of snow. Denser snow yields a climbing Young's modulus as do lower temperatures.

Mellor (1975) has given values for the Young's modulus for sintered snow of varying density [12]. These measurements have been averaged and depicted below. A range displayed in figure 86 accompanies these average values.

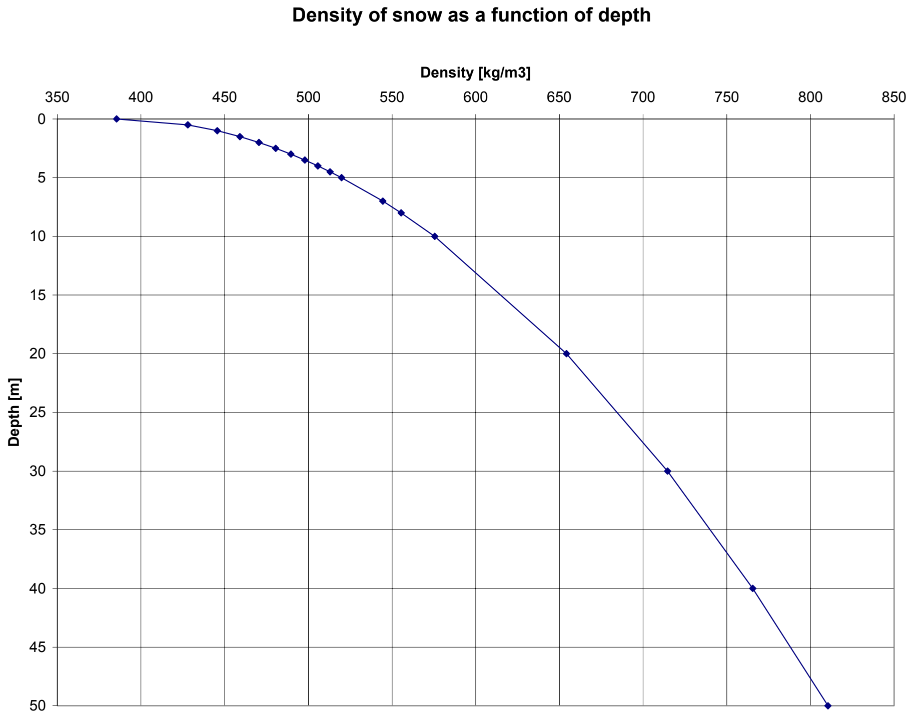


FIGURE 85: density of snow as a function of depth *(source Enß [12])*

An engineering value for the Young's modulus at the surface of an ice shelf during the summer season is $2*10^4$ kN/m^2.

The difference between elastic properties of sintered snow and natural compacted

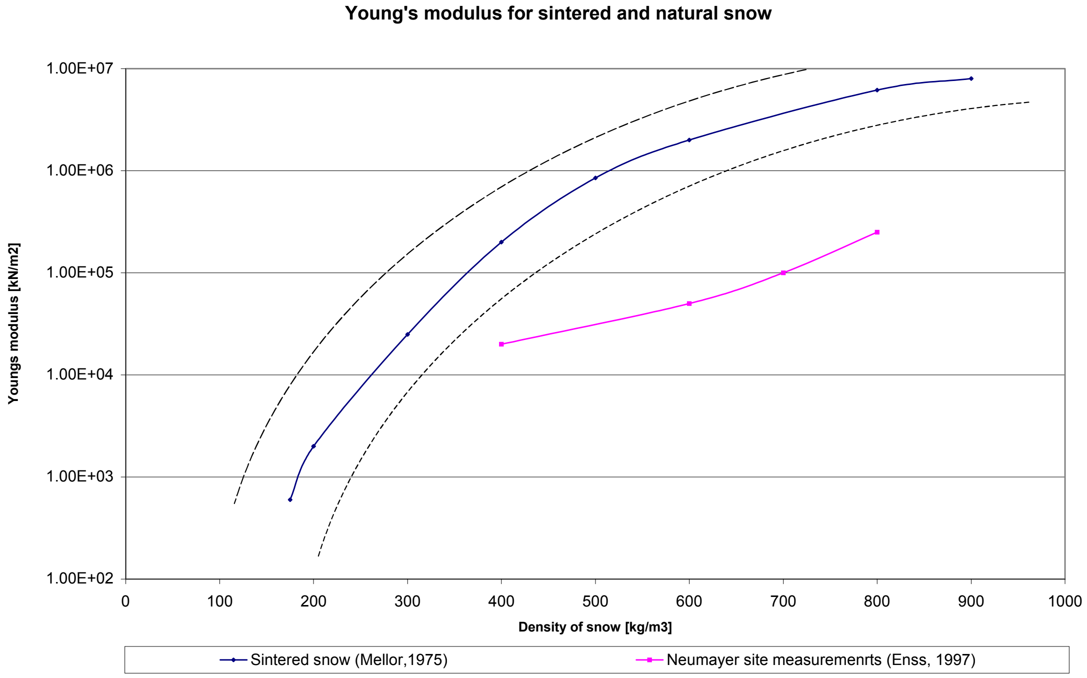


FIGURE 86: comparison of the Young's modulus of sintered snow and Neumayer site measurements *(source: Enß [12])*

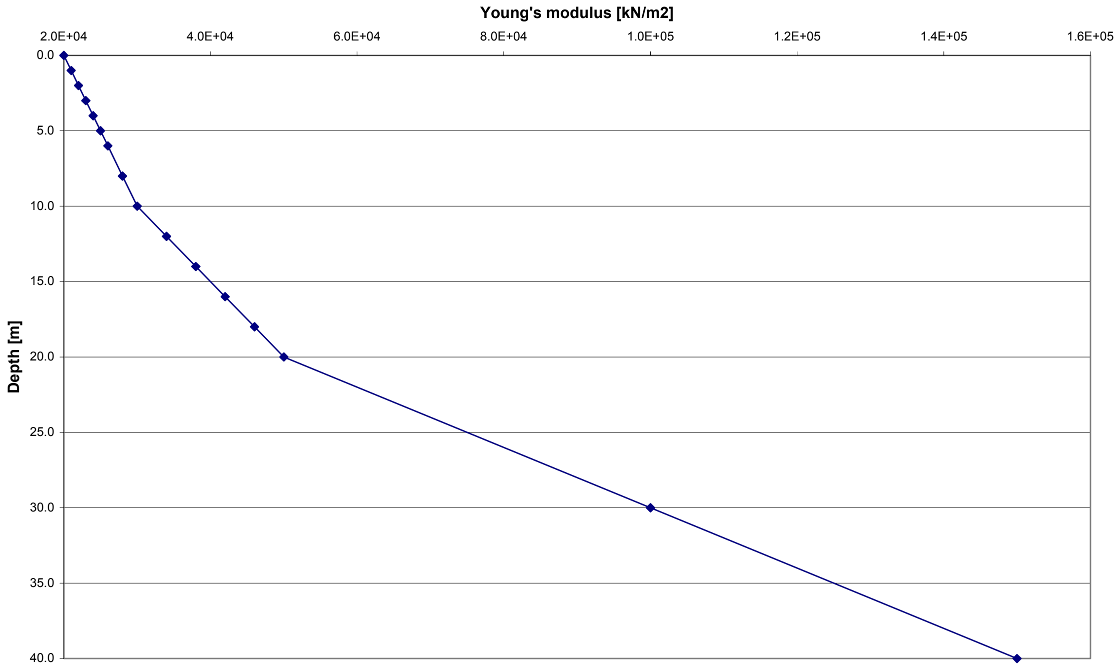


FIGURE 87: Young's modulus of ice at Neumayer Station *(source Enß [12])*

snow lies in the rate of compaction. Sintered snow is compacted mechanically and thus reaches a higher degree of compaction, leading to higher Young's moduli.

The Young's modulus measured for actual conditions at Neumayer Station is depicted in the figure below. This Young's modulus can be approximated with the following formulae:

- For 0 m < d < 10 m $E_{elast} = 1000d + 20000$
- For 10 m < d < 20 m $E_{elast} = 2000d + 10000$
- For 20 m < d $E_{elast} = 5000d - 50000$

These formulae form a line that is built up of three linear approximation intervals displayed in table 11.

TABLE 11: formulae for Young's modulus of snow at Neumayer Station

$E = A\,d + B$ [kN/m^2]	A [kN/m^3]	B [kN/m^2]
0 – 10 m	1000	20000
10 – 20 m	2000	10000
20 - .. m	5000	50000

Viscosity of the snow layer

Snow under loads initially deforms in a direct elastic manner. Slow plastic deformation will occur when the loads on snow remain for some time. This time dependent deformation is called viscous creep.

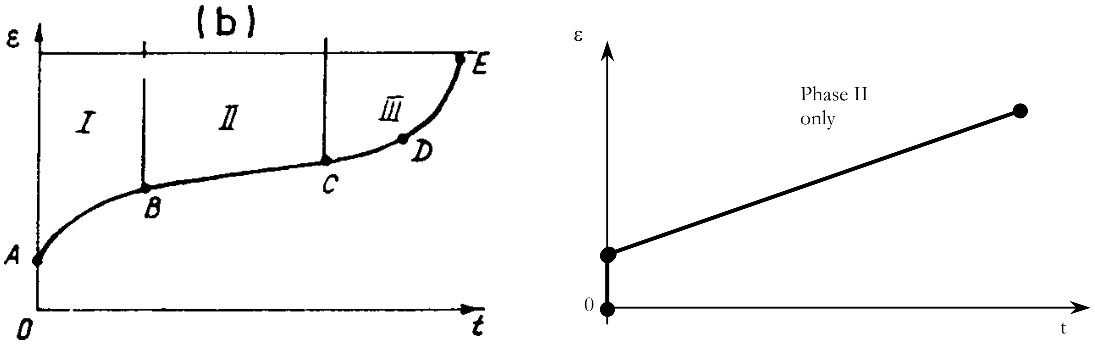


FIGURE 88: sketch of creep behaviour of ice and approximation *(source: Zaretski [43] and Saltner & Keij)*

The extent of the creep deformations depends on the stress. If the stresses are small, creep deformation is proportional to these stresses, for large stresses the deformations are more than proportional.

The creep curve is taken from tests under constant stress. Viscous creep is a time dependant phenomenon as shown in the sketch above. Three different phases can be distinguished.

I	Primary creep
II	Secondary creep
III	Tertiary creep

Due to these three phases in the creep process ice differs considerably from other materials. In order to choose proper parameters for ice for calculation purposes a linear viscous trajectory is considered. It is assumed that the primary creep phase is short and can be neglected in calculations. Also it is assumed that the ice does not reach the tertiary creep for the loads from the structure.

The behaviour of viscous creeping ice can be given in relation to the depth. This results in a viscosity parameter.

The relationship between viscosity and depth has been approximated with a fourth order function:

$$E_{visc} = a - b + c - e$$

where:

$a = 7.64d^3$

$b = 98.51d^2$

$c = 719.82d$

$e = 634.46$

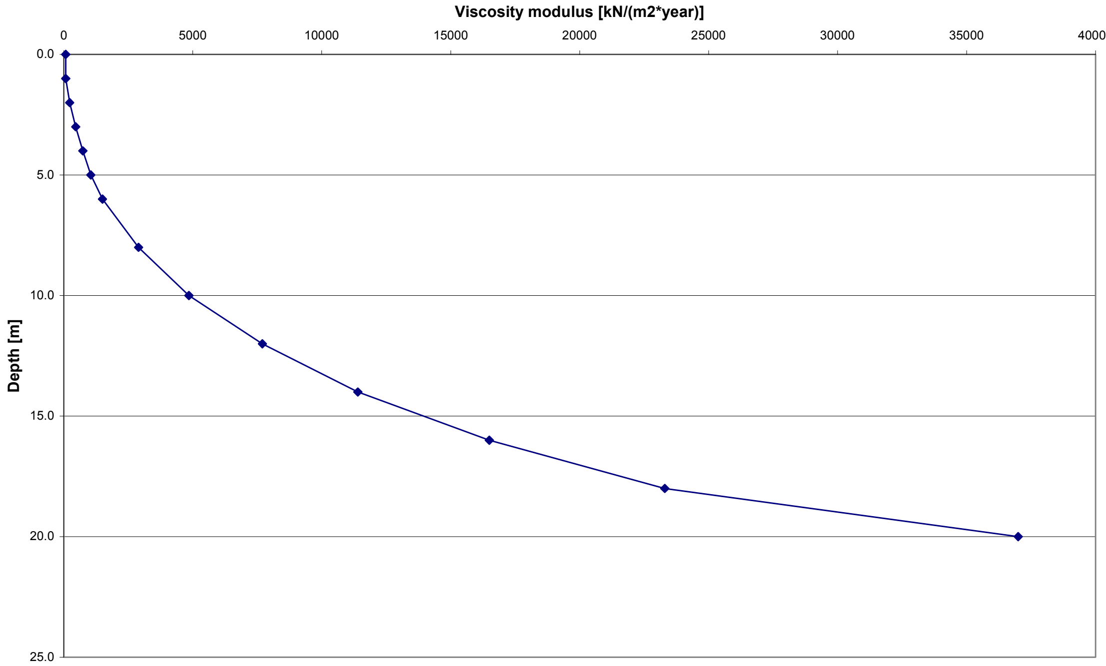


FIGURE 89: viscosity modulus of snow at Neumayer Station as a function of depth
(source: Enß, modified by Saltner & Keij [12])

This equation is valid for depths from 1 m up to 20 m depth. The simplifying assumption is made that at greater depths the increase in viscosity follows the same equation.

Measurements of parameters

Enß has performed measurements for density, Young's modulus and viscosity modulus in 1997. As can be seen in figure 86 the Young's modulus measured in the sintered case is higher than that of snow on site.

TABLE 12: snow parameters at Neumayer Station *(source: Enß [13])*

Depth (m)	Density (kg/m^3)	Young's modulus (kN/m^2)	Viscosity (kNyear/m^2)
0	416	2.0E+04	75
1	456	2.1E+04	75
2	483	2.2E+04	230
3	502	2.3E+04	463
4	518	2.4E+04	740
5	532	2.5E+04	1050
6	544	2.6E+04	1500
8	566	2.8E+04	2900

Depth (m)	Density (kg/m^3)	Young's modulus (kN/m^2)	Viscosity (kNyear/m^2)
10	585	3.0E+04	4850
12	603	3.4E+04	7700
14	619	3.8E+04	11400
16	633	4.2E+04	16500
18	647	4.6E+04	23300
20	660	5.0E+04	37000
30	710	10.0E+04	-----
40	760	15.0E+04	-----

A variation in the measurements is not given by Enß, an assumption is made based on the given order of magnitudes.

- Density of snow: ± 25 kg/m^3
- Young's modulus: ± 0.5 e+04 kN/m^2
- Viscosity modulus: ± 50%

Pressures

For vertical loads from snow the following empirical formula is used by Enß:

$$Q_v = 4.1d^{1.1} \text{ [kN/m}^2\text{]}$$

This formula can be checked when taking the measured density profile into account. From this density profile the vertical loads can be calculated with:

$$Q_v = \rho g d = (385 + 60d^{0.5})gd = 3.85d + 0.6d^{1.5}$$

The approximation by Enss is compared to the density based vertical stress. Enss values give an higher value for a given depth. This safe approximation for the calculation of the deformations will be followed.

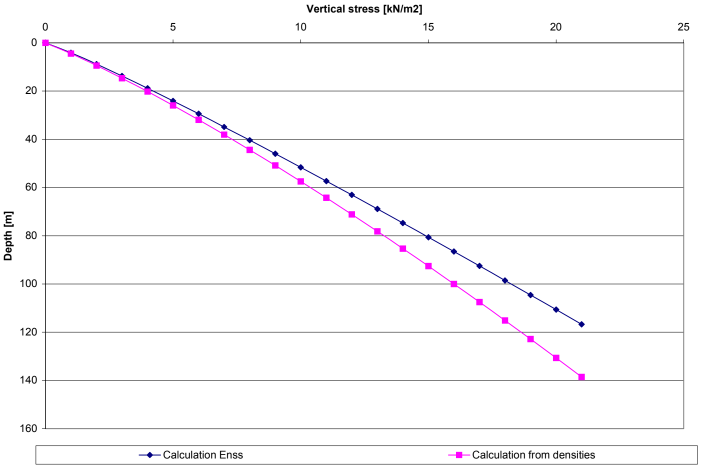


FIGURE 90: vertical stress calculations *(sources: Enß [12,13])*

The horizontal pressures are approximated with:

$$Q_h = 0.35Q_v = 1.44d^{1.1}$$

This formula uses the same relationship between horizontal and vertical stresses in ice as for clay, where the relationship between vertical stresses and horizontal stresses is equal to one third (≈ 0.35). The use of these formulae is limited for Neumayer Station because they are based on tests preformed on site.

Additional measurements of snow parameters on site

The parameters summarised in the paragraphs above are derived from either literature and or tests performed on site. They are used within this study under the assumption that no measurement errors have been found for these values. The properties of the snow next to the tubes and the variation of the properties in time after construction are not known.

Differential movements of the ice shelf

Ice moves from the higher parts of Antarctica to the sea edge. This movement generates horizontal differential forces on structures in the ice. These forces are mainly strain forces and compression forces due to differential movement of a snow/ice layer.

Structures in and on ice must be designed to cope with these forces and movements, which call for measurements and necessary design input.

Measurements are taken on the ice shelf by placing reference points on the surface and measuring the angles of these triangular shapes and their position (GPS or stars). The measurements can be interpreted to find the annual movements of the ice shelf. Predictions of future movements are usually made by extrapolating the measurements.

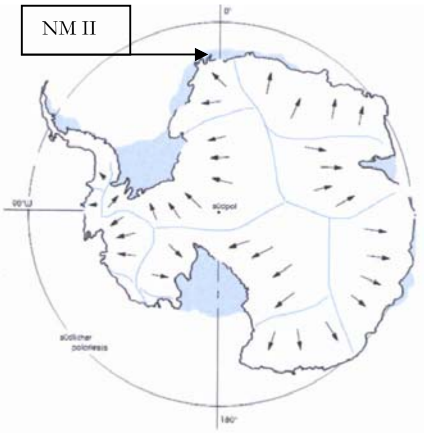
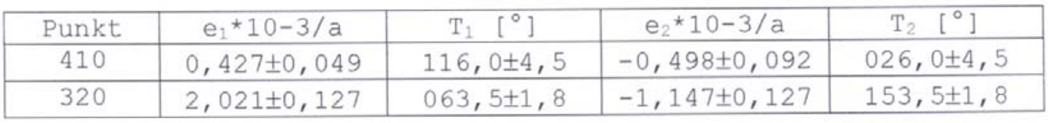


FIGURE 91: differential movement vectors *(source: Lechner [20, 21])*

The deformations of the ice shelf are measured in m per m and year (m/m year), or in promillage per year (‰/a). As applied in structural mechanics strain is defined as positive and compression negative.



Punkt	e_1*10-3/a	T_1 [°]	e_2*10-3/a	T_2 [°]
410	0,427±0,049	116,0±4,5	-0,498±0,092	026,0±4,5
320	2,021±0,127	063,5±1,8	-1,147±0,127	153,5±1,8

FIGURE 92: differential movement, measured at Neumayer Station *(source: Enß)*

At the location of Neumayer Station measurements were performed at two different points to get an idea of the differential movements. This lead to the following design parameters: The station must be able to handle a strain of 2E-03 m/m and year in East-

West direction and a compression of 1.2E-03 m/m and year in north-south direction [15].

Structural parameters

The steel tubes of Neumayer Station consist of 14 Armco plate profiles in every circle. The profile receives its rigidness against bending forces from a combination of plate thickness (d = 7 mm) and profile height (h = 55 mm).

For modelling purposes the profile's plane, it's moment of inertia and the Young's modulus must be defined (for the calculation see Appendix 3).

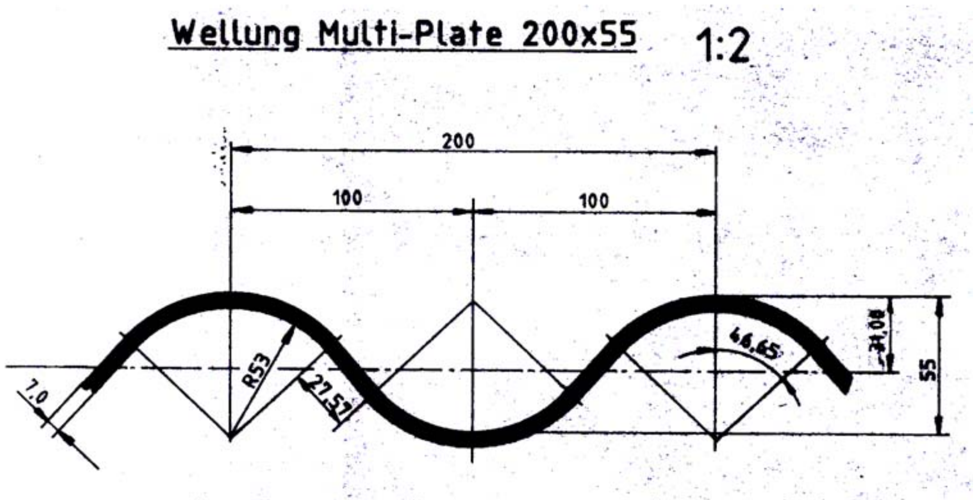


FIGURE 93: steel profile of the plates used for the outer hull of Neumayer Station *(source: Polarmar)*

E_{steel} = 2.1E+08 kN/m^2

$A_{profile}$ = 6400 mm^2/m

$I_{profile}$ = 3.0E+06 mm^4/m

Loads

There are several loads that act on the tubes of Neumayer Station. These loads can divided into:

- Service loads
- Traffic loads

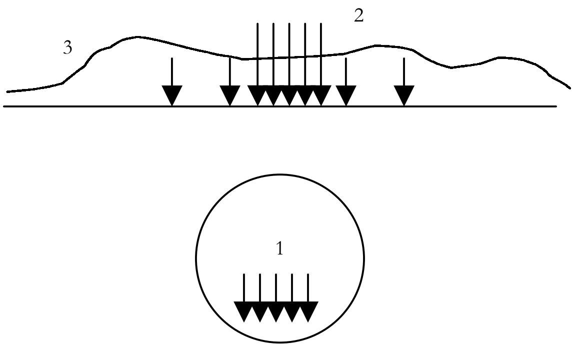


FIGURE 94: overview of types of loads on the tube *(Saltner & Keij)*

- Environmental loads

Service loads

Loads due to the use of the base can be described as loads from activities in the hull and on the hull itself. These loads vary per container according to its function and its use.

An estimate of the weight per container is given below in metric tons (1 metric ton equals 10 kN/m^2) [*Enß, 2001*]:

Fuel container	19 metric tons	(= 190 kN/m^2)
Power generator	12 metric tons	(= 120 kN/m^2)
Storage containers	9 metric tons	(= 90 kN/m^2)
Snowmelter	9 metric tons	(= 90 kN/m^2)
Water tank containers	9 metric tons	(= 90 kN/m^2)
Air-conditioning	9 metric tons	(= 90 kN/m^2)
Other technical	8 metric tons	(= 80 kN/m^2)
Laboratories	7 metric tons	(= 70 kN/m^2)
Living shelters	6 metric tons	(= 600 kN/m^2)
Other	6 metric tons	(= 60 kN/m^2)

The utilisation loads are transferred to the outer hull by the steel cylinders that are part of the platform structure that carries the containers. The loads on the cylinders on the outer hull vary from 49.3 kN to 91.3 kN per cylinder. A value of 100 kN per cylinder is taken for calculation purposes.

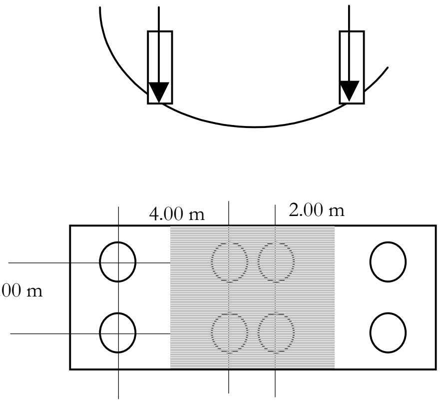


FIGURE 95: vertical load distribution over bottom of tube *(Saltner & Keij)*

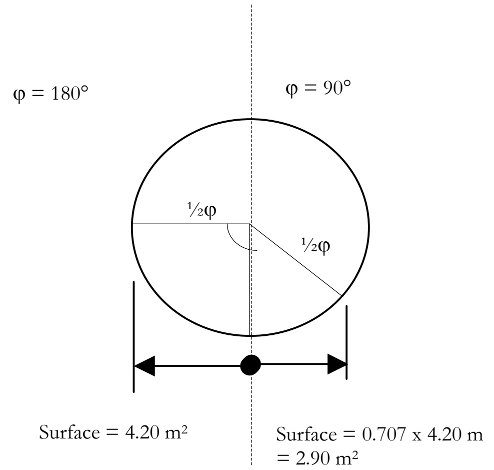


FIGURE 96: calculation of total vertical load *(Saltner & Keij)*

To obtain a value for the total vertical load from the structure (container, steel cylinders and steel hull) upon the ice the least favourable case is considered.

At the bottom section of the tube the steel cylinders are located as shown in figure 95. The distance between the two cylinders amount to 4.00 m in longitudinal and crosswise direction, followed by cylinders with a distance of only 2.00 m in longitudinal direction (see also Chapter 4).

At these points four cylinders are within 2.00 m of the tube. Under the assumption that the tube distributes the load evenly over the underlying snow the load of 400 kN is converted to 2*8.40 m = 16.80 m^2, making the total maximum load 20 kN/m^2.

When the load is not distributed evenly (over 180°) but over an angle of 90° [*Springler*, [19]), the total area that is subject to loading is reduced with 30% to 5.93 m^2. This means the maximum stress is increased to 28.30 kN/m^2.

For the weight of the cylinders and the tube itself a percentage is added making the total pressure from the tube on the ice 30 kN/m^2, well below the design maximum of 33 kN/m^2 [*Enß*].

Traffic Loads

Traffic loads in and around the base are approximated with 12 kN/m^2. For activities inside the steel tubes a load of 2.50 kN/m^2 is taken into account.

Environmental loads

The environment poses engineering challenges on the structure. The different loads due to the environment (wind, snow and temperature) will be presented and their consequences on the deformation calculation will be shown.

Wind loads

The following data are available regarding the wind on site:

- Main wind direction (95% of the strong winds) 082° to 090°
- Other directions of strong winds 170° to 240°
- Maximal wind speeds for calculations:
  - v = 61 m/s for directions from 070° to 100° and 160° to 250°
  - v = 33 m/s from all other directions

Neumayer Station is a sub-surface research base and was already covered with snow directly post-construction of the base. The effect of wind loads on the outer hull will thus not be taken into consideration.

Snow accumulation

The annual snow accumulation is 0.75 m per annum, which is an equivalent water mass of 320 kg/m^2/year. Snow measurements at Neumayer Station are performed since 1992 and a distribution of the snow accumulation can be determined.

An overview of the annual accumulation of snow as well as the cumulative snowfall is given in the table below. These rates are considered to be distributed according to a standard normal distribution.

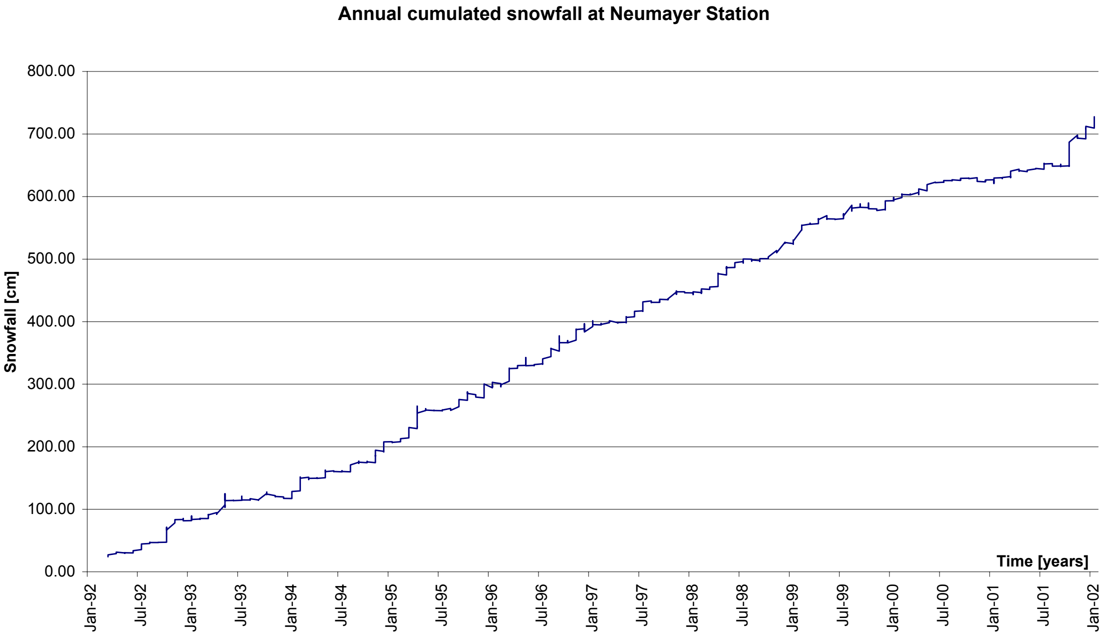


FIGURE 97: annual cumulated snowfall at Neumayer Station (Pegelfeld Süd) *(source: AWI)*

When the normal distribution is assumed, the variation in accumulation rates per year can be defined with a mean and a standard deviation. This has been calculated to be:

Annual snow accumulation = N(μ = 70.949 cm ; σ = 30.443 cm)

TABLE 13: snow accumulation as measured at Neumayer Station *(AWI, 2002)*

	Snow accumulation [cm]	Snow accumulation annual [cm]
Jan-92	0.00	0.00
Jan-93	81.89	81.89
Jan-94	117.19	35.30
Jan-95	207.89	90.70
Jan-96	294.21	86.32
Jan-97	392.17	97.96
Jan-98	445.87	53.70
Jan-99	524.69	78.82
Jan-00	593.43	68.74
Jan-01	626.49	33.06
Jan-02	709.49	83.00

This means that in 64% of the years an annual snow accumulation will be expected of between 40 and 100 cm.

Temperature loads

The temperatures measured at Neumayer Station differ according to the seasons:

These differences in temperature have different effects on areas within and around the base. Four areas can be distinguished:

1: Snow surface:

Temperatures at the snow surface range from -50ºC to +5ºC.

2 Snow cover:

Temperatures of the snow cover are less cool than the outside temperatures. The annual snow temperatures vary between 0ºC to -15ºC.

3 Steel hull:

The inside of the steel hull is not heated or air-conditioned and thus its temperature is equal to the temperature of the surrounding snow. Due to heat produces inside the tube some variations can occur. Temperatures inside the steel hull vary between 0ºC to -10ºC

4 Containers:

The working and living quarters are heated to provide normal living conditions. Temperatures vary between +15ºC and +25ºC

Loads for calculation

For calculation purposes the stress exerted on the ice due to the total weight of the tubes is taken as an average value of 30 kN/m^2, measured over the total length of the tubes.

No temperature effects will be taken into account, assumption being made that area 3 has the same temperature as area 2.

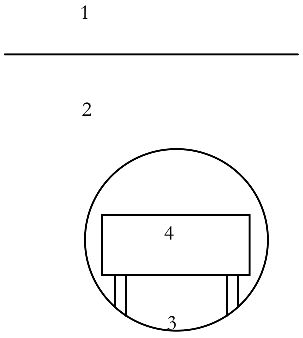


FIGURE 98: temperature zones within Neumayer Station *(Saltner & Keij)*

Survey of the Deformations of Neumayer Station

Surveys conducted at Neumayer Station

To assess the deformations of the Neumayer Station a survey programme was set-up in 1992, which has been carried out every half year to present.

During this survey the following measuring points at Neumayer Station are surveyed:

- bottom of the tubes (inside dimensions)
- top of the roof (inside dimensions)
- horizontal dimensions of the tubes
- levelling of the snow elevation above the base

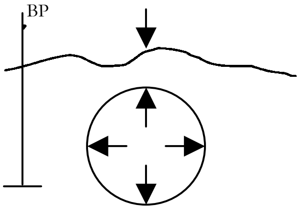


FIGURE 99: required measurements at Neumayer Station *(Saltner & Keij)*

The survey is a standard levelling survey using standard instruments. At Neumayer Station the elevation of the measuring points are calculated back to the 'Baupegel' (BP) - a plate that was buried when building Neumayer Station - and has been used as a set reference ever since.

The horizontal dimension of the tubes and the diagonals at the intersection points are determined using a measuring tape where opposite measuring points are accessible. In tube sections where containers are placed the horizontal dimensions cannot be measured directly. In this case the distance between the container and the tube hull is determined with a measuring tape. These measuring points are specially marked both at the tube and at the container. The horizontal dimensions can now easily be calculated adding the length of a container (6064 mm) between these points.

An overview of all measuring points at Neumayer Station is given in Appendix 5.

Standard measuring points

During the construction and after completion of the Neumayer Station a large number of measuring points, relevant for the analysis of the changes in shape and height of the station, have been marked and measurement using this initial data has been conducted. These measuring points are distributed over the circumference and length of the tubes in a way that the interpretation of the measurement results enables inference as far as the changes in shape and position of the tubes are concerned [13].

The measuring points are marked as shown in figure 100:

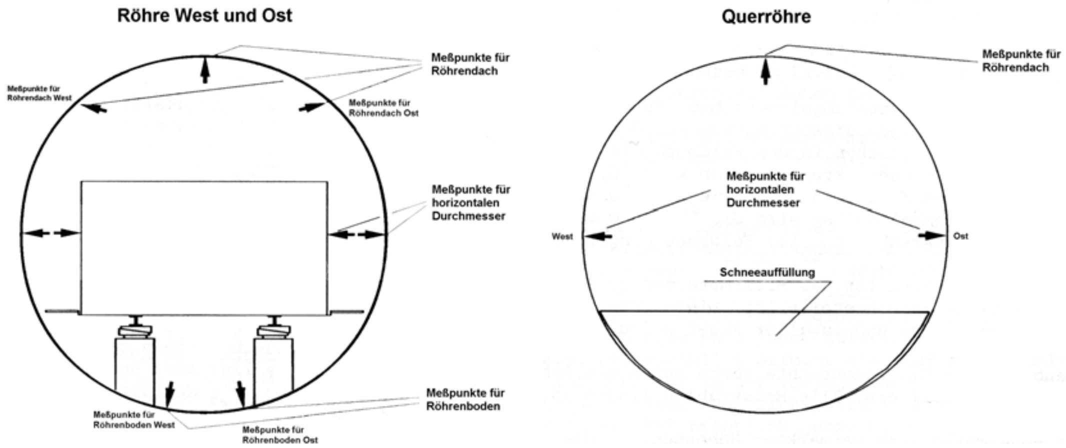


FIGURE 100: measurement points inside the circumference of the steel hull *(source: Polarmar)*

A comparison of early measurement data from 1992 and 1993 shows that, as expected, the tubular structure undergoes changes in shape and position in the firn. The measurement data collected during the following years give insight into the changes in displacements and make it possible that the planned lifetime of the station can actually be verified.

The survey is conducted twice a year, taking into account that measurements taken during the Antarctic summer season fit logically into a measurement programme because all former data has been collected during this period of the year.

Special measuring points

Within this surveying several measuring points are not mentioned because it is not necessary to include them regularly in the measuring. These measuring points are found on the roof and the foundation of the vehicle hall, at the joints of the base course of the containers and of the steel substructure of the tubes as well as in the tunnels. Measurements concerning these points are conducted by AWI personnel only and follow special requirements.

Calculations with the survey results

The data is prepared to give an overview of the station deformation status. For this the following usual surveying equations are used.

Calculation of the elevation of the measuring points

During the surveying the so called prospect from levelling instrument to the measuring point and the retrospect form measurement point back to a new level for the levelling instatement are noted in the notepad. The vertical position of a measured point is determined using equation:

$$\text{height}_{new} = \text{height}_{known} + \text{height}_{retrospect} - \text{height}_{prospect}$$

To assure the quality of the measuring it is important to integrate the starting point in the measurement. In case of an accurate measurement the last reading should come to terms with the initial height. Small deviations, up to ± 2 mm per relocation of the instrument are acceptable and are usually rebalanced. To do this first one must calculate the total measurement error from start of measurement to end of measurement. This is done by comparing the heights of the original level (BP) with the calculated BP at the end of the measurements. This check will result in an error that can be equally divided over all relocations of the levelling instrument.

Measurement of the horizontal dimensions of the tube

Usually the horizontal tube diameter can be determined directly using a measuring tape. In cases that containers are placed in the tube the distances between containers and tube hull are measured and the total horizontal diameter can be determined using equation:

$$\text{distance}_{tube-hull,east} + 6064mm + \text{distance}_{tube-hull,west}$$

A container width of 6064 mm is taken from the standard ISO containers that are used.

Results of survey calculations 2001/2002

The results of the measurements can be given in different formats. In all measurements the data need to be calculated back to the BP to be comparable. The formats that are possible and useful depend on the future user. Here the user will be defined as the Logistic Department of the AWI, using the data as a foundation for the evaluation of the end of lifetime of Neumayer Station.

An overview of the tubes in an x-y plane for different years gives a good insight in the total deformations for logistic use. Issues regarding local problems with differential settlements can be foreseen using these graphs.

The results of the measurements for the Antarctic season 2001/2002 have been summarised in a report [31, 32, appendices 6 and 7) and these data have been added to the measurement history dating back to 1992, forming a basic analysis. For the period 1992 – 2001 the following overviews are given in this basic analysis. For reference to the axis of the tube see figure 54 in Chapter 6:

East and West tube

- bottom of tube, West side
- bottom of tube, East side

- roof points, East side
- roof points, West side
- roof points, ridge

(All given for each year as function of the x-co-ordinate within the tube)

- subsidence of the bottom points at a certain x value
- subsidence of the roof points at a certain x-value

(Given as a function of time)

- horizontal dimension of the tube as a function of x
- horizontal dimension of tube at a certain x-value as a function of time

Tank hall and crosswise tube

- bottom of tube related to x co-ordinate
- roof of tube related to co-ordinate
- horizontal dimension related to x co-ordinate

A summary can be made for profiles within the tube. These profiles can be depicted in one graph, showing the deformation of the station in time. An example is given in the table below:

TABLE 14: average deformation of the tubes in time

	East tube	West tube
Bottom of the tube (1992)	1400 mm	1400 mm
Bottom of the tube (2001)	2300 mm	2400 mm
Roof of the tube (1992)	6400 mm	6400 mm
Roof of the tube (2001)	5300 mm	4900 mm

When the global deformation behaviour is considered the East tube deforms less than the West tube. This means that the deformations of the West tube will be critical for the lifetime of the base.

For the analysis in this research the West tube has been chosen as typical for the tubes of Neumayer Station and to use the data of the West tube for the model.

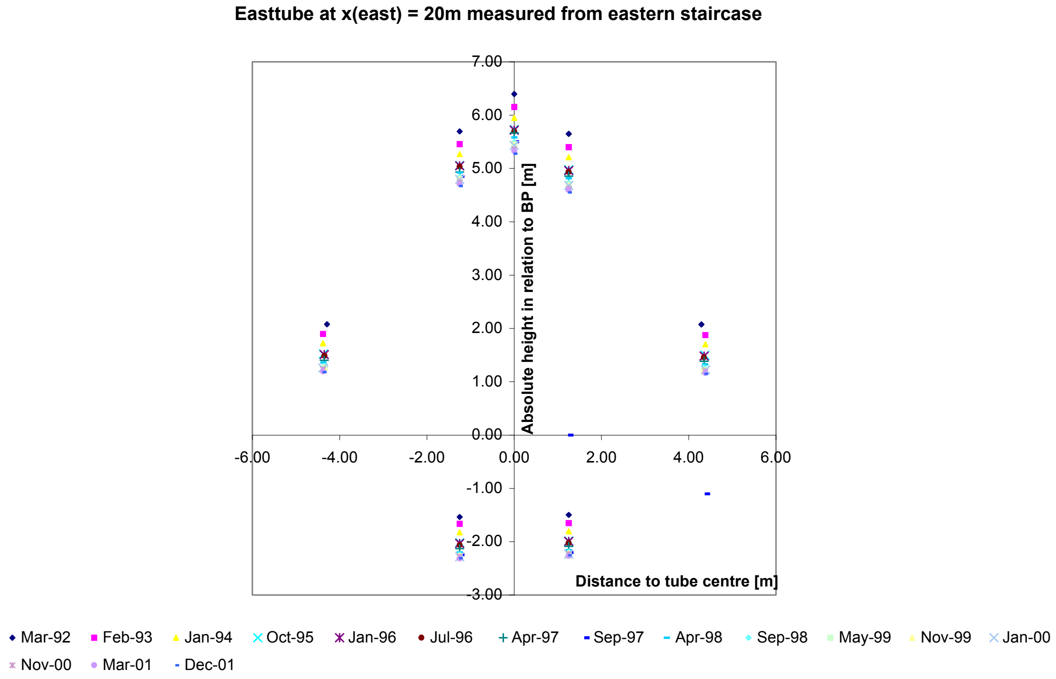


FIGURE 101: cross-section of the East tube, defined by measuring points in time *(Saltner & Keij)*

Thesis study graphs

The graphs needed for this study are graphs of deformations in a profile over time, a t-y plane. In time the varying parameters that are of influence for the deformations of the base are the time dependent top loads on the tube and the loads inside the tube.

The loads inside the tubes are assumed to have an unchanging standard value. The loads on the tubes consist mainly of the loads from snow that accumulates on the tubes.

For modelling purposes in time an average tube profile will be used. This means that the tube will be schematised:

- to have a top load q(t) that is independent of space and equal to the stresses caused by the average snow accumulation in time
- with an inside load that is also constant over space equal to the average service load.

The output of such a model must be evaluated to an average tube deformation profile. This can be done when taking all measurements along the tubular axis into account. Averaging the data over the length of the tube gives average deformation behaviour of the whole tube in time. This average deformation profile is depicted below:

The average deformation behaviour that is depicted above will be used to calibrate the model made for the Neumayer Station. From the graph a few remarks can be given:

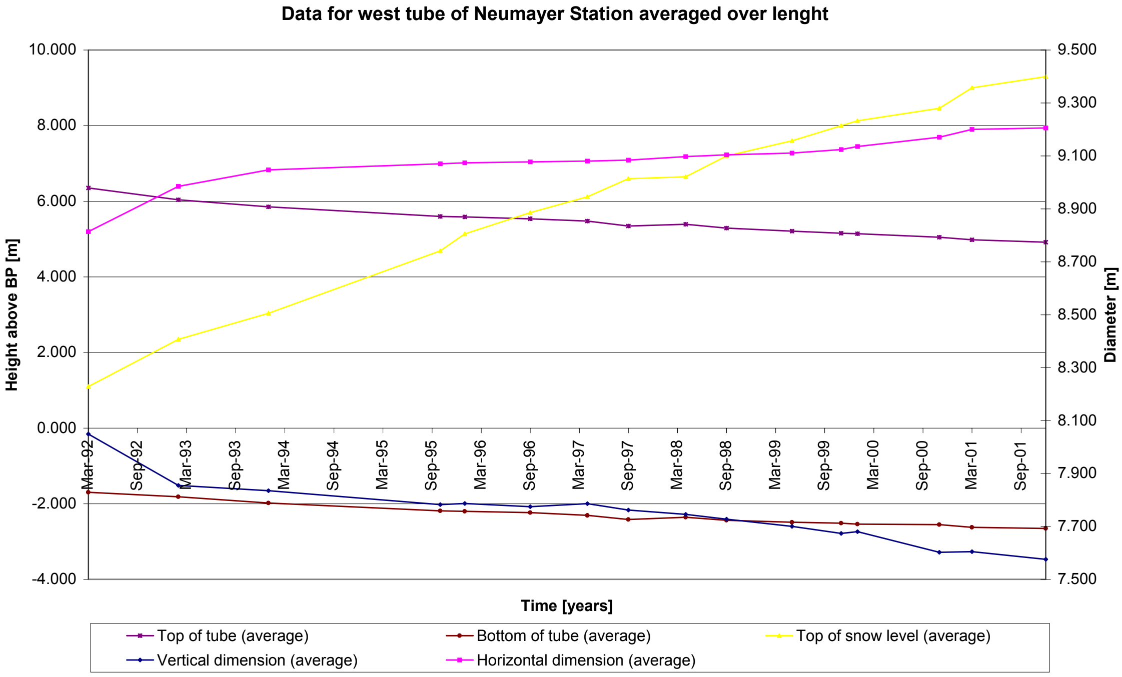


FIGURE 102: average height, dimensions and snowfall for the West tube *(Saltner and Keij)*

- Behaviour of horizontal and vertical dimensions answers to expectations. Due to higher loads the horizontal dimension increases and the vertical dimension decreases.
- The snow at Neumayer Station does not fully cover the tubes until the middle

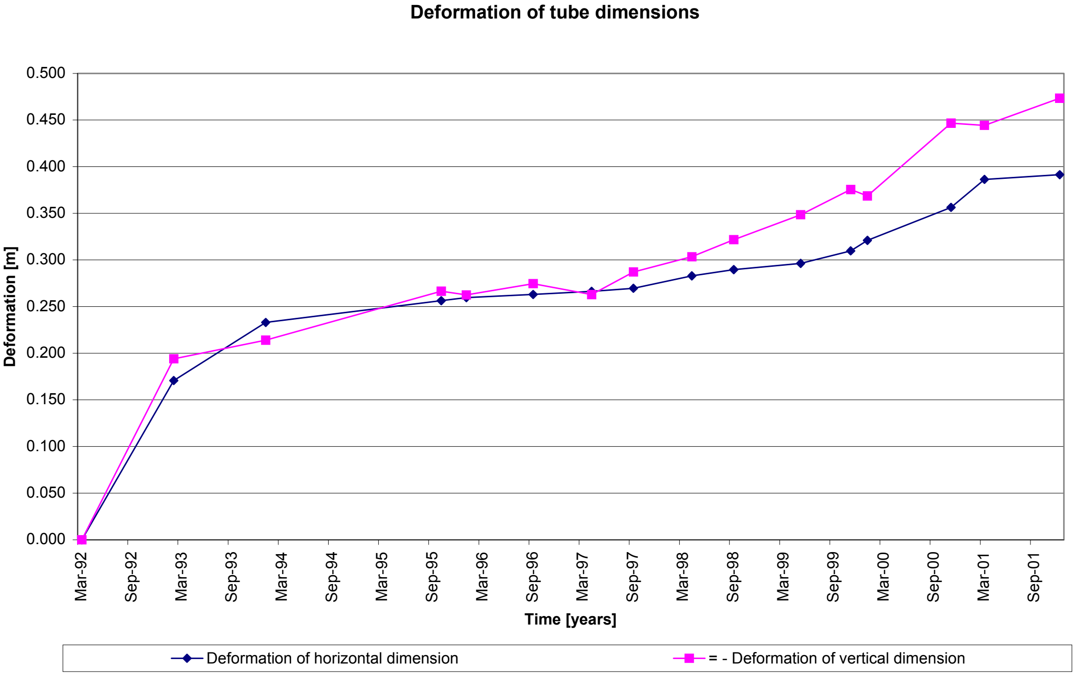


FIGURE 103: average deformations of the horizontal and vertical deformations of the tube *(Saltner & Keij)*

of 1996. Until this time a layer of snow placed during construction covers the tube.

- The deformation of horizontal and vertical dimensions has the same value and a different sign until September 1996 after which the vertical deformation slightly exceeds the horizontal deformations.

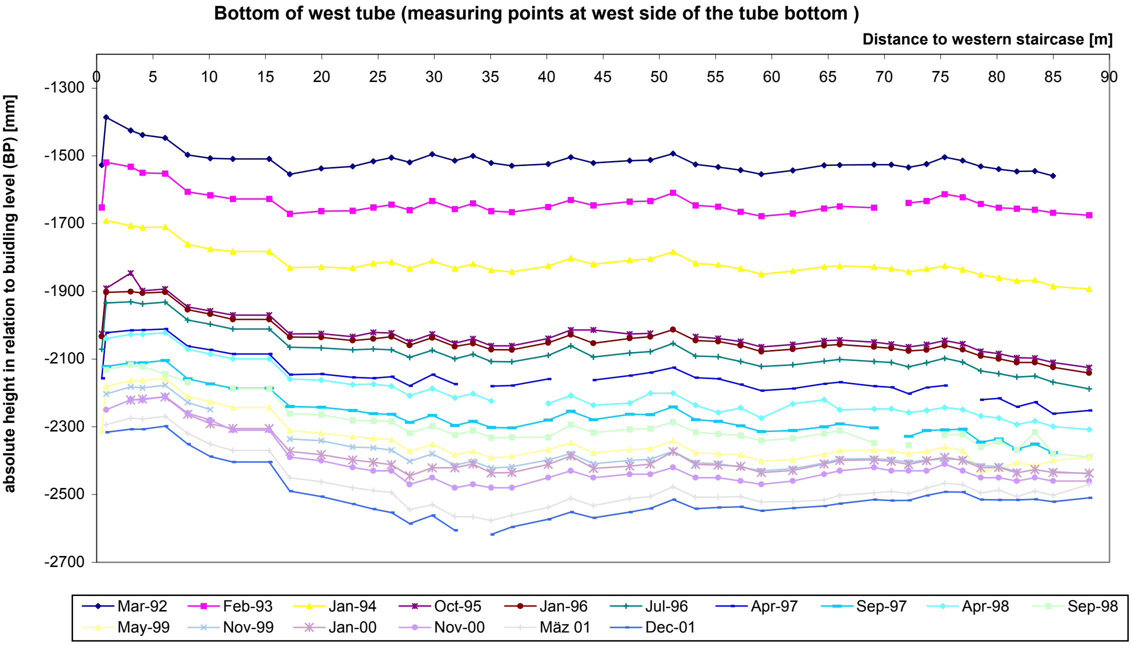


FIGURE 104: settlement of the West side of the floor of the West tube *(Saltner & Keij)*

In the model these aspects will be used to describe the different phases of deformation.

Observation and discussion of excess deformations

Next to the calibration of the model in this study, the measurement programme is used to observe and monitor the deformation behaviour and the present state of the tubes. This section will briefly describe some issues that were found during the measurements in the season 2001/2002. These issues were discussed in the report that is given in Appendix 7.

Settlements of the tubes

The settlements of the tubes are also depicted in graphs. These graphs show the slow settlement of both bottom and top of the tube in relation to the building level (BP). The graph below shows the output data for the bottom of the West tube (figure 104) and East tube (figure 107).

The main conclusion is that the East tube settles into the ice at the same pace throughout the whole tube, whereas the West tube has an interval at which the settlement is faster than the rest of the tube. This interval is between x (West) = 25 m and 35 m. The interval with greater settlement can be explained by the use of the snow

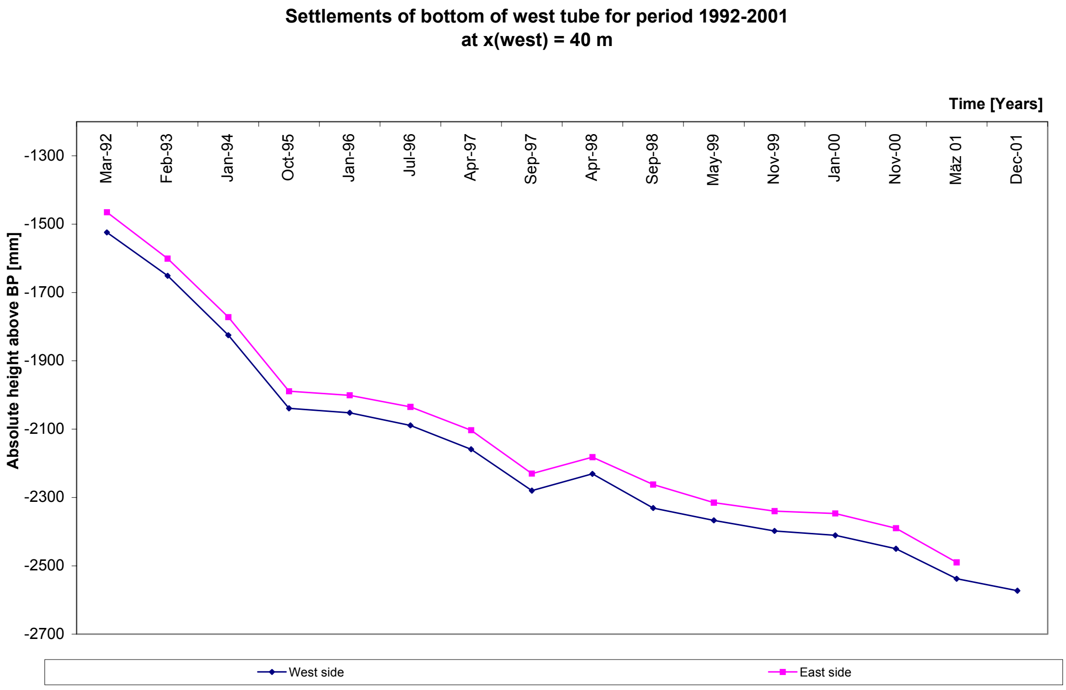


FIGURE 105: settlement of the bottom of the West tube (East and West side) *(Saltner & Keij)*

melter. This machinery is located at x (West) = 30 m, and is subject to dynamic loads from snow thrown down several times a day.

In these graphs the holes in the curves result from measuring points that could not be

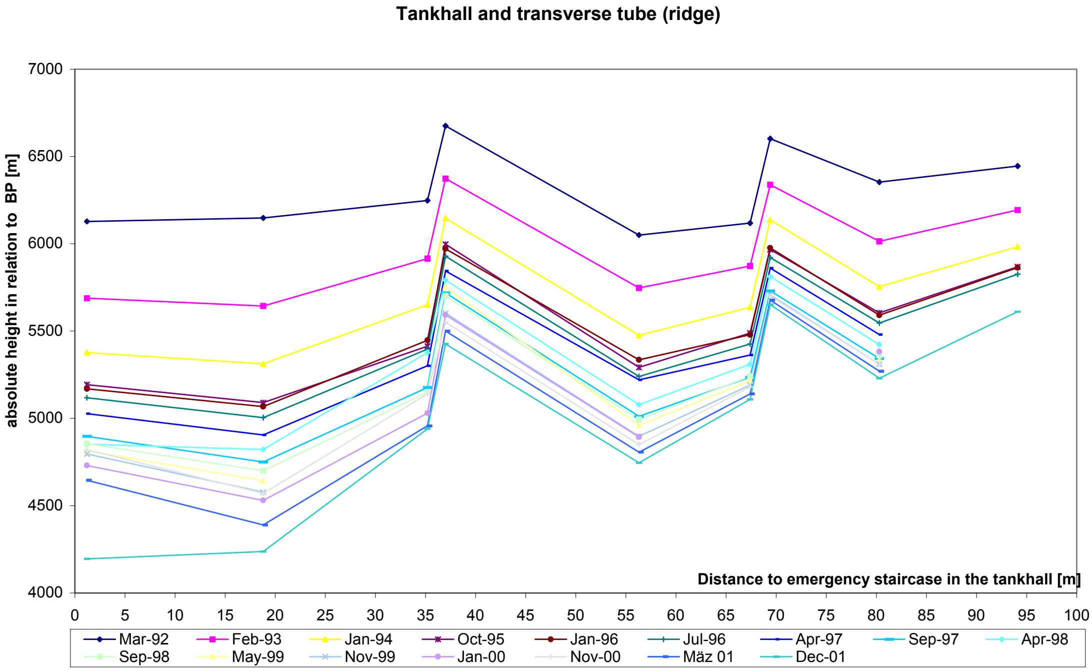


FIGURE 106: settlement of the crosswise tube and tank hall *(Saltner & Keij)*

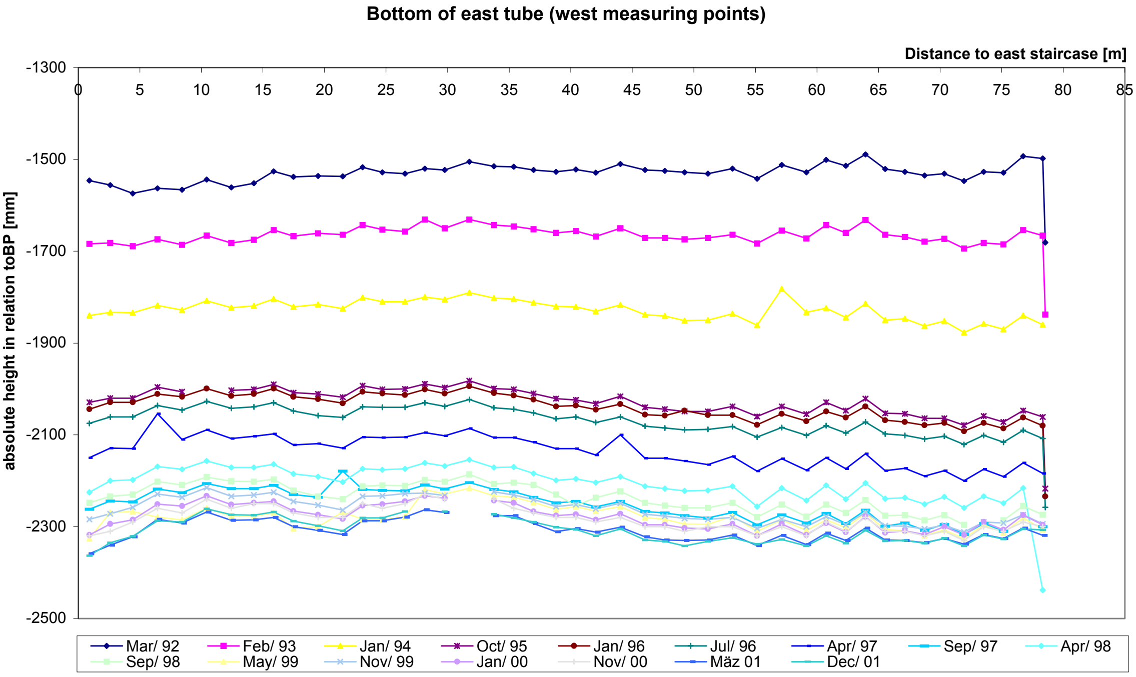


FIGURE 107: settlement of the West side of the East floor of the East tube *(Saltner & Keij)*

reached or were discarded due to recognisable measuring errors.

Differential settlements

When looking at the total settlement of the bottom of the West tube in time the graph depicted in figure 105 can be made. This graph would indicate that the West side of the tube is positioned lower in the snow than the East side. However, the measurement also indicates that this difference in elevation does not grow in time. It is therefore safe to assume that the differences in height of the points on the West and East side of the tube lie in the locations that have been chosen when building the base. Settlements are derived from these graphs; an example is given in figure 103.

Connections within tubes

In the graph for the transverse tube the influence of the connections with the West tube (at x = 35 m) and the East tube (at x = 68 m) on the deformations is visible. Where tubes are joined there are closure walls. These closure walls have foundation plates and therefore the settlement is less. The settlement of the rest of the transverse tube is suspended between these partition walls as big beams.

Measurement differences

Different persons carry out the measurements at Neumayer station annually. This leads to small differences in the execution of the measurements, which may lead to measurement errors. In the graph of the eastern tube, one can clearly see the measuring errors that haven been made in April 1997. The points at x (East) = 5, 44 and 63 m are obviously 30 cm too high. This can be explained when the levelling rod is not placed exactly on the measuring point, but on the corrugated steel bend over this point.

Conclusions for the measurement programme

The measurement programme at Neumayer Station is performed twice a year. This has been executed from the year of construction up to this time.

A measurement programme depends heavily on the operators of the base to execute a thorough survey. Because of the little time to hand over the stations' operation during the short summer season, the measurement programme, to be conducted in the middle of the winter must be clear to the stations technical staff. Other ways of performing the survey, involving different solutions for defining points and other orders of measuring the separate measuring points can lead to differences.

The measurement tools that are used at Neumayer Station are basic surveying equipment. Aging and use of such equipment can cause wear and inaccuracies. Observed measurements involving the survey rod indicate that at certain places the verticality of the rod cannot be guaranteed to satisfaction. Use of a water level on the rod can facilitate this.

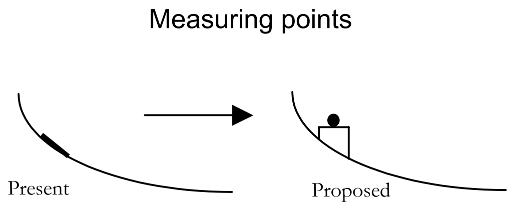


FIGURE 107: proposal for measurement points set-up *(Saltner & Keij)*

A recommendation for a better result with a future-measuring programme is the use of small fixed measuring point surfaces. At present, points are sprayed on the hull, leaving room for interpretation by the surveyor as to the exact location. With a fixed small surface this difference would not occur. Nor would there be a problem to keep the rod on the same point when making a prospect and retrospect view means having to turn the rod horizontally.

The results of the measurement programme at Neumayer Station show a clear advantage of a long and extensive survey. The deformations of the base are well monitored, and the adjustments to staircases and ventilation shafts can be made fit for purpose. A sub-surface base, as well as a base above ground can benefit from carrying out a measurement programme like performed at Neumayer Station.

Modelling Deformations of a Tubular Structure in Ice

Two phenomena can be considered to cause the deformation of the tube's profile. These two phenomena are:

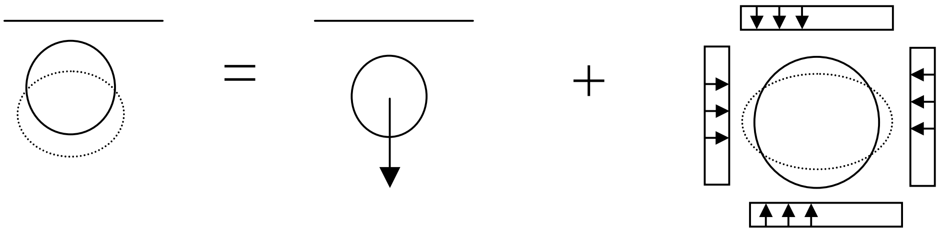


FIGURE 109: deformation of the tubular base profile divided in two phenomena *(Saltner & Keij)*

- Subsidence into the ice of the whole tube due to elastic and viscous deformation of the ice layers underneath the tube.
- Deformation of the tubular profile due to elastic reaction to top loading followed by horizontal viscous deformation.

The deforming tube suffers from extra subsidence by viscous deformation of the underlying ice strata. The deformation types are discussed separately and thus will be modelled separately. The two load cases are assumed to be non-interactive so that superposition of the separate models is valid.

A model for viscous deformation of snow layers

The viscous deformation of the snow layers under the tube is caused by stress resulting from the weight of the tube itself and loads on the tube by the snow on top.

For the total strain we will use a model for a linear elastic-viscous material:

$$\varepsilon = \varepsilon_e + \varepsilon_v t$$

with:

ε_e = Elastic strain

ε_v = Vicious strain

t = time

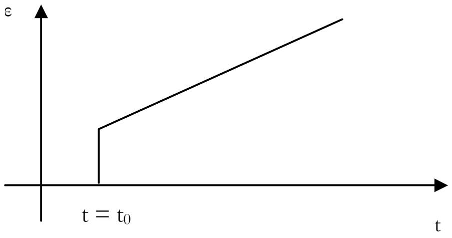


FIGURE 110: viscous deformation, schematic *(Saltner & Keij)*

Hooke's law can be used to describe the elastic strain:

$$\varepsilon_e = \frac{\sigma}{E_{elast}}$$

In this equation σ is the stress and E_{elast} is the elastic Young's modulus.

Newton's law quantifies the viscous strain rate that can be calculated with:

$$\frac{d\varepsilon}{dt} = \frac{\sigma}{E_{visc}}$$

Here σ is the stress and E_{visc} is the viscosity modulus, measured in kN/m^2 per year.

Global viscous strain for snow will occur only when the stress exceeds 100 kN/m^2. This means that elastic deformation will occur to a certain depth only, and after the vertical stress has exceeded the limiting value, viscous strain will occur.

The reaction of an ice layer with E_{elast} and E_{visc} can be calculated. This reaction will thus consist of an elastic part and a viscous part.

The scope of this thesis project does not include third order viscous effects. A simplifying assumption has been made that these effects can be discarded although they will lead to higher deformations.

Modelling a rigid tube in viscous material

To model the viscous settlement, a distinction is made into two phases of deformations during the stations lifetime. These two phases are the 'covering phase' and the 'covered phase'.

In the 'covering phase', the station is slowly covered by snow due to annual accumulation and additional wind accumulation due to wind blockage by the structure above the surface. In this phase little data is available on the exact snow cover on the station. What can be obtained from the graph in Chapter 10 (figure 102) is the fact that

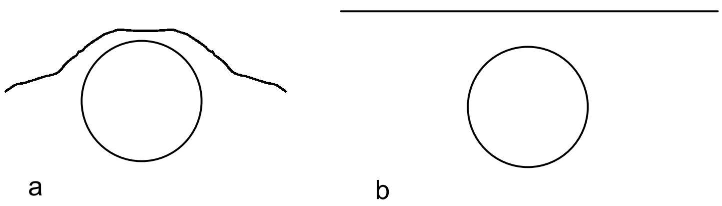


FIGURE 111: Neumayer Station during the (a) 'covering phase' (1992-1996) and (b) the 'covered phase' (1996 to present) *(Saltner & Keij)*

in 1996 the snow cover reaches the top of the tube, marking the end of the 'covering phase'.

The covered state of Neumayer Station takes place from 1996 onwards. The total snow cover on the station can be considered equal to the accumulated snow from this date.

With these two phases a settlement model can be made based on the equations presented earlier in this section. The calculation will use a non-deforming, rigid tube of diameter 8.40 m, which settles into the ice layers.

In the explanation of this model, first the 'covered phase' will be treated, after that the 'covering phase' will be added.

Calculation of the 'covered phase' for 1996 - present

For the 'covered phase' the following calculation procedure will be followed:

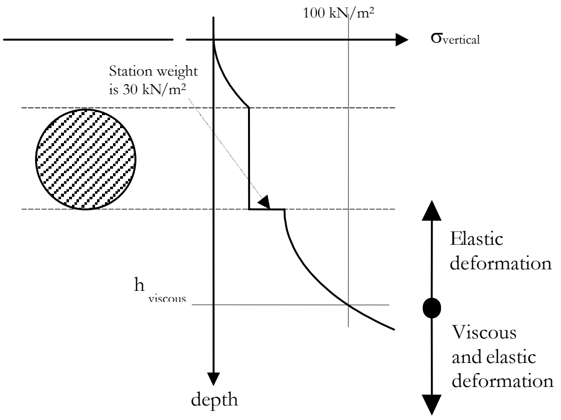


FIGURE 112: calculation of the 'covered phase' (from 1996 to present) *(Saltner & Keij)*

1. Calculation of the total vertical load on the tube:

Q_v (h)= $4.1h_{over}^{1.1}$, taken from Chapter 9, is the total vertical load per m^2 with h_{over} = the total accumulated snow from t = 1996.

2. Calculation of the total vertical load under the tube:

Total load is $Q_v h_{over}$ + 30 kN/m^2 from activities inside the tube. This load acts at a depth of h_{over} + 8.40 m.

3. Determining of the depth $h_{viscous}$ at which the vertical load equals the viscous initiation load of 100 kN/m^2:

After calculating the additional load needed to reach initiation of viscous behaviour from the vertical load under (2), one can use the formula for the vertical stress of snow to determine at what depth this stress is reached.

4. Calculation of the deformations as a function of depth:

From $h_{viscous}$ down, the equation below can be used to calculate the annual total deformation.

$$\varepsilon(t) = \varepsilon_e(t) + \varepsilon_v t = \frac{\sigma_v}{E_{elast}} + \frac{\sigma_v}{E_{visc}} t$$

The ice is divided into layers of 0.10 m. For each layer σ_v, E_{elast} and E_{visc} are calculated using the formulae presented in Chapter 9. The accumulation data are given in years, so a first estimate for the time step is one year. Due to this choice the total deformation equals:

$$\varepsilon = \frac{\sigma_v}{E_{elast}} + \frac{\sigma_v}{E_{visc}} = \frac{\Delta l}{l}$$

The total vertical deformation under $h_{viscous}$ equals the deformation of the layers multiplied by layer thickness, summed over the depth.

An estimate is made for the depth of calculation that is needed. For a general load case (3 ms of snow) the viscous effects take place at a depth of 21 m. At this depth the initiation load of 100 kN/m^2 is reached.

A 20-m snow layer under elastic and viscous effects has been calculated. The deformations that take place under these 20 m of snow comprise 0.30 % of the total deformations. This is considered to be an amount that can be neglected, which leads to assume that the model can be abbreviated from 20 m below $h_{viscous}$, allowing for a small underestimation of the deformations. Regarding the general load case this calculation will continue to a depth of 41 m.

5. Calculation of the extra elastic deformations from the tube to a depth of $h_{viscous}$:

The ice under the tube does not deform viscous to a depth of $h_{viscous}$. Elastic

$$\varepsilon = \frac{\sigma_v}{E_{elast}} = \frac{\Delta l}{l}$$

deformations, however, will be taken into account on this interval, limiting the deformations to:

For the appropriate snow layers the calculation will be executed. The elastic effect varies linearly over depth, making it possible to shorten the calculation intervals, saving time. This means that above $h_{viscous}$ layers can be calculated with 1-m steps.

6. Calculation of the total deformations, from 5 and 6:

In the Excel model that has been developed, the calculation for one year is executed in three steps. First the additional snowfall for that year is implemented, and then calculation of the total loads seek a value for $h_{viscous}$. These total loads will mark the point down from which deformations in the viscous range will occur.

Finally the total deformations are an addition of the elastic deformation under the tube and the viscous and elastic deformations below a depth of $h_{viscous}$. The snow layer in which viscous deformations take place is assumed to be 20 m thick.

In this model the loads from the snow on top of the tube, and the weight of the tube itself are not assumed to be subject to load spreading. The calculations are executed as if the loads are unchanged in depth, leading to deformations in the whole snow layer. In the viscous materials of snow and ice the deformation of an object that causes an increase in loads is in fact seen to be without limits.

The limits to the deformations that take place in ice are formed by the fact that the ice is exponentially more rigid and in the same manner less viscous with increasing depth, leading to limited deformations.

Input for the model in this phase is the annual snow accumulation from 1996 from the table below:

TABLE 15: snow accumulation in time (measured and cumulative)

Year	Snow accumulation [cm]
1996	0
1997	97.96
1998	151.66
1999	230.48
2000	299.22
2001	332.28
2002	415.28

Calculation of the 'covering phase' from1992 - 1996

The calculations from the 'covering phase' are similar to those of the 'covered phase', with the difference that the vertical stress on top of the tube is not defined in the covering phase. Theoretically the vertical stress on the tube is activated when more than half of the height of the tube has been covered. In this study the assumption is made that no snow loads are transferred on the tube before it is fully covered (1996).

The assumption made for the 'covering tube phase' is based on the data derived from site measurements. When these data are taken into account it shows that the bottom of the bottom is at a depth of 2.50 m under the surface at t = 0 (1992) and is covered in 1996 (t = 4).

Calculating an average snow cover of the tubes to match these data amounts to an average of 1.50 m per year due to snow accumulation and wind effects. When snow accumulation at Neumayer Station is considered to equal the average of 70 cm per year, this means a wind effect due to the structure out of the surface in the first years of 80 cm per year.

TABLE 16: bottom of tube under the surface, assumption for 1992-1996

Year	Thickness of cover above bottom of the tube [m]
1992	2.50
1993	4.00
1994	5.50
1995	7.00
1996	8.50

Results of non calibrated model

The excel model is given in Appendix 8, together with input values and the tables of output. The deformation behaviour answers to general assumptions. A rigid structure in a material of increased stiffness and viscous stiffness as a function of depth generates smaller deformations, as it gets deeper. In this case the relative deeper position of the tube is not caused by deformations alone, but foremost by the rise of the surface level.

The input values for E_{elast} and E_{visc} that are used for this model are obtained using the actual data given in Chapter 9. The results from the calculation in table 17 are given as a settlement relative to the position of the centre of the tube at the starting point, t = 1992.

TABLE 17: settlement in time calculated with the non-calibrated model

Year	Settlement rate [m/year]	Total settlement [m, relative to 1992]
1992	0.1490	0.0000
1993	0.1280	-0.1490
1994	0.1150	-0.2770
1995	0.1050	-0.3920
1996	0.0815	-0.4970
1997	0.0780	-0.5785
1998	0.0750	-0.6565
1999	0.0748	-0.7315
2000	0.0723	-0.8063
2001	0.0694	-0.8786
2002	----	-0.9480

In table 17 the total settlements are calculated in values relative to the original position of the tube. To obtain the settlement in relation to the top of the snow layer the snow accumulation as a function of time must be added.

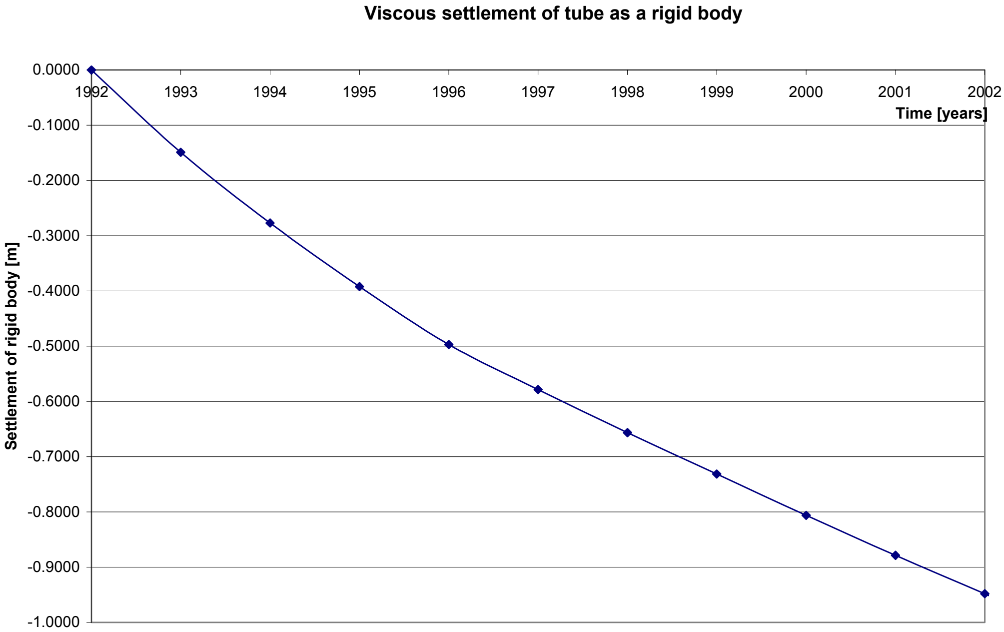


FIGURE 113: calculation of the viscous settlement of Neumayer Station into the ice (non-calibrated) *(Saltner & Keij)*

Preceding the model calibration in Chapter 12 the general behaviour of the follows the situation on site well. Total subsidence as measured at Neumayer Station is 0.959 m, compared to this model giving 0.948 m. This means that the non-calibrated model has an error of 2%.

The Excel model can be used for future cases, and is referred to under the name RiVi-model (rigid in viscous material).

Modelling a deforming tube under vertical load

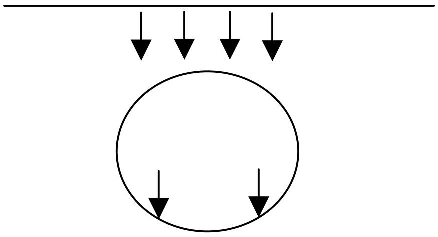


FIGURE 114: loads on/in the tube *(Saltner & Keij)*

The second phenomenon that has effect on the deformation of a tube in ice is the cylindrical deformation.

The occurring loads are assumed to be limited to the top load by the snow and the load inside the tubes by the containers and their activities.

The following kinds of load are not be taken into consideration due to simplification:

- loads from vehicles over the construction, occurring occasionally
- loads from the connected tubes
- loads from the deforming snow around the structure

The cylindrical deformation due to top loads is a local effect, which is seen to be smaller than the global vertical settlement treated in the previous section.

The deformations in this model depend on the top load on the tube. These top loads come into effect after 1996, when the accumulating snow first covers the tube totally. Before 1996 the deformations have been seen to amount to 0.263 m. The behaviour of the tubes from 1992 to 1996 will not be elaborated upon due to lack of data regarding snow cover and density of sintered snow that was used to cover the tubes partly after the construction. The deformations observed in 1996 are taken as a starting value, and deformations are calculated from t = 0 at January 1st 1996. The deformations at this starting point have an initial value of 0.25 m.

Several models are used consecutively to model the behaviour of the deforming tube. To gain understanding of the consequences of each model step, the first calculations are made according to a standard case, where the tube is covered with snow corresponding to data derived from the year 2001, 10 years after construction of the base. This means an average snow cover of 4.50 m.

Ice stresses are calculated using the formula given by Enß (see Chapter 9). The horizontal and vertical stresses in the snow are:

$$Q(v) = 4.1h^{1.1}$$

$$Q(h) = \lambda Q(v)$$

with:

h = depth

λ = varying, dimensionless factor, initially assumed to be 0.35 (Enß)

E_e and E_v are applied in the calculation as they are observed at Neumayer Station (Enß)

The consecutive models are explained below.

Tubular deformations from average soil pressures

In this model the deformation is calculated using the theory of Bouma [4]. For the input for this model the stress in the snow before the tube was placed is taken.

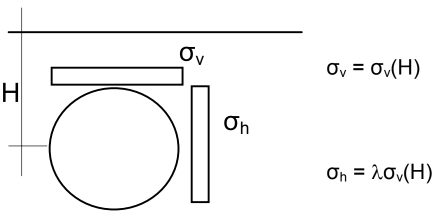


FIGURE 115: average soil pressures, schematic *(Saltner & Keij)*

These vertical stresses are used in the calculation of Bouma, which describes the deformation as a function of the radial angle. Figure 116 shows a calculation where σ_v = 48.2 KN/m^2 and σ_h = 16.9 kN/m^2 (with λ = 0.35), equivalent of a snow cover of 4.50 m.

Using Bouma, the formula that describes the prediction of the elastic deformations is:

$$w(\theta) = -(\frac{\sigma_v + \sigma_h}{2})\frac{r^2}{EA} - (\frac{\sigma_v - \sigma_h}{12})\frac{r^4}{EI}\cos(2\theta)$$

The stresses used in this model are derived from tensionless soil states without a structure, where values for σ_v and σ_h are taken at the point where the centre of the tube is going to be positioned. Thus the soil pressures are averaged over the depth.

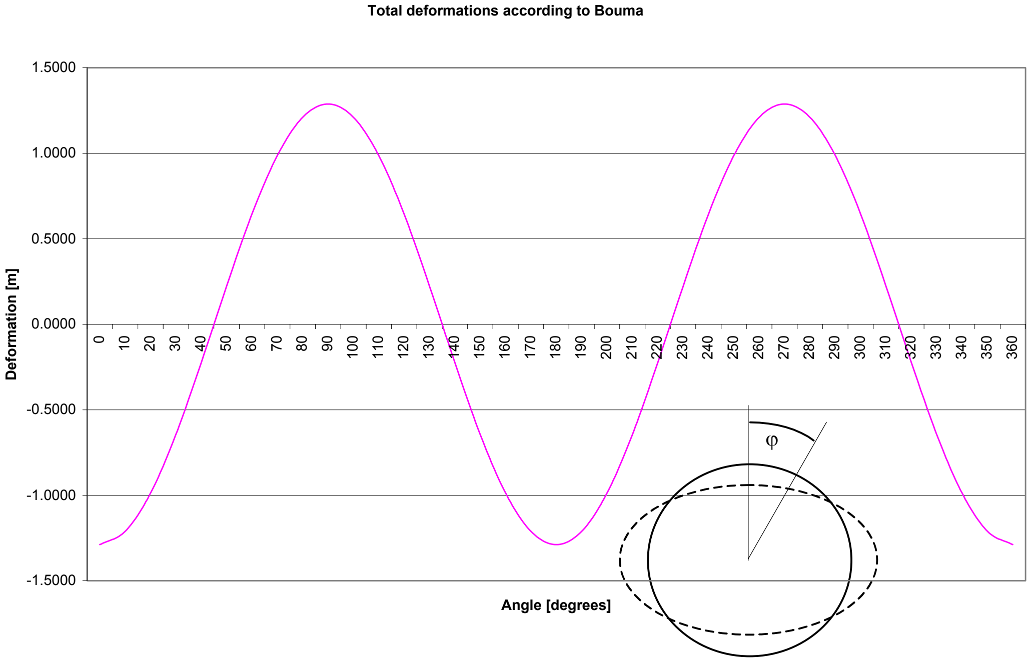


FIGURE 116: a tube on a rigid foundation calculated using the formula by Bouma for a 4.50-m snow cover *(Saltner & Keij)*

The calculation is made per 10° to cover the whole circumference of a circle. The deformation w (φ) is a cosine shaped function given the constant σ_v and σ_h in relation to the angle φ.

The maximum deformation is found at φ = 0° as well as φ = 90° and its absolute value equals 1.288 m.

Because of symmetry in the calculation the solution for the interval 180° - 360° is that of 0° - 180° mirrored. In the following sections we will therefore limit the display of deformations from φ = 0° - 180°.

Tubular deformations from actual soil pressures

In the first model the soil pressures were averaged over depth. When the real values for σ_v are used, a change in deformation can be expected, compared to the averaged case. This is because at the top of the tube, vertical stress will be lower than the average value and higher at the bottom of the tube.

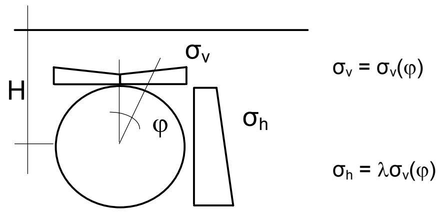


FIGURE 117: actual soil pressures, schematic *(Saltner & Keij)*

This behaviour has been modelled using the Bouma equation and implementing a depth dependent vertical stress. This vertical stress has value σ = 48.20 kN/m2 at φ = 90°, making this case comparable with the former Bouma calculation. The difference between Bouma and the adapted Bouma calculation is shown in figure 118.

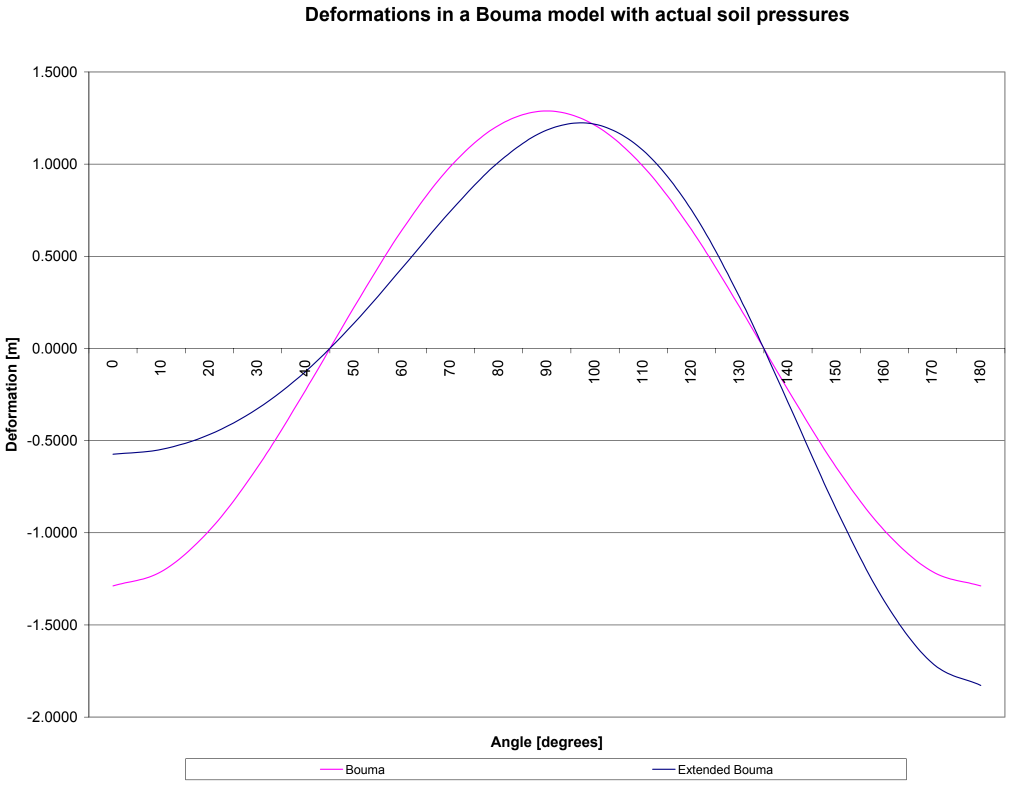


FIGURE 118: deformations in a Bouma-model with actual soil pressures *(Saltner & Keij)*

As predicted, the deformation at the top of the tube (φ = 0°) is reduced by this mode of calculation, and the value for the bottom deformation is larger than using the Bouma calculation. The maximum deformation is 1.828 m at the bottom of the tube taken into account the depth dependent vertical load. This value is larger following from the larger stresses at greater depths.

This Bouma model does not take into account the effect that is know as 'redistribution'. The loads acting upon the top of a structure will slightly deform it. Due to this deformation the stresses coming from the soil will be reduced at the top and increased at the sides. This redistribution of stresses will continue up until the stresses in the soil are equalled to the stresses in the liner. The models displayed above do not have possibilities to work with a reduction of stresses.

Tubular deformations with interacting surrounding material

The Duddeck model is used to calculate deformations in a ring where the redistribution does take place. The model is built up of two parts, forming a non-bedded roof of the tube while the rest of the ring is modelled in an elastically bed in the surrounding snow.

The model will follow the description given in Chapter 7.

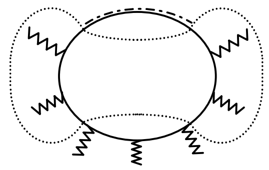


FIGURE 119: the Duddeck model *(Saltner & Keij)*

Calculating the deformations as function of the angle (φ) with Duddeck is a process consisting of three steps:

1. Input parameters:

Gamma soil: this is the density of the soil above the tube. Duddeck takes this density as a constant. This means that for the density-input in the model a small pre-calculation is necessary to obtain a typical density.

$$\gamma_{\text{typical}} = \frac{\sigma_v}{h}$$

with:

γ_{typical} = typical density of snow above the tube

σ_v = vertical soil stress

h = depth, taken at the centre of the tube

Factor λ: horizontal soil stress divided by vertical stress, taken to be 0.35 (Enß):

$$\lambda = \frac{\sigma_h}{\sigma_v}$$

Factor α: Value for in the equation for the soil reaction spring modulus C_b. Duddeck uses the under limit value for his model, factor $\alpha = 0.66$

Es: Young's modulus for snow. The average value over the height of the tube is taken in the calculations.

υ **soil:** Poisson ratio for ice (varying from 0.22 for sintered ice to 0.33 for natural compacted snow) is taken to be 0.33.

R(0): radius of the tube in undeformed state.

H: Depth of the tube's centre

E: Young's modulus of the steel

I: Moment of inertia of the tube (per metre)

β: Angle over which the tube is not supported elastically. As given by Duddeck, $\beta = 50°$.

2. Solution of the equation matrix:

The description of the model by Duddeck is a set of equations forming a matrix. This matrix consists of the equations for deformation, angle, moments and forces and symmetry.

The equation matrix has been solved by Duddeck as a function of the factor $u_{Duddeck}$.

$$u_{Duddeck} = \sqrt{\frac{a-1}{2}}$$

with

$$a = \sqrt{1 + \frac{C_b R^4}{B}}$$

with:

C_b	a value for the stiffness of the surrounding ice
R	the radius of the undeformed tube
B	a value for the stiffness of the tube (E times I)

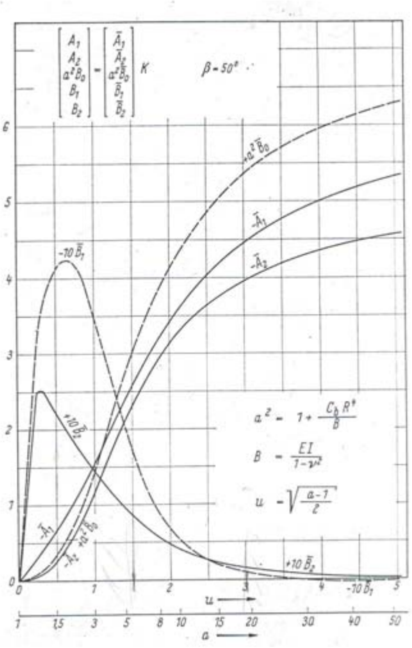


FIGURE 120: graph of numerical constants of the solution of the equation matrix *(source: Duddeck [9])*

This factor, through its relation with C_b, R and B gives a measure for the stiffness of the tube compared to the soil. When the tube is very stiff (B = large), the factor $u_{Duddeck}$ will be 0. When the soil is very stiff factor $u_{Duddeck}$ will be large ($u \rightarrow \infty$).

The solution of the equation matrix has been depicted in figure 120. In this figure the coefficients are give as a function of $u_{Duddeck}$, which due to the fact that it is made dimensionless facilitates general application.

An approximation has been made for the graph derived by Duddeck in the appropriate interval for $u_{Duddeck.}$ The minimum value of this interval is determined through a calculation of u with the minimum values, as are the maximum values:

TABLE 18: maximum and minimum values for Duddeck

Parameter		Min. Value	Max. Value
α	[-]	0.66	3
E_{soil}	[kN/m^2]	2.10E+04	15 E+04
R	[m]	3.0	4.2
C_b	[kN/m^2]	450	4620
E_{steel}	[kN/m^2]	2.1E+08	2.1E+08
I_{steel}	[m^4/m]	3.0E-06	3.0E-06
B	[kNm^2]	692	692
a	[-]	5.4	45
$u_{Duddeck}$	[-]	1.48	4.45

For $u_{Duddeck}$ within the limits 1 to 4.50 the approximating graph is given as a function of $u_{Duddeck}$. These curves have been approximated with fourth order equations for $u_{Duddeck.}$ This makes it possible to automate the Duddeck calculation.

3. Calculation of deformations with constants found in (2):

With the formulae given in [9] the deformation is calculated. As the deformations are symmetrical in respect of the point $\varphi = 180°$, the deformation graph is given with $0° < \varphi < 180°$ only.

An example is given, calculated for the input conditions of the year 2001.

To check the validity of the Duddeck model a calculation is made for a case similar to the Bouma calculation in the section above. A soil with $\gamma = 5$ and height of 4.50 m above the tube is loaded, without an elastic bedding ($E_s = 0$). Appendix 9 shows that the model gives a good comparison to the Bouma solution. Differences between these solutions are viewed by Duddeck to lie in the approximation of the radial pressure to allow for integration.

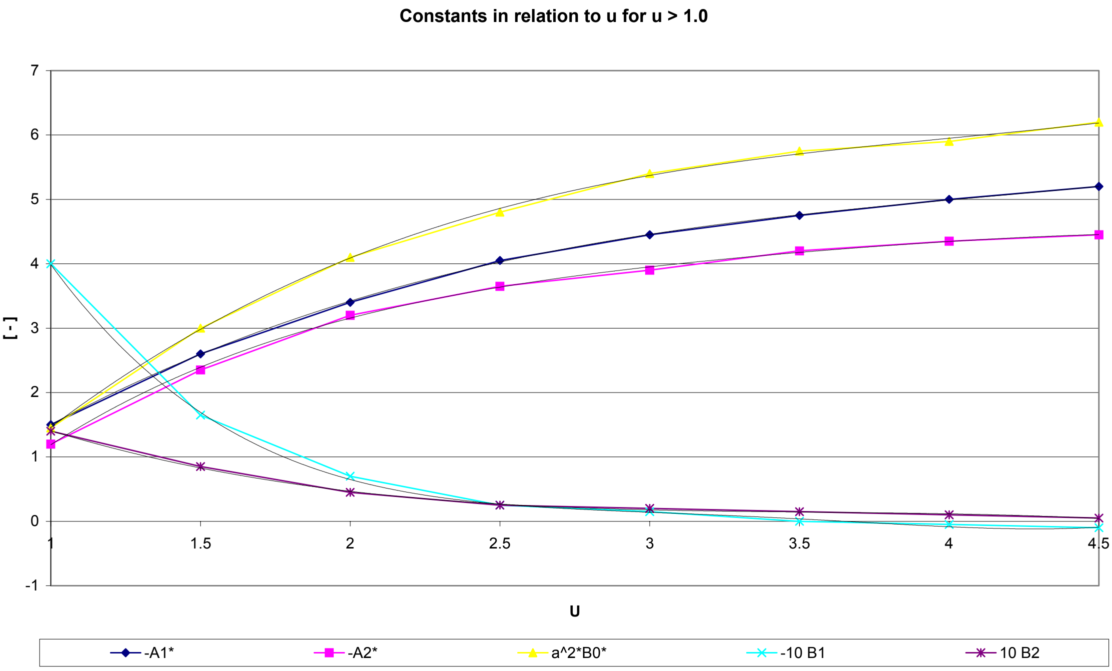


FIGURE 121: Duddeck parameters for equation matrix in relation to $u_{Duddeck}$ *(Saltner & Keij)*

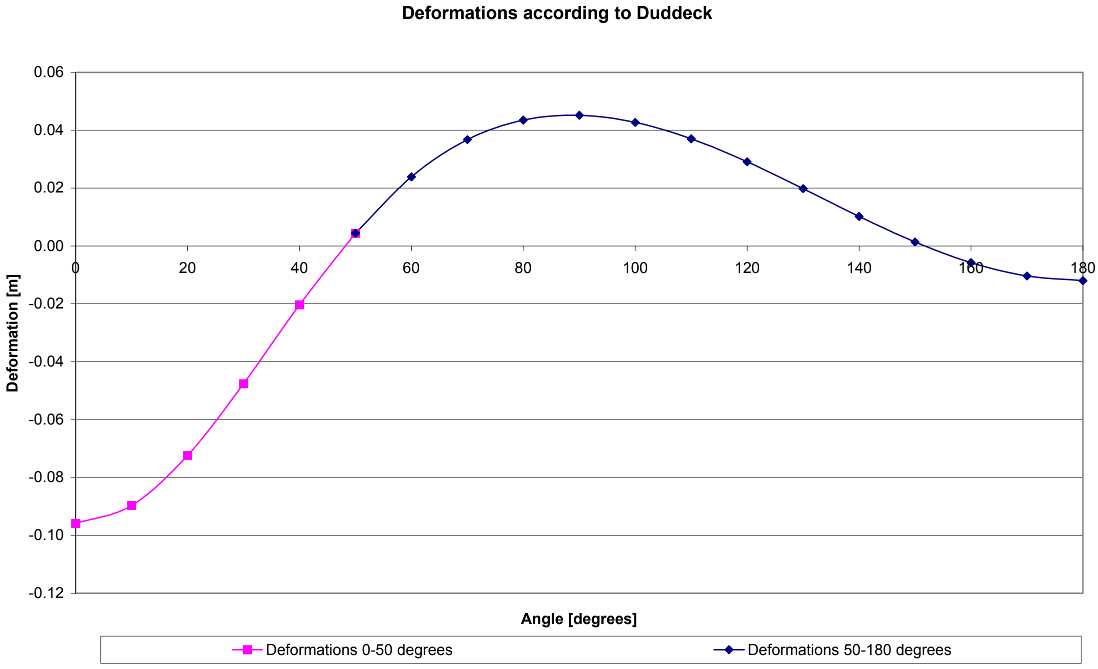


FIGURE 122: deformation of a tube, calculated with Duddeck *(Saltner & Keij)*

Tubular deformations with interactions and viscous creep

When loads are put upon a snow layer, elastic and viscous deformations take place. The elastic deformations, calculated from the Duddeck model above, are assumed to happen instantaneously. The viscous deformation then takes place where the loads on the snow are located

The viscous extension of the Duddeck model uses the output of the Duddeck model. Duddeck solves the equations for the stresses on the ring by introducing an extra stress, related to the deformations [9].

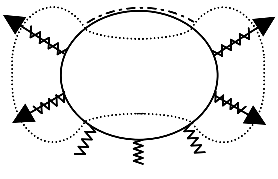


FIGURE 123: Duddeck extension for viscous material, schematic *(Saltner & Keij)*

$$p_r = p_{\text{radial}} + C_b w$$

Here p_r is the radial load on the tube, p_{radial} are the radial soil loads and $C_b w$ is the stress from the soil spring that is compressed. The soils springs with Duddeck are displaced until this equilibrium is met.

This equilibrium is reached after each calculation, and that aspect is an important contribution to the possibility of viscous calculation. Due to viscous effects the deformations along the circumference of the tube will, where they are positive, induce extra deformations due to the viscous effects.

This effect can be calculated with the same rheology as the rigid model. The elastic deformations are calculated with the Duddeck model, and the viscous deformation stresses are related to these deformations. Thus the following equation describes the total deformation.

$$\varepsilon = \varepsilon_e + \varepsilon_v t = \frac{\sigma_v}{E_{elast}} + \frac{\sigma_v}{E_{visc}} t = \text{'Duddeck'} + \frac{p_{\text{radial}} + C_b w}{E_{visc}} t$$

with 'Duddeck' being the elastic deformations obtained from the Duddeck model.

Calculating the deformations now comes down to calculating the Duddeck deformations at the beginning of a time step, and calculating with these deformations the stresses that will cause viscous deformations in this time step. After this the total deformations in the time step can be calculated.

With the data of 2001 the additional deformations that would be calculated with this model are given in figure 125. The extra deformations in this figure pose a problem for the calculation.

The problem that is presented when calculating the additional (viscous) deformations with the formula in the section is that of the tunnels diameter. In practice the viscous effects will not lead to lengthening of the tunnel diameter. When the figure is taken into account there are additional deformations over the entire tubular circumference, which is not conform reality.

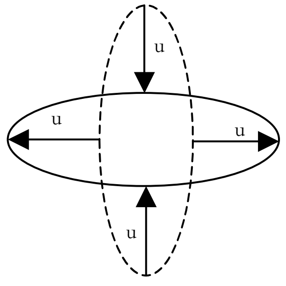


FIGURE 124: lengthening of the tunnel must remain zero *(Saltner & Keij)*

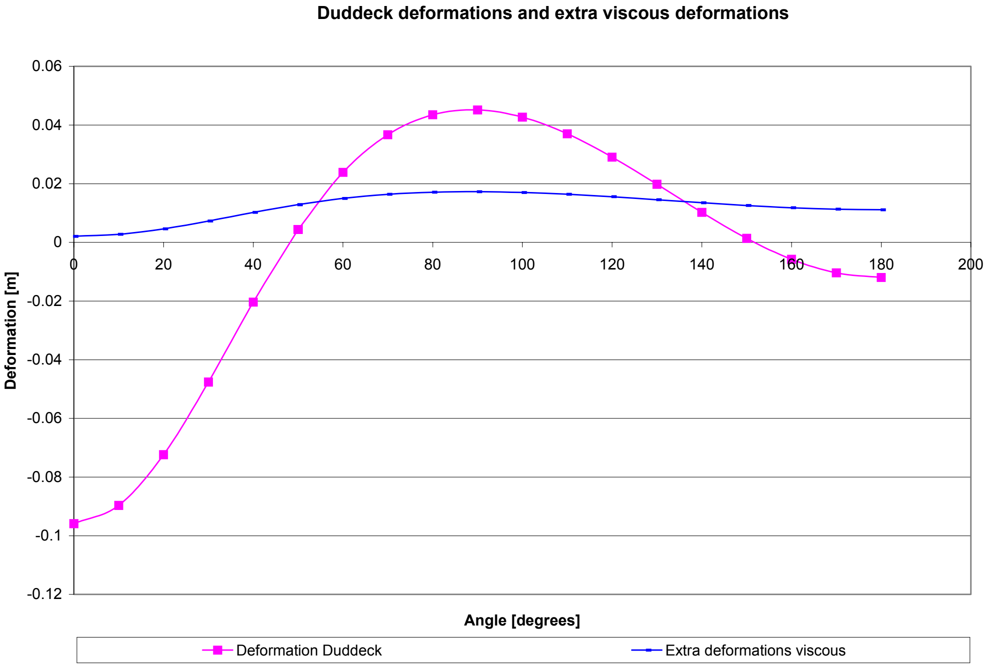


FIGURE 125: extra deformations in a viscous Duddeck model *(Saltner & Keij)*

The largest deformations in the viscous range take place at φ = 90°. The elliptical form of the profile dictates that u_{vertical} should equal $u_{\text{horizontal}}$, leading to a constant circumference.

Here the assumption is made that due to this distribution of circumference the extra viscous deformation will have a cosine shape, leading to:

$$u_{viscous,90^\circ} = \cos(2\varphi)u_{viscous,90^\circ} = \cos(2\varphi)\frac{p_{\text{radial},90^\circ} + \text{C}_{b,90^\circ}w}{E_{visc,90^\circ}}$$

This equation will be used in the deforming ring model in the next section. The assumption made here is that the tube does not deform plastically during the process that is calculated. Data show deformations between 0 and 0.50 m with a diameter of 8.40 m. The deformations are deemed to be in the elastic range.

Deforming Ring model (DeRi)

The deforming ring model (DeRi) is a model based on Excel, which is essentially a combination of the above-mentioned models. This model, however, calculates the different deformations of the tube's profile in time. The calculation consists of four parts.

Per time step, the appropriate amount of snow will be added, following the accumulation rate that is given as input to the model

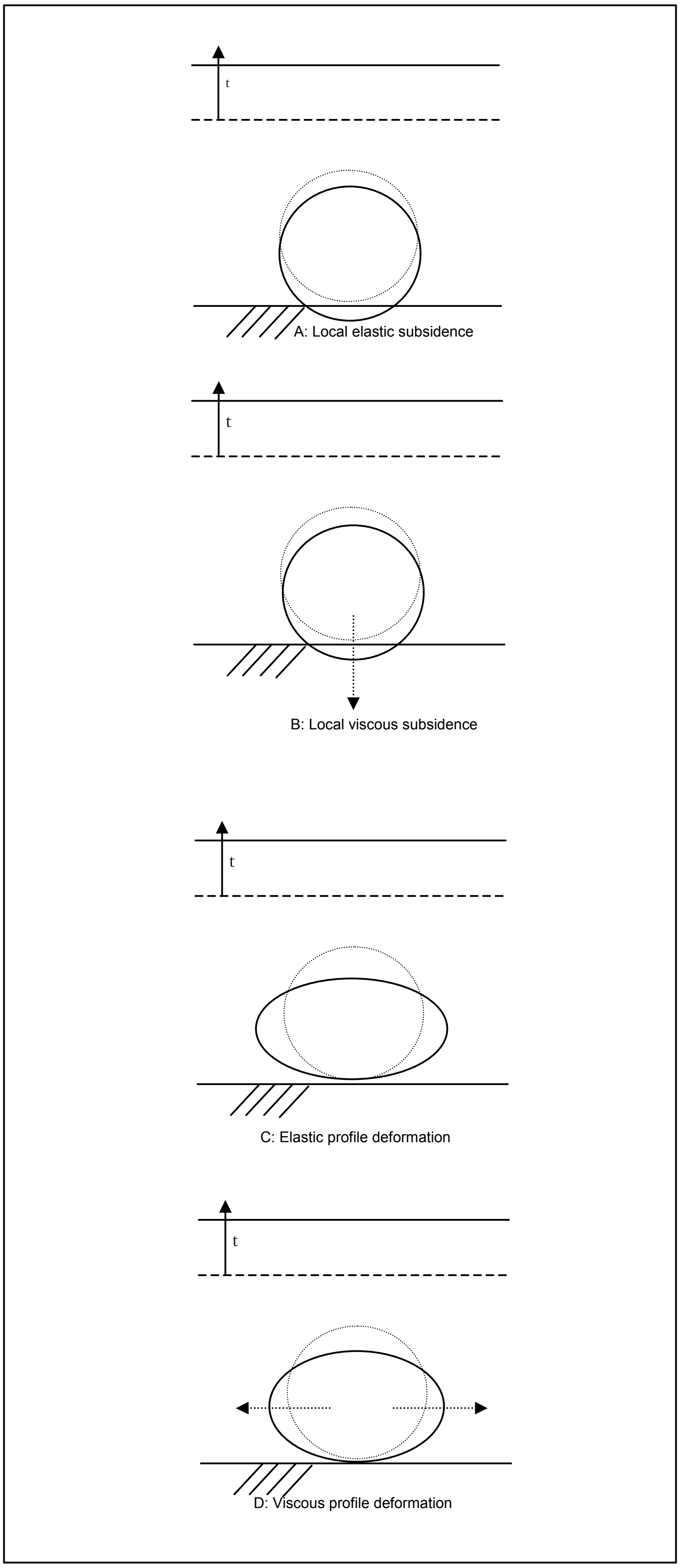


FIGURE 126: the deforming ring model (DeRi) *(Saltner & Keij)*

A: Local elastic subsidence

Per time step a small local elastic deformation will occur, originating from the extra load upon the tube caused by the snow accumulated in the time step. This extra snow generates an extra deformation. This can be calculated with:

$$\frac{de}{dt} = \frac{d\left(\frac{\sigma}{E_{elast}}\right)}{dt}$$

In this equation, both σ and E_{elast} are time dependent. This is caused by the fact that the origin of the x-y plane in this calculation lies at the surface of the snow. This surface is subject to accumulation, moving the grid of calculation up with Δh/Δt. Because σ(h) and E_{elast}(h) are given in Chapter 9, the calculation performed here will be:

$$\frac{de}{dt} = \frac{E_{elast}\frac{d\sigma}{dt} - \frac{dE_{elast}}{dt}}{E_{elast}^{2}} = \frac{E_{elast}\frac{d\sigma}{dh}\frac{dh}{dt} - \sigma\frac{dE_{elast}}{dh}\frac{dh}{dt}}{E_{elast}^{2}}$$

This is done using an Eulerian approach. In this approach the continuous functions for E_{elast} and σ are taken to have a constant derivative over the short distance Δh.

The excel sheet calculates Δh/Δt, Δσ/Δh, $\Delta E_{elast}/\Delta h$ with E_{elast} and σ. The values for E_{elast} and σ are taken at φ = 180°.

B: Local viscous subsidence

The local viscous subsidence is attached to the elastic subsidence treated above. Likewise an Eulerian approach will be followed. The parameters needed are Δh/Δt, Δσ/Δh, $\Delta E_{visc}/\Delta h$, σ and E_{visc} combined to:

$$\frac{de}{dt} = \frac{E_{visc}\frac{d\sigma}{dh}\frac{dh}{dt} - \sigma\frac{dE_{visc}}{dh}\frac{dh}{dt}}{E_{visc}^{2}}t - \frac{\sigma}{E_{visc}}$$

The model uses the input values for φ = 180°.

C: Elastic profile deformation

For the elastic profile deformation, the Duddeck model described above is used. At each time step the parameters that are needed for the Duddeck (elastic) calculation are put in place and the calculation is executed. The calculation is done with elastic, and snow properties as they are at φ = 90°.

D Viscous profile deformation

This calculation, as described earlier uses the output of step (C) to obtain the extra deformation due to viscous effects after the elastic profile deformations have taken place. These viscous effects are calculated with the parameters also used in the Duddeck calculation, with the additional E_{visc} at $\varphi = 90°$.

When one time step has passed these calculations are be summed for that time step. After this the small partial effects can be summed to a total deformation of the deforming ring (DeRi) model in time.

Output of deforming ring model

These total deformations can be given relative to the angle φ, but as mentioned earlier, the user has not measured the deformation as function of the internal angle in the tubes.

The user has not included all angles in the measurement programme, nor are the deformation limits defined relative to φ. The data that is available gives values for the vertical axis ($\varphi = 0°$ and $\varphi = 180°$) and the horizontal axis ($\varphi = 90°$). Thus the model output must be in the same format.

For comparison with the measured data the total vertical compression and the total horizontal widening is needed. These are obtained by calculating:

Vertical compression = deformation in x-y plane at $\varphi = 0°$ - deformation in x-y plane at $\varphi = 180°$

Horizontal widening = (deformation in x-y plane at $\varphi = 90°$)*2

The possibility of non-symmetrical effects or deformations is not taken into account.

When this calculation is executed for the situation from 1996 the following graph can be obtained. This graph does not incorporate actual accumulation data from 1996, but calculates an average accumulation of 70 cm. This can be changed in the actual calculation. Calculation input values and output are given in Appendix 10.

Total vertical deformation of the tube

The total deformation of the tube in its lifetime is a combination of the two models, the rigid in viscous material model (RiVi) from paragraph 2 and the deforming ring model (DeRi) from paragraph 3.

One can see from the figure that the major part of the vertical subsidence is obtained due to the RiVi model. This means that the distinction between a global (RiVi) and a local (DeRi) modelling as chosen is sound. The RiVi model thus calculates the major settlement of the tube calculated as a rigid body in a viscous material, and the DeRi model calculated the local effect of the ring deforming.

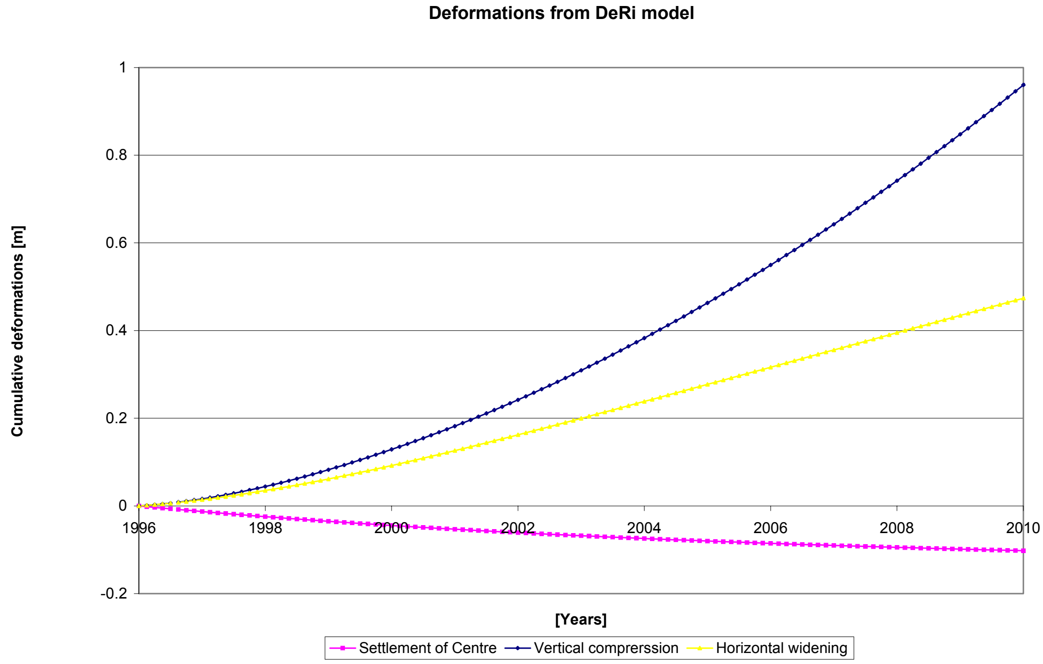


FIGURE 127: deformations resulting from the DeRi-model *(Saltner & Keij)*

The DeRi model does not start to work until t = 1996, making the vertical settlement equal the RiVi model until that time. The maximum effect of DeRi is 10% of the total vertical deformations of the tube's centre.

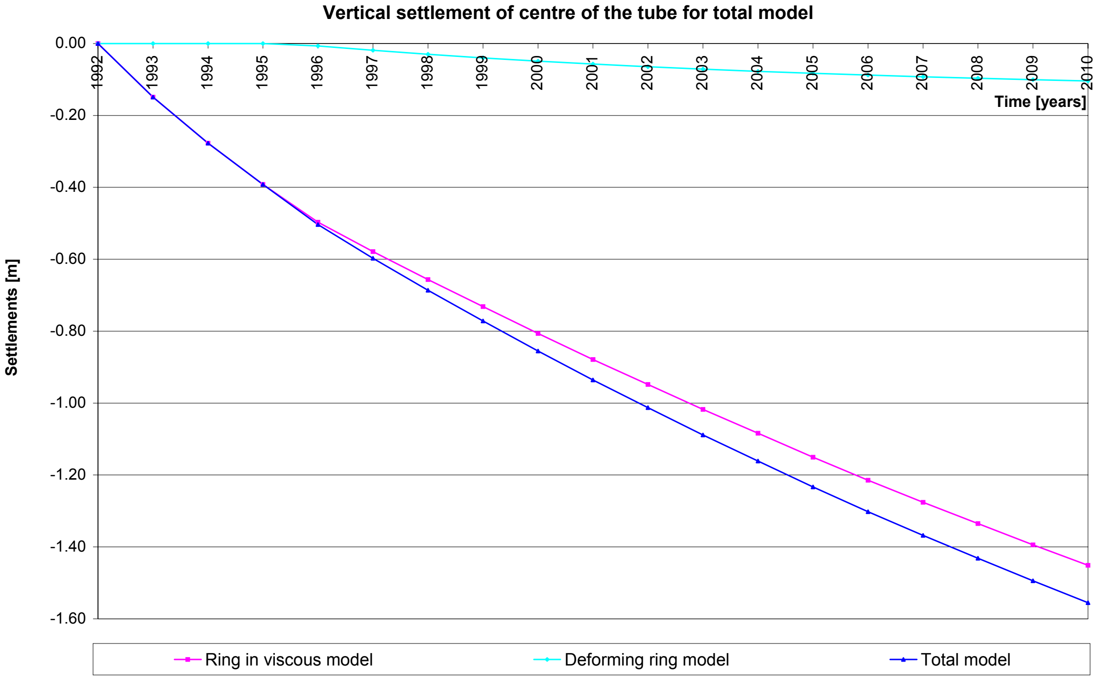


FIGURE 128: DeRi and RiVi model summed for vertical subsidence in ice *(Saltner & Keij)*

Sensitivity analysis and discussion

A sensitivity analysis is performed to get an idea of the effect of the input on the model's output. To do this all input parameters have been equipped with a percentage-adding tool. This enables the quick varying of input data using the formula:

$$(\text{new input}) = (\text{old input})\frac{xx\% + 100}{100}$$

This procedure has been done for three types of parameters:

1. Snow accumulation parameters
2. Snow parameters over depth
3. Steel profile parameters

Sensitivity to snow accumulation

The snow accumulation is defined by an accumulation rate per year. In the present model a rate of 0.70 m per year is taken. Varying this figure from 0.60 to 0.80 m the following behaviour is noted (see figure 129).

This figure shows that when less snow accumulates the vertical compression becomes less. A reduction of the accumulation with 14% reduces the compression with about 10%.

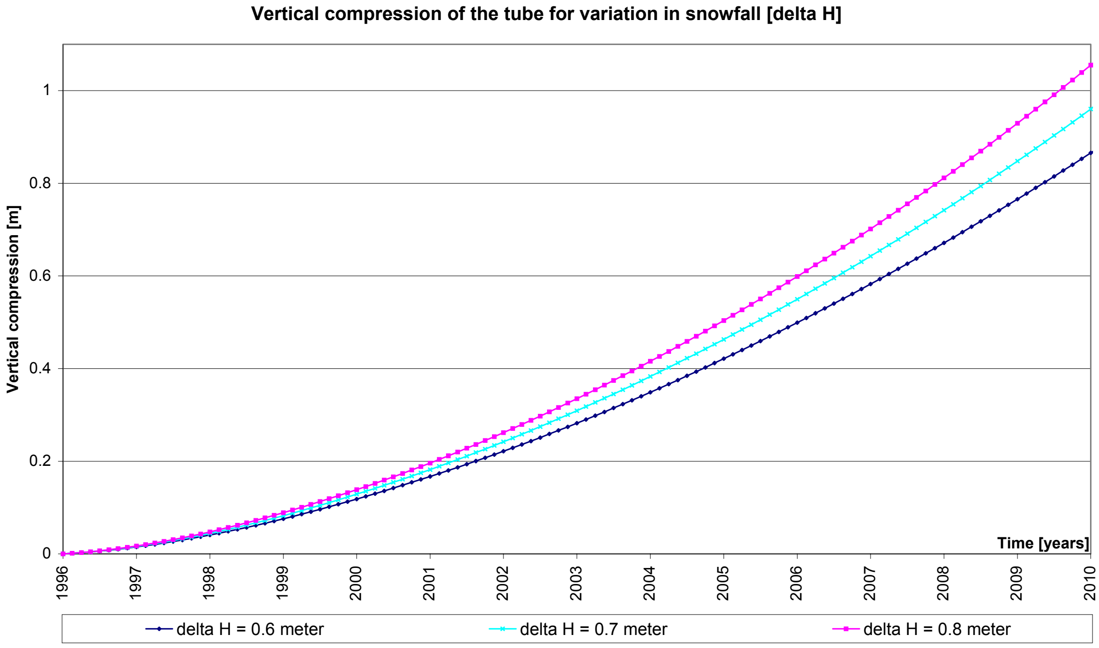


FIGURE 129: snow accumulation dependency of the DeRi/RiVi-model *(Saltner & Keij)*

Sensitivity to snow parameters over depth

The snow parameters that can be varied are the Young's modulus, the viscosity modulus and the density of snow. Each of these parameters has been varied with –25% and +25% (see figures 130 – 132).

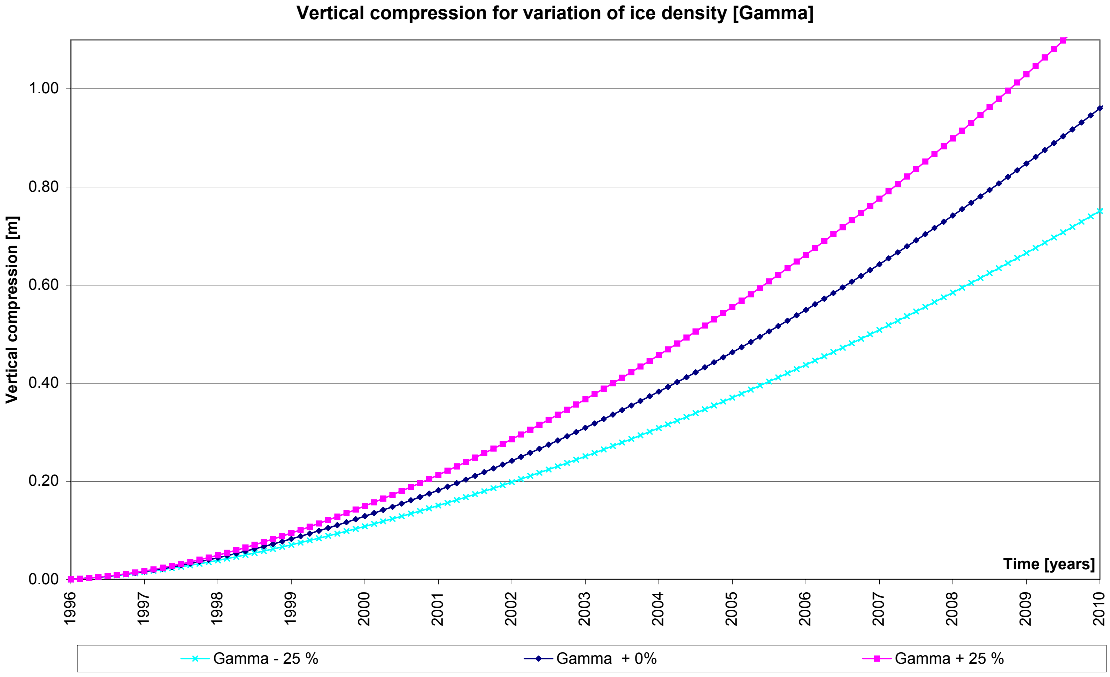


FIGURE 130: vertical compression for variation of the ice density *(Saltner & Keij)*

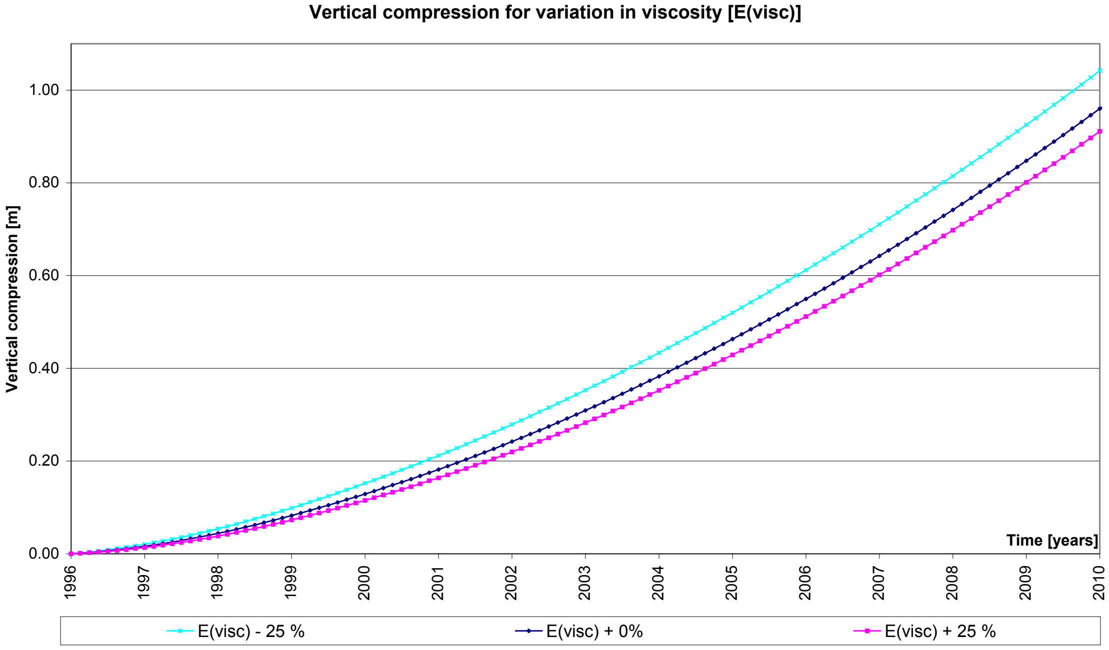


FIGURE 131: vertical compression for variation in viscosity *(Saltner & Keij)*

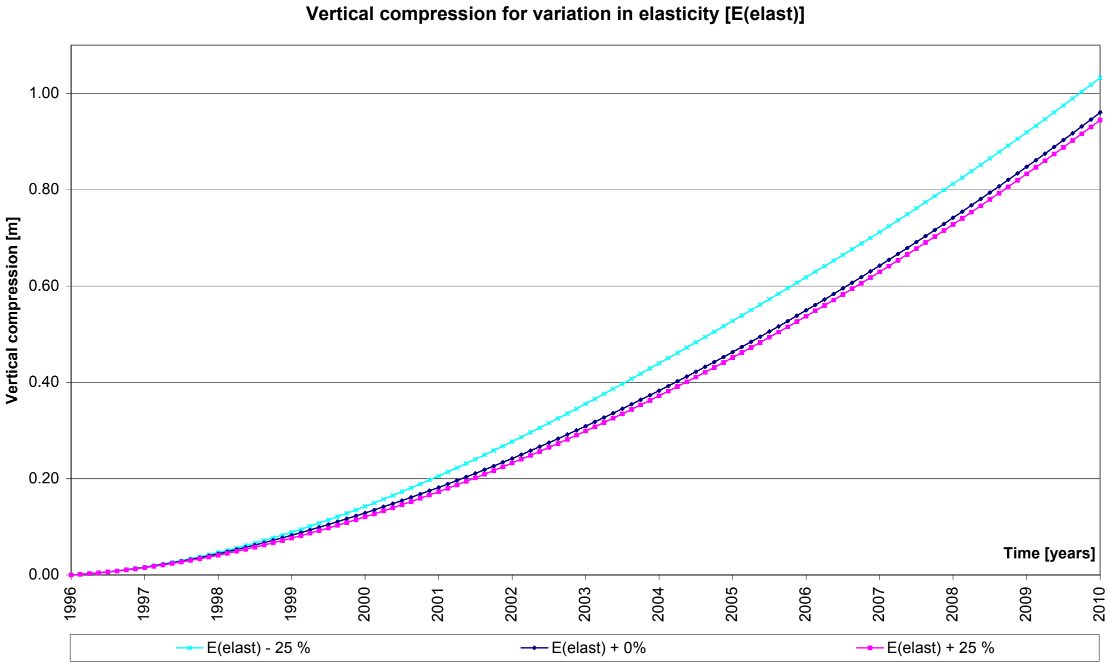


FIGURE 132: vertical compression fir variation in elasticity *(Saltner & Keij)*

The density of the snow seems an important input parameter. Reducing this parameter with 25% almost reduces the compression with 20%.

When the ice elastic and viscous properties are varied, the depth dependency becomes clear. When the parameters are reduced, this would mean lower moduli, and higher deformation reactions at the same pressure. This becomes visible in the graphs, reduction of 25% leads to additional 10 - 15% deformations. When the moduli are increased, leading to stiffer behaviour, the extra deformations caused by the more viscous ice are summed with less elastic effects.

Sensitivity to steel profile parameters

The steel profile is mainly determined by the profile parameter B, which is a multiplication of Young's Modulus of steel and moment of inertia of the steel profile (EI). Decrease of 25% leads to an increase of 20% of the deformations (see figure 133).

Increased stiffness of the steel profile leads to reduced deformations. Because values for $u_{Duddeck}$ at Neumayer Station are already at the right margin of the calculation interval ($u_{Duddeck}$ lies between 3.50 and 4.50).

Discussion of sensitivity

As can be expected, all input parameters influence the output of the model to some extent. None of the parameter changes has a more than linear effect, exploding or imploding the model output. To be able to decide upon which parameter to use to calibrate the model for the Neumayer Station site, the parameters are shortly analysed for their rang of error.

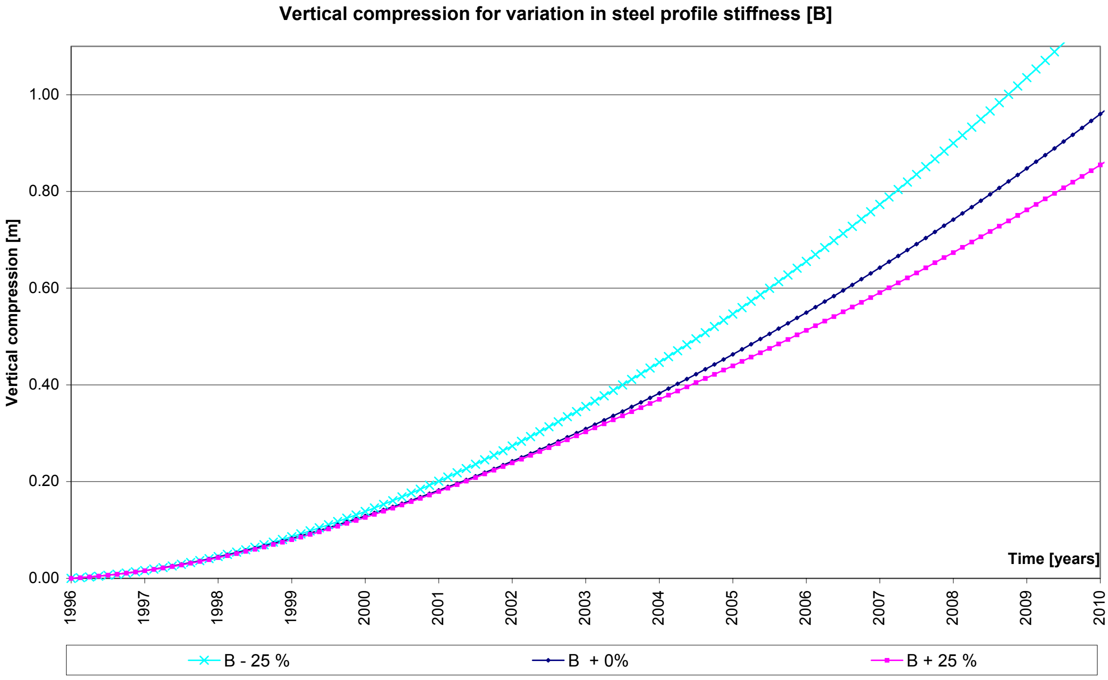


FIGURE 133: vertical compression for variation of the steel profile *(Saltner & Keij)*

TABLE 19: sensitivity of input parameters for the model

Parameter		Unit	Remarks
Snow accumulation rate	ΔH	cm	10 years measurement, weekly
Elasticity of snow	E_{elast}	kN/m^2	Error ± 0.5E+04 kN/m^2
Viscosity of snow	E_{visc}	kN/m^2	Error ± 50 %
Density of snow	γ_{ice}	kg/cm^3	Two measurements (GvN, Maudheim) ± 25 kg/m^3
Steel parameters	I (mom. of inertia)	m^4	Calculated from profile specifications, ± 10 mm^4

The local snow accumulation per year has been measured, and can be used for the model, making ΔH an accurately known parameter. The ice parameters available have been measured by Enß in 1997 and are thus known to us for the Neumayer location. However, for the viscosity of ice it is remarked that:

- Ice viscosity varies greatly per measurement, owing to difficult measurements
- Ice viscosity can have an additional 50% variation due to temperature effects (heating and refreezing)

The steel profile has been well documented, and actual values can be used for the calculation.

For the parameters at Neumayer Station at first the viscosity modulus of the ice will be taken as an input value subject to variation. This parameter will serve as a calibration value for the model. The model will be thus implemented with the actual Neumayer data in Chapter 12 after which the deformations will be calibrated by varying the viscosity modulus.

Limits to the model

As was concluded in Chapter 6 the limit states (ULS and SLS) for the Neumayer Station limit the interval over which the model may be used.

These limits are sketched in figure 134. Here the deformation Δ is drawn relative to the vertical load from the snow, q_v. Because in time more and more snow accumulates causing increasing vertical loads, the total vertical load on the tubes can be seen relative to time as well.

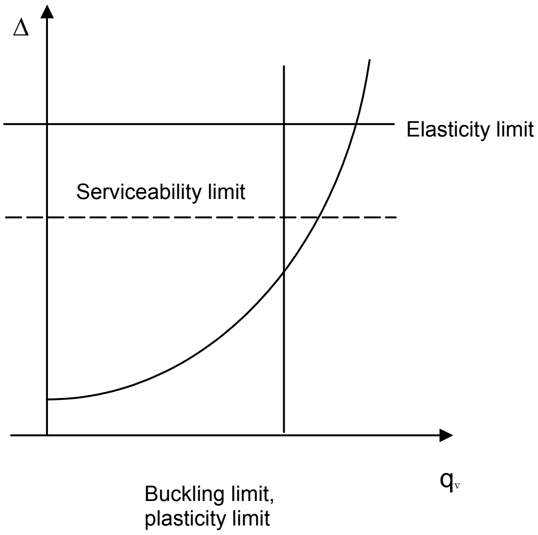


FIGURE 134: structural limit states *(Saltner & Keij)*

Four limits have to be calculated for the tubes of Neumayer Station:

1. Serviceability limit
2. Elasticity limit
3. Buckling limit
4. Plasticity limit

From the limits 3 and 4, one will prove to be the critical limit, so as to have one ultimate limit state on each axis.

Serviceability limit

This value can be taken from Chapter 6 and amounts to 1.00 m. However, this value has been obtained by taking the present situation and the present views of the operator of the station into account. Changing views can lead to a higher number.

Elasticity limit

This limit is set by the basic assumption of the model that all deformations are elastic. This assumption cannot be valid when the station is ovalised to a great extent, because vertical pressures will act on a greater surface, with smaller horizontal surface to counteract. This behaviour has been seen to become important when the ovalisation is more than 15%. Spangler [34] recommends that deformations remain below this point for elastic calculations.

For Neumayer Station, this means that the model is valid up to a deformation of 1.30 m.

Buckling limit

In the buckling limit state the local buckling behaviour is calculated. The corrugated steel profile is simplified to a plate profile with the same moment of inertia by calculating [38, 40]:

$I_{corrugated} = 3.0E^{-6}\ m^4 = 1/12h^3\ m \ \Rightarrow\ h = 33\ mm.$

With a circular ring of 33 mm thickness the calculation is executed. Here the maximum radial load is calculated at which local buckling takes place.

$$q_{\max} = \frac{Et^3\left(\frac{\pi^2}{\alpha^2} - 1\right)}{12r^3\left(1 - \nu^2\right)}$$

For the angle of the curve the angle β used by Duddeck is taken, because at this point the bending moments are zero making the area from $-\beta$ to β a suspended beam.

E = Young's modulus steel = 2.1E+08 kN/m^2

t = plate thickness = 33 mm

2α = angle of curvature = 50°

r = radius of tube = 4.20 m

υ = Poisson's ratio of steel = 0.30

The maximum allowable radial load from the snow on the tube is calculated to be 140 kN/m^2.

Plasticity limit

For the radial stress at which plastic deformations take place the calculation of Duddeck can be followed for the ring forces:

$$N = N_0 + \overline{N}_{\text{bending}}$$

With N_0 as the constant part of the normal stress in the circumference of the tube, and $N_{bending}$ as the normal stress due to bending, similar to the equation in Chapter 6. Duddeck gives the constant part as function of the radius and the constant radial pressure.

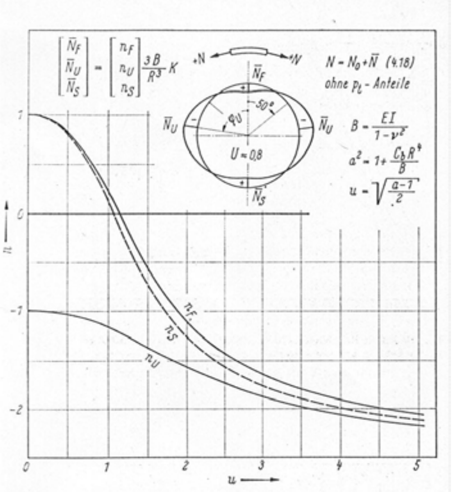


FIGURE 135: ring forces calculated by Duddeck *(source:[9])*

$$N_0 = -Rp_0$$

p_o can be related to the vertical soil pressure by:

$$p_0 = \frac{\sigma_v + \sigma_h}{2} = \frac{\sigma_v + 0.35\sigma_v}{2} = 0.68\sigma_v$$

The normal stress due to bending is obtained with figure xx.

$$\overline{N}_{\text{bending}} = \eta_f \frac{3B}{R^3} K$$

η_f can be read from the figure, and B, R and K follow from the Duddeck calculation. K depends on the vertical soil pressure.

To calculate the critical soil pressure the following equation must be solved.

$$N = N_0 + \overline{N}_{\text{bending}} = N_{critical} = 235 N/mm^2$$

In the equation, the soil stress is the only variable; a solution of the equation with snow

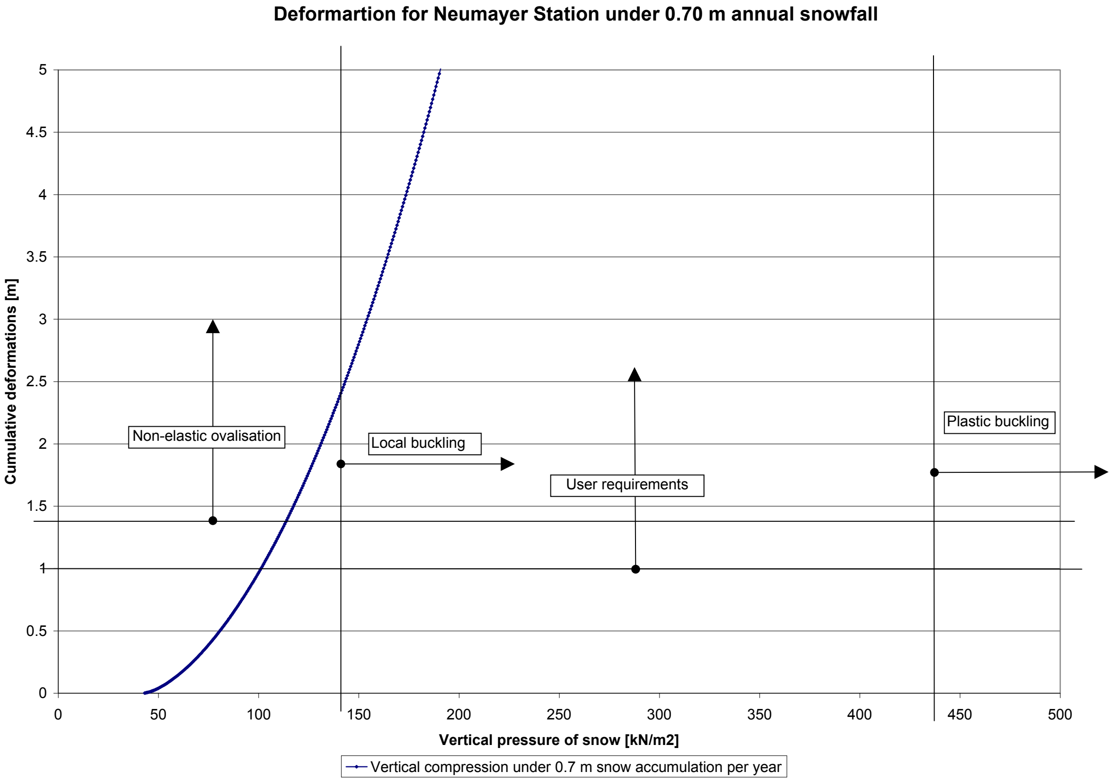


FIGURE 136: limits to the deformations, dictated by the structure, calculations and user requirements *(Saltner & Keij)*

instead of soil gives a critical value for the snow stresses. In Appendix 12 this calculation has been carried out. The critical value for the snow load is found at 430 kN/m^2, which is much larger than the limit found for local buckling.

Discussion and summary of limits

All limits can be summarised in one graph. In this graph the deformations of the profile are caused by an average annual snow accumulation of 0.70 m.

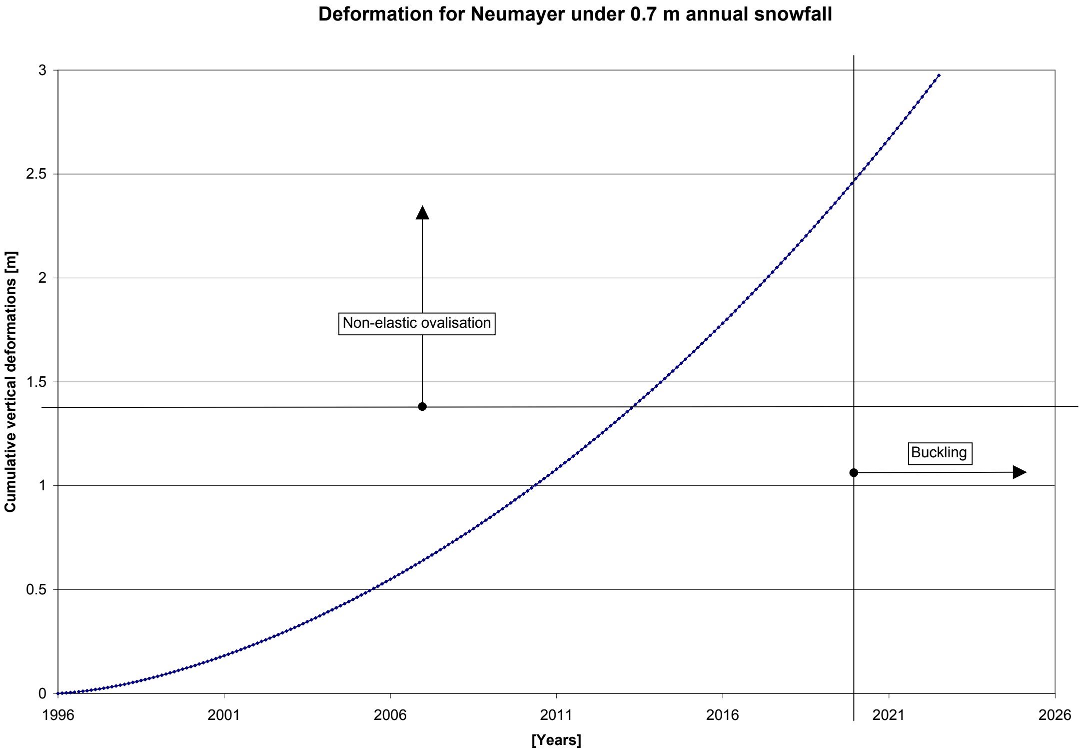
The limit states can be summarised in a table to compare the total allowable stresses.

TABLE 20: allowable stress for limit state comparison

Limit state	Maximum allowable vertical stress
User requirements (serviceability)	100 kN/m^2 from 1 m deformation
Elasticity limit	110 kN/m^2 from 1.30 m deformation
Plasticity limit	430 kN/m^2
Local buckling limit	140 kN/m^2

When the limit states are compared, the most important, and accountable limits are the local buckling limit and the elasticity limit. The user requirements are, as said earlier, not a given value, but can change according to need and adaptations to the station. When the plasticity limit is met, local buckling will already have taken place.

The calculation within the DeRi and RiVi model is thus valid up to an ovalisation of 1.30 m, and a total vertical ice stress of 140 kN/m^2. The total acceptable vertical deformations, as given by the AWI are 1.00 m.



FIGUR 137: deformations for Neumayer under 0.70 m snowfall (annual) *(Saltner & Keij)*

An example can be given of the possible output for a practical case. Here the annual accumulation at Neumayer Station is taken at 0.70 m. For this case the maximum vertical stress of 140 kN/m^2 is reached in 2020.

The calculation shows that the buckling behaviour of the tube is more critical than the plastic deformation behaviour. The calculation of the elastic deformation already pointed out a large reduction in deformation when the soil is modelled elastically. As the bending moments are also reduced due to the small deformations and the subsequent redistribution of the stresses, global plastic behaviour is not critical.
The limit of elastic calculation due to ovalisation, on the Δ-axis is seen to be decisive here.

The limits that are calculated here will be used in the following modelling of Neumayer Station.

Analysis of Lifetime for Neumayer Station

With the model presented in the previous chapter an estimate can be made for the lifetime of Neumayer Station. First the data from Neumayer Station will be extrapolated linearly using a least square method. After that the model will be fitted to the Neumayer data by small changes in the viscosity modulus of snow.

The future estimate for Neumayer Station will be composed of the model output, and a stochastic snow accumulation rate.

In this chapter a statement is made on the lifetime of Neumayer Station. This analysis of lifetime is made under the following assumptions:

- The analysis of lifetime is limited to a calculation of the deformations of Neumayer Station and a check of these deformations against the limit states defined earlier.

- The limit of the deformation in vertical dimension is an average value of 1 m.

Firstly the lifetime is calculated following a linear least square estimate of the measured data, after which the model output is presented. Each of the analyses of the lifetime gives the point in time at which the maximum deformation is reached. Also the deformation of the models in 2010 is calculated for direct comparison.

Linear least square estimate

The linear estimate is commonly used as an intuitive estimate when reading graphs. Here the estimate is used to get a first idea of the order of magnitude of the deformations over time. The model used is the definition for a line:

$$y = ax + b$$

A best fit for a and b is found by minimising:

$$Error = \Sigma(y_{approx} - y_{measured})^2$$

The line that is thus obtained can be extrapolated into the future to estimate the deformations. Here values for 2010 are calculated.

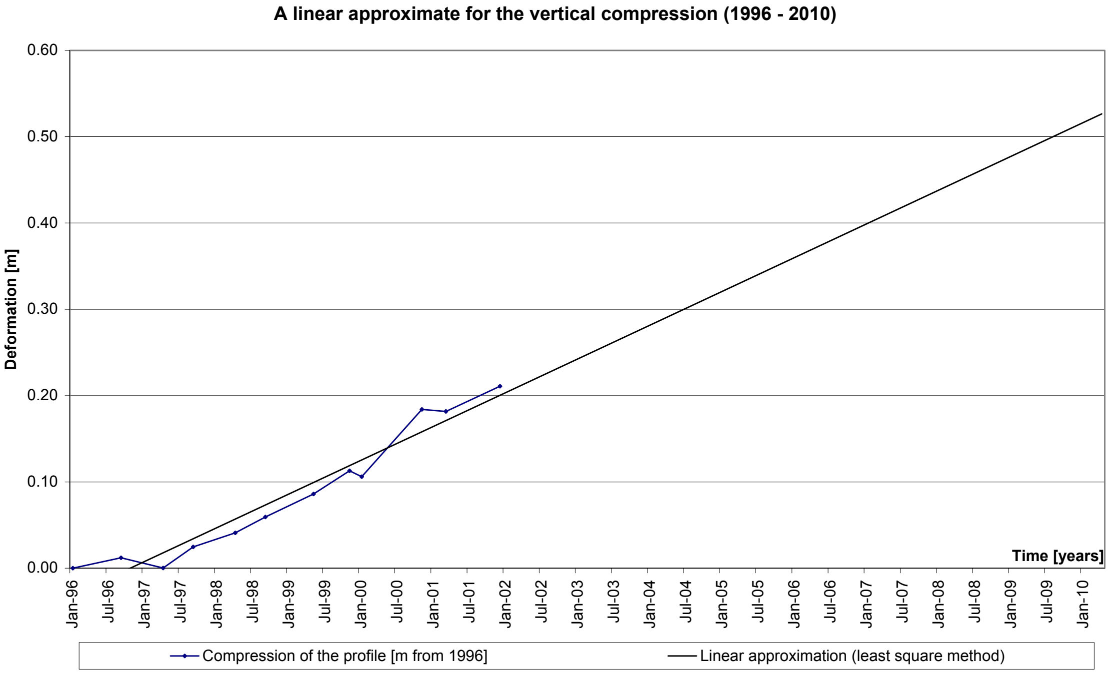


FIGURE 138: extrapolation of the vertical deformations of the tubular profile using a linear equation *(Saltner & Keij)*

The vertical deformations are depicted here, the horizontal deformations and the settlement extrapolation is given in Appendix 14.

The vertical deformation has a total value in 2010 of 0.525 m, and a rate of deformation of 4 cm a year. The total horizontal deformations are 0.300 m in 2010 and the total settlement equals 1.80 m.

Model calibration to measurements

The model that results from the previous chapter is made up of two parts. These two parts are:

1. Calculation of deformations of the tube into the ice (DeRi + RiVi). This part concerns the vertical settlement of the centre of the tube into the ice.

2. Calculation of the deformation of the vertical and horizontal dimension of the tube itself (DeRi). These deformations relate to the tubular profile only.

Calibration of vertical settlement

The vertical settlement that is calculated with the model is composed of a viscous deformation of the ice layers under the tube due to loading by tube and ice, derived from the RiVi model, and an extra local vertical deformation due to the deformation of the tube due to ring behaviour described by the DeRi model.

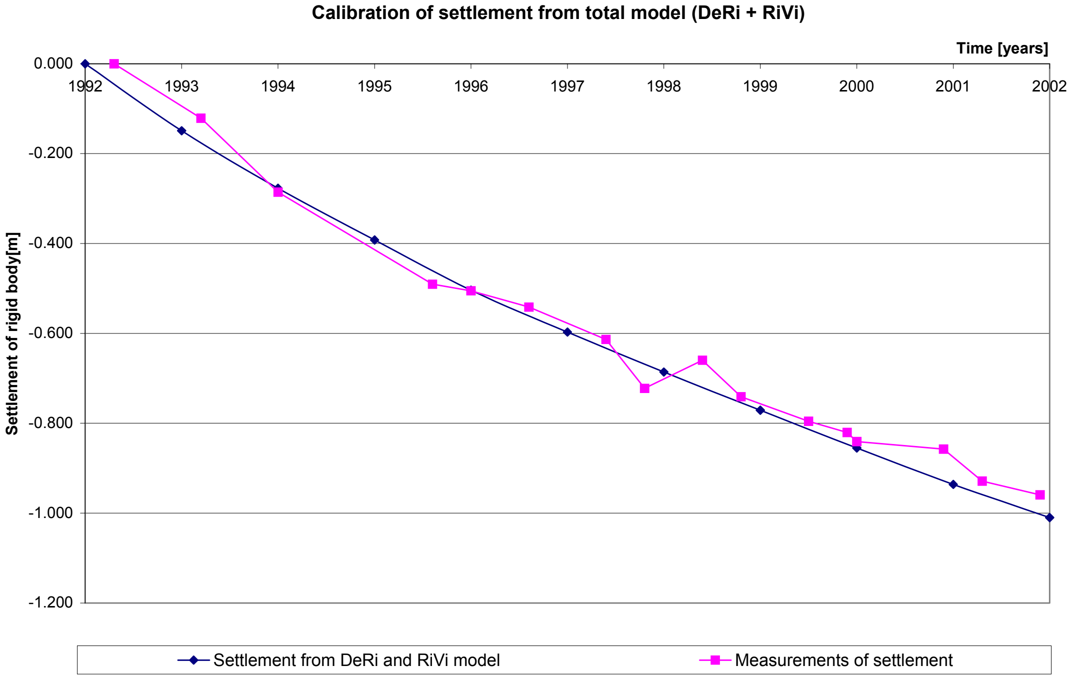


FIGURE 139: calibrated model output compared to measurements *(Saltner & Keij)*

The output of the model is compared to the measured data for the West tube. Figure 139 shows a good comparison for the model output to the measured data.

Both types of settlement in the DeRi and RiVi model depend on the viscosity of the ice. To calibrate the model a least square estimate is executed with the viscosity for a variable. The viscosity is increased by –1% to 6%. In each case the cumulative squared error is calculated.

$$\text{Error} = \sum \left(\text{settlement}_{aprox} - \text{settlement}_{measured}\right)^2$$

Figure 140 shows that the best fit is an increase in viscous effect of 2.5%. This means that the global measurements of snow layers are reasonably correct, owing to a small difference between model and measurement.

The increase of 2.5% is used to estimate the settlement into the ice of Neumayer Station. The maximum difference between measurements and model is 50 mm. This difference can be explained from human factors such as measurement or calculation mistakes after measurements. Another cause could be a possible material behaviour aspect that is not included in the model. The difference is relatively small leading to the simplifying assumption that measurement inaccuracies lay at the root of the differences.

In section *Output of the model for Neumayer Station* in this chapter the calibrated model output is given.

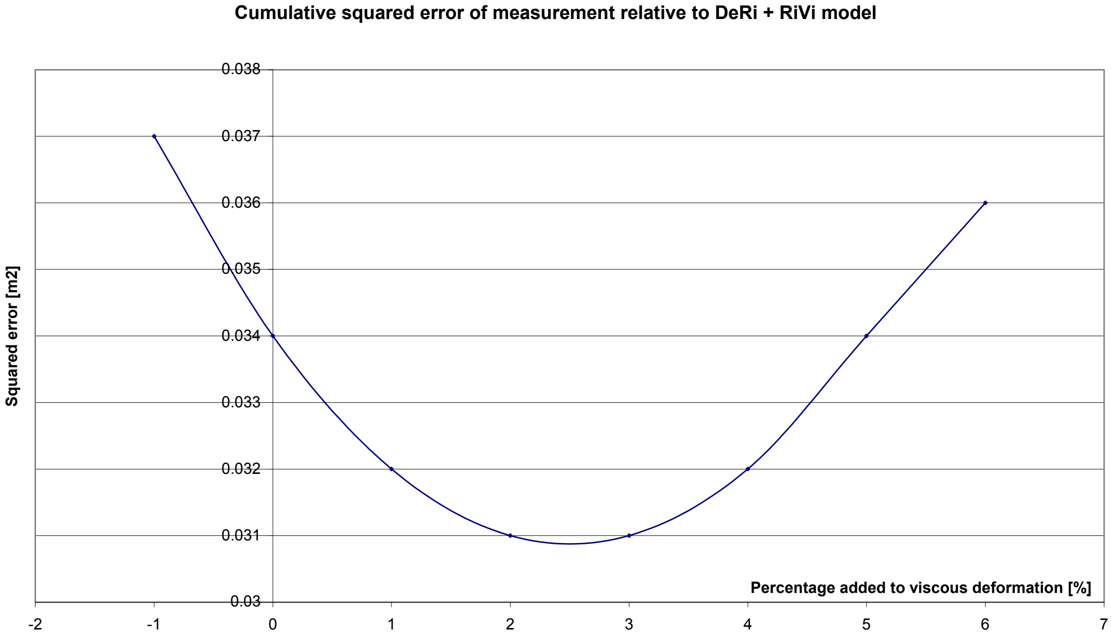


FIGURE 140: least square graph for the vertical settlements in the RiVi + DeRi-model *(Saltner & Keij)*

Calibration of deformations

The deformations in the tubular profile are calculated with the deforming ring model (DeRi) as mentioned earlier. In this model the snow accumulation data has been changed to resemble the data as measured and given in Chapter 9.

Implementing the actual historical snow data shows that the modelled deformations, as is to be expected vary dependent on the snow accumulation. The years 2001 and 1998 have relative small accumulation rates (33 and 53 cm per year respectively), which can be seen from the angle of the graph.

Again the least square estimate is used to perform a calibration. The sensitivity analysis shows that the best parameter to perform this calibration with is the viscosity modulus of snow. Enß remarks that a temperature difference of 10° can vary moduli of snow up to 50% [e-mail contact]. The variation of the viscosity will be taken in this interval.

For the least square fit an analysis is made regarding the difference between the measured data and the model output. An overview of horizontal and vertical deformations as measured, compared to the un-calibrated model is given below.

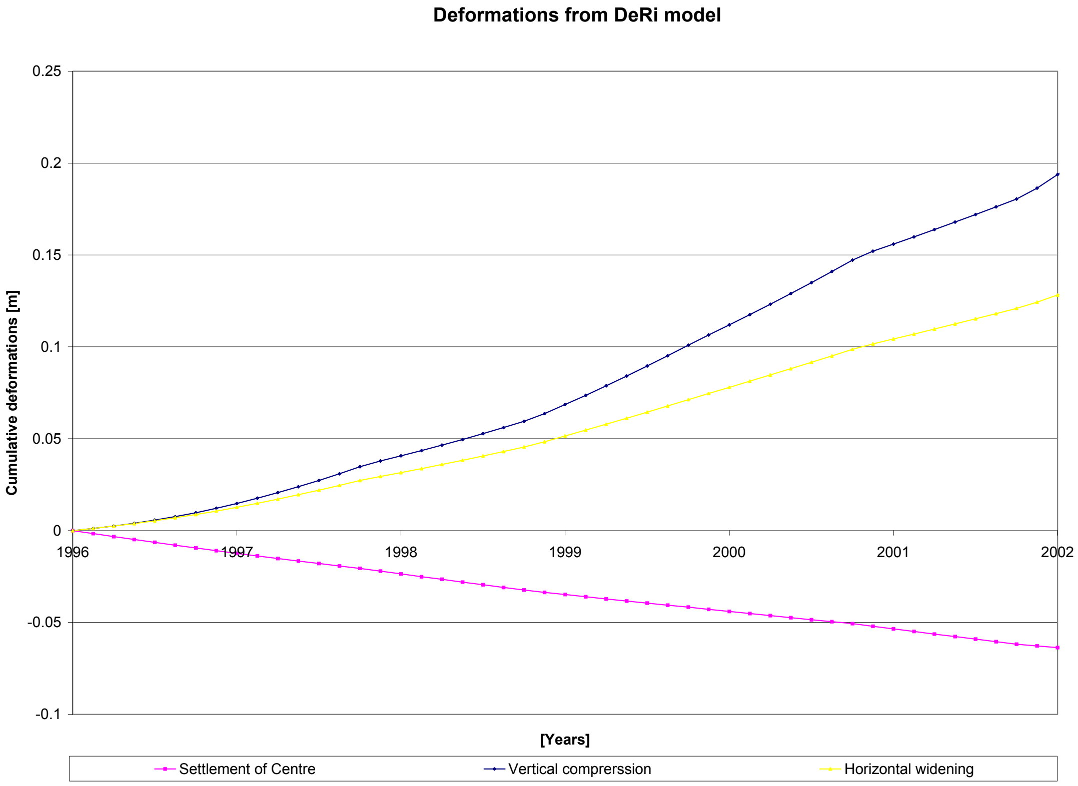


FIGURE 141: deforming ring model *(Saltner & Keij)*

The calibration results in an error for the vertical case and an error for the horizontal deformations. As the total error needs to be minimised the two errors are summed and then minimised.

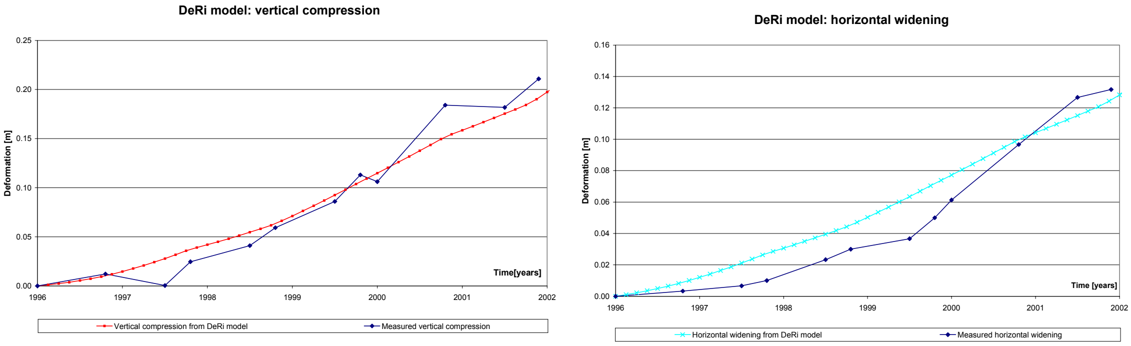


FIGURE 142: uncalibrated model output compared to measurements *(Saltner & Keij)*

Two calibrations are executed, to show the effect of not only a variation in the viscosity of the snow layers around the station, but also the elasticity effect. The temperature effects from the tubes on the surrounding snow layers are taken to be small at the bottom of the tubes due to lower temperatures and smaller daily temperature variations deeper into a snow layer. The calibration will focus on the characteristics of the snow next to the tube, at $\varphi = 90°$.

First the viscosity modulus $E_{visc,90°}$ is varied. The lowest cumulative error of 0.0055 is found at $E_{visc,90°}$ is 30%, which means an increase in the viscosity of 30%.

When the viscosity of a material is higher the increase of other rheological parameters can also be expected. For the calibration it is assumed that there is a positive linear dependency of viscosity and elasticity.

$$E_{visc}\tau_{calibration} = E_{visc,used}$$

$$E_{elast}\tau_{calibration} = E_{elas,used}$$

The assumption made includes the same parameter τ for both equations.

When the calibration is executed this way, the point with the least squared error is 25%. The total squared error is however higher than in the case with only the viscosity (0.006 vs. 0.0055). This means that the best fit varies only the viscosity, with 30%.

The hypothesis describing the snow behaviour that is adapted here is:

'The snow at Neumayer Station has a viscosity behaviour that is 30% more rigid than the measurements of Enß (1997) show. Elastic behaviour in depth is not adjusted.'

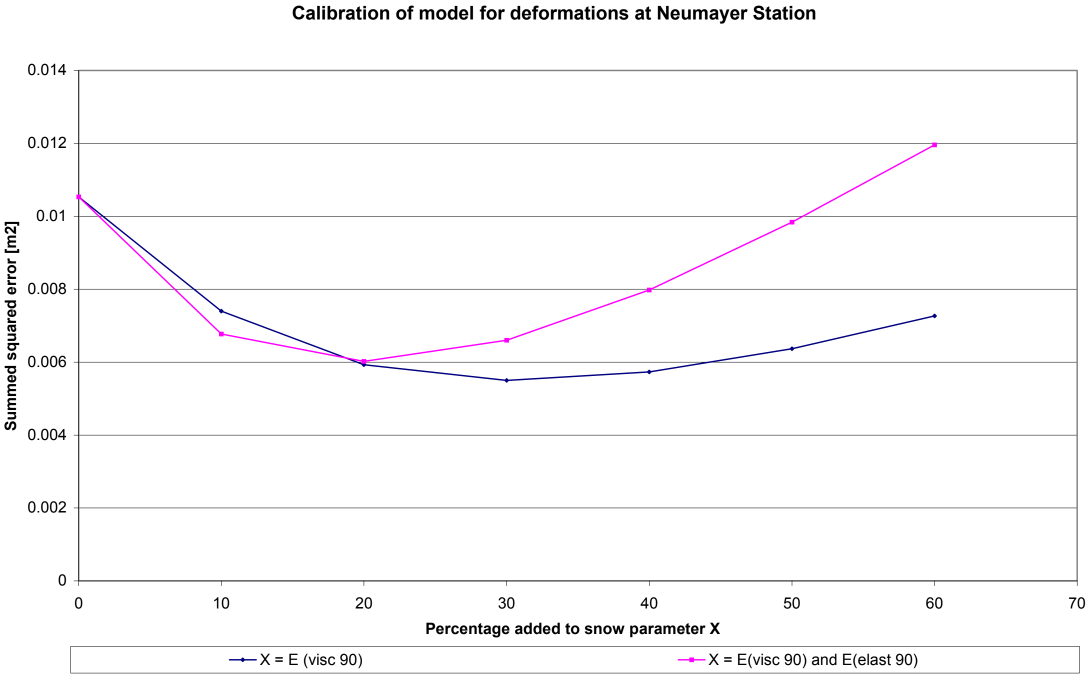


FIGURE 143: least squared error between measurement for Neumayer Station and model with varying snow parameters *(Saltner & Keij)*

This can be due to the compression effect of the deforming ring. Also the melting and refreezing of the snow layer directly around the tube can have effect on the snow and ice parameters around the station.

The reason for the increase in viscous rigidness whilst the elasticity remains the same is not a subject of research for this report, but can be of interest for further study.

The largest difference between model and measurement is 35 mm, which lies within the error obtained in the previous section. This figure lies within the error range that is present when involved in a measurement programme of multiple points and possible measurement errors.

Output of model for the future of Neumayer Station

Deformation of the Neumayer Station is presented in two formats. Firstly the vertical settlement of the whole station into the ice will be discussed which originates from the global ice layer behaviour. Secondly the model for the local behaviour around the tube's circumference is presented and discussed.

Settlement into the ice

The settlement into the ice is depicted below. The settlement is valid for the whole profile. Together with the snow accumulation data a good overview can be constructed to assess the total extra coverage per year.

The extra coverage per year can be of importance when planning the lengthening of the

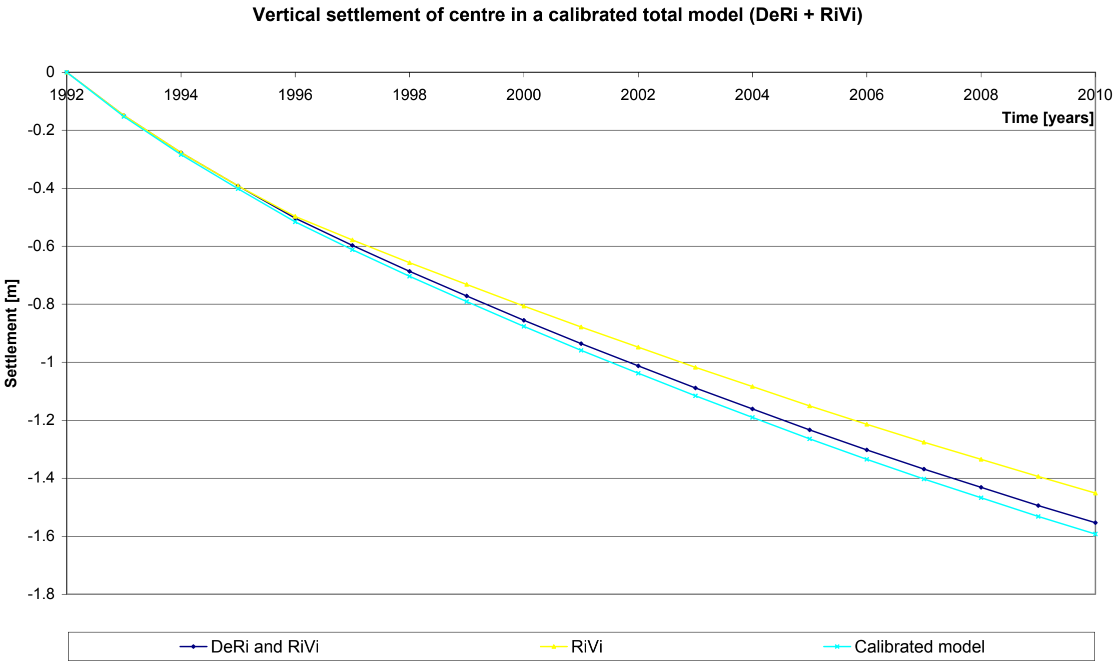


FIGURE 144: output of the model for the vertical settlement of the tube *(Saltner & Keij)*

staircases, the ventilation shafts and the heightening of the outside facilities.

The figure is presented up until 2010, which is three years past the stations as-built lifetime estimate.

Vertical deformations

For the vertical deformations the calibrated DeRi model has been run for the snow accumulation situation at Neumayer Station. When the distribution of the annual accumulation is assumed to be a normal distribution the found parameters are an average annual accumulation of 0.70 m and a variation of $(0.22)^2$. Using this distribution values can be found for an upper limit and a lower limit of snow accumulation.

The upper limit of snow accumulation is defined as the accumulation rate at which the probability of exceeding is 5%. The lower limit is defined as the as the accumulation rate at which the probability of sub-seeding is 5%.

TABLE 21: snow accumulation for different probabilities

Probability of exceedance	Snow accumulation [m/year]
5% (unsafe)	1.06 m
50% (average)	0.70 m
95% (safe)	0.33 m

For the normal distribution mentioned, the limits are given in the table below. The probability of exceeding is taken as a measure for safety. There is, for instance a 50% chance that more snowfall will occur than the 'normal' case, and 5% in the 'unsafe' case.

TABLE 22: end of lifetime for deformations and snow accumulation

m	5%	50%	95%
0.75	2005	2006	2009
0.85	2006	2007	2010
0.95	2006	2008	2011
1.00	2007	2009	2013
1.15	2008	2010	2014
1.25	2009	2011	2015
1.35	2009	2012	2016
1.45	2010	2012	2018
1.55	2010	2013	2019
1.65	2011	2014	2020
1.75	2011	2014	2020
1.85	2012	2015	2020
1.95	2012	2016	2020
2.05	2013	2016	2020
2.15	2013	2017	2020
2.25	2013	2017	2020

For each of these snow accumulation figures, a calculation of the deformations of the tubes of Neumayer Station has been made (see table 22).

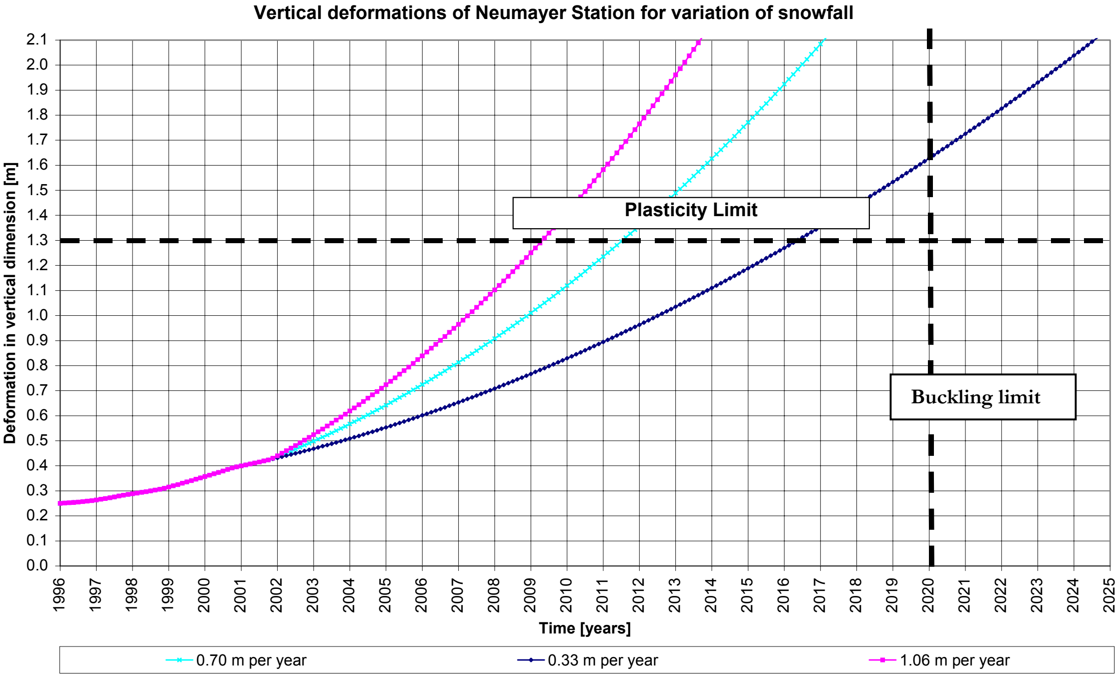


FIGURE 145: estimates of the lifetime for Neumayer Station *(Saltner & Keij)*

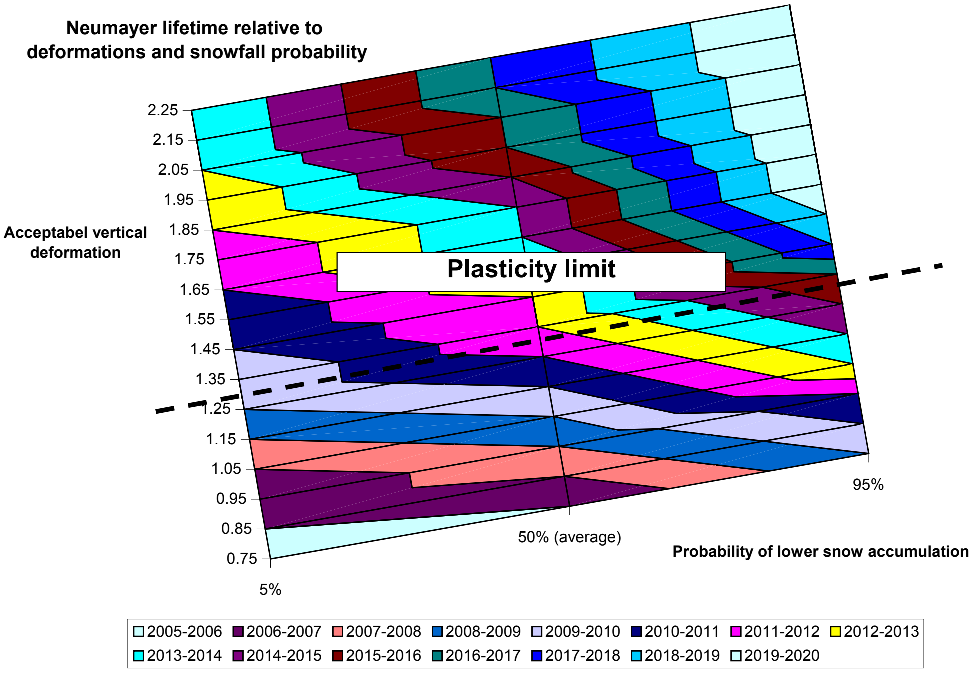


FIGURE 146: lifetime of Neumayer Station for variation in allowable deformation and annual snow accumulation *(Saltner & Keij)*

From these graphs a table is derived to serve as a decision tool. The 5, 50 and 95% boundaries are given in full years, allowing an easy decision based on operator's wishes. The input for this table is the graph of the deformation after 1996.

When the operator allows a deformation of 1.00 m, as discussed in Chapter 6, the table shows that in a case of normal (50%) snow accumulation Neumayer Station will reach this maximum deformation at the end of 2008. With 90% reliability the profile of free space will be reached between 2007 and 2013.

These figures can also be presented in a graph. A given probability and an allowable deformation are input to find the appropriate time at which the lifetime ends.

The graph in figure 146 can be used to find values for the end of lifetime quickly. Input for the use is the allowable deformation and the accepted snow accumulation probability. For instance when a deformation of 1.25 m is allowed, under an average snow accumulation the lifetime will end in 2011.

Comparison of the analysis of lifetime for Neumayer Station

The lifetime of Neumayer Station has been estimated in two different ways in this study. An overview of these estimates is given and the estimates of AWI at the start of the stations operation, and that of Enß from the report from 2001 are added.

The first estimate of the lifetime was set to 15 years based on earlier experiences with GvN. The GvN base had a lifetime of 11 years and the lifetime of Neumayer Station was improved by four years due to:

- Selection of a site for the base that was subject to less relative snow movements
- Choice for a circular profile for NM instead of the semi-elliptical profile of GvN.
- Horizontal prestress of the circular profile to a horizontal ellipse

The estimation made by Enß (2001) was based on the measurements at the base in 1992-1995 and 2000. The value for the deformations in 2007 are obtained using:

- an estimate for the snow accumulation rate per year of 0.70 m
- an extrapolated deformation per additional vertical stress of 0.031 m/kN, measured from data between 1994 and 2001.

The estimate for 2007 is calculated from the extrapolated data to give values for after 2000 as displayed in figure 147.

The deformations from these calculations are enlarged by a factor to account for the buckling of the bottom side of the tubes. The buckling of the tubes was measured from

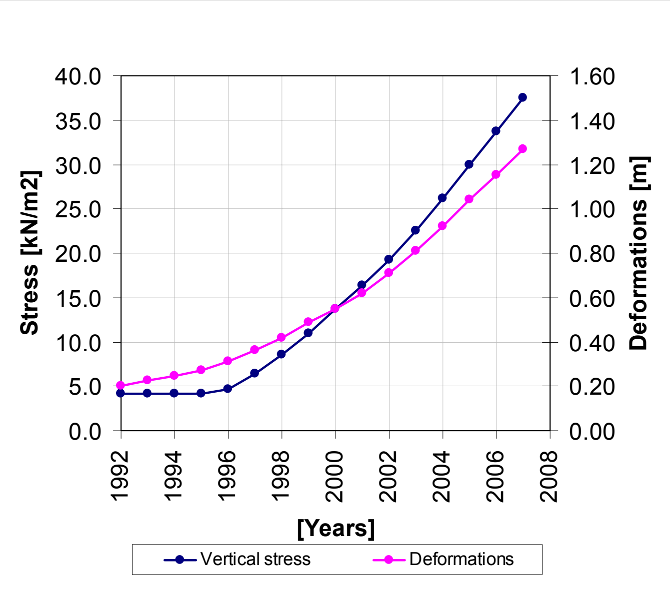


FIGURE 147: calculations for vertical deformation of Neumayer Station
(source: Enss, 2001)

the inclination of the steel tubes under the containers. The final lifetime expectation was then set at 14 years ± 1 year.

The following table gives an overview of the calculations from this thesis and the earlier estimations.

TABLE 23: estimates for the lifetime of Neumayer Station

	Maximum deformation allowable:	Max. deformation reached in:	Deformation in 2010:	Settlement of centre in 2010:
Least sq. estimate (TUD, 2002)	1.0 m	2015	0.78 m	1.8 m
DeRi + RiVi (TUD, 2002)	1.0 m	2009	1.12 m	1.6 m
AWI (1991)	No value	2007	No value	No value
Enß (2001)	1.3 m (1.0 m)	2007	1.7 m (1.4 m)	No value

This overview confirms that the least squared solution gives an oversimplification of the deformation mechanisms and the extra viscous deformations involved. The estimation of Enß uses a mixed form for the estimate, combining a linear assumption for the deformations with additional vertical stress. However, by combining deformation data between 1994 and 2000 with stress data that remains a constant from 1992 to 1996 an overestimate is made on account of the deformations directly caused by the snow accumulation. This is the reason the estimate made by Enß is deemed a lower limit for the end of lifetime of the base.

The model presented in this report is based on material behaviour as well as a calibration to the Neumayer Station site conditions and is viewed to give a realistic view of the deformations, taking into account the decrease of deformation rates over time due to increasing Young's modulus and viscosity modulus of deeper layers of ice.

Conclusion for lifetime for Neumayer Station

When Neumayer Station was designed the estimated lifetime was 15 years. This would mean an abandonment of the station in the year 2007. While it was undefined whether this is to be the beginning or end of that year, it is assumed that the station's operational lifetime was planned to last until the season 2006 - 2007 and to be abandoned early 2007.

In Chapter 6 the maximum deformations that can occur were set to 1 m. This means that when the vertical deformation is greater than 1 m the functional use of spaces around the container must be changed.

The conclusions of this study are valid only under the assumptions made, which are:

- Snow parameters as measured by Enß (Chapter 9)
- Viscous effect as assumed by Duddeck (Chapter 11)
- Profile of free space as discussed with H. Ahammer (Chapter 6)
- Stresses in the steel ring remain below the strength limit of steel and the bolts
- Stochastic properties of snow accumulation rates only

The output of the model presented in this report shows that 1 m of deformation is reached at the beginning of 2009, considering a normal case snow accumulation. The chance that due to greater accumulation rates the station needs to be abandoned before the planned end of lifetime (2007) is less than 5%, taking into account the snowfall probability only.

The output of the model gives a more progressive deformation of the tubes than a linear estimate as made in the first section of this chapter. The practical use of the linear estimate is limited, because viscous effects, progressing over time are not included in the estimate.

Chapter 13

Recommendation for a replacement of Neumayer Station

This chapter is added to show the possibilities of the model that was developed in this thesis. When designing a base it is useful to be able to vary certain design parameters to obtain the effect on the lifetime of the base.

This chapter aims to describe the design changes that are possible for Neumayer Station, would it be built again, and their influence on the deformations. The second part of this chapter gives a broad overview of the different options there are for the base that replaces Neumayer Station at the end of its lifetime.

Possible options for continuing presence on Antarctica

Before Neumayer Station has reached the end of its lifetime the decision must be made to continue the German Antarctic scientific effort. The cost of a newly built base will be an important factor in the discussion to ascertain the course of action.

The options for the Alfred-Wegener-Institute to continue research on Antarctica are threefold.

Building a new base:

Over the last 3 years designs have been made for a new base at the present location of Neumayer Station. For these bases three types of designs can be named, a sub-surface base, a base over the surface and a base of a hybrid form. The detailed design of a base will take two to four years.

Finding a partner:

For all national Antarctic agencies, building and re-building bases to keep a permanent presence on the continent is important. Working together with another country would enable sharing of logistic and facility costs. The downside of closer Antarctic co-operation would be the loss of a network of bases covering the whole continent during the whole year.

Conducting different type of research:

The research at Neumayer Station has always been planned with the presence of an over-wintering crew in mind. The nine-headed over-wintering team consists of 5 supporting members (cook, doctor, radio operator, electrical and mechanical engineer) to serve the four scientists (meteorology, geophysics and air chemistry). When automatic instruments could replace the research that is executed at Neumayer Station, this would reduce the need for a large station or over-wintering personnel. Use of the Internet and a continuous connection to the main office via satellite may enable a remote automatic base to function.

FIGURE 148: placing an automatic weather station *(source: [B])*

Possible design changes for a replacement for Neumayer Station

The calculations for Neumayer Station in Chapter 12 have been executed with values for the tube dimensions, the steel parameters and the snow loads as measured at Neumayer Station. In a design phase these parameters may be varied to obtain an idea of the influence of different parameters on the deformation and thus the lifetime.

The parameters that will be varied are respectively:

- Radius of tube
- Thickness of tube
- Moment of inertia of tube
- Density of snow

The options regarding these changed parameters will all be discussed by calculating the deformations in time, specifically the vertical deformations, with a reference value in 2010.

The DeRi + RiVi gives a vertical deformation of 1.12 m in 2010

Radius

When the base is designed with a larger radius, this can have a positive effect on the deformation behaviour. With a larger radius, the deformations that can be accepted are equally bigger. The larger tube surrounds the same container-based living sections, which leaves the profile of free space the same.

The radius here is varied for reference only. An arbitrary smaller radius (3.70 m) and a larger radius (5.00 m) are taken to illustrate the effect on the deformations. In figure 149 the original situation is the calibrated 'normal' snow accumulation case.

TABLE 24: deformations of a tube for variation in radius

Radius [m]	Max. deformation allowed [m]	Time max. def. reached	Deformation in 2010 [m]
3.70	0.50	2003	0.89
4.20	1.00	2009	1.12
5.00	1.80	2010	1.80

When the radius is increased, the 'covering' phase in the calculations, as a rigid body will be longer because the tube will take longer to be covered with snow. This effect is not taken into account here.

A smaller radius leads to smaller deformations, but also a smaller profile of free space. The profile of free space effect is larger than the smaller deformations, making a smaller tube an option that is not favourable.

A larger tube allows larger deformations, which leads to a longer lifetime. This behaviour is limited because larger radii also lead to higher deformation rates. The graph shows that a tube that is almost 1 m larger leads to a longer lifetime of 1 year under the same assumptions as the present station.

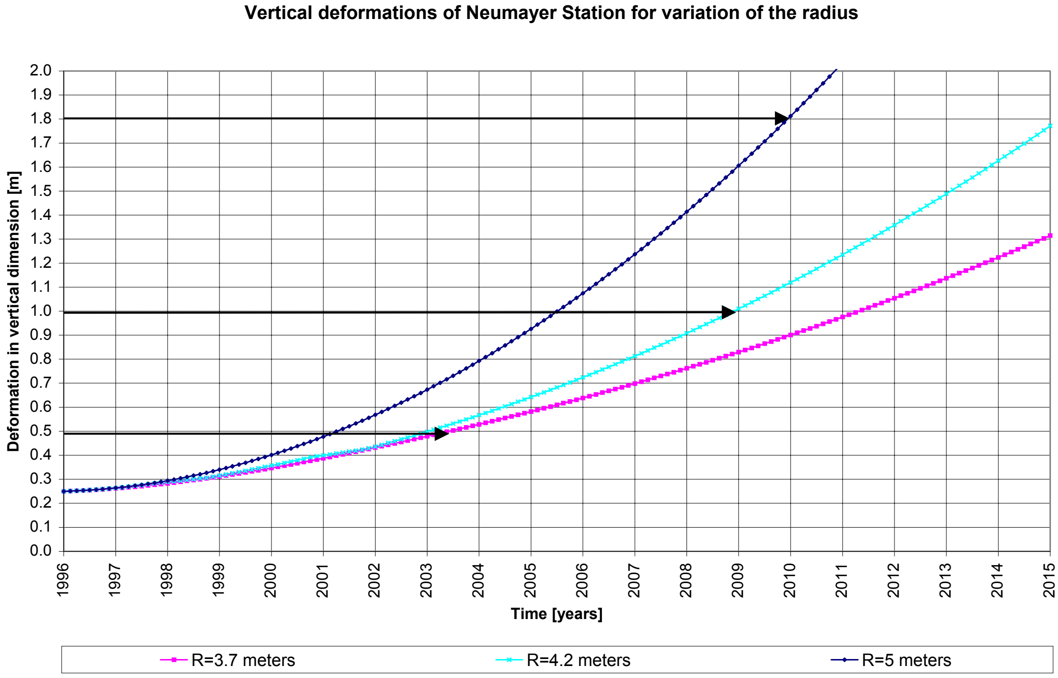


FIGURE 149: effects of variations of the radius on the lifetime of Neumayer Station *(Saltner & Keij)*

Profile properties

For the profile of the tube, a 60 mm high corrugated steel profile was chosen with a plate thickness of 7 mm. The stiffness properties of the tube, determined by the Young's modulus of steel and the moment of inertia of the profile could be altered by changing the profile of steel. Two cases have been calculated: weakening the tube by 10% and stiffening the tube by this amount.

Plotting both measures in one graph shows that a stiffened profile extends the lifetime of the base by less than one year and a weakened profile shows the opposite behaviour.

A stiffened profile will mean that either the wall thickness will rise, or the profile height will be increased. Because the moment of inertia is defined by the area of the steel multiplied by the squared distance of the material from the profile centre line, changing the latter will have the largest influence. Theoretically it is possible to increase the profile height under the same area and thus increase the inertia.

Snow properties

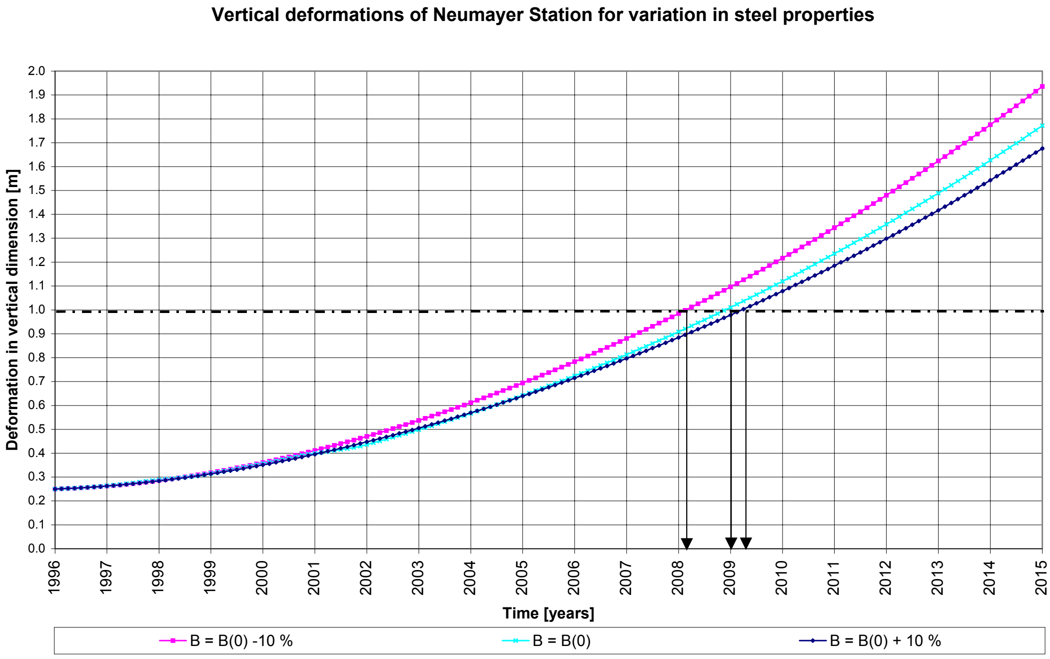


FIGURE 150: reduction of the deformations due to variations of the steel profile *(Saltner & Keij)*

When snow falls under natural conditions the snow crystals form a grid that does not have the ideal level of coherence. These natural connections between the snow crystals are decisive for snow properties such as rigidness and viscosity. Changing the natural crystal structure can alter the snow properties.

When stiffer snow is needed on-site it is usually sintered. With a mechanical milling machine the snow is mixed and milled and placed back into the dug trench.

The sintered snow surrounds the station and provides a more rigid foundation material around the circumference. The sintering of the snow must therefore be done while building the base.

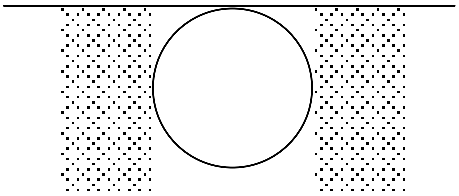


FIGURE 151: sintered snow layers, next to the tube *(Saltner & Keij)*

As data on the exact possibilities of sintered snow are not available for Neumayer Station, an assumption is made that the sintered snow will be placed in two trenches next to the station, with snow that equals the snow at 10 m of depth in elasticity and viscosity. This is a reasonable assumption, because sintering has been successfully executed up to these depths successfully at Neumayer Station.

For this case the deformations have been calculated for non-sintered and sintered snow, showing smaller deformation for the sintered case.

Radial fixation

The graphs for Neumayer Station show that during the period when the base was covered, the outer hull deformed fully elastically (horizontal widening equals vertical compression). When it would have been possible to fix the hull up to the end of this period, the deformations would have been 25 cm less, which means a reduction of 25% of the acceptable deformations.

This structural aspect can be taken into account in the future but is a design change

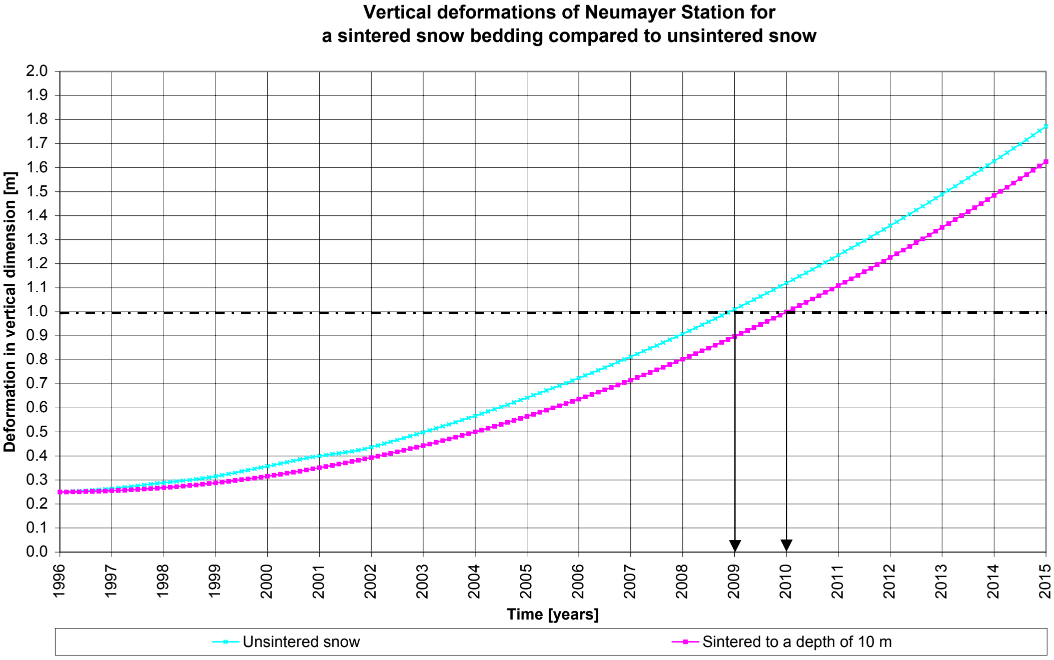


FIGURE 152: sintered snow vs. unsintered snow *(Saltner & Keij)*

relating to the execution of the works to build the base. Unforeseen weather can hinder the construction progress, limiting the possibilities to apply the pretension.

Comparison of design alternatives

To compare the design changes three criteria have been evaluated. First the deformations in 2010 have been summarised from the sections above. The best deformation improvement is gained by placing the base in a sintered snow bed.

TABLE 25: comparison of several structural alternatives with assumptions for cost comparisons

	Existing	Radius 5 m	Steel	Sintered snow
Lifetime under 1 m criterion	2009	2010	2009	2010
Deformations in 2010	1.12 m	1.00 m	1.06 m	0.98 m
Cost of steel (est.)	100 %	116 %	110 %	100 %
Cost of installation (est.)	100 %	120 %	110 %	140 %

The cost of steel is an estimate, based upon the need for extra construction steel for the various options. The raising of the steel stiffness parameter will most probably not result in more steel, but in a higher profile, which raises the costs.

The costs of installation will not differ greatly when installing a tube with higher stiffness. A larger radius leads to larger scaffolding creating higher costs. The most expensive option would be the construction of a 10 m deep trench in which the structure is erected. Here the 40% extra costs will lead to a lifetime improvement of 1 year.

The best measure of those presented here is to be devised by the logistic control at AWI. Further study is needed to measure the exact extra building costs against the extra lifetime in the sintered snow case.

Extension of the lifetime of Neumayer Station

As the end of the lifetime for the base draws closer, there are still options to lengthen the number of operative years at Neumayer Station. In this study, the end of lifetime depends on deformations only. It has been shown that when the deformations start to hinder the use of the station, the structural integrity is not yet compromised.

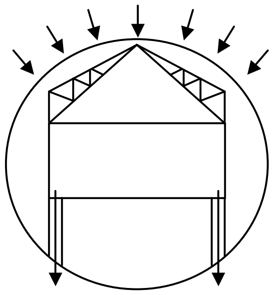


FIGURE 153: construction adapted for the deforming base *(Saltner & Keij)*

The possibilities for living in a base where the profile of free space has been reached are twofold. On the one hand evaluating all activities on and around the containers can enlarge the station's profile of free space. When at critical points the top use of the containers are limited, another 0.50 m can be gained, which after 2009 means 3 - 4 years of prolonged use.

On the other hand attempts can be made to prevent the deformations of the tubes and divert the forces that come into play to the subsurface. This can be done by building a top construction on the containers that will take on the loads from the top of the tube, and guide the loads to the steel cylinders through the containers.

To prevent the accumulation of stress in the neighbourhood of the contact points between the outer hull and this additional construction care must be taken to ensure a support over the full length of the tunnel. This support can be made using beams that are suspended between two top portals.

Whether this solution can be put into practice depends on the costs that are involved in planning, designing and testing this construction. This is a subject for further research.

Chapter 14

Conclusions and recommendations

The original research goals for this thesis will be repeated here to put the outcome of this project in perspective:

Processes

What are the processes involved in the deformations of the steel tubes?

Analysis of lifetime

At what point in time does Neumayer Station have to be abandoned by the Alfred-Wegener-Institute due to deformations of the steel hull?

Design

What are possible (future) design changes to prolong the lifetime of the base?

The conclusions will focus on each of the goals after general conclusions have been given.

Conclusions

In this study the deformation of a tubular structure in ice has been modelled for the Neumayer Station at the Ekström Ice Shelf. This base is subject to an average of 70 cm of snowfall annually.

The model has been focussed on the deformations of the tube in cross section, as this was seen to be the most important issue by the station operators, the Alfred-Wegener-Institute. Other deformations of the base, such as those caused by movements of the ice sheet in a lateral direction, or differential deformations along the tunnel axis have not been taken into account.

In the model, ultimate limit state calculations have been taken into account, providing a clear interval within which conclusions from the model are deemed to be valid. This interval is defined by the elastic ovalisation limit for the deformations, and the local buckling limit for the vertical snow forces.

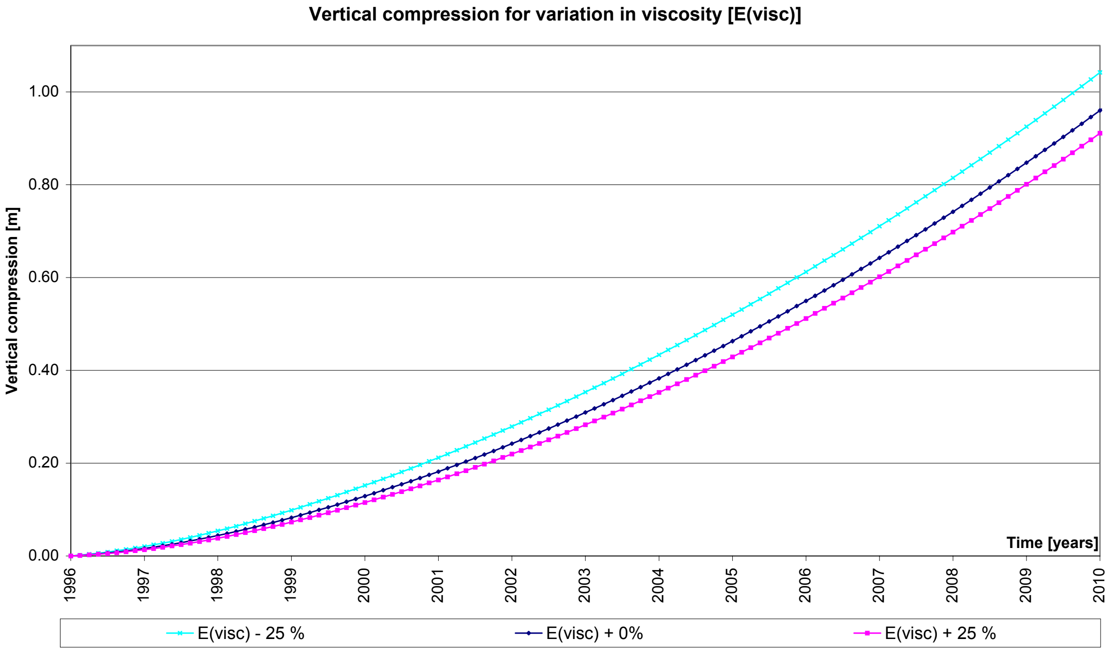


FIGURE 154: changing deformations for variation in viscosity *(Saltner & Keij)*

General

When an Antarctic base is designed and constructed care should be taken that sufficient data is collected for monitoring the deformations of the structure. Construction on ice is an essentially different venture to conventional building, for which extra monitoring is advisable.

Processes

The deformations of a cylindrical tube in snow can be modelled with a summation of a Duddeck model for the deformations of a compressed ring, and the linear visco-elastic model for the settlements of a rigid body into snow.

Visco-elastic behaviour of the snow around tubes is seen to be of major importance. Viscous creep is cause for deformations to take place, even when the calculations are executed with the assumption of higher rigidness of snow.

Abandonment

Under an average load case of 0.70 m snow per year the maximum allowable deformation for the serviceability limit state is reached in 2009. The 90% confidence interval is from 2007 to 2013. This interval does not take into account uncertainties in the material properties of snow and steel and focuses on the stochastic distribution of accumulation rates only.

The graph presented here is valid up to 1.30 m of deformations after which extra deformations due to large ovalisation must be taken into account. The buckling limit lies at a vertical load of 140 kN/m^2, which is not reached until 2020. For this calculation the average annual snow accumulation is 0.70 m.

Design of a new station

The options to prolong the lifetime of tubular sub-surface bases lie in optimising radius, steel parameters or snow parameters. The greatest effective reduction of the deformations is obtained by sintering the snow next to the station up to a depth of 10 m. Another option that is not further elaborated is the fixation of the radius until the station is fully covered, after which the deformations of the radius are released.

A prolonged lifetime of the existing base can be achieved through a combination of a reduction in the necessary profile of free space and at places of local high deformations providing scaffolding relaying the forces directly via the containers to the under-construction. The concentration of forces in the hull close to the connection points is a construction challenge that will have to be met.

Recommendations

The conclusion of this project points out the end of the lifetime of Neumayer Station under given limitations. The scope of this project was to focus on the deformations of the base and derive an estimate of the lifetime through an analytical model of the phenomena involved in deformations in ice.

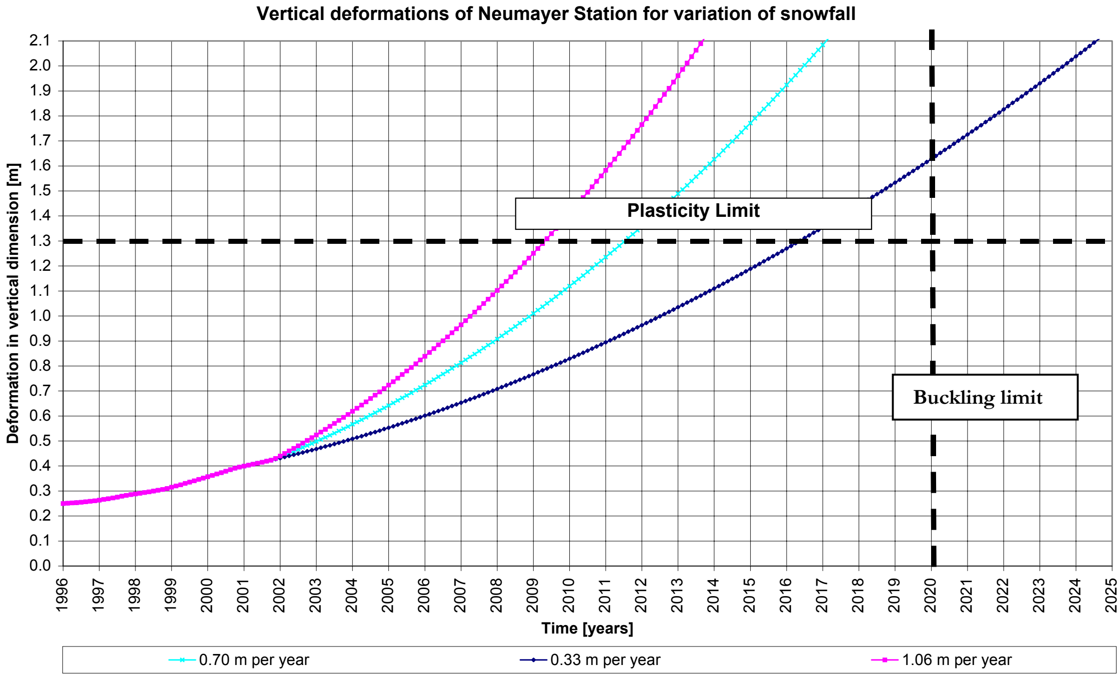


FIGURE 155 : total deformation for snow accumulation scenario's *(Saltner & Keij)*

During the project some matters have come to attention that lie outside the scope of the project, but deserve to be mentioned here:

- Survey at Neumayer Station: The survey programme that has been executed since 1992 enables the Logistic Departments of the AWI to monitor the deformations of the bases over time. The data obtained from this measurement programme has served as the basis for the calibration of the model in this study. An evaluation is recommended for the protocol and the survey equipment to ascertain if the present way of surveying reaches a desired accuracy. A switch to a more accurate system, for instance based on laser technology, can be an improvement, for Neumayer Station or future bases.

- Ice next to the tubes: The tubes are warmed during summertime due to solar radiation that protrudes through the snow. The heat affects the snow directly in contact with the tubes to the extent that at some locations in the tube melted water is visible. The exact snow properties directly next to the tubes are unknown. A study into the layer of snow directly around the base can lead to a better understanding of the effects of the heating of the tubes on the properties of the snow and the forces on the structure and its consequent deformations.

- Analysis of lifetimes: The analysis that is given in this study is based on the probabilistic distribution of the snow accumulation rates. Using these distributions, the deformations can be calculated from a point in time (x, here 2001) onwards.

  The actual failure of the construction can be assessed per year for the next years by including the measured deformations from 2001 into the calculation. Doing this will give a better estimate for the preferred time of abandonment of the station. When assessing multiple years in advance the snow accumulation uncertainties will have an increasing effect.

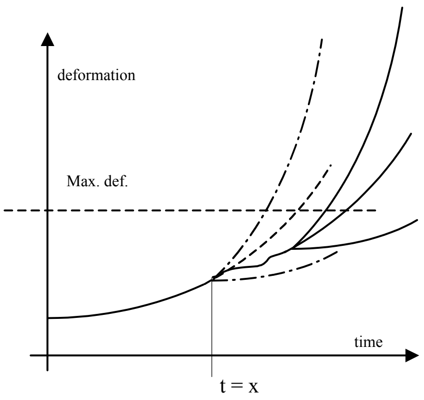


FIGURE 156: actual failure estimate is done annually *(Saltner & Keij)*

- Snow measurements: It has not been possible to obtain snow parameters through measurement in one season. These parameters can be important as an input for future modelling. To gain a better understanding of the deformations of a cavity in snow, a longer measurement programme can be executed. This measurement programme should focus on the arching properties of ice that is suspended, for instance in a trench.

- This study has shown that it is possible to use a Duddeck model with a viscous extension to model tubes in a viscous material. Practical use of the solution, when translated from ice to typical soils can be explored.

- The demand for practical solutions and construction concepts for research bases on Antarctica is high. When more institutes reach the end of lifetime of their bases more research is needed into designing and building these stations. Civil engineering can contribute to this research.

List of Symbols

Symbol	Definition	Unit
A	area	m^2
A	Young's modulus line parameter	[-]
a	constant in Duddeck calculation	[-]
A_0	vertical dimension in cross section	m
A_1	vertical dimension in cross section	m
A_2	vertical dimension in cross section	m
A_n	constant in Duddeck calculation	[-]
A_z	temperature at depth z	°C
b	viscosity modulus parameter	[-]
B	steel stiffness parameter (= EI)	kNm^2
B	vertical dimension in cross section	m
B	Young's modulus line parameter	[-]
B_1	vertical dimension in cross section	m
B_2	vertical dimension in cross section	m
B_n	constant in Duddeck calculation	[-]
c	viscosity modulus parameter	[-]
C	horizontal dimension in cross section	m
C	constant in density/depth equation	$kg/m^3m^{-0.5}$
C_b	soil reaction spring modulus	kN/m^2
d	depth	m
e	viscosity modulus parameter	[-]
E	Young's modulus	kN/m^2
E_{elast}	Young's modulus	kN/m^2
E_s	Young's modulus for steel	kN/m^2
E_{soil}	Young's modulus for soil	kN/m^2
E_{visc}	viscosity modulus	kN/m^2
$f_{y,rep}$	steel limit stress	N/mm^2
g	gravity parameter	m/s^2
h	vertical dimension	m
H	depth of tube's center	m
h_{over}	depth of roof of tube	m
$h_{viscous}$	depth of viscous deformation start	m
I	moment of inertia	m^4
K	soil pressure vs ring influence parameter	m

Symbol	Definition	Unit
k_r	radial sub grade reaction modulus	kN/m^2
k_t	tangential sub grade reaction modulus	kN/m^2
l	length	m
M	bending moment	kNm
N	normal force	kN
n	frequency of temperature changes	[-]
$N(\mu,\sigma)$	normal distribution with average and variance	[-]
Q	tangential force	kN
q_h	horizontal soil load	kN/m^2
q_{max}	maximum load (buckling criterion)	kN/m^2
q_r	radial load	kN/m^2
q^r_n	the n-th order approximate of q^r	kn/m^2
q_t	tangential load	kN
q^t_n	the n-th order approximate of q^t	kN/m^2
q_v	vertical soil load	kN/m^2
r	radius of the tube	m
R_0	undeformed radius of the tube	m
s	distance along the circumference	m
t	plate thickness	m
t	time	years
T	temperature	°C
$u_{Duddeck}$	soil stiffness parameter	[-]
v	wind speed	m/s
w_1	radial displacement in Duddeck interval 1	m
w_2	radial displacement in Duddeck interval 2	m
w_r	radial displacement	m
w_t	tangential displacement	m
x	distance along the axis	m
z	depth	m
α	value for soil spring modulus	[-]
α	heat diffusion factor	cm^2/s
α	angle of curvature	degrees (°)
β	angle of non elastic support in Duddeck	degrees (50°)
γ	density of material	kg/m^3
$\gamma_{typical}$	typical density of snow for calculation	kg/m^3
Δl	change in length	m
ε	strain	[-]
$\dot{\varepsilon}$	strain rate	[-/year]
ε_e	elastic strain	[-]
ε_v	viscous strain	[-]
η	Newton viscosity parameter	$kN/(m^2\ year)$
θ	angle inside the tube	degrees (°)

Symbol	Definition	Unit
λ	ratio for horizontal vs. vertical stress	[-]
μ	average of normal distribution	[-]
ν	Poisson ratio of steel	[-]
π	pi	[-]
ϱ	density	kg/m^3, g/cm^3
σ	variance of normal distribution	[-]
σ	stress	kN/m^2
σ_h	horizontal stress	kN/m^2
σ_h	horizontal stress in the snow	kN/m^2
σ_{lim}	limit stress for global buckling	kN/m^2
σ_{lim}	limit stress for global buckling	kN/m^2
σ_v	vertical stress in the snow	kN/m^2
$\tau_{calibration}$	calibration parameter for rheological moduli	[-]
φ	angle inside tube	degrees (°)
ω	angle in tube (Duddeck)	degrees (°)

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Appendices

Appendix 1

The Antarctic Treaty

The Governments of Argentina, Australia, Belgium, Chile, the French Republic, Japan, New Zealand, Norway, the Union of South Africa, the Union of Soviet Socialist Republics, the United Kingdom of Great Britain and Northern Ireland, and the United States of America,

Recognizing that it is in the interest of all mankind that Antarctica shall continue for ever to be used exclusively for peaceful purposes and shall not become the scene or object of international discord;

Acknowledging the substantial contributions to scientific knowledge resulting from international cooperation in scientific investigation in Antarctica;

Convinced that the establishment of a firm foundation for the continuation and development of such cooperation on the basis of freedom of scientific investigation in Antarctica as applied during the International Geophysical Year accords with the interests of science and the progress of all mankind;

Convinced also that a treaty ensuring the use of Antarctica for peaceful purposes only and the continuance of international harmony in Antarctica will further the purposes and principles embodied in the Charter of the United Nations;

Have agreed as follows:

ARTICLE I

1. Antarctica shall be used for peaceful purposes only. There shall be prohibited, *inter alia*, any measure of a military nature, such as the establishment of military bases and fortifications, the carrying out of military manoeuvres, as well as the testing of any type of weapon.

2. The present Treaty shall not prevent the use of military personnel or equipment for scientific research or for any other peaceful purpose.

ARTICLE II

Freedom of scientific investigation in Antarctica and cooperation toward that end, as applied during the International Geophysical Year, shall continue, subject to the provisions of the present Treaty.

ARTICLE III

1. In order to promote international cooperation in scientific investigation in Antarctica, as provided for in Article II of the present Treaty, the Contracting Parties agree that, to the greatest extent feasible and practicable:

    a. information regarding plans for scientific programs in Antarctica shall be exchanged to permit maximum economy of and efficiency of operations;

    b. scientific personnel shall be exchanged in Antarctica between expeditions and stations;

    c. scientific observations and results from Antarctica shall be exchanged and made freely available.

2. In implementing this Article, every encouragement shall be given to the establishment of cooperative working relations with those Specialized Agencies of the United Nations and other technical organizations having a scientific or technical interest in Antarctica.

ARTICLE IV

1. Nothing contained in the present Treaty shall be interpreted as:

    a. a renunciation by any Contracting Party of previously asserted rights of or claims to territorial sovereignty in Antarctica;

    b. a renunciation or diminution by any Contracting Party of any basis of claim to territorial sovereignty in Antarctica which it may have whether as a result of its activities or those of its nationals in Antarctica, or otherwise;

    c. prejudicing the position of any Contracting Party as regards its recognition or non-recognition of any other State’s rights of or claim or basis of claim to territorial sovereignty in Antarctica.

2. No acts or activities taking place while the present Treaty is in force shall constitute a basis for asserting, supporting or denying a claim to territorial sovereignty in Antarctica or create any rights of sovereignty in Antarctica. No new claim, or enlargement of an existing claim, to territorial sovereignty in Antarctica shall be asserted while the present Treaty is in force.

ARTICLE V

1. Any nuclear explosions in Antarctica and the disposal there of radioactive waste material shall be prohibited.

2. In the event of the conclusion of international agreements concerning the use of nuclear energy, including nuclear explosions and the disposal of radioactive waste material, to which all of the Contracting Parties whose representatives are entitled to participate in the meetings provided for under Article IX are parties, the rules established under such agreements shall apply in Antarctica.

ARTICLE VI

The provisions of the present Treaty shall apply to the area south of 60° South Latitude, including all ice shelves, but nothing in the present Treaty shall prejudice or in any way affect the rights, or the exercise of the rights, of any State under international law with regard to the high seas within that area.

ARTICLE VII

1. In order to promote the objectives and ensure the observance of the provisions of the present Treaty, each Contracting Party whose representatives are entitled to participate in the meetings referred to in Article IX of the Treaty shall have the right to designate observers to carry out any inspection provided for by the present Article. Observers shall be nationals of the Contracting Parties which designate them. The names of observers shall be communicated to every other Contracting Party having the right to designate observers, and like notice shall be given of the termination of their appointment.

2. Each observer designated in accordance with the provisions of paragraph 1 of this Article shall have complete freedom of access at any time to any or all areas of Antarctica.

3. All areas of Antarctica, including all stations, installations and equipment within those areas, and all ships and aircraft at points of discharging or embarking cargoes or personnel in Antarctica, shall be open at all times to inspection by any observers designated in accordance with paragraph 1 of this Article.

4. Aerial observation may be carried out at any time over any or all areas of Antarctica by any of the Contracting Parties having the right to designate observers.

5. Each Contracting Party shall, at the time when the present Treaty enters into force for it, inform the other Contracting Parties, and thereafter shall give them notice in advance, of

   a. all expeditions to and within Antarctica, on the part of its ships or nationals, and all expeditions to Antarctica organized in or proceeding from its territory;

   b. all stations in Antarctica occupied by its nationals; and

c. any military personnel or equipment intended to be introduced by it into Antarctica subject to the conditions prescribed in paragraph 2 of Article I of the present Treaty.

ARTICLE VIII

1. In order to facilitate the exercise of their functions under the present Treaty, and without prejudice to the respective positions of the Contracting Parties relating to jurisdiction over all other persons in Antarctica, observers designated under paragraph 1 of Article VII and scientific personnel exchanged under sub-paragraph 1(b) of Article III of the Treaty, and members of the staffs accompanying any such persons, shall be subject only to the jurisdiction of the Contracting Party of which they are nationals in respect of all acts or omissions occurring while they are in Antarctica for the purpose of exercising their functions.

2. Without prejudice to the provisions of paragraph 1 of this Article, and pending the adoption of measures in pursuance of subparagraph 1(e) of Article IX, the Contracting Parties concerned in any case of dispute with regard to the exercise of jurisdiction in Antarctica shall immediately consult together with a view to reaching a mutually acceptable solution.

ARTICLE IX

1. Representatives of the Contracting Parties named in the preamble to the present Treaty shall meet at the City of Canberra within two months after the date of entry into force of the Treaty, and thereafter at suitable intervals and places, for the purpose of exchanging information, consulting together on matters of common interest pertaining to Antarctica, and formulating and considering, and recommending to their Governments, measures in furtherance of the principles and objectives of the Treaty, including measures regarding:

a. use of Antarctica for peaceful purposes only;

b. facilitation of scientific research in Antarctica;

c. facilitation of international scientific cooperation in Antarctica;

d. facilitation of the exercise of the rights of inspection provided for in Article VII of the Treaty;

e. questions relating to the exercise of jurisdiction in Antarctica;

f. preservation and conservation of living resources in Antarctica.

2. Each Contracting Party which has become a party to the present Treaty by accession under Article XIII shall be entitled to appoint representatives to participate in the meetings referred to in paragraph 1 of the present Article, during such times as that Contracting Party demonstrates its interest in Antarctica by

conducting substantial research activity there, such as the establishment of a scientific station or the despatch of a scientific expedition.

3. Reports from the observers referred to in Article VII of the present Treaty shall be transmitted to the representatives of the Contracting Parties participating in the meetings referred to in paragraph 1 of the present Article.

4. The measures referred to in paragraph 1 of this Article shall become effective when approved by all the Contracting Parties whose representatives were entitled to participate in the meetin1gs held to consider those measures.

5. Any or all of the rights established in the present Treaty may be exercised as from the date of entry into force of the Treaty whether or not any measures facilitating the exercise of such rights have been proposed, considered or approved as provided in this Article.

ARTICLE X

Each of the Contracting Parties undertakes to exert appropriate efforts, consistent with the Charter of the United Nations, to the end that no one engages in any activity in Antarctica contrary to the principles or purposes of the present Treaty.

ARTICLE XI

1. If any dispute arises between two or more of the Contracting Parties concerning the interpretation or application of the present Treaty, those Contracting Parties shall consult among themselves with a view to having the dispute resolved by negotiation, inquiry, mediation, conciliation, arbitration, judicial settlement or other peaceful means of their own choice.

2. Any dispute of this character not so resolved shall, with the consent, in each case, of all parties to the dispute, be referred to the International Court of Justice for settlement; but failure to reach agreement on reference to the International Court shall not absolve parties to the dispute from the responsibility of continuing to seek to resolve it by any of the various peaceful means referred to in paragraph 1 of this Article.

ARTICLE XII

1. a. The present Treaty may be modified or amended at any time by unanimous agreement of the Contracting Parties whose representatives are entitled to participate in the meetings provided for under Article IX. Any such modification or amendment shall enter into force when the depositary Government has received notice from all such Contracting Parties that they have ratified it.

b. Such modification or amendment shall thereafter enter into force as to any other Contracting Party when notice of ratification by it has been received by the depositary Government. Any such Contracting Party from which no notice of ratification is received within a period of two years from the date of entry into force of the modification or amendment in accordance with the provision of subparagraph 1(a) of this Article shall be deemed to have withdrawn from the present Treaty on the date of the expiration of such period.

2. a. If after the expiration of thirty years from the date of entry into force of the present Treaty, any of the Contracting Parties whose representatives are entitled to participate in the meetings provided for under Article IX so requests by a communication addressed to the depositary Government, a Conference of all the Contracting Parties shall be held as soon as practicable to review the operation of the Treaty.

b. Any modification or amendment to the present Treaty which is approved at such a Conference by a majority of the Contracting Parties there represented, including a majority of those whose representatives are entitled to participate in the meetings provided for under Article IX, shall be communicated by the depositary Government to all Contracting Parties immediately after the termination of the Conference and shall enter into force in accordance with the provisions of paragraph 1 of the present Article

c. If any such modification or amendment has not entered into force in accordance with the provisions of subparagraph 1(a) of this Article within a period of two years after the date of its communication to all the Contracting Parties, any Contracting Party may at any time after the expiration of that period give notice to the depositary Government of its withdrawal from the present Treaty; and such withdrawal shall take effect two years after the receipt of the notice by the depositary Government.

ARTICLE XIII

1. The present Treaty shall be subject to ratification by the signatory States. It shall be open for accession by any State, which is a Member of the United Nations, or by any other State, which may be invited to accede to the Treaty with the consent of all the Contracting Parties whose representatives are entitled to participate in the meetings provided for under Article IX of the Treaty.

2. Ratification of or accession to the present Treaty shall be effected by each State in accordance with its constitutional processes.

3. Instruments of ratification and instruments of accession shall be deposited with the Government of the United States of America, hereby designated as the depositary Government.

4. The depositary Government shall inform all signatory and acceding States of the date of each deposit of an instrument of ratification or accession, and the date of entry into force of the Treaty and of any modification or amendment thereto.

5. Upon the deposit of instruments of ratification by all the signatory States, the present Treaty shall enter into force for those States and for States, which have

deposited instruments of accession. Thereafter the Treaty shall enter into force for any acceding State upon the deposit of its instruments of accession.

6. The present Treaty shall be registered by the depositary Government pursuant to Article 102 of the Charter of the United Nations.

ARTICLE XIV

The present Treaty, done in the English, French, Russian and Spanish languages, each version being equally authentic, shall be deposited in the archives of the Government of the United States of America, which shall transmit duly certified copies thereof to the Governments of the signatory and acceding States.

The Antarctic Treaty

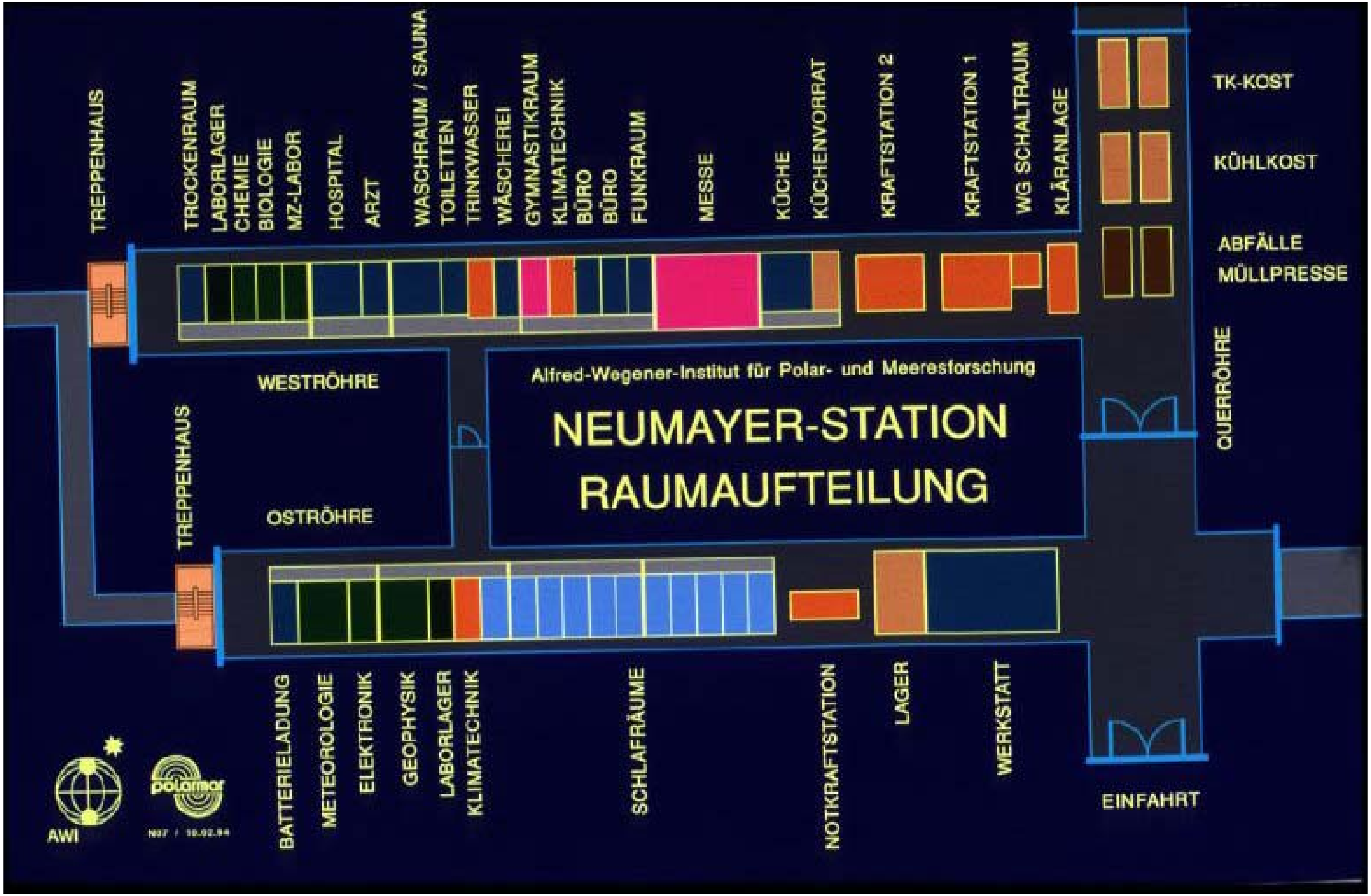
signed in Washington on 1 December 1959

entered into force on 23 June 1961

Appendix 2

The Neumayer Station

Room layout
3D image


Alfred-Wegener-Institut für Polar- und Meeresforschung
NEUMAYER-STATION
RAUMAUFTEILUNG
TREPPENHAUS
TROCKENRAUM
LABORLAGER
CHEMIE
BIOLOGIE
MZ-LABOR
HOSPITAL
ARZT
WASCHRAUM / SAUNA
TOILETTEN
TRINKWASSER
WÄSCHEREI
GYMNASTIKRAUM
KLIMATECHNIK
BÜRO
BÜRO
FUNKRAUM
MESSE
KÜCHE
KÜCHENVORRAT
KRAFTSTATION 2
KRAFTSTATION 1
WG SCHALTRAUM
KLÄRANLAGE
TK-KOST
KÜHLKOST
ABFÄLLE
MÜLLPRESSE
QUERRÖHRE
WESTRÖHRE
OSTRÖHRE
TREPPENHAUS
BATTERIELADUNG
METEOROLOGIE
ELEKTRONIK
GEOPHYSIK
LABORLAGER
KLIMATECHNIK
SCHLAFRÄUME
NOTKRAFTSTATION
LAGER
WERKSTATT
EINFAHRT
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APPENDIX 3


Alfred-Wegener-Institut für
Polar- und Meeresforschung
NEUMAYER-STATION
AWI
polarmar

Appendix 3

Calculation of profile parameters

Young's modulus of steel

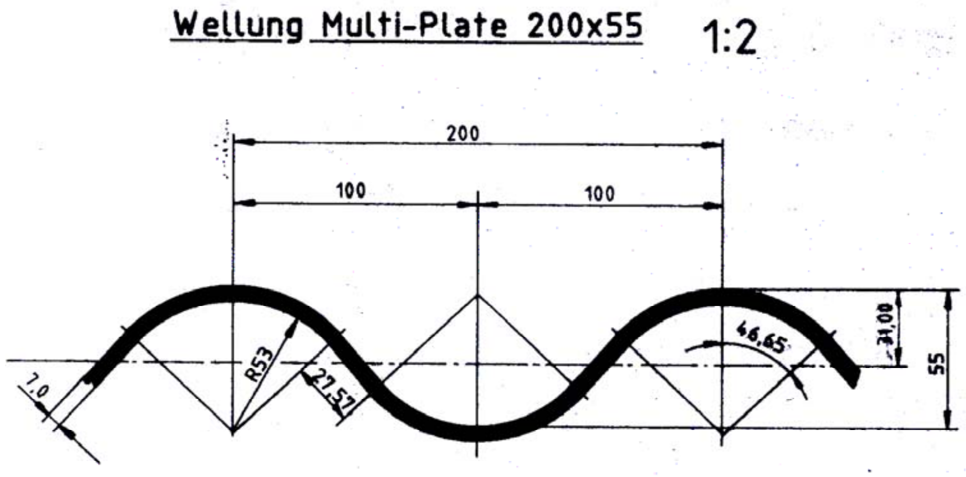
The Young's modulus of steel is taken at a standard value of

E_{steel} = 2.1E+05 N/mm^2 = 2.1E+08 kN/m^2

The simplifying assumption is used that for cold temperatures the Young's modulus remains a constant

Area of profile

The profile of the steel is a corrugated iron profile of 62 mm high, with a waved shape per 200 mm.



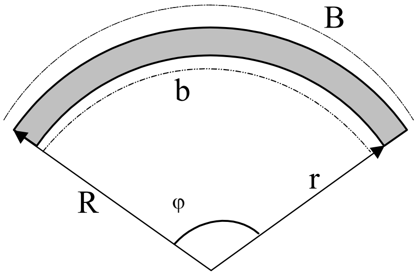
Calculation of the area of the profile will be carried out per 100 mm. The profile per 100 mm has two circular segments and one rectangular mid piece.

$A_{total} = 2A_{circular} + A_{rectangle}$

$A_{rectangle}$ following from the profile specifications, equals 27.57 x 7.00 mm^2 = 193 mm^2.

$2A_{circular}$ can be calculated by using the theory for circular segments as in '*Stahl im Hochbau'* [40]. Here the two circular elements are calculated together.

$2A_{circular} = ½(RB – rb)$



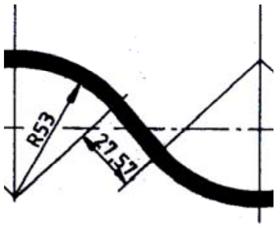
with:

R = outer radius = 53 +7 mm = 60 mm

r = inner diameter = 53 mm

B = outer circumference of partition = 2πRφ/360

φ = angle of circular partition = 46.65°*2 = 93.9°



B = 97.60 m

b = inner circumference of partition = 2πrφ/360 = 86.2

Thus:

$2A_{circular} = ½(RB – rb) = 644\ mm^2$

$A_{total} = 2\ A_{circular} + A_{rectangle} = 837\ mm^2$

This is the area for 100 mm of profile length. For 1 m the area will be 10 times higher.

$A_{total} = 8.40E+3\ mm^2/m = 8.40E-3\ m^2/m$

Moment of inertia for profile

The moment of inertia is calculated for a cross section to be :

$$I = \sum_i \left(A_i e_i^2\right)$$

The calculation is performed for 100 mm of profile. In these 100 mm there are two areas:

- Rectangle with area 193 mm
- Circular segment with area 644 mm

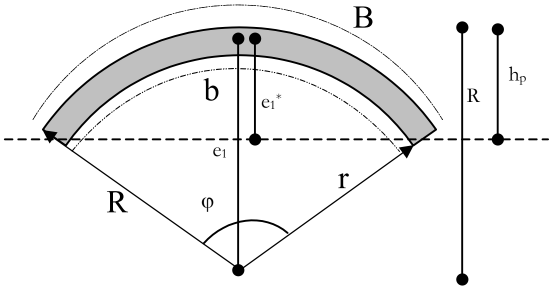
The distance to the centre line must be calculated with geometry rules. The distance for the rectangle equals:

e = ½(1/2*27.57)cos(45°) = 4.70 mm

$I_{rectangle} = 2(193*4.70^2) = 8.40E+3\ mm^4$

For the circular profile the e is found relative to the centre of the circle with:

$$e_1 = \frac{2}{3}\frac{R^3 - r^3}{R^2 - r^2}\sin(\frac{\varphi}{2})\frac{360}{\varphi\pi}$$



Which amounts to e_1 being 50.3 mm. This is relative to the circle centre, while the moment of inertia is needed relative to the centre of the profile.

$e_1^* = e_1 - R + h_p = 50.30 - 60 + 31 = 21.30$ mm

$I_{circular} = 644*21.3^2 = 2.90E+5\ mm^4$

$I_{total} = I_{circular} + I_{rectangle} = 3.00E+5\ mm^4$ per 100 mm.

The total moment of inertia per meter is therefore 3E+6 mm^4/m = 3E-6 m^4/m

Appendix 4

Deformation experiment in ice

As discussed in chapter 9 an attempt has been made to measure deformations in ice during an experiment in the Antarctic summer season of 2001/2002.

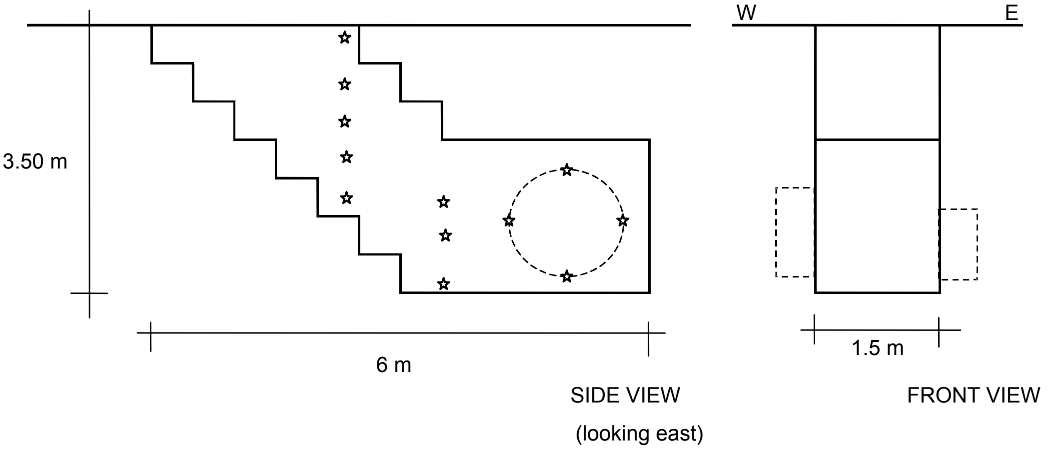
Objective

Objective of the experiment was to gain an idea of the extent of deformations of snow. The deformations were to be measured for a cylindrical cavity in the snow as well as for a vertical wall. By measuring the deformations a value can be found for the elastic and visco-elastic part in the equation:

$$\varepsilon = \varepsilon(e) + \varepsilon(v)t$$

Measurement programme

In order to measure the snow deformations on site a trench has been made. The trench was hand sawed out of the snow to three to four metres below the surface. The outer dimensions of the trench were approximately l*w*d = 6*1.50*3.50 m. Because of the hand sawing the dimensions of the trench could not be strictly maintained, leading to maximum differences in width of 0.50 m.



trench measurements at Neumayer Station

The measurements in the trench were built up of two parts.

- Measurement of cylindrical deformations
- Measurements of the deformations of a vertical wall

The measurements of cylindrical deformations were carried out in two cylinder-shaped cavities in the snow. These cylinders were sawed out horizontally with different radii. The eastern cylinder was designed to have a diameter of 1.50 m, the western cylinder 1.70 m. Both cylinders had a longitudinal dimension of 30 cm. The measurement of these diameters was carried out between two measurement points that were placed on opposite sides of the cylinders circumference. By measuring the horizontal and vertical dimension of the cylinders daily the deformation in both directions can be monitored.

The vertical wall measurements were executed in two intervals. The measurement from the top of the snow layer to –2.00 m was executed next to the cut out staircase, the measurement from –2.00 to –3.00 m took place at the beginning of the trench floor. The measuring points were marked, and measurements were repeated daily at the same points.

In the trench measurements have been carried out daily from January 6th – 31st. All measurements have been carried out with tape measure, following a standardised procedure to reduce errors.

The trench was covered up with wood during the measurement period, thus safeguarding the trench from snowdrift. Total drift on the trench after four weeks was 1 m of snow.

For safety purposes the trench has been backfilled after the experiment. After removal of the wooden roof and the measuring points the excavated snow was replaced.

Outcome of the experiment

The measurements have all been calculated back to deformations in relation to the measurement at the beginning of the period.

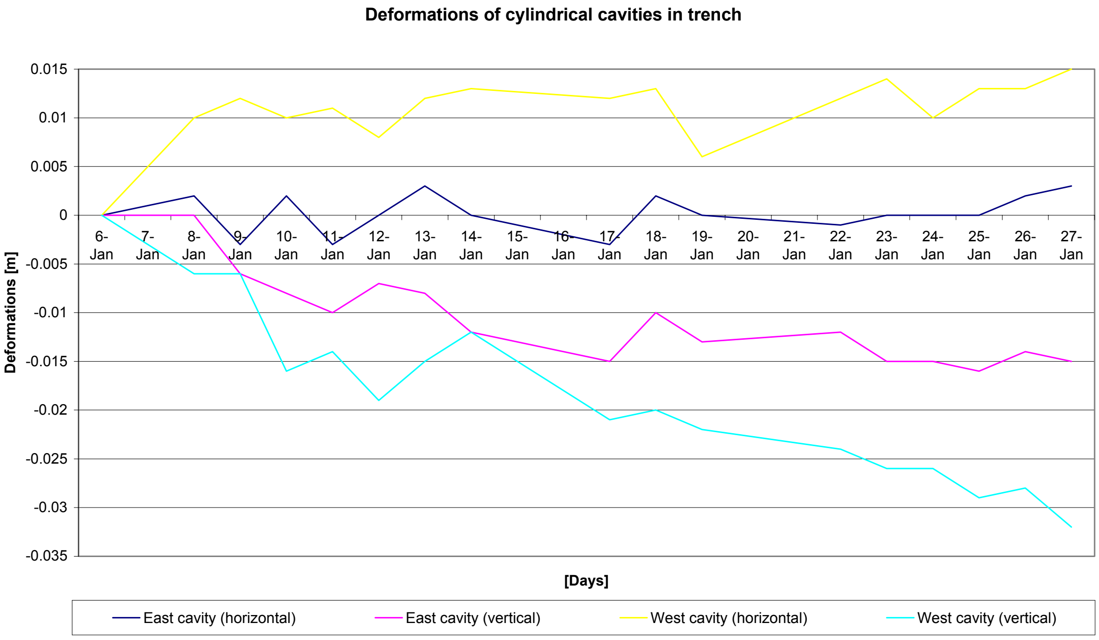
The cylindrical measurements have been given in the graph below.

Visible is the horizontal widening of the cavities in time. Most clearly the West cavity increases its horizontal dimension in time .The West cavity shows a bigger widening than the East cavity, which is related to its bigger diameter. In vertical direction the cavities both are deformed to a smaller vertical dimension, with the West cavity compressing the most due to bigger diameter as said above.

The deformations in a vertical plane are measured on a vertical wall. Although the measurements are composed of two intervals they have been combined in the graph below. The two intervals are 0 to 195 m and 195 to 295 m.

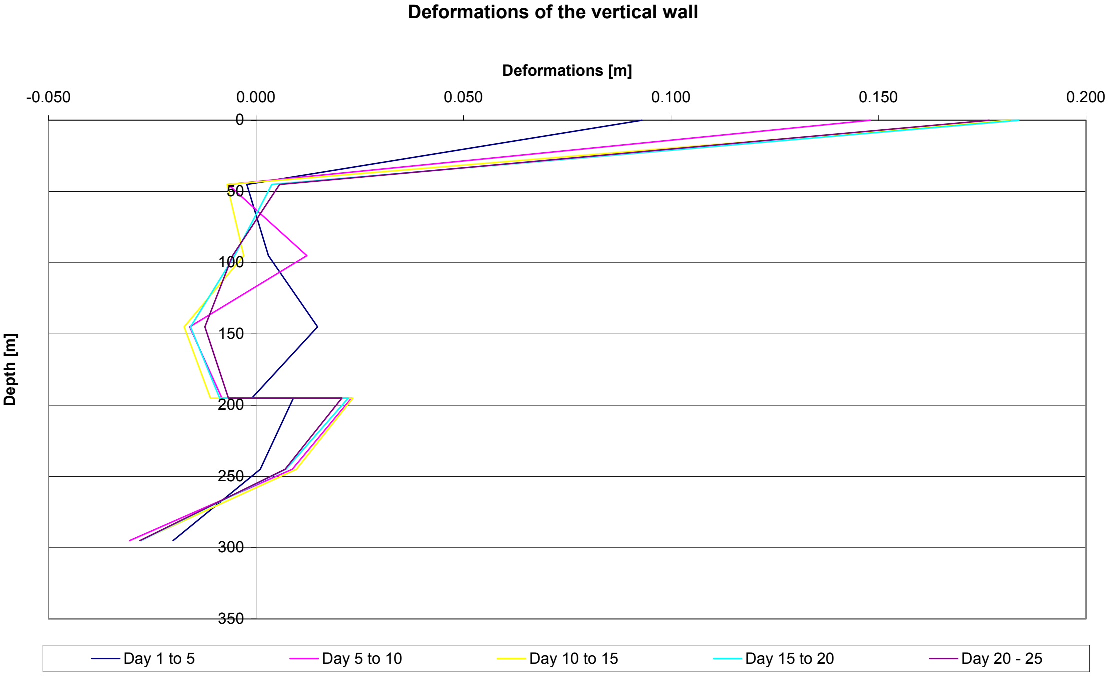
Deformations are measured as positive when the trench widens and as negative when the trench's width is reduced.

The deformations seem to be divided into two phenomena:



measurement results for the vertical wall

- To a depth of 50 cm the trench clearly widens in time.
- From 50 to 300 cm the trench measurements show little consistency. The values are small (0 - 5 cm) and positive and negative values are both present.



measurement deformations of the horizontal cavities

Discussion

For the cylindrical measurements, the western cavity shows a typical behaviour, widening horizontal dimensions and compressing vertical dimensions. Two objections against these measurements can be made, one being that for the measurements a large difference between measurements is observed. For instance the measurement of the horizontal deformation at the West cavity differs 0.80 cm from January 18th and 19th. The actual value at that point is 1 cm, making the variation 80%. This high variation is caused by the method of measurement and the conditions under which the measurement has been carried out.

The other objection for the cavity measurements is the fact that the eastern tube shows a different behaviour, with the horizontal dimension remaining approximately the same, and the vertical dimension decreasing. Both arguments pose a problem for the calculation of viscosity parameters from these calculations.

The vertical wall measurements show the same difference in the order of consecutive measurements. Especially between 50 and 200 cm of depth the measurements show a large variation in number and sign. For these measurements the same conclusion must be drawn as above, measurements have a too large error compared to the measured value to be of help for calculation.

Another cause for the meagre results can be the warm days that have occurred in January 2002. Warm weather gives more evaporation that can lead to differences in measurement.

What has finally not been taken into account is the possibility that due to the small diameters and the small length of the cavity arching effects in three dimensions have reduced the measured deformations.

What can be concluded from this experiment is that measuring snow deformations in a satisfactory manner depends highly upon the measurement programme and the duration. A longer programme will enable bigger deformations, and a better value for the error due to measurements. To decrease these errors in measurement, the measurement with tape measure is to be replaced with laser or similar techniques.

For this report we will not use the measurements to calculate deformation in snow and ice. The calculations will be executed with the values given by Enß.

Appendix 5

List of measuring points

Appendix 6

Meßprotokolle und – ergebnisse der Vermessung der Neumayer Station in der antarktischen Saison 2001/2002

Appendix 7

Basisanalyse der Vermessungsdaten der Neumayer Station für den Zeitraum 1992-2001

Appendix 8

Model for a rigid body in viscous material (RiVi)

Appendix 9

From Bouma to Duddeck

Appendix 10

Model for a deforming ring in a viscous material (DeRi)

Appendix 11

Sensitivity analysis

Appendix 12

Limit state calculation for plasticity

Plastic deformation will occur when the stress in the steel profile exceeds the critical value of 235 N/mm^2.

The stress in the steel profile is calculated with:

$$\sigma_{steel} = \frac{N}{A} + \frac{Mh}{2I}$$

with:

N:	Normal force in profile	[kN]
A:	Area of profile	[m^2]
M:	Bending moment in the profile	[kNm]
h:	Profile height	[m]
I:	Moment of inertia of the profile	[m^4]

The calculation is done in two parts, the first part calculating the stress due to normal forces, the second part due to bending moments.

Duddeck (1964) calculates the total normal force in the same manner. The total normal force is:

$$N = N_0 + \overline{N}(bending)$$

Thus the total stress in the cross section is:

$$\sigma_{steel} = N / A = (N_0 + \overline{N}(bending)) / A$$

The total stress is calculated this way in accordance with Duddeck and the calculation by Duddeck is adapted for the Neumayer Station load case in the excel sheet added here.

Calculating N_o

$$N_0 = -R * p_0$$

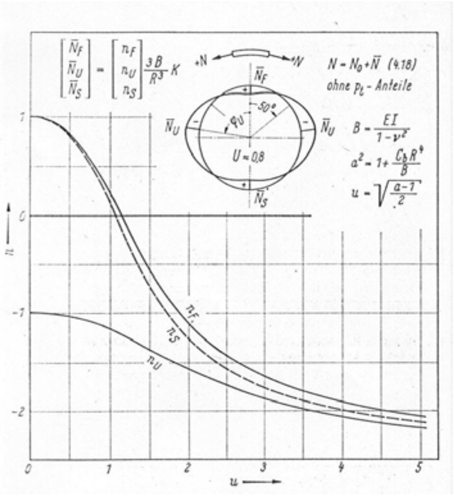
In a given case, the radius of the tube is given. The simplifying assumption is that the normal forces are calculated for an un-deformed tube.

P_0 is the constant radial pressure, which can be taken as equal to the average value of the horizontal and vertical pressures. Here the assumption of a cosine pressure distribution is used.

$$p_0 = \gamma \frac{1+\lambda}{2}\left(H - 0.3R_0 \frac{3+\lambda}{1+\lambda} \right)$$

The calculation for N_0 is given in the sheet.

Calculating $\overline{N}(bending)$



Duddeck has made a calculation of $N_{bending}$ relative to the factor $u_{Duddeck}$. The graph below depicts this relation. As in the Duddeck calculation tangential forces are deemed neglectable.

The calculation of $N_{bending}$ from this graph is executed with:

$$\overline{N}(bending) = \eta_f * \frac{3B}{R^3} * K$$

This is executed with the data from the calculation, and an input of the factor η by hand.

The total stress in the steel is calculated, and the total vertical stress from the snow.

The sheet can be used to model a situation where plastic deformation is encountered. This means that the stress in the steel must be set to 235 N/mm^2 by changing the value of the depth. This depth relates to a linear density profile in the snow, and cannot be used as a actual value for the depth in the actual situation. However, the vertical snow stress can be calculated, which can be used to check later calculations.

The outcome is that a value of 235 N/mm^2 in the steel is reached at a vertical snow stress of 430 kN/m^2. This is the limit for plastic deformation of the whole profile.

Appendix 13

Linear estimation

Appendix 14

The total model

Appendix 15

Atka Express d.d. January 2002

Glossary

Polar engineering as well as Antarctic research requires terms and expressions a lot of people are not familiar with. This glossary contains expressions used during this study to give the reader the necessary background information. Above that several expressions and abbreviations (including a range of WebPages) are given that are not used in this report but deal with Antarctica, Antarctic institutes and research programmes and that can provide the reader with additional information.

AAD: Australian Antarctic Division (http://www.antdiv.gov.au/)

AARI: Arctic and Antarctic Research Institute (of Russia)

Ablation: all processes by which snow and ice are lost from a glacier, floating ice, or snow cover; or the amount, which is melted. These processes include melting, evaporation, (sublimation), wind erosion, and calving. Synonym: wastage.

Abrasion: the mechanical wearing or grinding away of rock surfaces by the friction and impact of rock particles transported by wind, ice, waves, running water, or gravity.

Accumulation: all processes that add snow or ice to a glacier or to floating ice or snow cover: snow fall, avalanching, wind transport, refreezing...

AC: Arctic Centre, University of Groningen, the Netherlands

ACSYS: Arctic Climate System Study

ADDS: Antarctic Data Directory System

AEON: Antarctic Environmental Officers Network

AFIM: Antarctic Flight Information Manual

AGO: Automatic Geophysical Observatory

AGONET: Antarctic Geospace Observatory Network

AIROPS: Air Operations Working Group

Albedo: reflectivity of a surface. High albedo means that the majority of the incoming radiation is reflected (for example snow); low albedo means that the majority of the incoming radiation is absorbed (for example water).

Altitude: vertical distance above a surface, usually the height above sea level.

AMAP: Arctic Monitoring and Assessment Program

AMD: Antarctic Master Directory

AMEN: Antarctic Managers' Electronic Network

ANARE: Australian National Antarctic Research Expeditions

AnITRP: Antarctic Ice Thickness Research Program

Annual: yearly

Antarctic Convergence (Polar Front): surface oceanographic boundary at which the colder, saltier Antarctic Surface Waters sink beneath the northerly warmer, less salty Sub Antarctic Surface Waters.

Antarctic Divergence: an oceanographic feature that coincides roughly with the atmospheric Antarctic Circumpolar Trough at 60°S to 65°S. The Antarctic Divergence separates eastward flowing surface waters to the north (West Wind Drift) from westward flowing surface waters to the south (East Wind Drift).

Antarctica NZ: Antarctic New Zealand (Antarctic Program) (http://www.antarcticanz.govt.nz/)

ANTEC: group of specialists on Antarctic Neotectonics

ANTOSTRAT: Antarctic Offshore Stratigraphy Program

APIS: Antarctic Pack Ice Seals

Arid: very dry. Arid describes an area with little rain or precipitation, usually less than 25 centimetres (10 inches) of rainfall annually.

ASIZP: Antarctic Sea-Ice Zone Project

ASMA: Antarctic Specially Managed Area

ASOC: Antarctic and Southern Ocean Coalition (http://www.asoc.org/)

ASPA: Antarctic Specially Protected Area

ASPECT: Antarctic Sea-Ice Processes and Climate

ATCM: Antarctic Treaty Consultative Meeting

ATCP: Antarctic Treaty Consultative Party

Atmospheric sciences: the study of the atmosphere. Analysis of the envelope of gases that surrounds the Earth. Atmospheric studies include meteorology and climatology.

ATOM: Antarctic Telecommunications Operations Manual

ATS: Antarctic Treaty System

Aurora: the display 'dancing' light patterns seen in areas of high latitudes. Auroras are caused by magnetic sun storms that release huge amounts of energy. The energy travels toward Earth as an ionic cloud that interacts with Earth's magnetic field. The ions move Earth's magnetic poles where they interact with the ionosphere. The ions energize the oxygen and nitrogen, causing them to emit light. The occurrence of light is called the Aurora Borealis in the Northern Hemisphere and Aurora Australis in the Southern Hemisphere.

AWI: Alfred-Wegener Institute of Polar and Marine Research (http://www.awi-bremerhaven.de/)

BAS: British Antarctic Survey (http://www.antarctica.ac.uk)

BEDMAP: Antarctic Bedrock Mapping Project

BELSPO: Belgian Scientific Research Program (http://www.belspo.be/antar/)

Benthic: pertaining to or living on bottom of a body of water. Benthic marine organisms are those creatures living on (or in the sediment of) the seafloor.

Bergy Bit: a large piece of floating glacier ice, generally showing less than 5 metres above sea level but more than 1 metre and normally about 100-300 square metres in area.

BIOMASS: Biological Investigation of Marine Antarctic Systems and Stocks

BIOTAS: Biological Investigations of Terrestrial Antarctic Ecosystems

Black Ice: newly-formed iced over seawater. It is thin enough for the dark water to be visible through it and can be crossed only at speed by a light sledge.

Blizzard: a cold windy storm with winds of at least 56 kilometres per hour (35 miles per hour) and temperatures below -6.7°C (20°F). There may be little snow brought by the blizzard; the high winds pick up snow from the ground and carry it, reducing visibility to less than half a kilometre or about a quarter of a mile.

Brash Ice: accumulations of floating ice made up of fragments not more than 2m cross, the wreckage of other forms of ice.

Breakout: the summer breaking up and floating away of fast ice that has built up during winter.

BSRN: Baseline Surface Radiation Network

CAA: Chinese Arctic and Antarctic Administration

CAAS: Convention on the Conservation of Seals

Calving: breaking off and floating away as icebergs of either a tidewater glacier or an ice shelf. Calving is a very efficient form of ablation, thus helps stabilize the extent of ice sheets (like Antarctica), which might otherwise expand continuously from a positive mass budget.

CARA: Center for Astrophysical Research in Antarctica (http://astro.uchicago.edu/cara/about cara/)

CARP: Canadian Antarctic Research Program

Cavity: a hole or opening, as at the bed of a glacier. When the rate of deformation into a space behind an obstacle is less the rate of movement past the obstacle, a cavity will form.

CCAMLR: Convention on (or Commission for) the Conservation of Antarctic Marine Living Resources (http://www.ccamlr.org/)

CCAR: Canadian Committee on Antarctic Research

CCAS: Convention for the Conservation of Antarctic Seals

CEDAT: Coordinating Group on Education and Training

CEE: Comprehensive Environmental Evaluation

CEMP: CCAMLR Environmental Monitoring Program

CEP: Committee for Environmental Protection (of the ATCM) (http://www.npolar.no/cep/)

CGA: Composite Gazetteer of Antarctica

CHINARE: Chinese National Antarctic Research Expedition(s)

Climatology: the study of atmospheric (weather) conditions over periods of time measured in years or longer.

CLIVAR: Climate Variability and Predictability Program

CNR: National Research Council

COMNAP: Council of Managers of National Antarctic Programs (http://www.comnap.aq/)

CONAAN: National Antarctic Commission of Peru (http://www.rree.gob.pe/conaan/)

Continental shelf: the region between the shoreline and the continental slope. The continental shelf has formed by slow deposition of sediment eroded from the continent. The continental shelf has a gentle slope (1°) and is the shallowest portion of the ocean floor. Usually the shelf is in ocean water depths of less than 200 metres (650 feet); in Antarctica the continental shelf averages 500 metres in depth (1640 feet).

Continental: referring to a large land mass or a continent.

Convergence: a region where two or more objects come together. The Antarctic Convergence occurs where two surface water masses meet. Convergent ice flow describes where two ice streams or glaciers flow together.

Convergent margin (plate tectonics): a plate margin where two or more plates are moving toward each other.

Core: the central zones of the Earth. The outer core extends from 2900 kilometres to 5100 kilometres from Earth's surface and is believed to be of molten material (1800 to 3200 miles). The inner core, from 5100 kilometres to the centre of Earth at 6400 kilometres, is believed to be solid (3200 to 4000 miles).

COSPAS-SARSAT: international satellite system for search and rescue (http://www.cospas-sarsat.org/)

CPC: Canadian Polar Commission (http://www.polarcom.gc.ca/)

CRAMRA: Convention on the Regulation of Antarctic Mineral Resources

Crevasse: a deep, almost vertical, crack or split in a glacier. Crevasses over 10 m deep would be healed by internal flow, but much deeper crevasses can be maintained by continued tension. Because crevasses can become covered by blown snow, expeditions crossing ice and snowfields must be careful to avoid them.

Cross section: a slice through an object that exposes the interior structure of the object. A cross-section of a layer cake would show layers of cake and layers of frosting. Such a cross-section should be eaten quickly.

DBCP: Data Buoy Cooperation Panel

DCDB: Data Centre on Digital Bathymetry

Desert: an area where there is little moisture because precipitation is low and evaporation is high. Precipitation usually is less than 25 centimetres a year (10 inches). Large deserts include widely varying climates such as the Sahara Desert in Northern Africa or the continent of Antarctica.

Divergence (divergent): a region where two or more objects move apart. The Antarctic Divergence marks the location where two surface water masses flow in different directions. Divergent ice flow describes where ice streams or glaciers flow apart.

Divergent margin (plate tectonics): plate margin where two or more plates are moving away from each other

DNA: Direccion Nacional del Antarctico (Argentine Antarctic Institute) (http://www.dna.gov.ar/)

Drift Snow: loose snow that has been moved by the wind and has not yet compacted.

Drift: speed and direction of an iceberg in the water. The size and shape of the iceberg, wind direction and speed, surface currents in the water, and other factors such as surrounding land and sea ice, and depth of the water control iceberg drift.

Dynamic: active or energetic. Also relating to the forces that produce motion in objects.

EASIZ: East Antarctic Sea-Ice Zone (Program)

ECG: Environmental Coordinating Group

ECMWF: European Centre for Medium-Range Weather Forecasts (http://www.ecmwf.int/)

Ecology: the study of the relationship between plants and animals and their environment.

Ecosystem: a community of plants and animals and the environment, large or small, in which those plants and animals live.

EISMINT: European Ice Sheet Modelling Initiative

ELINF: Electronic Information Working Group

EMRAC: Emergency Response and Contingency Planning Working Group

ENACH: Instituto Antartico Chileno (Chilean Antarctic Institute) (htpp://www.enach.cl)

ENEA: Agency for New Technology, Energy and Environment (of Italy)

ENMAN: Energy Management Working Group

EPICA: European Polar Ice Coring in Antarctica

ESF: European Science Foundation

ESMR: Electrically Scanning Microwave Radiometer

EXCOM: Executive Committee

FARO: Forum of Arctic Research Operators (http://www.iasc.no/faro/)

Fast ice: sea ice that forms along the coastline and remains permanently attached.

FIBEX: First International Biomass Experiment

FIDS: Falkland Island Dependency Survey

Firn: a transitional stage between snow and glacial ice. Firn is a type of snow that has survived a summer melting season and has become more compact than freshly falling snow.

Frazil ice: ice crystals in the water column, usually near the water surface. Frazil ice crystals are not oriented in an organized manner, and have the appearance of slush. Frazil ice marks the first stage in the formation of sea ice

FROST: First Regional Observation of the Statosphere

GARP: Global Atmospheric Research Programme

GCOS: Global Climate Observing System

GEBCO: General Bathymetric Chart of the Ocean

Geographic South Pole: the point where all the lines of longitude meet

Geology: the study of Earth, its history, and the processes that have occurred and are occurring on and within it. Geologists are interested in how the Earth formed, and what processes have been active in the past, and how those processes might be different from those of today.

Geomagnetic pole: the points on Earth's surface where the axes of the Earth's magnetic pole intersect. In the Southern Hemisphere, the south geomagnetic pole is approximately 1160 kilometres (725 miles) north of the south geographic pole.

Geophysics: the study of the physical properties of Earth as a planet. A geophysicist might study the interior layers of Earth, or the geomagnetic field of Earth, or Earth's gravity field.

GERG: Geochemical and Environmental Research Group (at University of College Station, Texas, USA)

GEWEX: Global Energy and Water-cycle Experiment

GGI: Geodesy and Geographic Information (Working Group) (http://www.scar-ggi.org.au/)

GGTP: Global Geoscience Transects Project

GIANT: Geodetic Infrastructure for Antarctica

GIS: Geographical Information System

Glacial Drift: the general term for all glacial deposits, both unsorted and sorted

Glacial Ice: compacted and intergrown mass of crystalline ice with a density of 830-910 $kg{\cdot}m^{-3}$.

Glacier: a large mass of ice, air, water, and rock debris formed at least partially on land. Glaciers are amounts of ice large enough to flow with gravity because of internal deformation. Glaciers include small valley glaciers, ice streams, ice caps, and ice sheets. The term glacier also includes ice shelves if they are fed by glaciers.

Glaciology: the study of the physical and chemical properties of snow and ice. Glaciologists might study the movement of ice sheets, and how ice flows. Glaciologists also study how snow slowly changes to glacier ice

GLOBEC: Global Oceans Ecosystems Dynamics Research

GLOCHANT: Group of Specialists on Global Change in the Antarctic (http://www.antcrc.utas.edu.au/scar/)

GLOSS: Global Sea Level Observing System

Gondwana: former super-continent situated in the southern hemisphere, which contained the areas we now call Antarctica, South America, Africa, Australia, India and New Zealand. About 160 million years ago Gondwanaland began to break up and individual landmasses moved to their current positions.

GOOS: Global Ocean Observing System

GOSEAC: Group of Specialists on Environmental Affairs and Conservation

GOSSOE: Group of Specialists on Southern Ocean Ecology

GPS: Global Positioning System

Grease ice: thin plates of organized ice crystals on the water surface. Grease ice is an early stage in the growth of sea ice.

Grounded Ice: any floating ice, which is aground in shallow water.

Grounding line: when a glacier extends into the sea or a lake, the grounding line marks the place where the glacier loses contact with seafloor and begins to float as an ice shelf. The grounding line can be a region of high sediment accumulation.

Growler: a piece of sea ice smaller than a bergy bit.

GTS: Global Telecommunication System

HF: High Frequency

HSM: Historic Sites and Monuments

Hydrology: the study of water (in liquid and solid form) and its flow between the atmosphere, the land, and the ocean.

IAATO: International Association of Antarctica Tour Operators (http://www.iaato.org/)

IACS: International Association of Classification Societies (http://www.iacs.org.uk/)

IAGP: International Antarctic Glaciological Project

IanZone: International (Coordination of Oceanographic Research within the) Antarctic Zone

IAPO: International Antarctic Project Office

IARPC: Interagency Arctic Research Policy Committee

IARPC: Interagency Arctic Research Policy Committee (of the USA) (http://www.nsf.gov/od/opp/arctic/iarpc/)

IASC: International Arctic Science Committee (http://www.iasc.no/)

IAU: Uruguayan Antarctic Institute (http://www.iau.gub.uy)

IBEA: International Biomedical Expedition to Antarctica

ICAIR International Centre for Antarctic Information and Research (of NZ) (http://www.icair.iac.org.nz/icair/)

ICAO: International Civil Aviation Organisation (http://www.icao.org/)

ICAPP: Ice-core Circum-Arctic Paleoclimate Program

Ice age (glacial period, glacial epoch): recurring periods in Earth's history when the climate was colder and glaciers expanded to cover larger areas of the Earth's surface.

Ice cap: a large dome-shaped mass of ice that is thick enough to cover all topography underneath it. Ice caps are smaller than ice sheets, usually with an area less than 50,000 square kilometres (19,000 square miles). Ice caps are large enough to deform and flow with gravity and spread outward in all directions.

Ice cliff: walls of ice where glaciers meet the sea, such as at the edge of land or the edge of an ice shelf. Ice cliffs occur in areas where drainage of the ice from the continent diverges and slows.

Ice crystals: tiny particles of ice produced when a state of super saturation of moisture is obtained in the atmosphere. Ice crystals account for the majority of the accumulation on the Polar Plateau. Often ice crystals precipitate when the sky is clear! Ice crystals may be called ice needles, although they do not have the shape of needles.

Ice dome: slow moving areas of accumulation on an ice sheet. Ice domes are roughly symmetrical in outline, and dome-shaped in cross-section. An ice sheet might be comprised of several ice domes.

Ice Edge: demarcation between the open sea and sea ice of any kind whether fast (fixed to the shore) or drifting.

Ice fall: a region on a glacier where rapid extension (as down steep slopes) causes brittle failure and intense crevassing.

Ice Field: an extensive area of interconnected glaciers in a mountain region, or of pack ice at sea.

Ice floe: a large, flat, sheet of ice that has broken off of the coast and floats in open water.

Ice Foot: the ice that remains attached to the land after a breakout.

Ice sheet: a large mass of ice that is thick enough to cover the topography under it. Ice sheets are large enough to deform and move with gravity. Ice sheets are larger than ice caps. Ice sheets cover large parts of Greenland and Antarctica.

Ice shelf: a large flat-topped sheet of ice that is attached to land along one side and floats in an ocean or lake. More ice is added to the ice shelf from flow of the ice on land and from new snow. Ice is removed from the ice shelf by calving and melting

Ice stream: a rapidly moving current of ice in an ice sheet or ice cap. An ice stream flows more quickly than the surrounding ice and pulls ice out of the ice sheet. Antarctic ice streams flow about one kilometre per year (0.6 miles per year

Ice tongue: long, narrow, projection of ice out from the coastline. Ice tongues form where a valley glacier flows rapidly to the sea or a lake. Ice tongues may float. Drygalski Ice Tongue is a large ice tongue in Ross Sea

Iceberg: a large piece of floating ice that has calved, or broken off, a glacier or ice shelf. Icebergs occur in lakes and the ocean and can be quite large.

ICSU: International Council for Science (http://www.icsu.org/)

IEE: Initial Environmental Evaluation

IFRTP: French Institute of Polar Research and Technology (of France)

IGBP: International Geosphere-Biosphere Program

IGCP: International Geological Correlation Program

IGY: International Geophysical Year (1957-58)

IHO: International Hydrographic Organisation (http://www.iho.shom.fr/)

IMAU: Institute for Marine and Atmospheric Research, University of Utrecht, the Netherlands (www.imau.nl)

IMDG: International Maritime Dangerous Goods (Code)

IMO: International Maritime Organisation (http://www.imo.org/)

INACH: Antarctic Institute of Chile (http://www.inach.cl/)

INFONET: Antarctic Information Officers Network

INMARSAT: International Maritime Satellite (http://www.inmarsat.org/)

INTELSAT: International Telecommunications Satellite (http://www.intelsat.com/)

International Geophysical Year (IGY): the International Council for Scientific Unions agreed to coordinate a research program with special emphasis on meteorology, oceanography and geomagnetism in Antarctica during 1957-58. IGY was so successful in Antarctica that the Scientific Committee on Antarctic Research (SCAR) was set up to continue its work.

IOC: Intergovernment Oceanographic Commission (http://ioc.unesco.org/iocweb/)

IPAB: International Program for Antarctic Buoys

IPCC: Intergovernmental Panel on Climate Change

ISMASS: Ice Sheet Mass Balance and Sea Level Contributions

ISTP: International Solar Terrestrial Physics Programme

ITASE: International Trans-Antarctic Scientific Expedition

ITEX: International Tundra Experiment

ITRF: International Terrestrial Reference Frame

IUBS: International Union of Biological Sciences

IUCN: World Conservation Union (http://www.iucn.org/)

IUGS: International Union of Geological Sciences

IWC: International Whaling Commission

JARE: Japanese Antarctic Research Expedition(s) (http://www.nipr.ac.jp/english/ara01.html)

JCADM: SCAR-COMNAP Joint Committee on Antarctic Data Management (http://www.jcadm.scar.org/)

JGOFS: Joint Global Ocean Flux Study

Katabatic winds: a wind that results from dense, cold air flowing down slope as a result of gravity. The flow can be channelled by topography.

KORDI: Korean Research and Development Institute

Krill: small shrimp-like creatures that exist in huge numbers in the southern ocean and provide a vital link in Antarctic food chains between producers (plants) and herbivores.

Land-based ice sheet: a large body of ice with a base mostly above sea level. The East Antarctic Ice Sheet is a land-based ice sheet

Latitude: angular distance of a point on the Earth's surface north or south or the equator, measured along a meridian, the equator being latitude 0°, the north pole latitude 90°N, and the south pole latitude 90°S.

LOICZ: Land-Ocean Interactions in the Coastal Zone

Longitude: imaginary lines that wrap around Earth intersecting at the north and south geographic poles ("vertical lines"). Lines of longitude are numbered from 0° (Greenwich Meridian, passing through London, England) to 180°. Longitudes are designated East if they fall East of the Greenwich Meridian, and West if they fall West of the Greenwich Meridian

Magnetic South Pole: the point to which the 'south' end of a magnetic compass points.

MARPOL: International Convention for the Prevention of Pollution from Ships (of the IMO)

McMurdo: site of McMurdo Station, America's main research outpost in the Antarctic.

MEDS: Marine Environmental Data Service

MEPC: Marine Environment Protection Committee (of the IMO)

Meteorology: the study of Earth's atmosphere and the motion within the atmosphere. Meteorology includes understanding the aspects of the atmosphere for weather forecasting.

MiniATOM: Antarctic Communications Directory

MNAP: Manager of National Antarctic Programs

MOLIBA: Working Group to Monitor the Liability Annex

Monitoring: the process of observing, measuring, and/or recording information about an object or activity. Monitoring glacier flow provides data that allow scientists to understand how ice moves and to predict how ice movement may change in the future.

MOU: Memorandum of Understanding

NADC: National Antarctic Data Centre

NARE: Norwegian Antarctic Research Expedition

NASA: National Aeronautical and Space Adminsistration (of the USA)

NCAOR: National Centre for Antarctic & Ocean Research (India) (http://www.ncaor.org)

NERC: National Environment Research Council (of the UK)

Névé: Firn (French equivalent of German term)

NGDC: National Geophysical Data Centre

NGO: Non-Government Organisation

NIC: National Ice Center (of the USA)

NIPR: National Institute for Polar Research (of Japan) (http://www.nipr.ac.jp/)

NIWA: National Institute for Water and Atmospheric Research (of New Zealand)

NOAA: National Oceanographic and Atmospheric Administration (of the USA) (http://www.noaa.gov/)

Northern Hemisphere: the half of the globe that is north of the equator (the northern half (hemi) of the global sphere).

NPI: Norwegian Polar Institute (http://www.npolar.no/)

NSF: National Science Foundation (of the USA) (http://www.nsf.gov/)

Nunatak: an isolated peak of bedrock that sticks above the surface of an ice sheet. Nunataks offer important information about ice-covered regions because they provide a sample of the rocks that lie under the ice.

NOW: Netherlands Organization for Scientific Research, the Hague, the Netherlands (www.now.nl)

Oceanography: the study of the ocean, including the physical properties of the ocean such as the currents and waves (physical oceanography), the chemistry of the ocean (chemical oceanography), the geology of the seafloor (marine geology), and the organisms that carve their niche within the ocean realm (marine biology and marine ecology)

ODP: Ocean Drilling Program

OPP: Office of Polar Programs (of the NSF, USA) (http://www.nsf.gov/od/opp/)

Ordinary katabatic wind: gusty, short-lived katabatic winds with a constant direction but a highly variable speed.

Ornithology: the study of birds.

Ozone layer: a layer in the upper stratosphere of Earth's atmosphere that contains almost 90% of Earth's ozone. The ozone layer occurs approximately 25 kilometres (16 miles) above the surface of Earth.

Ozone: a chemically active bluish gas that is made of three oxygen atoms (O3). Ozone occurs in the atmosphere at altitudes of approximately 15 to 30 kilometres (9 to 19 miles). Ozone acts as a protective barrier for Earth's surface by blocking much of the potentially damaging ultraviolet radiation that comes from the sun.

P&I Clubs: International Association of Protection and Indemnity Clubs (http://www.ukpandi.com/2about.html#International)

PA: Preliminary Assessment

Pack ice: used interchangeably with sea ice. Pack ice is a general term for tightly or loosely spaced pieces of thin floating ice.

Paleontology: the study of the plants and animals of the past. Paleontologists study the rich fossil record to reconstruct the organisms and environments of the past.

Pancake ice: coherent plates of ice that can reach a few metres across (a few feet). Pancake ice grows from thickened grease ice and resembles pancakes or lily pads. The edges are upturned because the plates bump into each other.

Pangaea: geologists have proposed that about 250 million years ago the continents were together in a single supercontinent called Pangaea. That continent broke apart starting about 200 million years ago, and the individual continents slowly drifted to their present positions. The movement of plates is part of the plate tectonic theory.

PCSP: Polar Continental Shelf Project of Canada (http://polar.nrcan.gc.ca/)

PELICON: Project for Estimation of Long-term Variability in Ice Concentration

Physical oceanography: the study of the physical aspects of the ocean. Physical oceanographers study the characteristics of water masses, such as temperature, salinity, and density variation, and the optic and acoustic properties of the ocean. Physical oceanography also includes the study of nature of currents, waves, and tides.

PICE: Paleoenvironments from Ice Cores (Planning Group)

PIPOR: Program for International Polar Oceans Research

Plate tectonics: a theory that ties together many observations made about the activity and movement of Earth's crust (earthquakes, volcanoes) and creation of ocean basins. Plate tectonics divide the surface of the globe into several rigid lithospheric plates that move on a ductile asthenosphere.

PNRA: Italian National Antarctic Research Program

PNRA: Italian National Antarctic Research Program (http://www.pnra.it/)

Polar Climate: a type of climate of latitudes greater than 66°C characterized by temperature of 10°C and below. The two types of polar climates in Koppen's classification are tundra climate and perpetual frost climate (temperature always <0°C).

Polarmar GmbH: a former Polar and Marine Consultant, Bremerhaven, Germany. The Polarmar GmbH was involved in the design an construction of Neumayer Station and several other polar research bases.

Polar Plateau: the relatively flat, elevated central region of the East Antarctic Ice Sheet. The plateau has an average height of 2000 metres (about one mile) above sea level and a smooth surface with a small slope

Polar: having to do with the regions of the north and or south poles of Earth. The poles are areas of high latitudes and typically are cold, icy regions. A polar climate is a cold climate, with temperatures less than 10°C (50°F).

Polynyas: areas of open water in pack ice or sea ice. Polynyas can be kept open by consistent winds or upwelling. Polynyas tend to recur in the same locations year after year.

PORT: Maritime Information Gateway of the National Maritime Museum, Greenwich, UK (http://www.port.nmm.ac.uk/)

PRAC: Antarctic Research Program of Canada

Pressure melting point: the temperature at which a solid melts changes with changes in pressure. With increasing pressure, the temperature of melting is lowered. At the base of thick glaciers, the ice may melt at -2°C (28°F) rather than at 0°C (32°F). The pressure melting point is important to ice movement because the addition of a little water at the base of an ice sheet can greatly increase the rate of the flow of ice.

Pressure Ridges: columns of ice formed by movement of ice against a shore. Usually a haphazard pile.

PRIC: Polar Research Institute of China

PROANTAR: Programa Antartico Brasiliero (Brazilian Antarctic Program) (http://www.mar.mil.br/~secirm/proantar.htm)

PROANTEC: Ecuadorian Antarctic Program

Proglacial: the area and features in front of a glacier.

RADARSAT: Radar Satellite

RAE: Russian Antarctic Expedition

Rafted-up Iceberg: large pieces of ice which have ridden up over each other.

RAMP: Radarsat Antarctic Mapping Project

RAPAL: Reunion de Administradores de Programas Antarcticos Latino Americanos (Meeting of Latin American Antarctic Program Managers)

Regelation: refreezing of meltwater to ice at the bed of a glacier, often associated with the transition from high pressure (forcing melting) to low pressure (allowing refreezing) around a basal obstacle.

Ridge: a long, narrow feature that is higher than the geography surrounding it. The mid-ocean ridge is a large ridge on the ocean floor. Eskers are ridges that trace the path of meltwater tunnels in glaciers. Esker ridges are MUCH smaller than mid-ocean ridges!

SAER: State of the Antarctic Environment Report

SALE: Subglacial Antarctic Lake Exploration (SCAR Group of Specialists on) (http://salegos-scar.montana.edu/)

SANAE: South African Research Expedition(s)

SANAP: South African National Antarctic Program

SAR: Synthetic Aperture Radar

Sastrugi: sharp irregular ridges formed on a snow surface by wind erosion and deposition.

SCALOP: Standing Committee on Antarctic Logistics and Operations

SCAR: Scientific Committee on Antarctic Research (http://www.scar.org/)

SCOR: Scientific Committee on Oceanic Research

SDLS: Seismic Data Library System

Sea ice: a general term for the seasonal ice that forms from seawater. Sea ice can cover large parts of polar waters in the winter. The sea ice melts back in the summer

SHIPOPS: Ship Operations Working Group

Shoreline: the region where land and a body of water meet.

SIBEX: Second International Biological Experiment

Skidoo: tracked personnel carrier for one or two people used on snow or ice, and towing sleds.

Snow: distinct crystals (of many forms) of ice. Commonly accumulates with a density of 50 - 200 kg·m^{-3}, although wind-abraded and -packed snow may have a higher initial density.

Snowdrift: an accumulation of windblown snow deposited in the lee of obstructions.

South geographic pole: 90°S. The south geographic pole is the southern location where the axis of rotation of Earth intersects Earth's surface. It also is home to Amundsen Scott Station.

South geomagnetic pole: the point on Earth's surface in the Southern Hemisphere where the axis of the Earth's magnetic pole intersects. The south geomagnetic pole is approximately 1160 kilometres (725 miles) north of the south geographic pole. The south geomagnetic pole is tilted about 12 degrees to the axis of rotation of the Earth (geographic pole).

South magnetic pole: the point on Earth's surface that a south-seeking compass needle seeks. This point is off the coast of Wilkes Land.

Southern Hemisphere: the southern half of the Earth. The part of the globe 'below' the equator.

SPA: Specially Protected Area (now ASPA) (http://www.npolar.no/cep/innhold/cep_archive/Docs/Forva…)

SPRI: Scott Polar Research Institute (of the UK) (http://www.spri.cam.ac.uk/)

SPRS: Swedish Polar Research Secretariat (http://www.polar.kva.se/)

SRA: Specially Reserved Area (http://www.npolar.no/cep/innhold/cep_archive/Docs/Forva…)

SSSI: Site of Special Scientific Interest (now ASPA) (http://www.npolar.no/cep/innhold/cep_archive/Docs/Forva…)

STADM: Joint SCAR/COMNAP Group for Data Management

STAR: Solar-Terrestrial and Astro-physical Research

START: System for Analysis, research and Training

STEP: Solar-Terrestrial Energy Program

SWEDARP: Swedish Antarctic Research Program

SYMP: Symposium Working Group

Tabular iceberg: a flat-topped iceberg formed by calving from an ice shelf or glacier tongue.

TANGO: Tourism and NGOs Working Group

Tectonic: relating to the forces and the movements of Earth and its crust. Earthquakes, volcanoes, and mountain building are related to tectonic activity.

TEWG: Transitional Environmental Working Group (of the ATCM)

TOGA: Tropical Ocean Global Atmosphere Program

TOMS: Total Ozone Mapping Spectrometer

TRAINET: Training Network

Trench: a long, narrow, deep, steep-sided depression on the sea floor. Trenches mark the location where oceanic lithosphere is being sub ducted under either oceanic or continental lithosphere.

UHF: Ultra High Frequency

UNCLOS: United Nations Convention on the Law of the Sea

UNEP: United Nations Environment Program (http://www.unep.org/)

USAP: United States Antarctic Program (http://www.nsf.gov/od/opp/antarct/)

Valley glacier: a glacier flowing within the walls of a mountain valley

VHF: Very High Frequency

VLBI: Very Long Baseline Interferometry

WAIS: West Antarctic Ice Sheet (Program)

WCRP: World Climate Research Program

WG-GGI: Working Group on Geodesy and Geographic Information

WG-HBM: Working Group on Human Biology and Medicine

WG-PACA: Working Group on Physics and Chemistry of the Atmosphere

WG-SEG: Working Group on Solid-Earth Geophysics

WG-STAR: Working Group on Terrestrial and Atmospheric Research

White-out: a weather condition in which the horizon cannot be identified and there are no shadows. The clouds in the sky and the white snow on the ground blend. White out conditions are potentially dangerous because it is difficult to find a point of reference.

Wind chill: an expression of temperature that incorporates wind speed in the temperature reported. Wind can make the temperature feel cooler. The wind chill factor is a way of expressing how cold the wind might make the temperature feel.

Wind Force: measurements of the wind on a scale of one to twelve used by mariners.

Wind scoops: scours in a snow slope or surface caused by wind erosion.

WMO: World Meteorological Organisation (http://www.wmo.ch/)

WOCE: World Ocean Circulation Experiment

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