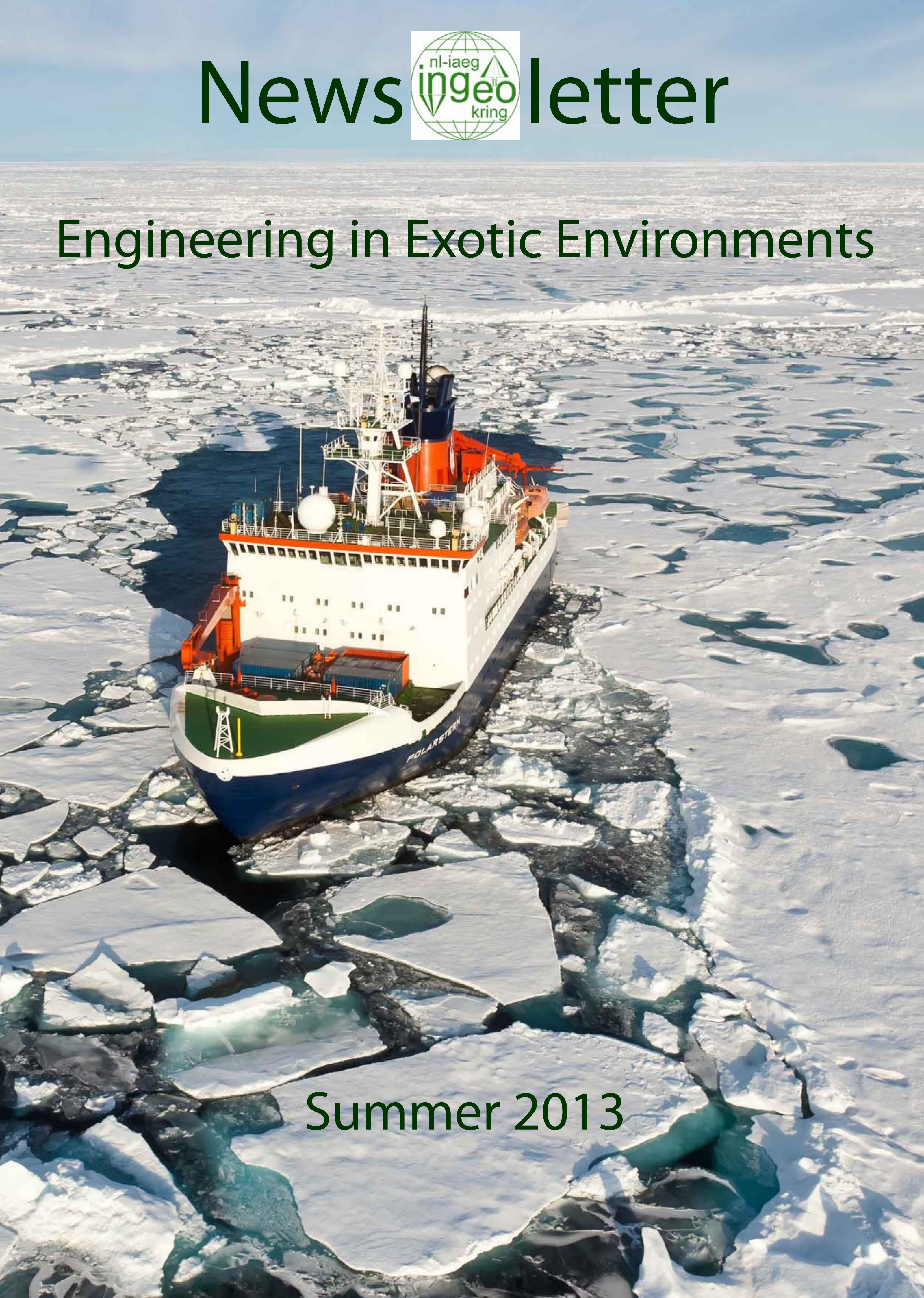
Newsletter

Engineering in Exotic Environments



Summer 2013

Colophon

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The objective of the Newsletter is to inform members of the Ingeokring and other interested parties about topics related to engineering geology, varying from detailed articles, book reviews and student affairs to announcements of the Ingeokring and current developments in the field of engineering geology. The Newsletter wants to make engineering geology better known by improving the understanding of the different aspects of engineering geology.

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RV 'Polarstern' at the North Pole

German research icebreaker 'Polarstern' is operated by the Alfred Wegener Institute for Polar and Marine Research (AWI) in Bremerhaven, Germany. The 'Polarstern' was commissioned in 1982 and is mainly used for research in the Arctic and Antarctica. Photo taken on 23 August 2011, during expedition ARK-XXVI/3 in the Arctic Ocean.

Photo taken by: Mario Hoppmann, Alfred Wegener Institute (source: www.awi.de).

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Total geological history approach for dredging projects in the Scandinavian Baltic Sea

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Introduction

This paper emphasises the use of knowledge of the local geology when interpreting data of a geotechnical site investigation for dredging projects. When confronted with an 'exotic environment', which by definition will be an environment that is new or strange to the engineering geologist, it is wise to familiarise oneself with the regional and local geology through literature study, site visits, and contact with specialists. We have used a 'total geological history' approach to study the coastal geology of Finland, which has helped us in the interpretation of tenders for dredging projects in the Baltic Sea area. Detailed understanding of the geological and geomorphological history of an area is fundamental to the total geological history approach (Fookes, Baynes & Hutchinson, 2000). The approach creates a site specific preliminary engineering geological model based on several conceptual models, related to global scale tectonics, site scale geology, and geomorphology. The preliminary model helps with the anticipation, observation, and understanding of the site conditions and possible expected problems of future dredging projects. Fookes' model contains the premise that the geotechnical characteristics of a site are the product of its total geological history: stratigraphy, structure, previous and present geomorphological processes, and climate conditions. Understanding of that history has to be well developed at the earliest possible opportunity in any project for it to be successfully engineered (Van Yperen, 2012). The geology of the Scandinavian countries surrounding the Baltic Sea is known for its hard Precambrian bedrock, which is abraded and eroded by the ice sheets that covered the Baltic shield during the Pleistocene glacial periods. These rocks are at many places covered by glacial sediments such as glacial till (moraine) and esker sands and gravels. After the last ice age (ca. 10000 years ago) (Wohlfarth et al., 2008), a marine transgression occurred and bedrock and glacial deposits were covered with nearshore or marine deposits. Since the retreat of the ice cover the Baltic shield is rising with a current rate of 9 mm/year in the north, to 4-5 mm/year in the south-west of Finland, and 0 mm/year in the south of Sweden (Figure 1). Eronen et al. (2001) expect that isostatic uplift will continue for several thousand years, with an expected rise in the order of 90 m in the northern part of the Baltic. In the northern part of the Baltic the rise of the land is one of the factors that contribute to the need of dredging existing harbours. Much of the information needed to develop a preliminary engineering geological model is readily available. The geological surveys of both Sweden and Finland provide access to digital geological maps on the Internet. Marine geological maps are also available, on a scale of 1:50000 for parts of the coast, especially near harbours. The Finnish Geological Survey uses a combination of multi-beam survey, side scan sonar, and pinger, chirp, and boomer sub-bottom profiling systems to create these maps. We will first describe the traditional type of site investigation information that is provided in Scandinavia for dredging projects and then show what the total geological history approach has contributed.

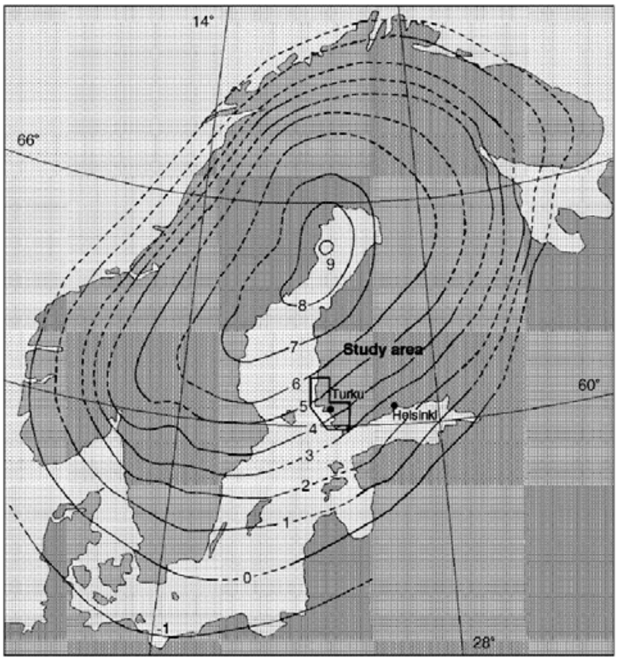

Figure 1 Isostatic uplift (in mm) in Scandinavia caused by removal of the Weichselian ice sheet (Eronen et al., 2001).

Dredging in the Scandinavian Baltic Sea

Traditional dredging along the Baltic coast occurs with bucket dredgers, grab dredgers, and backhoe dredgers (BHDs). Increasingly, projects are executed with backhoes assisted by trailing suction hopper dredgers (TSHDs) and cutter suction dredgers (CSDs). Soft sediments such as post-glacial marine clays and silts and loose sand deposits can be dredged by a trailer suction hopper dredger with high production rates, compared to the traditionally used backhoe dredger. But a dredging hazard is imposed by the presence of dense moraine deposits, erratic rock blocks, and hard bedrock in the shallow subsurface.

Scandinavian nearshore site investigation

During site investigations erratic rock blocks can cause inconvenience when using wireline drilling techniques. Therefore, special site investigation techniques have been developed in Scandinavia. Tests such as Swedish weight soundings, static-dynamic penetration testing, and percussion drilling use small diameter probes to test the subsurface. These methods are complemented by sampling but the amount of soil and rock samples is very low to nonexistent in many dredging projects. In a dynamic penetration test (Figure 2) the cone sinks under static load through the soft sediments and is subsequently lowered by hammering under standard conditions. The cone has a larger diameter than the drill rods and remains in the borehole after testing. Number of blows per 20 cm is automatically recorded by the drill computer. Testing continues until refusal (in practice when 200 blows per 20 cm are needed). For the percussion drilling test (*jord-berg sondering* in Swedish) a 51 mm drill bit is used (see Figure 2). This drill rod is used as a sounding tool when penetrating soft sediments or sands, but when a rock boulder or bedrock is met percussion drilling allows drilling through the rock. Thrust pressure, penetration rate, and other drilling parameters are monitored and entered into the drill computer. The drill master indicates his interpretation of the encountered soil or rock type. The colour and content of the returning flush water helps to identify the drilled material (see Figure 2). In Sweden many nearshore site investigations are based on a large number of percussion drilling soundings. This sounding method is fast and leads to a large amount of data, but the interpretation of the soil is hinging very much on the observations of the drill master. The output of site investigation tests is typically presented in AutoCAD drawings. Commonly more than one sounding method is used and a standardised symbol representation system (SGY 201) ensures uniformity

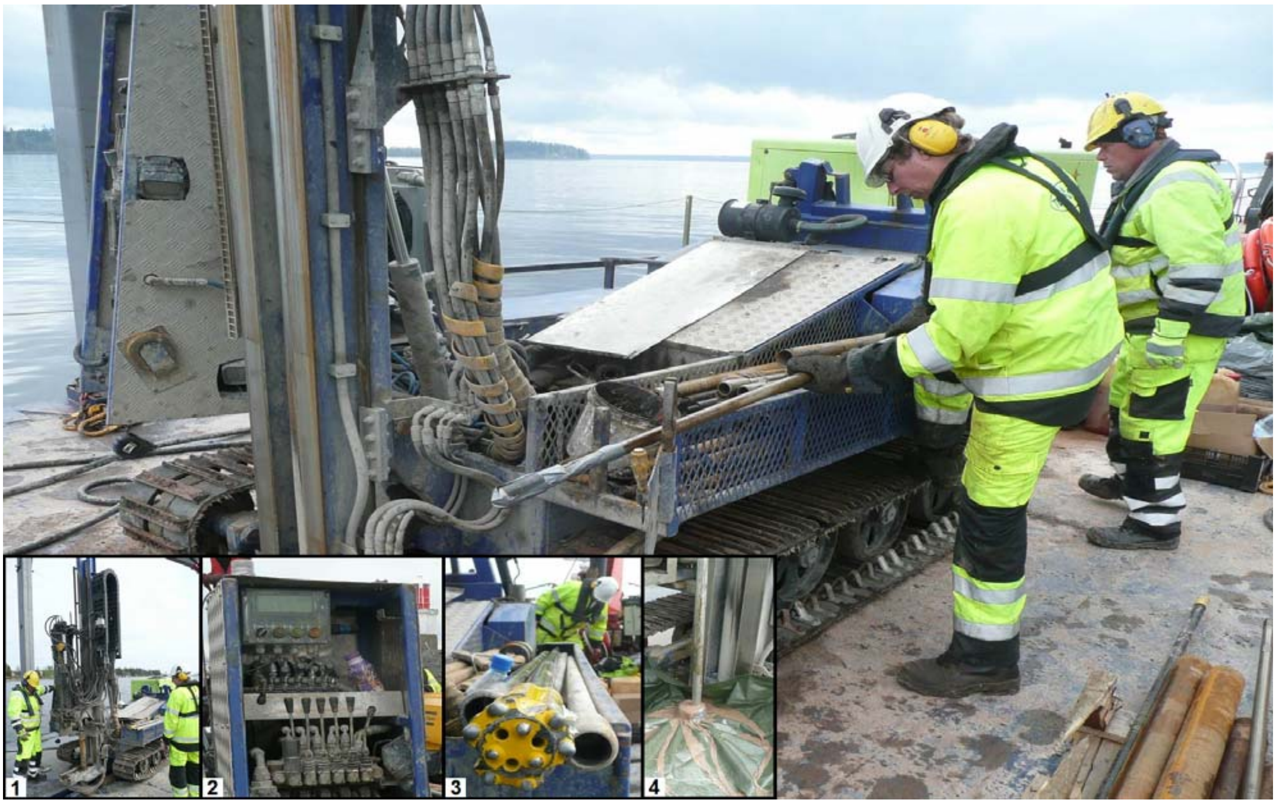

Figure 2 Cone and drill rods are being prepared for a dynamic penetration test. Inset 1: overview of the drill rig; inset 2: drill master computer; inset 3: 51 mm drill bit; inset 4: flush water particles indicate composition of penetrated soil or rock.

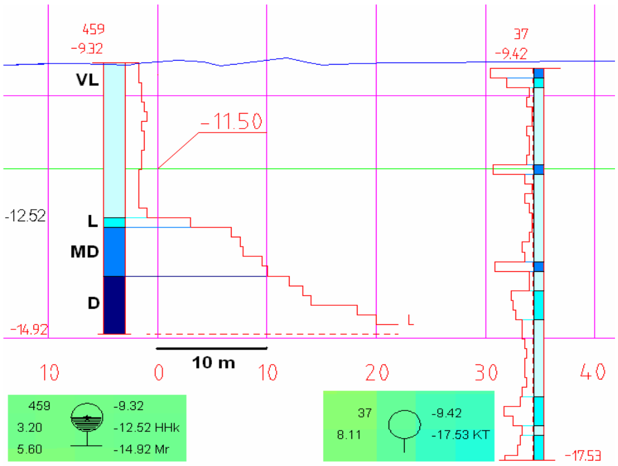

Figure 3 Left: Swedish weight sounding log. Penetration by rotation (half turns per 20 cm) is plotted. L indicates presence of hard rocks or stones. In blue an interpretation of the compaction of the soil is shown (very loose to dense). Right: a dynamic penetration test log. In green the type of method is shown as AutoCAD symbol. Layer depth is shown on the right of the symbol (Mr: moraine; HHk: sand; KT: medium dense soil), drilling number and layer depth from the top on the left.

in the presentation of data. Examples of a typical Swedish weight sounding (SWT) and a dynamic penetration (DPT) log are given in Figure 3. Both in Sweden and Finland the current presentation of the results in AutoCAD drawings and sounding logs is not directed to digital processing of the data. To use the information in a GIS system a small part of the available data can be extracted from the AutoCAD drawing. The rest of the information has to be processed by hand, which is extremely time-consuming. In Finland, a research group (BIM, Building Information Modelling) is working on data processing systems to improve this situation. The advantage of the Scandinavian sounding methods is that the results give an interpretation of geotechnical properties that can be used in the assessment of dredgeability. For granular soils, the results are correlated with relative density (Table 1). For dredging purposes ground investigation techniques should be supplemented by sampling. Additional information could come from geophysical surveying, which has the advantage of providing a 3D framework for the quantity estimation of the dredging work.

Table 1 Rough correlation between cone penetration test (CPT), standard penetration test (SPT), Swedish weight sounding (SWT), and dynamic penetration test (DPT) results with relative density of granular soils (after Dahlberg (1974) and Bergdahl & Ottosson (1988)).

Density Class	Relative Density D_r [%]	CPT q_c [MPa]	SPT N [blows/0.3 m]	SWT [ht/0.2 m]	DPT [blows/0.2 m]
Very loose	<15	0-2.5	0-4	<10	<5
Loose	15-35	2.5-5	4-12.5	10-30	5-15
Medium dense	35-65	5-10	12.5-25	30-60	15-25
Dense	65-85	10-20	25-40	60-100	25-40
Very dense	>85	>20	>40	>100	>40

Total geological history approach for the Scandinavian Baltic coasts

Especially during the site investigation phase of a project, a study of the geology is fruitful, taking into account the specific bedrock, and glacial and post-glacial history. It is essential to place the detailed drill core or log information within the context of the overall geological environment. The total geological history approach of Fookes et al. (2000) aims to create a site specific preliminary engineering geological model based on a choice of given conceptual models. These models relate to global scale tectonics, site scale geology, and geomorphology and should match the described features of the study area. The preliminary model helps with the anticipation, observation, and understanding of the site conditions and with the formulation of issues relevant to dredging projects. The steps taken to arrive at an Engineering Geology Environment model for the Baltic Sea coast are visualised in Figure 4. The Scandinavian Baltic coast is located in a cratonic or intraplate setting, consisting of deformed and metamorphosed rocks. For the geomorphological model the (peri-)glacial influences and coastal influences are of importance. The Engineering Geology Environment of the area is shown in Figure 5, and visualises the possible processes and features that can be used to anticipate possible dredging problems or mechanical properties in the area.

Engineering Geological Environment model for the Finnish coasts

For the Finnish coasts the global model has been further developed by considering the spatial variation along the coastal area. Several factors which are of importance for the interpretation of the Quaternary cover (with the application of dredging in mind) are further worked out and visualised in Figure 6. These factors are bedrock type, transport distance of erratic rock blocks, type (or absence) of Quaternary cover, and fine content (<63 µm) in till deposits and glacial landforms. When assessing the sediments, two grain size limits are taken into account: when are deposits so coarse that production rates of TSHDs or CSDs will be significantly reduced (we have chosen the boundary at the start of the boulder size: 200 mm in diame-

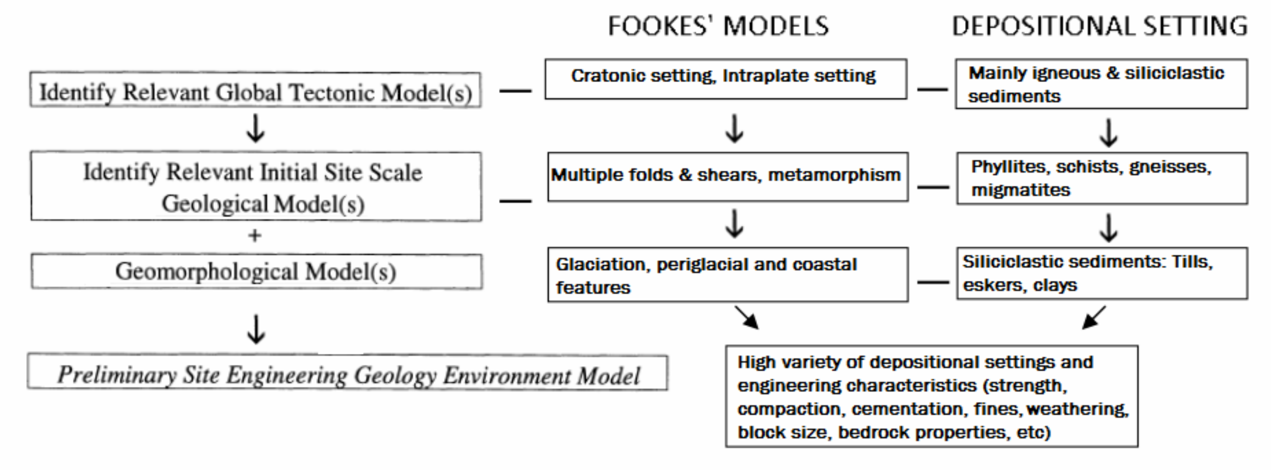

Figure 4 Models and associated geological and depositional settings for the Baltic Sea coast.

ter) and when can boulders/rock blocks (size larger than 600 mm) create problems for the cycle time of BHDs. Each layer in Figure 6 visualises one of these limits in a different way, or gives tools to get a better grip on these limits. Only the 'outer' rim of Finland is assessed since the focus of the model is on the coast of Finland.

Transport distance and direction: implications for boulder locations

The most critical clast mode for dredging is the boulder mode (>200 mm). Therefore it is useful to understand how far bedrock blocks 'quarried' by the scouring ice (Figure 7) are transported before deposition. Bedrock type and rock properties are often much better known than till composition. Therefore, when ice

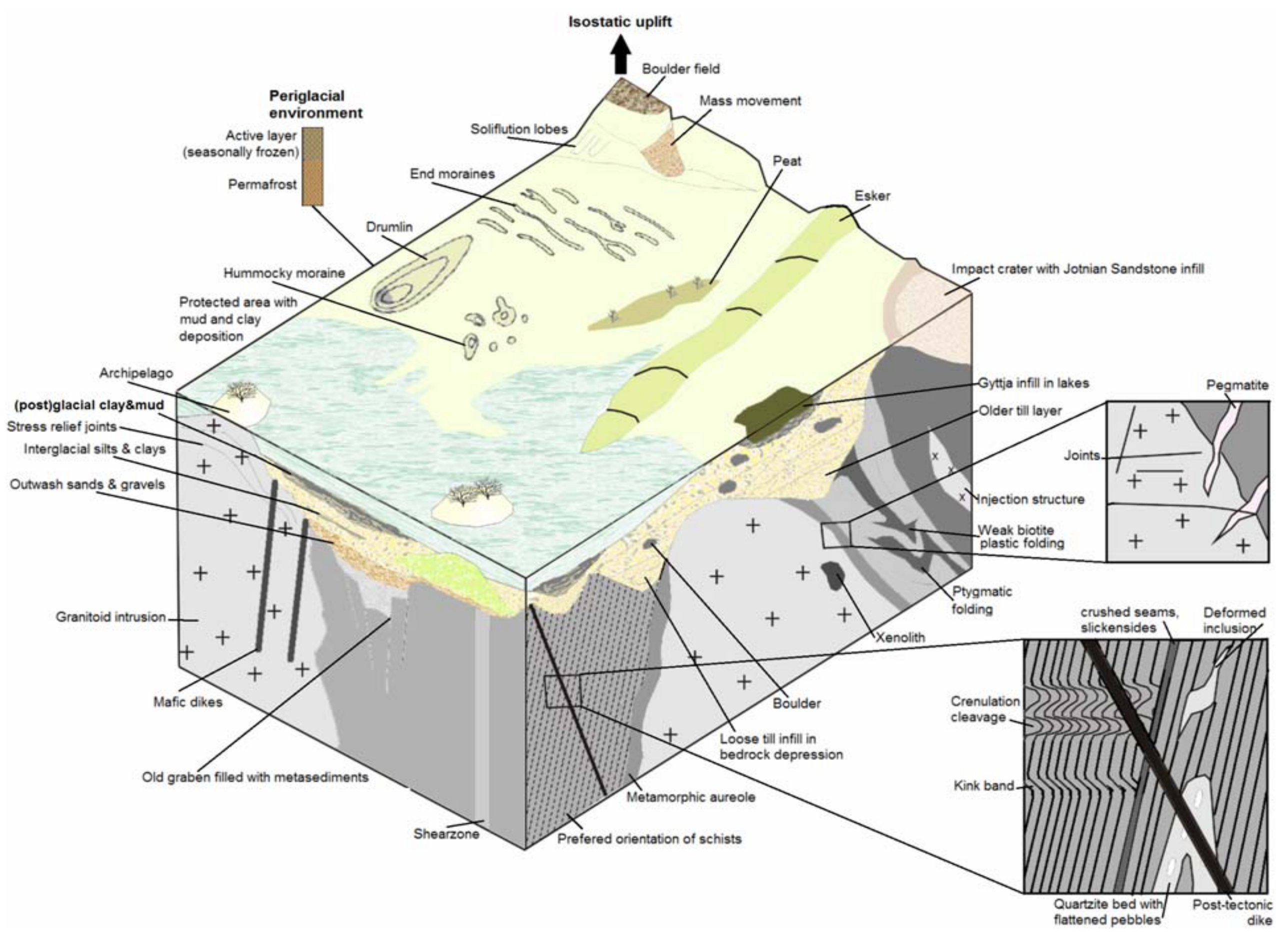

Figure 5 Engineering geological model of the Finnish coast.

movement directions in an area are known, this can give, in combination with a relatively small transport distance, observations and risks concerning size, amount, and type of possible boulders in the till. Figure 6a is based on the boulder transport distance map of Bouchard & Salonen (1990) and shows in blue areas with boulder transport distances of less than 3-5 km. These areas cover the largest part of the west coast. In this figure also ice movement (and therefore transport) directions are indicated. These arrows are from the glacial landform map (1:2500000, GTK, 1986). Field experience from the Hamina-Kotka area (south-east Finland) shows that directly south(-west) of bedrock hills often large amounts of interlocking boulders can be expected, which is in accordance with indicated transport directions and possibly fits the quarrying principle: on the lee side of bedrock highs the normal stress is much lower, allowing the ice sheet to pluck the bedrock by a mechanism similar to joint-block removal (Figure 7 and Boulton & Jones, 1979).

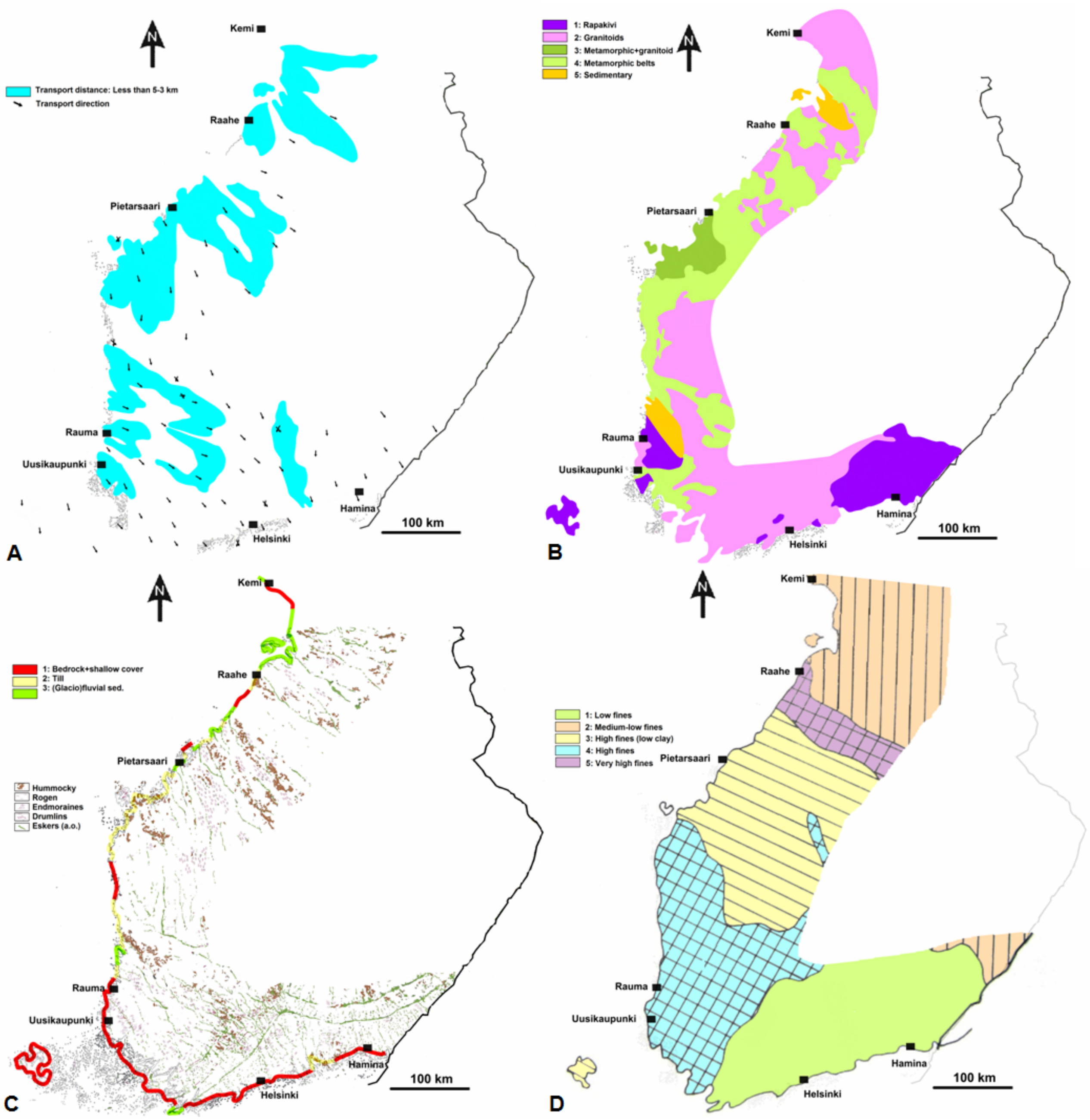

Figure 6 Different layers of the geotechnical model. A: transport distance and direction; B: bedrock type; C: main Quaternary cover and landform type; D: till fines.

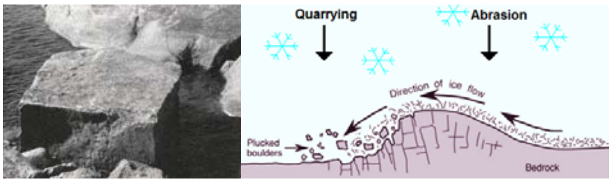

Figure 7 Left: glacial erratic of Rapakivi granite (Laitakari, 1989); right: scouring and excavation by moving glacier ice. The plucking and excavating of rock blocks is termed 'quarrying' after Sugden & John (1976).

Bedrock types: implications for boulder size

To estimate boulder sizes in till, differences in bedrock properties should be assessed. The most influencing rock mass parameters for block size properties are thought to be discontinuity spacing and abrasion resistance of the rock mass. If the discontinuity spacing is large, the glacier can incorporate large blocks during transport and if the rock mass has a high resistance to abrasion, the blocks are fragmented less quickly into smaller pieces. In Figure 6b the following rock types are distinguished with decreasing boulder risk: Rapakivi granites, granitoids, metamorphic rocks with granitoid intrusions, metamorphic rocks (gneisses and schists), and sedimentary rocks. The figure is based on a map of Salonen (1986) and fine-tuned with the detailed geological map of Finland (1:100000, GTK, 1997). Rapakivi granite is a typical bedrock type in Finland which released large rock blocks due to its very widely spaced joints (2-6 m or more). During the dredging project in Hamina rock blocks of more than 40 m^3 were found. The second category (granitoids) comprises granite, (grano-) diorite, tonalite, monzonite, and syenite. They contain mainly widely spaced joints (0.6-2 m) giving caution for large (0.6-2 m) blocks. Metamorphosed schistose rock units in Finland (cat. 3 and 4) mainly comprise schists and gneisses and have a low risk for very large (>2 m) rock blocks. Gneisses might loosen small cobbles (6-20 cm) to 20-60 cm sized, cubic to tabular shaped boulders. Schists have smaller spaced discontinuities which results in coarse gravel (<6 cm) to small (6-20 cm) tabular cobbles. Sandstones and shales (cat. 5) are evaluated to have 'low boulder risks' because of their relative lower resistance to abrasion (an exception must be made for larger quartzite outcrops).

Dredgeability of Quaternary cover

The next step, assessing the dredgeability of the Quaternary cover (Figure 6c), is based on the Quaternary map of the GTK (1:1000000, GTK, 1984) combined with the glacial landform map (1:2500000, GTK, 1986). Three types of bedrock cover are distinguished: a shallow cover with (mainly) exposed bedrock, (mainly) till cover, and a cover of (mainly) glaciofluvial deposits. Areas with mainly bedrock have to be blasted. A till cover is expected to be dredged mainly by a BHD with possibly some smaller areas by a TSHD or CSD. Fluvial deposits have to be studied in more detail on site. When particle sizes of fluvial deposits are small enough (small cobble content) and the sediments are not highly overconsolidated, then they can be dredged with a CSD, otherwise a BHD is needed. Clay areas are present along the coast in depressions, but they are not encountered in such large areas that they can be visualised on this scale. These deposits should be identified by desk study and during site investigation. When a considerable amount of glacial clays, post-glacial clays, and mud deposits are present in the top of the sequence, the use of a TSHD or CSD should be considered. Most common glacial landforms in the area (Figure 6c) are drumlins, end moraines, hummocky moraines, rogen moraines, and eskers (not taking into account the large ice marginal formations). All are deposited during different phases of glaciation. Most difficult to dredge are hummocky moraines, often having large rock blocks on the surface. Large amounts of end moraines are also expected to contain too many boulders for other excavation equipment than BHDs. For drumlins and coarser basal till the provenance area should be verified, or samples should be taken to assess if a CSD can be used. Fine basal till may (partly) be dredged by a CSD and also eskers have a high chance of successful dredging by a CSD.

Fine fraction of till

Figure 6d indicates areas with increasing fines content in the till, based on the map of Lintinen (1995). Transport distances of fines are difficult to quantify because fine fragments will preferentially be eroded and redeposited during consecutive glaciations. Bedrock type only has a slight influence on amount and composition of fines, till redeposition and esker occurrences appear to have a larger influence (Lintinen, 1995). Large amounts of fines (especially a large silt fraction) can generate high cavitation forces or high degrees of compaction, increasing dredging effort. Five categories are distinguished with increasing fines content. Coastal areas with the highest clay fraction are located in areas 4 and 5. The largest amounts of fine silts are located in area 3 and coarse silts are most abundant in the supra-aquatic area 2. Along the south coast (area 1) the percentage of fines is generally relatively low.

Dredging for the Port of Hamina

Introduction

In Hamina, Terramare Oy (Boskalis Nordic) performed dredging works in the harbour and channel during 2008-2010. The dredging work was performed with BHD *Nordic Giant*, using a 16 m^3/18 m^3 bucket, the TSHD *WD Medway*, and a Manitowoc dragline excavator, while bedrock was fragmented by drilling and blasting using drill barges *Playmate* and *Rockbuster*. From the global engineering geological environment model, a first impression of the situation at Hamina Port can be obtained from Figure 6. Hamina is situated in the south-east corner of Finland near the Russian border. The model predicts:

- Rapakivi bedrock (wide spacing of rock discontinuities, large rock blocks from glacier quarrying expected).
- Transport distance of rock blocks longer than 5 km, transport direction NNW to SSE.
- Shallow soil cover of bedrock (red colour); NNW to SSE alignment of end moraines.
- Low fines content in till deposits.

The bedrock in the area of Hamina consists of the large Wiborg massif Rapakivi intrusion, which due to its low joint density released large rock blocks during glacial quarrying. A large amount of big rock blocks was expected during dredging. The glacial deposits in Hamina are characterised by dense stony basal till, small end moraine ridges, large boulders of Rapakivi granite, and esker ridges. The observed glacial landforms continue offshore: multi-beam surveys some kilometres south of Hamina show small end moraine ridges. In this area basal till sheets are observed on land that are thought to be of early Weichselian or Saalian age (personal communication Palmu and Kielosto, October 2010). A characteristic of this till is the higher density, more fines (<63 μm), and higher compaction degree due to various glacial loadings. The geological observations were consistent with dredging experiences on site. A large amount of Rapakivi boulders needed blasting, which was successfully done with the *Rockbuster* supplemented with an underwater camera, the CodaOctopus sonar camera. The (silty) till was very dense and on the south side of bedrock highs often very boulder-rich and interlocking tills were encountered.

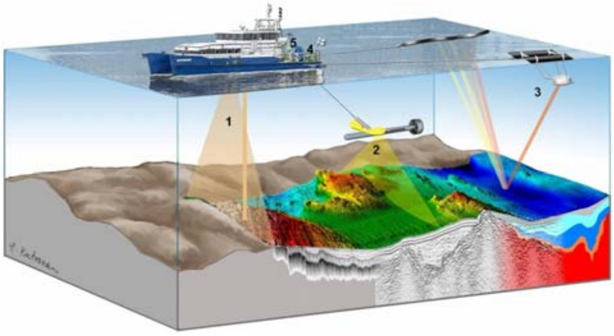

Figure 8 Geophysical equipment of the Geomari. *1: multi-beam; 2: side scan sonar; 3: ELMA; 4 and 5: pinger and chirp systems (source: H. Kutvonen, GTK).*

Geophysics

At Hamina we examined the additional value that geophysical surveys can give to the interpretation of site geology. Theoretically, implementing geophysical surveys in Finnish site investigations seems to be the designated method to accurately estimate the depth and volume of the different geotechnical units and locate hidden boulders in till layers. In practice, boulder rich layers in tills can disturb or block further penetration of the signal, making it difficult to estimate the amount and size of the boulders or the volume of till located below this layer. Choosing the right geophysical equipment is therefore essential. In the preparation phase of the dredging project, Stema from the Netherlands carried out a seismic survey in the harbour area to improve the geotechnical ground model. With this model the location of the top soft layer dredged by *WD Medway* was identified more precisely. Stema used a portable SILAS EBP-10, a versatile echosounder/sub-bottom profiler. The frequency of the transducer can be set between 3.5 kHz and 50 kHz, where 4 kHz has a maximum penetration of 10-20 m in clay and 5 m in sand. During the survey the frequency was 5 kHz. In 2010 an additional seismic survey was done with the well-equipped geophysical survey vessel of the marine department of the Geological Survey of Finland (GTK) to obtain more geophysical data. The GTK uses a unique combination of equipment on their 20 m long, 8 m wide catamaran *Geomari* (see Figure 8). For bathymetry images a high resolution multi-beam echosounder (Atlas Fansweep, 20-200 kHz) is used. The acoustic camera (Klein side scan sonar SA 350) creates high resolution images of the seafloor by transmitting two frequencies at the same time (100 and 500 kHz). For

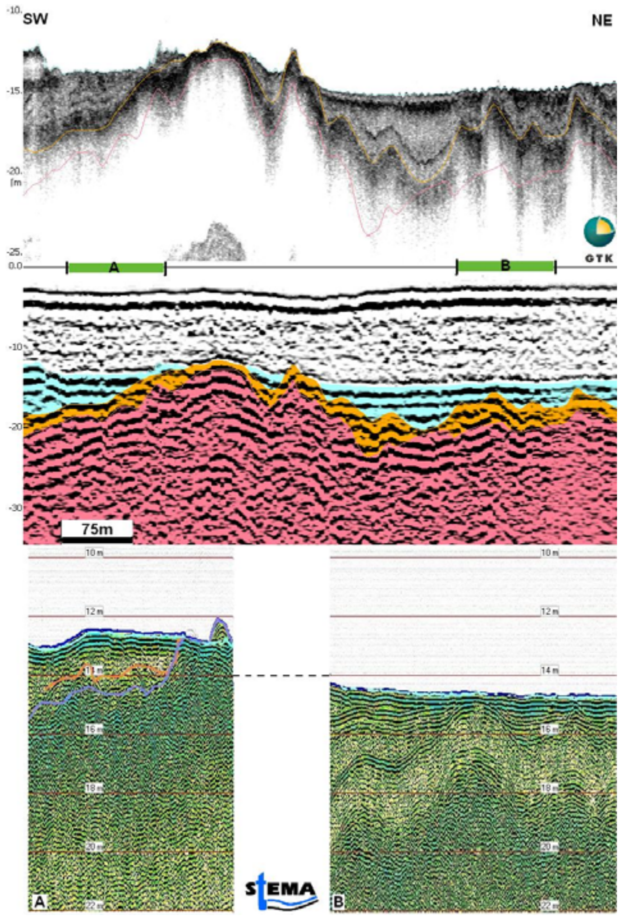

Figure 9 Two seismic profiles. Top: pinger and boomer of GTK; bottom: profile of Stema. Overlapping areas indicated with green bars (A and B).

the soft sediments two echosounders are used simultaneously: a pinger (MeriData MD 28 kHz transmitter) and a chirp (4-5 kHz). With these echosounders thickness and inner structure of clay and mud layers can be identified. For till thickness and bedrock depth a boomer-like seismic device is used, made by GTK. This is an acoustic-seismic sounding device (ELMA) with an electro-magnetic implosion type sound source of ca. 400-700 Hz. The resolution of the ELMA is ca. 2 m. The GTK also has a GPY in storage, which is a low frequency (5 kHz) sub-bottom profiler with a directed acoustic source instead of spherical (like the ELMA) and only one signal pulse and therefore the seismic image is clearer (Figure 10). In Figure 9 a profile of the harbour of Hamina is shown, comparing the seismic image of Stema with the pinger and ELMA boomer profile of the GTK. Weather conditions were poor during the GTK survey, therefore the pinger and ELMA profiles are more disturbed than usual. The strength of the various GTK equipment is that they are complementary. The main interpretation of the subsurface is done using pinger and boomer data. Subsequently the side scan sonar gives essential data for fine-tuning these interpretations. To interpret the sediments from top to bottom first the (GTK) pinger profile is assessed. On top, sub-horizontal post-glacial sediments are visible. Below this, the glacial clays follow more or less the till topography. Within the glacial clays often an extra reflector is visible; the boundary between Ancylus Lake and Littorina Sea sediments. The orange reflector of the till layer and green reflector of the fluvial deposits is determined by combining pinger and boomer profiles. The pinger does not penetrate very deep into the till, therefore the orange reflector is often called the 'hard bottom'. To double-check the hard bottom the boomer profile is used. The reflector of the bedrock can only be found on the boomer data. This reflector can be verified by checking the double echo which occurs at twice the depth of the actual reflector (not visible in this figure). Experience with seismic interpretation and Finnish sediments is needed to be able to distinguish the till and bedrock reflector in the ELMA profile. Glaciofluvial sediments (e.g. eskers) are not visible in Figure 9. In general they are acoustically more transparent than till because of their good sorting and lack of large stones (Nuorteva, 1994). An advantage of the Stema profile over the GTK data is that in some areas boulders (>1 m^3) could be recognised by large/irregular hyperbolic reflections (not in this figure), although size, exact location, and amount are difficult to estimate. The disadvantage of the profile is that distinction between a boulder rich layer, the top of the till, and the top of bedrock is not very clear or even absent. Also the continuity of the interpretation of the reflectors is quite low. According to Stema their results can be improved using post-processing techniques. Overall it can be summarised that because of the large sediment variations over short lateral and vertical distances, the benefit of a seismic survey in addition to penetration sounding for the site investigation of a dredging project is significant, especially when the use of a CSD or TSHD is considered. Geophysics can be used to correlate the sounding data and create an improved 3D model of the subsurface. The top of the hard bottom below

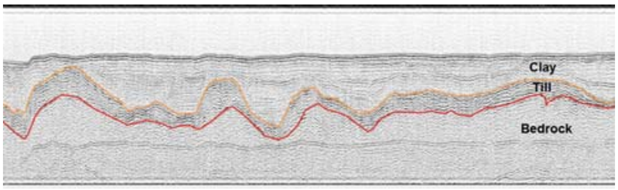

Figure 10 GPY profile in the area of Pori, Finland. In dark grey the till layer is clearly visible (source: GTK).

which you need a BHD and the volume of the top soft part can be determined more accurately, so volume calculations will be more realistic. A multi-beam survey should be standard in this type of nearshore terrain. It gives information on the exact bathymetry, shows amount and size of surface boulders and outside the channel glacial landforms might be recognised, which can be used in assessing till properties. In combination with a side scan sonar survey, information concerning seafloor sediment type and morphology can be obtained. Internal variations in till deposits should not be expected to be visible. But in combination with sediment samples the sediment model will be improved significantly. Only when gas is present in the sediments geophysics is of limited use, which is a risk in areas with thick soft sequences. According to Stema a multi-beam system can be expanded with snippets, which replace the side scan sonar and create a more detailed image (Lockhart, Saade & Wilson, 2001). This multi-beam snippet system could be expanded with a transducer of a chosen frequency and used as sub-bottom profiler. The ideal sub-bottom profiler or boomer for 3D information of the till and depth of the bedrock has not yet been determined. A lower frequency device with more penetration capacity is needed. Ideally the device should have a higher frequency than ELMA, possibly ca. 1000 Hz. A compromise between the SILAS EBP-10 and the ELMA could be used and maybe this can be found in the GPY data of the GTK (Figure 10). The bedrock reflector (red) is clearly visible, as well as the till reflector (orange) and some internal reflectors in the clay. This profile is made under very good weather conditions.

Conclusions

The coastal geology of the Baltic Sea is characterised by the presence of an irregular bedrock surface below a relatively thin veneer of glacial and fluvioglacial deposits locally covered by relatively recent marine and fluvial deposits (clays and sands). This setting requires a detailed site investigation, which is hampered by the heterogeneous composition of the till deposits. It is shown that a study of the local geology can improve the understanding of the nature of the deposits to be dredged. For the Finnish coast, the Total Geological History approach developed by Fookes et al. (2000) has helped to define a framework in which the local geology can be understood. A set of interpretative maps of the coast of Finland furthermore helps to judge in an instant the type of soil conditions that can be expected at a certain coastal location. The main factor influencing the dredging operations and the choice of dredging equipment is the presence of boulders or rock blocks on the surface or within deposits, and the presence of bedrock within the dredging area. If powerful high-production rate equipment such as TSHDs or CSDs are considered to be used, the composition and volumes of soil units should be well defined. This study has made it clear that geophysical surveying using a suite of sub-bottom profiling techniques combined with multi-beam and single-beam echosounding is likely to enhance the accuracy of the ground model and hence helps with making a decision to apply the use of a TSHD or CSD in a project. Most geotechnical site investigations are based on the application of Scandinavian sounding and drilling techniques to probe the subsurface, which are regarded as the optimal ground investigation tools for the local ground conditions. While these techniques allow for a dense net of sounding points and give an indication of the types and properties of the soil and rock, a disadvantage of the current reporting of sounding data is that only part of the data can be directly used in GIS programs for interpretation and modelling. Another disadvantage for dredging applications is the low to nonexistent sampling and testing of the soil. Significant improvement of offshore site investigations for dredging works can be accomplished if, in addition to the Scandinavian sounding methods, efforts are taken to sample sufficient material of the soil and rock types that have to be dredged.

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Cover article: Arctic Engineering

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Challenges in Arctic Engineering

When working in an arctic environment numerous problems are encountered which are specific to arctic conditions. In this article some of these problems will be mentioned. The most influential problem of any offshore design in an arctic environment, the loads of moving ice, is discussed in more detail and the large variety of ice failure modes and ice load types is summarised. The majority of the examples given in this article are related to offshore and nearshore projects. Onshore projects are hindered by some of the challenges mentioned in the first part, but ice loads are obviously not applicable, provided that nobody builds in front of a glacier.

Temperature

One of the most obvious issues in the arctic is the temperature, which is below zero a large portion of the year and can drop to values in the order of -50 °C. Even with protective clothing, the maximum time that can be spent working outside is limited. Low temperatures also have a large impact on equipment. Standard solutions do not always work and the wear and tear of equipment is often higher than in moderate climates.

Location

This leads us directly to the next challenge, as project locations are often remote and supply lines are long. This has a large influence on the initial mobilisation time but also on the time needed to bring in spare parts when necessary or additional parts if other types of testing or site investigation techniques turn out to be desirable. Concise planning and a careful desk study before starting site investigations is therefore even more important when working in the arctic environment. An example of travel distances is given by the following: for a recent harbour project the distance to the nearest existing dock was approximately 3000 km. All offshore equipment had to be brought in from this location, leading to a travel time of at least a week for parts that could not be transported by airplane, provided that it was available in the mentioned port.

Ice coverage/available construction time

Supply roads may be covered by ice and even the project site itself is typically covered by ice during a large part of the year. This severely hinders the available (offshore) construction time. Even though ice breakers can keep the major routes open, relatively small ice thicknesses can make construction activities almost impossible. For example, installing sheetpiles is impossible through ice and a guidance frame will be easily dislocated by drift ice.

Ice formation and ice types

Ice formation

Ice types can be divided into two major categories: first year ice and multiple year ice. As suggested by the names, first year ice contains all the ice types which have formed in the current winter, while multiple year ice contains ice formed in multiple winters. Multiple year ice is often stronger, thicker, and more layered than single year ice, although this is not necessarily the case. Multiple year ice typically is to be considered in arctic regions, where first year ice generally is dominant for sub-arctic and temperate regions. Besides ice thickness, the most important ice properties for ice engineering are the strength and stiffness of the ice. A first observation in this respect is that ice is normally strongly anisotropic. In general a vertical UCS of 4-8 MPa is found, while for the horizontal UCS, values in the range of 1-2 MPa are common.

Ice types

The different ice types that can be encountered while working in arctic environments have vastly different behaviour. It is therefore important to have some knowledge of these different ice types.

Ice formation starts with loose and thin sheets of ice. The thickness of this ‘ice floe’ or ‘pan’ is between 0 and 1 cm. For engineering purposes this type of ice has no influence. In practice it will indicate that it is probably time to hurry and make all installations ready for the coming winter.

The following phase in ice formation is often level ice. Level ice is a more or less continuous ice sheet covering a large part of the surface of the water. Thicknesses of level ice can vary greatly, however, on large surfaces level ice will soon transform to rafted ice under influence of the wind. Rafted ice is a stack of level ice which can be any number of layers thick and can contain ice sheets of multiple years. Even though level ice also contains anisotropy, this effect is much stronger in rafted ice. Since rafted ice can reach large thicknesses the amount of force exerted by drifting rafted ice can have a severe impact on structures loaded by drifting rafted ice.

When rafted ice or sheet ice is colliding with structures or with the shore, the ice can be crushed and broken into loose shards, thereby forming rubble fields. Rubble fields are not necessarily stationary, since a change in wind direction might also change the ice drift direction leading to floating rubble fields. In addition, rubble fields can also be formed by colliding ice sheets, leading to rubble fields without the aforementioned structures or shoreline in sight. When the collision of ice sheets has only lead to local deformations the ice form is called an ice ridge.


Figure 1 Stamukha, a grounded rubble pile.

When rubble fields or stacked ice are getting grounded to the seabed, large rubble piles are formed which are called *stamukhi* (see Figure 1). These stamukhi can reach large heights and can be dragged along the seabed by the ice drift. Obviously this can have disastrous consequences for insufficiently protected piping on the seabed.

The last ice form mentioned here is the iceberg, well known in relation to unfortunate cruise ships and the climate change discussion. A collision with an iceberg is a situation which is only applicable to locations with a large water depth. Obviously the impact of an iceberg on any structure will potentially be incomparable to any other design load and therefore it can be concluded that designing to resist such a collision is nearly impossible and if a collision with an iceberg is likely in the chosen project location, reconsidering the location might be the most viable option.

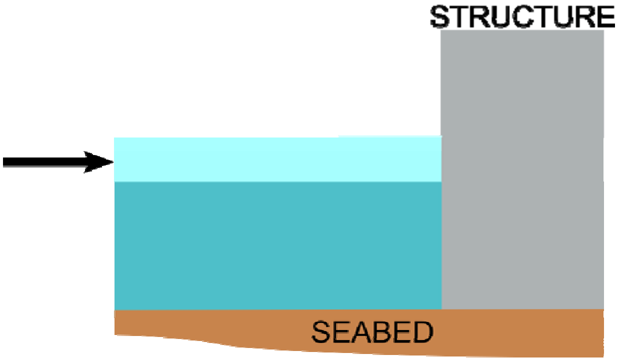

Figure 2 Creeping.

Ice loads

When level ice or stacked ice comes in contact with a rigid structure, a sequence of failure modes starts. Whether the sequence is followed completely or some phases are skipped depends on the ice type and on the drift direction and speed. All load phases lead to a different loaded surface and a different load magnitude.

At low drift speeds the ice will exert a load on the structure without any obvious damage to the ice sheet itself. This load type is called *creeping* (see Figure 2). The amount of force associated with this ice load mode depends predominantly on the thickness of the ice sheet and the wind speed (or the ice drift speed). Theoretically the ice force is limited by the UCS of the ice. However, normally the load will be somewhat lower. When the drift speed is higher and the ice collides more violently with the structure, small scale crushing will occur. This crushing takes place only at the interface between ice and structure. The ice sheet

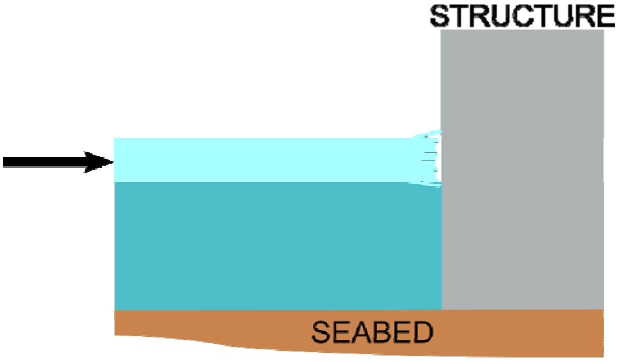

Figure 3 Ice splitting.

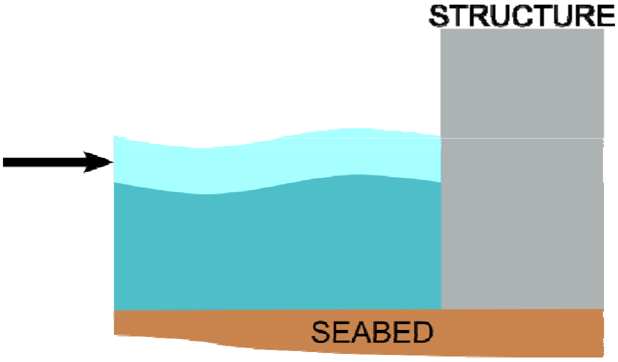

Figure 4 Elastic buckling.

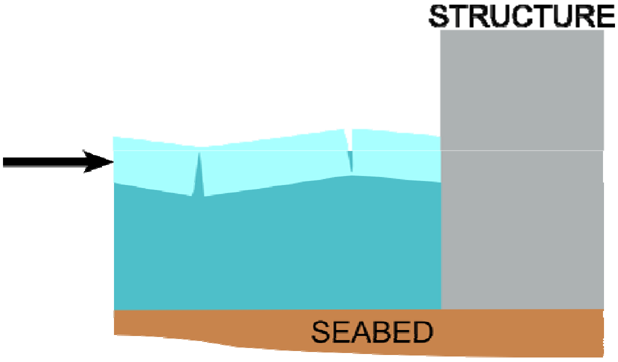

Figure 5 Buckling.

itself remains intact. Often the loads are highest in the centre of the ice sheet, while towards the top and the bottom of the ice sheet layers get separated from the sheet which is called *ice splitting* (see Figure 3). In the next loading phase the ice sheet itself will start deforming. Initially an elastic deformation is found, where the ice sheet as a whole is deformed in the vertical direction. The tension forces in the ice will cause breakage of the ice sheet. If such a failure of the ice sheet occurs the failure mode is called *buckling*. The previous phase is sometimes referred to as *elastic buckling*. As a result of ice buckling a large pile of loose blocks of ice will start to form at the interface between the ice sheet and the structure. These piles of loose ice blocks will be pushed towards the structure by the ice sheet on the backside of the rubble pile.

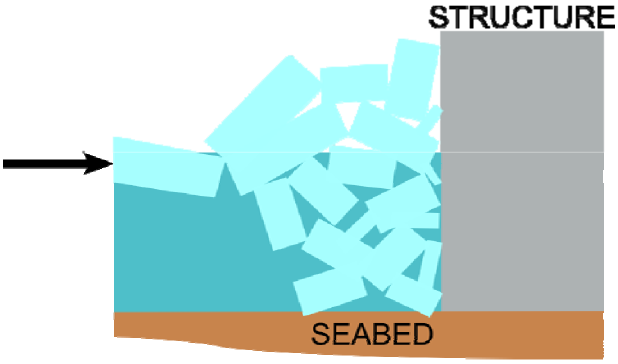

Figure 6 Rubbling.

This failure mode often leads to high global loads spread over a large surface and is referred to as *rubbling*. However, locally rubbling loads are typically lower than crushing loads for a similar contact area. When the ice fails through the pile of loose blocks, the failure mode is *shearing*. Shearing failure will only occur after a large rubble pile has formed.

A separate load case is found for sloping structures, where in some cases the ice encroaches the structure and the sheet is lifted from the water by the driving force of the ice drift. In this case both a vertical and a horizontal force are exerted on the structure. This failure mode is called *bending*. Where bending actions may be dominant for local ice loads, it is generally not the controlling global load scenario for sloping structures. Due to ongoing ice movement a rubble pile will form and the ice load scenario will switch to rubbling.

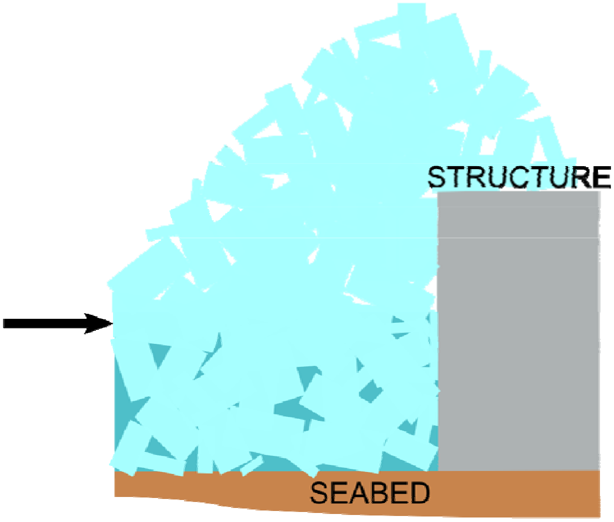

Figure 7 Shearing.

Breakwaters

Breakwaters in arctic areas often serve a double purpose. Obviously they are built to protect a structure or a harbour basin from wave attack, but they also act as a protection against high ice loads. In this latter case breakwaters are also referred to as ice protection structures (IPS). In the normal situation for breakwaters the only external loads that can lead to instability are wind and wave action (which are often negligible from a geotechnical engineering viewpoint) and seismic loading. In an arctic environment however, the ice loads lead to different potential failure mechanisms which will be discussed in some more detail in this section. The main difference between normal loads on a breakwater and ice loads is that ice loads

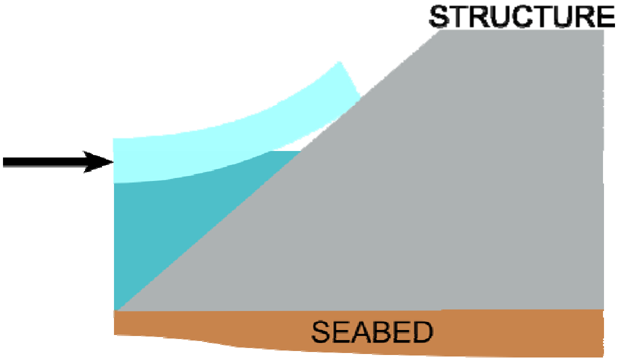

Figure 8 Bending.

work on a limited surface of the breakwater. Through this local loading, local failures can occur of which the most important ones are shown in Figure 9. It should also be mentioned that global horizontal loads due to ice loading may be high and the breakwater's sliding resistance may be critical.

Line A in Figure 9 shows a shallow edge failure of the breakwater. This local failure has only a small effect on the total stability and function of the breakwater and is therefore often permitted to occur in extreme situations. The breakwater can easily be repaired when the ice has melted away.

Line B is a somewhat more serious failure. Along the shown failure plane, the topside of the breakwater is completely sheared off by the ice loading. This failure type is referred to as a 'decapitation' failure. Assuming the material which the breakwater consists of is homogeneous and isotropic and the standard rules of geomechanics apply, the horizontal failure plane of the decapitation failure is very illogical. It is caused by freezing of the pore water in the breakwater, which will create a potential horizontal failure plane along which the decapitation failure will occur.

A deep slide failure is indicated by line C. The deep slide failure can occur when high local ice loads are present and the breakwater is founded on relatively weak soil. The risk of this failure is highest in the first winter after construction of the breakwater since it is often caused by undrained behaviour of the underlying soil. A soil improvement or vertical drainage can remediate this instability.

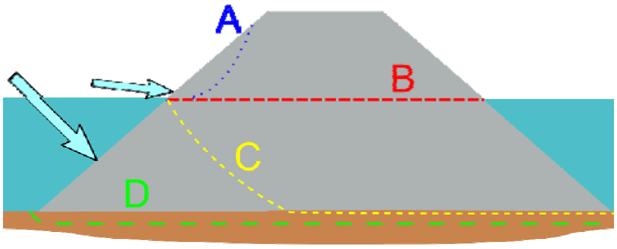

Figure 9 Failure planes through a breakwater under ice loading.

The last of the typical failure modes for a breakwater loaded by ice is the global slide failure which is shown by line D. This failure mode is caused by a more global loading of the breakwater, for example by rubbling loads. A large pile of loose ice blocks forms on the slope of the breakwater and the combination of high vertical and horizontal forces leads to a horizontal sliding failure through the subsoil. As was the case for the deep slide failure, the global slide failure is also mostly caused by undrained behaviour of the subsoil. The most severe stage of global ice loading due to rubbling related to this failure mechanism is the stage where the rubble has not grounded yet. If grounding occurs the global horizontal ice loads acting on the breakwater will be reduced as the total horizontal load is partially transferred to the subsoil in front of the breakwater.

Figure 10 Exploration drilling barge protected by four IPS.

In some situations special ice protection structures are made which can be placed around important offshore structures to protect them against the ice loads. These IPS can only be deployed in relatively shallow water but can form a viable and flexible alternative to applying sufficient ice protection to a structure itself. For example, in the Caspian Sea IPS have successfully been deployed as protection of wellheads, exploration drilling barges, main hub islands, etc. (see Figure 10).

Engineering Geologist abroad: an international experience

Paula Tulha Moutinho MSc *(Senior geotechnical engineer, Fugro In Situ Geotecnia Ltda, Brazil)*

Over 10 years ago I left my country, Portugal, to get a Master's degree in Engineering Geology at Delft University of Technology in the Netherlands. At that time I could never have imagined that geotechnics/geology would take me so far, considering I always had the plan to go back to my home country by the end of my studies. It was a study trip of one day to Fugro's office in Leidschendam that changed the course of my life.

Botanic garden in Rio de Janeiro (April 2011).

The sea has always been one of my passions. Therefore, when I got acquainted with the existence of a highly specialised company at the forefront of offshore geotechnics such as Fugro, I tried to bring together work and pleasure. After I had finished my studies in Delft I sent them my CV for their consideration. This process took one year and when I was about to give up and return to Portugal I received a call long awaited by me. I did not think twice and readily accepted the offer of employment and career that Fugro presented me. Going back to Portugal was not in my plans anymore. During the years that I worked at Fugro's office in Holland I had the opportunity to be part of in-office teams integrating interesting engineering design projects for offshore foundations, as well as travel to distant seas and oceans for various geotechnical campaigns. In those campaigns I have used different tools and techniques either for sample collection or for in situ testing. I've collected geotechnical data in many different seas such as the Caspian Sea, Mediterranean Sea, Andaman Sea, and Barents Sea, in Ireland, in the North and South Atlantic Ocean and obviously in the North Sea! I was even involved in data collection at the Equator, at a latitude of zero degrees! It was also a Fugro campaign that brought me to Brazil for the first time in 2010 as lead project engineer responsible for a site investigation for Petrobras, the biggest Brazilian oil company and one of the world's giants. We performed an extremely successful campaign in very deep water (>2000 m).

Between 2010 and 2012 I returned to Brazil several times attending other campaigns in Brazilian waters for companies such as OGX, Anadarko, and more recently, Statoil. Always on board of ships as well as on highly specialised jack-up platforms. During those two years I became increasingly charmed by Brazil and began desiring the change from the long winters in Holland to the eternal Brazilian summers. Once again perseverance and of course a bit of luck to the mix (being at the right place, at the right time) finally brought me to the lands of Vera Cruz. One of the Brazilian projects that I keep great memories of was in Bahia, more specifically on the island of Itaparica. I've spent there five weeks describing and testing rock samples in a garage of a former manor facing a fantastic blue sea. Every day our cook was preparing homemade cookies and meals as well as natural fruit juices like mango, passion fruit, and watermelon which I savoured on the terrace during regular breaks.

Bahia project: view from the garage (April 2012).

It was during this project that I was invited to come and lead the technical department of a new Fugro office in the area of marine geotechnics in the wonderful city of Rio de Janeiro. It was like, once again, combining both work and pleasure. Together with my

Rio de Janeiro: view from Corcovado to Sugarloaf Mountain (May 2010).

husband and our pet rabbit we moved to this wonderful city where we have lived since September 2012, in the gorgeous neighbourhood of Ipanema, three blocks from one of the world's most famous beaches. Rio is really a city where everything is happening and this is visible everywhere. Most of its inhabitants, despite not having the advantages and opportunities that we have in our European cities, are extremely cheerful and friendly. Rio is no longer the violent and dangerous city which it was a few years ago. Taxi drivers now do stop at red lights! Great international events like the 2014 World Cup football and the 2016 Summer Olympics are motivating and catalysing many works in the engineering and architecture areas and contribute to great developments at other levels, such as the social and economical, extremely important for the success of a country.

Much remains to be done, especially in my area of marine geotechnics, ranging from new ports and harbours along the Brazilian coast to offshore windmills, not forgetting the oil and gas industry with many miles of pipelines to lay, seabed structures to be placed such PLEMs (Pipeline End Manifolds), and the developments in many Pre-Salt fields. There are many and huge challenges and this for me is highly motivating. In my opinion, this is an ideal place to live and work in the coming years.

And, every February…we have CARNIVAL!!!

Nuno and Paula at Carnival.

Weathering and deterioration as quantitative factors in slope design in humid tropical areas: case study Northern Kota Kinabalu, Sabah, Malaysia

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Abstract

Deterioration of rock masses in cut slopes is a main cause for slope failure along road corridors. Deterioration is mainly due to stress relief and weathering. Deterioration rates depend on the properties of the rock mass including its history and the environment in which it is exposed. The rate decreases with time due to formation of a layer of residual material that prevents further contact between fresh mass and weathering agents. This research has been carried out to establish the relationship between weathering intensity rate *and exposure time for the* intact rock strength (IRS) *of sandstone in the area around Kota Kinabalu (Sabah, Malaysia), which has a humid tropical climate. The geology in the area consists of interbedded thickly bedded sandstone and thinly laminated shale beds belonging to the Crocker Formation. The research shows that IRS is related to time following a logarithmic function:* IRS (t)*=105-34 log (1*+t*). This relationship is likely also valid in other tropical areas and thus can be used for prediction of the intact rock strength development of sandstone over the engineering lifetime of man-made slopes in tropical areas.*

Introduction

Road construction in mountainous areas, especially in humid tropical climates, is often afflicted by slope instability. Road cut slopes are designed to be stable over a certain time span, i.e. the engineering lifetime, however many slopes or parts of slopes fail before the end of this lifetime. Reasons for failure at some point after construction are likely stress relief and weathering. Stress relief and weathering are often marginally quantified or simply neglected in slope design due to a lack of understanding and appreciation of the processes. In addition, the limited quantitative information available makes it difficult to incorporate the degradation in design. A proper design of a slope for the entire engineering lifetime of the slope, say up to 50 years, should include quantitative factors accounting for the degradation of the rock mass over its lifetime. Therefore, research has been done to develop quantitative factors for incorporation in the design of slopes to account for stress relief and weathering in humid tropical areas.

Figure 1 Rock slope failure on road cut slope due to stress changes and weathering.

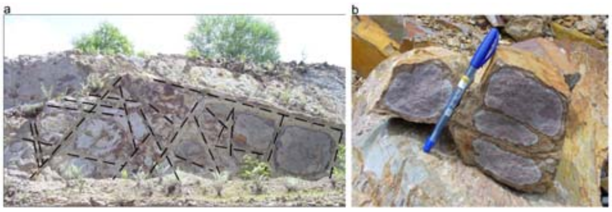

Figure 2 Weathering effect characteristics on (a) rock mass and (b) intact rock. Note the formation of a residual layer that decreases the rate of weathering.

Slope deterioration

The dominant deterioration processes that affect the durability of a man-made rock slope after excavation are stress relief and weathering. These cause the physical, geotechnical, and chemical properties of the slope material to change in response to the new environment. Excavation of a slope causes a change in stress regime in the rock mass, often denoted as stress relief. This may be a change in magnitude or orientation. Stress relief allows for opening of existing discontinuities and may lead to formation of new discontinuities such as stress relief fracturing in shaly rock types (Price & De Freitas, 2009). Weathering on the other hand is the chemical and physical breakdown of minerals due to physical, chemical, and biological processes. The weathering affects intact rock but also the fabric and nature of discontinuities and the rock

Figure 3 Weathering will cause the formation of new joints in massive rock that will affect the durability of the rock mass.

mass. Weathering is influenced by local conditions such as local climate, surface, and groundwater conditions, chemicals dissolved in groundwater, land and fertilizer use, etc. Stress relief and weathering mutually influence each other and the effects of both processes are to a certain extent similar. Therefore, it is mostly impossible to differentiate between the effects of both processes, and both are commonly included in weathering or geotechnical deterioration.

Slope rock mass weathering with time

The rock mass response to the process of weathering and exposure time can be expressed in two different terms: 'weathering intensity' and 'weathering intensity rate'. Weathering intensity refers to the degree of decomposition or amount of alteration from the original state shown by rock mass material at a certain point in time, whereas the weathering intensity rate refers to the amount of change in this weathering intensity per time unit (Bland & Rolls, 1998; Huisman, 2006). The weathering intensity and weathering intensity rate of a rock mass respond to the particular combination of weathering controlling conditions at the site of its exposure. This may be referred to as the susceptibility of the rock mass to future weathering (Hack, 1998). Several methods are used to quantify weathering or weathering intensity rates such as based on the availability of time control and quantification of weathering variables (Colman, 1981; Fookes, Gourley & Ohikere, 1988). Generally, the change brought by weathering to a particular property is established in time. This is done by comparing the initial property value before and after weathering. In a rock slope, the initial property value may be the value at the time of excavation whereas the weathered property value is the observed value at a certain time after the excavation (Irfan & Dearman, 1978; Selby, 1993; Hack & Price, 1997; Huisman, 2006).

Weathering intensity rate

Weathering intensity rate can be determined if the exposure time for the rock mass is known. The time relation is corresponding to the expression proposed by Selby (1993) and Ruxton (1968):

$$C_t = C_o e^{-kt} \tag{1}$$

where C_t is the property value at time t, C_o is the initial property value (original value in fresh state), k is a constant, and e is the base natural logarithmic. An alternative empirical relationship to describe change of the property value as a function of time is suggested by Colman (1981):

$$\frac{C_t}{C_0} = a + b\log(1+t) \tag{2}$$

In which a and b are constants, C_t is referring to the parameter value at time t, and C_o is the initial parameter value (original value in fresh state).

The same equation is used in this research to describe the change of rock properties as function of time. The ratio C_t/C_o corresponds to the property change at a certain time after the rock mass is excavated with respect to the initial value of the property. Property refers to the geotechnical properties such as intact rock strength (IRS), and rock mass internal *angle of friction* and *cohesion*. These properties are preferred as they are directly related to slope stability. The constant a is replaced by the initial property value (IRS_{init}), b is the apparent rate of the IRS change, and IRS_t is the IRS value at exposure time t:

$$IRS_t = IRS_{init} + R_{IRS}^{app}\log(1+t) \tag{3}$$

The property value change rate in this equation refers to the 'apparent rate' which is quantified by the change in property value from the initial state divided by a function of the total exposure time. The property value assessment made during a successive time series divided by the elapsed time between the assessments is the 'dynamic rate' of the property value change at a particular time and location (Figure 4).

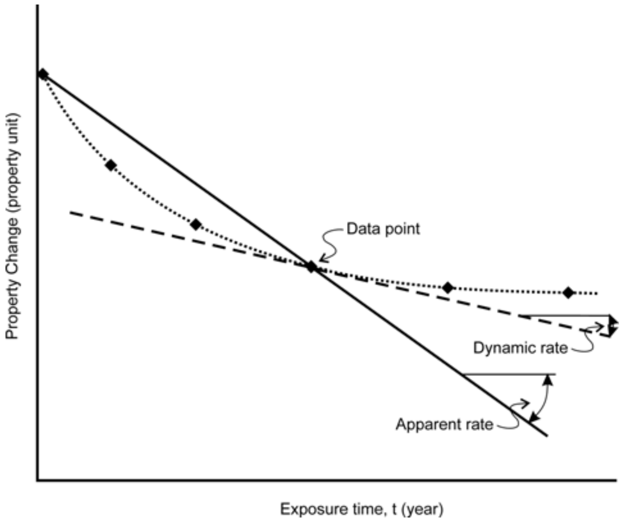

Figure 4 Definition of apparent and dynamic property change rates (modified after Huisman, 2006).

Location and climate of the study area

Data for the study has been collected from cut slopes with different dates of excavation in the northern part of Kota Kinabalu, Sabah, Malaysia (Figure 5). The eastern part of the area is a hilly area, whereas the western part comprises flat and slightly undulating areas with isolated hills. Most of the western parts have been cleared from vegetation and excavated since 1995 for industrial development. In addition to some already existing roads in the area and vicinity, many new roads with road cuts have been made in the area between 1995 and 2011. Data from fresh rock has also been collected from three quarry sites in the vicinity of the area. The date of excavation of the road cuts is well documented providing a good time control for the data. The dimensions of the slopes range from less than one meter to more than 80 m in height and between a few meters to over 50 m in width. Data from 97 cut slopes is used for the study. The area has a tropical climate with a uniform temperature and high humidity throughout the year. The daily temperature ranges from 22-33 °C (average 27 °C) and the average humidity is about 70%. The annual rainfall ranges from 1920 to 3190 mm with an average of 2075 mm.

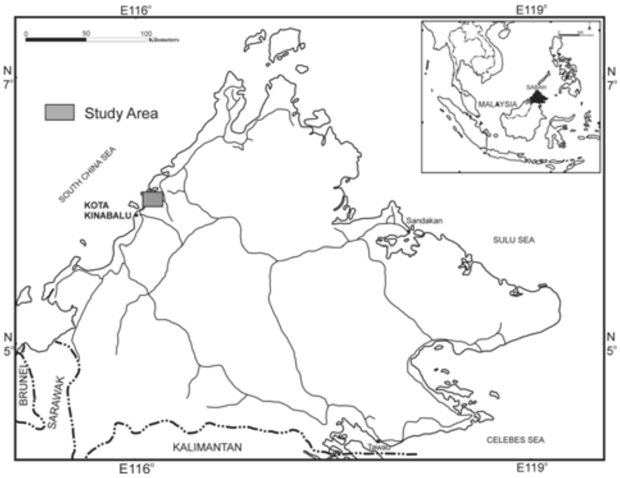

Figure 5 Location of the area (modified after Tating, 2003).

Geology

The geology consists of a thick sequence of interbedded Eocene-Oligocene grey to bluish grey fine to medium grained sandstone and red and/or grey shale beds belonging to the Crocker Formation (Collenette, 1958). The rock sequence can be divided in three main lithological units based on the bedding thickness, sandstone to shale ratio, sedimentary structure characteristics, rock type, and colour (Tating, 2003), namely thickly to very thickly bedded (sometimes massive) sandstone unit (SST unit), interbedded thickly to medium bedded sandstone, and thinly laminated shale unit (IB unit), and a grey or red thinly laminated shale unit (SH unit) (Figure 6 and Table 1).

Figure 6 Detailed lithological map of the study area (modified after Tating, 2003).

The stratigraphic succession in the Kota Kinabalu area can be divided further into two main sequences based on the lithological dominance; i.e. Sandy sequence and Shaly sequence (Tongkul, 1987; Tating, 2003) (Figure 7). The Sandy sequence consists predominantly of sandstone from the SST and IB units, whereas the Shaly sequence consist mainly of the SH units.

Table 1 Description of rock units. The same units are used to define the geotechnical units.

Formation	Units	Description
Crocker (Eocene to Oligocene)	Thickly to very thickly bedded Sandstone (**SST**)	Bedding spacing from 0.6 to over 2 m with some bedding spacing exceeding 8 m. Grey to bluish grey in color. Fine to coarse grained with locally sparse pebbles at the base. Intercalated with thin pelitic layers with ratio of 9:1.
	Interbedded Sandstone, Siltstone and Shale (**IB**)	Interbedding between sandstone, siltstone and shale beds. Bedding spacing from 0.01 to 0.6 m. Sandstone and pelitic layer ratio varies. Divided into three subunits based on ratio: classical type (ratio 1:1), shaly type (ratio 1:3), and sandy type (ratio 9:1).
	Red/Grey Shale (**SH**)	Red and Grey shale bands thickness from 0.6 to over 25 m. Red shale characterised by distinctive red to brownish red color and massiveness; occasional interbedding with siltstone. Grey shale consists of thinly interbedded between grey shale, siltstone or fine-grained sandstone (1-20 cm). Shale and sandstone ratio from 3:1 to 10:1.

Methodology

Data for this research was collected and organised via a systematic approach following the SSPC methodology (Hack, Price & Rengers, 2003). The rock mass is divided into different homogenous geotechnical units and then each unit is characterised based on standard field forms with standardised descriptions. Intact rock strength was estimated by a simple field test (Hack & Huisman, 2002) and verified by 'L' type Schmidt Hammer, Point Load, and Uniaxial Compressive Strength tests. The exposure time of the rock material is an important parameter in establishing the relationship between weathering and time. The date of excavation is obtained from the agencies responsible for the excavation or slope cut (such as Public Works Department of Malaysia (PWD) for most road cuts, and quarry operators for rock quarries) or from enquiring the local residents in the vicinity of the excavation (for privately excavated slopes). Other rock geotechnical parameters such as cohesion and friction angle values are estimated by optimising the Mohr-Coulomb failure criterion with intact rock strength (IRS), discontinuity spacing (SPA), and condition of discontinuity (CD) in the SSPC system. The equations are given by:

$$Friction_{mass} = 0.2417IRS + 52.12SPA + 5.779CD \quad (4)$$

$$Cohesion_{mass} = 94.271IRS + 28629SPA + 3593CD \quad (5)$$

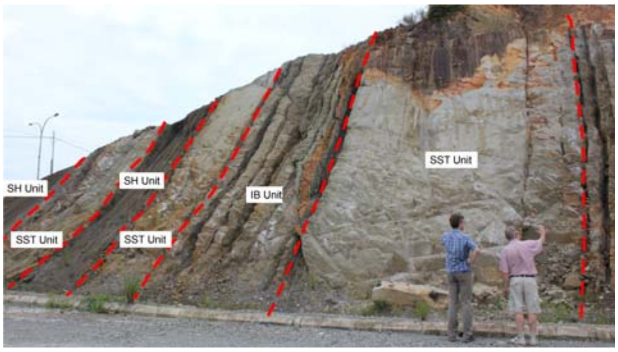

Figure 7 Exposure with typical geotechnical units in the Kota Kinabalu area.

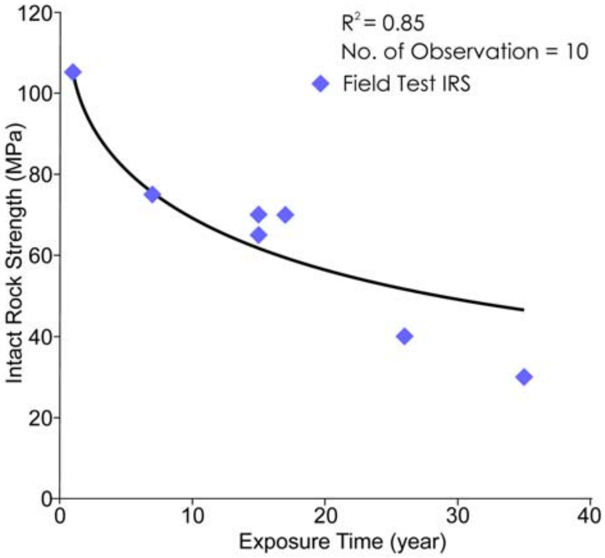

Figure 8 Relationship between the IRS *and* exposure time *of SST unit expressed in logarithmic function.*

$Friction_{mass}$ is the angle of internal friction of the rock mass (in degrees) and $Cohesion_{mass}$ is the rock mass cohesion (in Pascal). The relationship between weathering and time is determined by plotting the average IRS (MPa) of the SST unit against the *exposure time* (in years). Data has been fitted to a logarithmic function by least square fits. Most rock masses, especially in tropical areas, are weathered before excavation. Therefore, the time from when first weathering occurs to present had to be back calculated by using equation (3). This gives the 'adjusted exposure time' for the SST unit that has been weathered to a certain grade at the time of excavation.

Results

The relationship between the IRS and *exposure time* in the SST unit (Figure 8) shows that the IRS of the SST unit decreases non-linearly with time. This weathering effect can be expressed by:

$$IRS_t = 105 - 34\log(1+t) \quad (6)$$

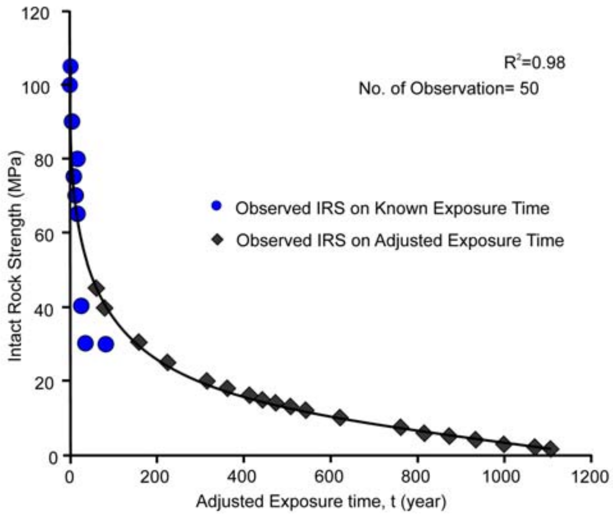

Figure 9 Relationship between the IRS *and* exposure time *of the SST unit expressed in a logarithmic function for the whole observation. The exposure time is determined by back-calculation from equation 6.*

IRS_t (MPa) is the intact rock strength of sandstone at the time t, and t is the time since exposure in years. 105 is the initial value of the IRS in MPa of the fresh SST unit at the time of excavation, and 34 is the apparent reduction rate in MPa/log [year] for this type of rock mass in the environment of the research area. This initial IRS value for the SST unit determined by this function is within the range of IRS values for fresh material of the SST unit determined in various other studies (i.e. 88-130 MPa) (ML Geoscience Services, 2008; Rodeano, Sanudin & Abd Kadir, 2006; Ismail, Sanudin, Baba & Shariff, 2009; STL Geotechnical Engineering, 1997; Applied Geotechnics (Sabah), 2004). The 'adjusted exposure time' for the SST unit is determined by back-calculation (from equation 6) as described in the previous paragraph (Figure 9). Alternatively, the same methodology can be used to predict the future reduction of intact rock strength from the initial value (i.e. fresh rock) over the engineering lifetime of man-made slopes in this particular environment. Similar analyses are carried out for the cohesion and friction angle for the SST unit, which is estimated by using the SSPC method. This is shown in Figures 10 and 11. Based on the graphs, the SST unit cohesion reduction in time is expressed as:

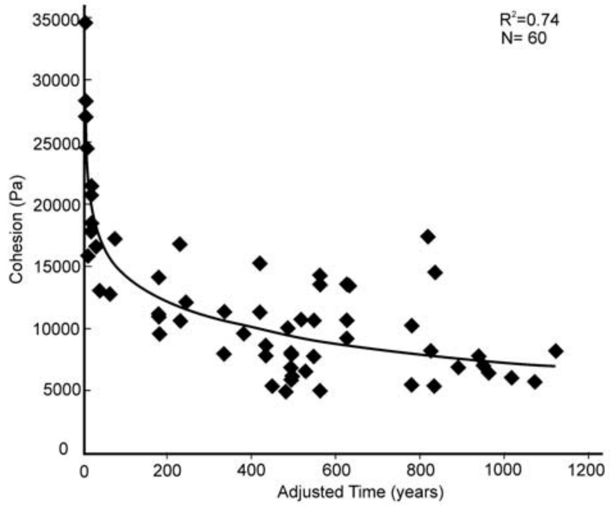

Figure 10 Relationship between the cohesion *and* exposure time *of the SST unit expressed in a logarithmic function for the whole observation.*

$$Cohesion_t = 27004 - 6850.3\log(1+t) \qquad (7)$$

$Cohesion_t$ (Pa) is the intact rock *cohesion* of SST at time t, and t is the time since exposure in years. 27004 is the initial value of the cohesion in Pascal of the fresh SST unit at the time of excavation, and 6850.3 is the apparent reduction rate in Pa/log [year].

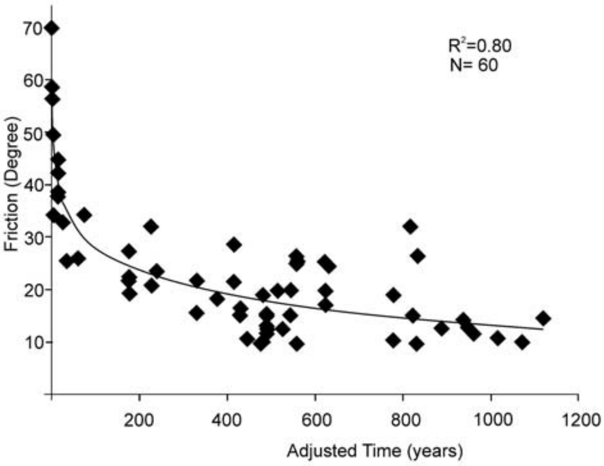

Figure 11 Relationship between the friction angle *and* exposure time *of SST unit expressed in logarithmic function for the whole observation.*

For the SST unit friction angle, the relationship is expressed as:

$$Friction_t = 56.1 - 15\log(1+t) \qquad (8)$$

$Friction_t$ (Deg) is the intact rock *friction angle* of the SST unit at the time t, and t is the time since exposure in years. 56.1 is the initial value of the cohesion in degree of the fresh SST unit at the time of excavation, and 15 is the apparent reduction rate in Degree/log [year].

Discussion and conclusions

The quantitative factors for the design of slopes in the thickly to very thickly bedded sandstone to account for stress relief and weathering after excavation have been established for the SST unit in the Kota Kinabalu area. The relationship is expressed as a logarithmic function (Equations 6, 7, and 8). This study shows that the change of the *IRS* value as well as the cohesion and friction angle values with time are non-linear in accordance with published previous research. Figures 9, 10, and 11 show that the reduction of the SST unit geotechnical parameters (*IRS*, *Cohesion*, *Friction angle*) reduces after a certain period (noticeably after 50 years of exposure) and eventually becomes constant when the whole rock mass is transformed into a soil mass. The decrease of these parameter change rates is explained by the formation of a protective residue, which prevents the weathering agent from direct contact with the fresh rock. The analysis of the change of *IRS* in terms of residual strength ratio from this research was compared to the residual strength ratio changes at 0.01 m depth of the study by Hachinohe, Hiraki & Suzuki (2000). It shows that both studies exhibit a quite similar trend of residual strength ratio changes over time (Figure 12). Both show a higher residual strength ratio change rate directly after exposure of the rock mass that gradually decreases with time. The change rates are different which is likely due to differences in lithological and physical properties of the rock mass and in the climatic environment in which the studies were performed. Hachinohe et al. (2000) used a needle penetrometer to establish the relationship between strength ratio and time of two different sedimentary (sandstone and mudstone) rocks in a humid temperate climate in Japan. The reliability of the prediction of weathering with time depends on many site and location specific factors as discussed before. Thus, the prediction may only be applicable in an area where similar factors apply. All the weathering processes (i.e. chemical, physical, and biological processes) and stress relief are assumed to affect the *IRS* of the SST unit simultaneously. Also, it is assumed that the surface erosion of the rock mass (i.e. thickly to very thickly bedded sandstone) is slower than the weathering processes. In this research, the relationship of the reduction of *IRS*, *Cohesion*, and *Friction angle* for thickly to very thickly bedded sandstone with exposure time has been established. The relation allows prediction of sandstone geotechnical parameters reduction within the 'serviceable lifetime' of the slopes made in the SST unit in Kota Kinabalu. The weathering-time relation is likely also applicable in other areas for cut slopes in humid tropical areas, and the methodology used in this research may be applicable to areas in other climates as well. Better prediction of future *IRS* values will help in better design of slope cuts and thus in a reduction of maintenance costs.

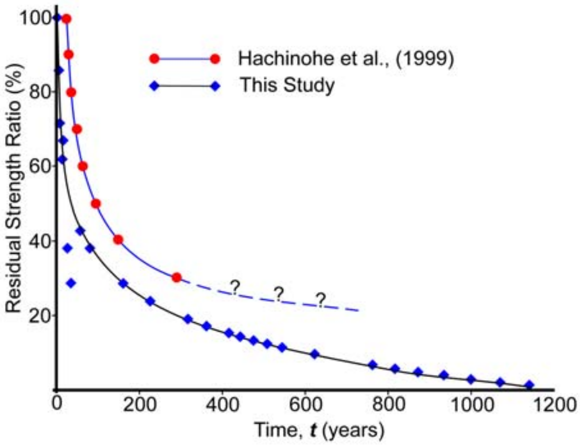

Figure 12 Comparison of the results with other similar studies on weathering over time (Hachinohe et al., 2000).

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Conductance
Seismic

11th IAEG Congress (Auckland, New Zealand): congress notes and official and personal post-congress tours

Part 1: Friday 3 September - Monday 13 September 2010

Michiel Maurenbrecher MSc CEng

Friday 3 September 2010: arrival in Auckland

My first visit to New Zealand was in March 1983, when I returned to Holland from Dubai after managing Fugro Middle East for three years. I decided to take the longer route east to return to Holland, a trip that took me to Thailand, Singapore, Sydney, New Zealand, Tahiti, Los Angeles, and Ottawa with longer stopovers in Bangkok, New Zealand, and Ottawa to visit relatives. This time (2010) I flew over Sydney after having changed planes with a short morning rest in the airport hotel of Kuala Lumpur International Airport (KLIA) and before catching my connecting flight straight to Auckland. I assume we flew over Sydney: the pilot announced this and I didn't have a window seat to check it. I try and obtain a window seat just to look out over the geology beneath or otherwise at the clouds. The first leg of the flight from Schiphol to Kuala Lumpur offered me impressive views of the northern shores of the Caspian Sea, including the Volga Delta. The remainder of the flight was in darkness with daybreak just starting when I settled into my transit hotel room at KLIA. Flying onward to Auckland over Indonesia and Australia, had I had a window seat, I would have just about seen Sumatra and Java before darkness of the next short night brought the Thursday to an end. By Friday morning 3 September 2010, 30 hours after leaving Schiphol on Wednesday, I landed at Auckland in a rather overcast early spring day (in Amsterdam, Thursday 2 September 2010 was approaching midnight). Not long afterwards I took the airport bus to downtown Auckland almost under the impression that, just like the previous IAEG Congress in Nottingham, I was again in the UK. The architecture resembled suburban Nottingham. The green hills resembled the English countryside, the bank notes contained an image of Queen Elizabeth and, of course, one drove on the left. I had two full days to start adjusting to 10 hours of jet lag before registering at the SKYCITY Auckland Convention Centre close to my hotel on Hobson Street.

Saturday 4 & Sunday 5 September 2010: time off

On Saturday morning I was confronted with 'breaking news' when I switched on the hotel room television. There would be a statement given by the Minister of Internal Affairs. A strong earthquake had occurred at Darfield, 40 km west of Christchurch. The first scenes of familiar damage and features caused by an earthquake were being shown. Welcome to a 'Geologically Active' country, the theme title given to the 11th IAEG Congress. The weather in Auckland was cool and sunny on Saturday so I went for the Sky Tower which is a good place to take in the volcanic landscape of Auckland and watch weekend sailing races in Auckland Harbour. Auckland was more a city than when I left it in 1983, for all I know it could have been a different place altogether. A similar spring day in Holland with sun and waterfront would attract more weekend crowds than could be seen now in the bistros and terraces situated on the wharfs of Auckland Harbour. On Sunday the street beneath the Sky Tower was cordoned off, someone was attempting to jump off the tower and thereby not using a bungy (the latter being a New Zealand invention).

Monday 6 & Tuesday 7 September 2010: 11th IAEG Congress

On the morning of Monday 6 September 2010 Hamish Campbell, geologist with GNS (Geological Nuclear Sciences), gave the opening key lecture of the IAEG 2010 Congress with a title suited to the Saturday morning news: *New Zealand geology: A story of contorted crustal edge effects*. With words such as 'active' and 'contorted' one would expect any moment for an eruption or two in the Auckland volcanic area. Auckland volcanism has been active for 250000 years. The last eruption in the volcanic area that Auckland occupies was ca. 600 years ago from the volcano Rangitoto, situated on an island with the same name east of the entrance to Auckland Harbour. Campbell's presentation was essentially a tour of our eighth continent, Zealandia. Was that not the Latin name for the Dutch province of Zeeland? Another

Dutch province, Holland, had also for a time given its name to a continent: New Holland. When Britain secured its claim on New Holland the sixth continent became known as Australia. But that was only for starters. Soon the audience was confronted with more: an eighth continent which unknowingly was the second that Abel Tasman saw and which was 100 years later, in 1769, discovered by James Cook on an exploration voyage to find 'Terra Australis', the supercontinent believed to exist in the Southern Hemisphere and thought, then, to balance the large land masses in the northern half of the world. New Zealand and its Pacific island dependencies and territories extend from near the Equator to the South Pole. Coincidentally much of this stretch is submerged granitic continental crust which is known as Zealandia. It was part of the eastern extremity of Gondwanaland, separating and submerging from its Gondwanaland neighbours Australia and Antarctica (the seventh continent) as a result of extensional tectonics since the Cretaceous. Previously, Zealandia's eastern boundary formed the eastern boundary of Gondwanaland and was since the Cambrian subject to plate tectonics. New Zealand's North and South Islands and New Caledonia are the main land masses of Zealandia that rise above sea level.

Since the Cretaceous there appears to have been mid-ocean spreading and ridge forming in the Tasman Sea as the Zealandia Plate moved away. Inevitably, in about the Miocene, the Zealandia Plate came into twisted collision with the Pacific Plate. This Kermadec-Tonga Subduction Zone is a convergent plate boundary which stretches from the North Island northward, and includes the Hikurangi Trough, the Kermadec Trench, and the Tonga Trench. Along this subduction zone, the Pacific Plate is subducting beneath Zealandia. At the northern part of South Island, not far north from Christchurch, this trough/trench subduction system switches to the transverse-normal ('transpressional') Hope Fault through the island and then turns into the Alpine Fault along the coast of the Southern Alps. The collision zone eventually leads to the south-western Puysegur Trench.

Figure 1 Muriwai Beach. Left: pillow lavas on beach; right: gannet colony on stack of pillow lavas. Beach consists of black iron sand (titanomagnetite grains, an erosional product of the volcanic rocks).

Figure 2 Topography of the southern extremity of the Northland Allochthon with in the background Kaipara Harbour.

By now I had reached the limits of my geological comprehension. I may be excused as 2012 (at the time of writing this belated geological travelogue) is the 100th anniversary of Alfred Wegener and the 50th of Harry H. Hess both at their time presenting their controversial exposés (for uniformitarian geologists) on continental drift and its mechanism respectively. If one wants to learn more about the twisted geology (both in plan and in section) of New Zealand, start with New Zealand's government web site, www.teara.govt.nz. Or, as I eventually managed to do, obtain two books co-authored by Hamish Campbell (Campbell & Hutching (2007) and Hicks & Campbell (1998)).

Wednesday 8 September 2010: mid-week field trip

I used the word subduction a few times to give the introduction to trips associated with the 11th IAEG Congress. By Wednesday I got used to the word 'allochthon' as a geological term in plate tectonics and not the term used in Dutch politics. A word which describes the process of creating an allochthon is 'abduction'. As the Pacific Plate subducted off the east coast of the North Island, part of the plate split (like a flat nosed crocodile with its lower jaw moving into the ground and upper jaw over the ground surface trying to lunge forward to grab a flat sunbathing human being) and moved over the existing Zealandia continental plate creating a large sliver of Pacific oceanic crustal rocks covering all of Northland (the peninsula north of Auckland). Just to cause more confusion the first stop was to look at cliff faces with associated stability problems consisting of ocean formed basaltic pillow lavas. The sediments and basalts are from the Miocene and Pleistocene, but contain the volcanic rock which is part of the Auckland volcanic area and these pillow lavas have formed in shallow seas. The location was a seaside resort at Muriwai Beach (see Figure 1). The pillow lavas have spread over sedimentary layers and in turn have been overlain unconformably with further sedimentary layers. Quarrying has steepened the cliff face so that slopes are prone to failure through sliding and toppling. Large old landslides associated with cliff erosion are being reactivated by urban influence (leakages of holiday homes).

The general landscape depicted in Figure 2 shows the typical topography of the Northland Allochthon: abducted 'slithers' of deep-water Cretaceous and Oligocene sedimentary and igneous rocks (in this instance its southern extremity). The slithers consist of numerous sequences of thrust faults with shearing taking place over large distances. The combination of plastic sediments and shear zones presents problems associated with slope stability and effects of moisture which causes swelling when wet and shrinkage when dry. For local councils expenditure is relatively high for maintaining the roads situated in the Northland Allochthon. The water inlet in the background in Figure 2 forms part of the much larger Kaipara Harbour inlet, the largest natural harbour in the southern hemisphere, with its narrow entrance on the west coast. Design studies are underway to create a tidal power scheme at the entrance. Projects are underway for windmill farms on the distant hills consisting of ocean basin volcanic rock from the Pacific Plate.

Figure 3 Left: vineyard of the Ascension Wine Estate; right: White Bluff Headland cliff instability.

Continuing north to stop 3, we descended to picturesque Port Albert, which is a tertiary inlet of Kaipara Harbour. On the road from Port Albert towards stop 4 further east and thereby crossing the main north-south Highway 1 at Wellsford, we turned south on a tertiary road. At this point, approximately, we passed a basement rock inlier being quarried for greywacke gravel, an indication that we had moved briefly into an autochthonous zone and left the abducted sliver of the Pacific Plate. Heading due south halfway to the town of Matakana we stopped for lunch at Ascension Wine Estate. The vineyards (Figure 3) looked waterlogged but the white wine with lunch tasted good. After lunch the trip took us further south along the east coast of Northland and to a stop at the neck of Mahurangi Peninsula south-west of the town of Warkworth at the seaside resort of Snells Beach. The gentle slopes leading down from the town to the beach have always been unstable due to the underlying rocks of the Waitemata Group of the Northland Allochthon consisting of tectonically sheared and crushed very weak mudstone with minor fine silty sandstone having residual friction angles as low as seven degrees caused by shallow low angle thrust faults in the Snells Beach area. Despite these conditions the relative stability of slopes at Snells Beach is better than in other parts of the Northland Allochthon. This is attributed to better drainage and less infiltration from sewerage and damaged water pipes and drains. The headland (White Bluff) is relatively stable except for its steep coastal cliffs and the sides of gullies. The lithology comprises dark grey to brownish grey, weak to moderately strong, generally massive siliceous mudstones. It weathers to white, light grey, and whitish brown. The rock is of the Wangai Formation, one of the oldest in the Northland Allochthon. It has undergone a high degree of tectonic deformation and is moderately to highly shattered and sheared, folded, and contorted. Figure 3 shows an example of instabilities along the cliffs of the headland.

The final stop in the Northland Allochthon brought us within commuting distance of Auckland. In Silverdale a large property development in the Dannemora subdivision is being undertaken in an area rezoned from farmland to urban development. We had retraced our route from Snells Beach to Warkworth and joined State Highway 1 to head south to Auckland. About halfway to Auckland we stopped to look at a development in the southern reaches of the Northland Allochthon. At this location, there are sufficient chal-

Figure 4 The highly jointed and fractured nature of this rock mass makes it unsuitable as building and cladding stone.

lenges for engineering geologists to anticipate and prevent the engineering problems associated with the allochthonous slither from the Pacific Plate. At Silverdale, the rock comprises mainly brecciated mudstone and siltstone. The Allochthon at Silverdale, probably at the head of the abducted slither, appears to have detached and moved more south-easterly causing further more pervasive shearing and softened with numerous slickensided surfaces. Hydrothermal processes have further reduced the rock strength. The weathering profile on sloping ground has a 'softened zone' gradually changing with depth into a 'broken zone' immediately above the in situ rock mass. The softened zone exhibits soil properties. These soil properties gradually change to rock mass properties in the broken zone. In sloping areas the broken zone slickensides trend parallel to the slope and further can have high pore water pressures build up quickly because of high permeabilities. This results in slope movements.

Thursday 9 September 2010: visit to a greywacke quarry

Despite having been on the road the day before, I was persuaded to make up numbers for a Thursday afternoon visit to a quarry producing crushed greywacke gravel for aggregates for use in concrete and asphalt paving. This was a good opportunity to work up an appetite for the congress barbecue that evening and to look more closely at the greywacke rock. The rock is derived from sedimentation of sands and silts on the continental margins of Gondwanaland, which because of their age and deep burial have become indurated and metamorphosed. It is the dominant source of suitable aggregate in New Zealand. The aggregates are manufactured from rock which has been excavated by blasting and subsequently crushed to obtain suitable grading for construction purposes. The quarry is run by Stevenson Aggregates who purchased it in 1939. The expected life is 150 years. Despite more extensive outcrops to the east (the quarry is at the western edge of the greywacke outcrops), much of these areas have been 'sterilised', designated as parks, as urban developed areas, or competing land use so that outcrops of suitable high quality aggregates are few. Production consists for one third of soft pit run (highly weathered), one third of primary products, and one third of tertiary products (sealing chip, concrete aggregates, road base course). The plant consists of the usual equipment, tools for transport, and crushing installations. The final processing is done in an automated 'pug mill' that blends aggregates so that suitable quality is maintained for buyers' specific uses.

Friday 10 September 2010: congress closing and start post-congress tours

At previous IAEG congresses (the first being Amsterdam in 1990) I have participated in the official post-congress tours. They all took me to exotic places. Even the one I helped organising (visit to South Limburg, while staying at the Rolduc monastery and with David Price as guide) could be considered exotic, looking at the artwork: drawings and sculptures of novice priests during their time off in the Jesuit Caves at Neerkanne, Maastricht. Amsterdam was followed by Portugal (7th Congress, Lisbon, 1994) and they chose a tour to what could be the mythical Atlantis: the Azores and Madeira. Lisbon was followed by Vancouver (8th Congress, 1998) including a post-congress tour to the vineyards of the Cascades. During the duration of that tour the sky remained blue and the volcanoes were in full view. This seemed quite normal to the 8th Congress tour delegates but was beyond belief to our tour guide ('freak weather', he said). The next was the 9th Congress in Durban, South Africa (2002), the first in the new millennium with a choice assortment of exotic trips. Having been to many African game reserves I opted for the prime wine producing area of the African continent, the Cape. Exotic appears to be the operative word for these tours. The following congress in the UK (10th Congress, Nottingham, 2006) resembled the very successful but unfortunately discontinued annual engineering group meetings of the Geological Society including the one day post-conference tour to look at a rather exotic area of Keuper Marls subject to underground solution weathering. This time the congress was held in the most distant venue of all: New Zealand, with many outward similarities to the UK (areal extent, appearance, being an island nation, green, rainy, suburbia, and a mutual head of state). Geologically, though, very different: volcanics, plate tecton-

Figure 5 Tertiary road branching off from the Thermal Explorer Highway.

ics, Alpine mountains, seismically active, and even abducted slivers of the Pacific Plate that can be viewed at close quarters. The closest comparison could be more or less at the opposite end of the Pacific in British Columbia and Washington State: coastal alpine range, the Olympic Mountains, plenty of plates bumping into each other and subducting, and the ensuing volcanism. I have to hear about an allochthon in Canada or the USA but no doubt there is one. Rather than partake in the 11th Congress tour I organised my own ad hoc last minute tour. The object was to visit my relatives after seeing them last almost three decades ago. It took quite an effort to obtain telephone numbers and e-mail addresses. I seemed to have more success with female second cousins so that on the spur of the moment after the closing session of the congress I managed to get a second cousin on the phone, Noes Butte-Maurenbrecher. That same evening, Noes and her husband Jack drove from their house near Pukekohe (not far from Drury, quarry visit the previous day) to Auckland to meet me at my hotel on Hobson Street. Noes had booked a restaurant, in SKYCITY of all places. The dinner was excellent and inexpensive which explained the queues I noticed there all week. At the bus terminal, beneath the SKYCITY complex, I could not get a place to travel south to Taupo so Jack and Noes suggested I check out of my hotel and travel with them and that we would continue the next day by car to Taupo and stay there with her stepbrother Peter Cox. From there I would be picked up by her brother Tony Maurenbrecher who was skiing with family on one of the volcano resorts and continue after a day in Taupo to Hawke's Bay. So within a few hours of the closing session of the congress my personal post-congress tour was arranged!

Figure 6 The author, Noes, and Tante Fran.

I have a AA Road Atlas of New Zealand, purchased in 1983 and which, as I write this travelogue, I refer to. A 2010 AA tourist map of North Island shows a modern trend in naming the major routes. Highway 1 together with route 18 in Northland which we drove frequently on (or crossed) on the Northland Allochthon tour is named 'Twin Coast Discovery Highway'. When Noes, Jack and I left Auckland on Highway 1 south to Pukekohe the name changed to 'Thermal Explorer Highway'. This promised more geologically active New Zealand.

Saturday 11 September 2010

After lodging one night at their snug timber structured bungalow in the countryside near Pukekohe we continued south towards Taupo. Noes had in the meantime arranged to have a coffee stop on the way at another family member, Tante Fran. "Tante Fran?" I asked. She turned out to be the widow of Hans Maurenbrecher who perished in 1966 on his solo tour around the world in a severe storm on his yacht off the Great Barrier Reef in the region of Cairns (north-east Australia). As far as I know she is the last of my parents' generation (my mother had passed away four weeks previously at over 95 years of age). Tante Fran, who I had not met before, turned out to be a spritely 95 year old, and had especially driven to the baker in town (Putaruru) that morning to purchase some cakes to have with the coffee. My own mother must have stopped driving twenty years ago. She showed me a photo album of the trip she made part of the way with her husband from his temporary anchorage at Tauranga to Russell and then she flew to Brisbane to join him for the coastal stretch to Cairns. Tante Fran had a photo in the album of a single propeller light aircraft (either a Cessna or Piper Cub) flown by Ton, and Lily Hartevelt signalling Godspeed and farewell (I had met Ton and Lily Hartevelt on my first journey to New Zealand; in-laws of my sister Madelon). Ton Hartevelt was, like Hans Maurenbrecher, a fighter pilot during the war. I told Tante Fran she had misspelled Hartevelt, that it should be like the Dutch genever and hence not the more common Harteveld! Up to Putaruru I had not seen any thermal activity. The highway did follow the Waikato River; New Zealand's largest river with its source Lake Taupo being New Zealand's largest lake. Much of the water in the river, though, would have its source from hot springs and geysers in the Taupo volcanic area. My attention was diverted from geology to architecture: corrugated iron was being used to build houses, shops, and cafes with artistic flourish and at Wairakei Volcanic Activity Centre the entrance represents a volcano (see Figure 8).

There was still time left after our arrival to make three visits in the afternoon, the Volcanic Activity Centre at Wairakei (it had just closed for the day), followed by nearby Huka Falls lookout, and a hike over and along the torrential Waikato River upstream of Huka Falls. The Waikato has its source about 10 km to the south at Taupo on the shores of the largest lake from which the town derives its name. The weather consisted of almost continuous rain which I assumed caused the torrent. I used my camera on film mode and suggested to Jack he jump in to see how far the water would take him; if he did it would probably take him all the way back to Pukekohe which is just north of the Waikato estuary into the Tasman Sea. The information boards at the pedestrian bridge across the Waikato from the car park to the right bank offered some information. The water surging through the narrow gut (channel) of the Waikato is flowing from Lake Taupo. The river is at this point confined by hard geothermally altered rock. Over time it has carved a channel about 15 m wide and 10 m deep through the underlying softer sedimentary layers. The water churns along this channel towards Huka Falls at a rate much faster than the river's average flow of 40 m³/s. Hour by hour the rushing water continues to erode this gut. Gradually the river scours more from its bed and Huka Falls will move upstream.

Figure 7 White waters of the raging Waikato River at Huka Falls.

Figure 8 Posing at the entrance to the Volcanic Activity Centre in Wairakei: Jack Butts (left), Peter Cox (middle), and the author (right).

The major geological features I could not observe were e.g. the mighty Taupo Caldera Lake with its backdrop of New Zealand's highest volcano Mount Ruapehu (2797 m, last erupted in 1995) with sister volcanoes Mount Ngauruhoe (2291 m, last erupted in 1977), Mount Tongariro (1978 m), and Mount Pihanga (1325 m). One would almost believe it was payback time compared with my last 'Ring of Fire' excursion in 1998 to the Cascades: no rain, sunny, and excellent visibility. The town of Taupo is situated on the south-eastern end of Lake Taupo. The basin in which the lake is contained are the remains of large calderas formed principally by the mega Oruanui eruption of 26500 years ago and subsequent eruptions including the last of 200 AD (see Figure 9, which shows the relative sizes of eruptions). The semi-circular bays of the northern shore of Lake Taupo are testament to these past eruptions. The Oruanui eruption is in the same league as Yellowstone. The cloud for the Taupo eruption of 200 AD represents 50 km³ of volcanic ash from pyroclastic flows producing ignimbrites, pumice,

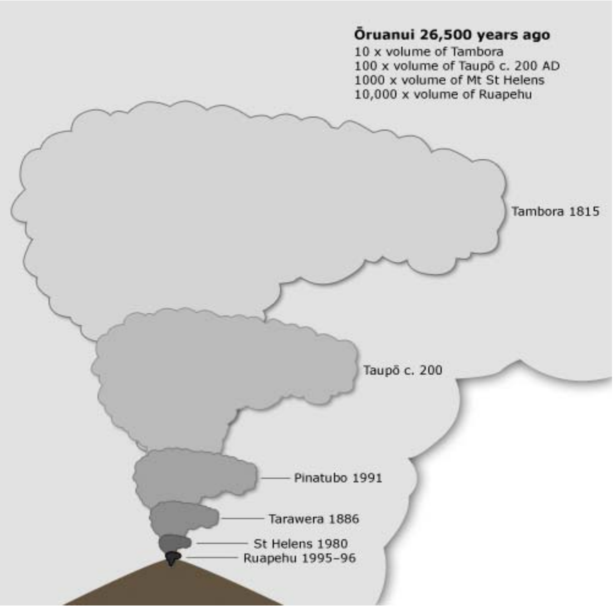

Figure 9 Taupo eruptions (Oruanui, 26 500 years ago and Taupo, 200 AD) relative to other well-known volcanoes. Mount Tarawera is in the Rotorua volcanic area.

and exploded rock. I only read afterwards in the book by Campbell & Hutching (2007) that one frequently can see carbonised wood (charcoal) fragments amongst the volcanic ash deposits in the Taupo to Napier road cuttings through the thick ignimbrite deposits from the 200 AD eruption of Taupo.

Sunday 12 September 2010

Peter Cox is sitting on an overdue time bomb. The magma chamber below the lake is filling with mantle rock and should have burst, estimated on average (since Oruanui) every 900 years. The last is 1800 years ago, so it could be that the volcanoes to the south are relieving pressures in Taupo's magma chamber. Not so according to the literature however. These volcanoes are the result of subduction taking place as the Pacific Plate moves beneath the Zealandia-Australia continental plate. The Taupo volcanic eruption is associated with a hot spot beneath relatively thinned crust stretching as a result of V-shaped rifting with the rift fault fanning out from the Ruapehu volcanoes toward the north-east representing the Taupo Volcanic Zone (TVZ) and also encompassing the Ruratoa volcanic field to the north and the very active volcanoes of the Bay of Plenty. We returned to the Volcanic Activity Centre on Sunday morning. A tour bus stood outside and there were quite a number of visitors. They looked very familiar; the IAEG post-congress tour! Like me they had to make do with the exhibits to appreciate the potential of the dramatic fine scenery of Taupo.

The final visit was a brief stop to look over the fence at the Wairakei geothermal power station not far from the previous stop. Wairakei Power Station uses steam extracted from the fluid produced in the steam field at this site to generate electricity. Initial investigation and exploratory wells in this field were undertaken in the 1950s. There have been more than 200 wells drilled and there are currently 60 wells in production. Wells up to 2000 m deep tap into zones of hot fluid, at temperatures of 230-260 °C. When the fluid reaches the surface it is separated at the well head into dry steam and hot water in a cyclone separator. Hot water is either collected or piped to secondary 'flash' separators where additional dry steam is produced at lower pressure or reduced to atmospheric pressure in well head silencers. The residual hot water is either piped to the Binary Power Plant at the power station, to re-injection wells on the steam field perimeter, or discharged to open drains. 1400 tonnes per hour of steam is produced in the field and transmitted to the power station through insulated pipelines varying in diameter from 300 to 1200 mm. Steam travels at about 200 km/h through the pipelines. Many of these steam wells have been in production since the power station was commissioned in 1958 generating renewable steam and sustainable energy.

By Sunday afternoon Noes' brother Tony with his wife Julie and daughter Michelle had descended from the ski resort on Mount Ruapehu to pick me up at Peter's house to continue after lunch to travel on to Hawke's Bay. Because of the bad weather they left behind their son Julian who still had to compete in poor visibility delayed ski events. We followed Route 5 from Taupo to Hawke's Bay which is also described as, similar to Highway 1, the Thermal Explorer Highway though more appropriately it could be called the Volcanic

Figure 10 Mount Te Mata lookout point.

Ash, Ignimbrite, or Pyroclastic Highway as much of it is in the maximum fallout zone of the Taupo explosions which have left thick deposits on the eastern half of the middle region of North Island. The drive to Hawke's Bay I remember through rolling countryside with now and then a steep road cut in the volcanic ash. On my previous visit in 1983 I drove through similar volcanic ash country more to the east of Ruratoa and Taupo through impressive ravines of almost vertical slopes of volcanic ash and ignimbrite up to 150 m high. That these deposits do not collapse I attribute to a combination of slight cementation caused by coalescence of the ash when still hot, the high roughness of the grains, and having a high negative pore water pressure (suction effects). One could easily scrape the materials into a loose pile using the pick of a geological hammer. Rather belatedly but timed right for the coast the weather cleared when we drove into Napier, the principal seaside resort on Hawke's Bay. Tony parked his car along the esplanade and we went to a bar for a beer. The premises had a glass floor (seems to be fashionable in New Zealand) in which you could look into a cellar room containing a display of a bar having pirates and witches as patrons. This caught the attention first of Michelle. Could this allude to skulduggery lurking much deeper below ground level? We may still be in Taupo's fallout zone but we were now in a major fault collision zone of the Pacific Plate and the Zealandia-Australian Plate with a twist. It is little wonder that hidden mischief lurks beneath the alluvial gravels of Hawke's Bay; the blind Poukawa fault, unknown to exist before 1931. In Campbell & Hutching (2007) the events that occurred in 1931 are described under the heading 'our worst earthquake'. The initial epicentre was at Napier, followed by aftershocks south-west towards Hastings and north-east towards Wairoa along the then 'hidden' Poukawa Fault (the Darfield Fault which caused the previous weekend's earthquake near Christchurch was also a hidden, unknown fault before the event). We then continued to Huamohana south-east of Napier along the shore of Hawke's Bay where nearby Tony and Julie have their orchards farm consisting principally of apple orchards and sizeable plots of boysenberries and raspberries. Julie was straight on the phone to organise an annual early spring spraying of the apple trees before they would flower. I could at last inspect their homestead which early descriptions sent by Tony to Holland sound as if made from soil; a self-built structure of moulded tamped/ rammed soil cement mixture walls. These support the wooden top structure floor beams, floor, and roof. My concern was if such a structure was sufficiently earthquake resistant to allow escape from injury. Even though it was summer when the 1931 earthquake occurred it appears most of the damage was caused by fires which suggests people then were using wood or coal burning stoves which could topple and thus trigger fires.

Monday 13 September 2010

On Monday, Julie showed me round the area as Tony had to survey someone's property boundaries (he is a chartered surveyor) and later supervise the spraying in the orchard. Julie took me round to some vineyards for wine tasting and choosing a bottle for dinner. The next visit was the Mount Te Mata lookout point over southern Hawke's Bay area (Figure 10). On our return to the farm we stopped at a book store at Havelock North, the second of the three main towns of Hawke's Bay Province, all situated in the south-west corner of Hawke's Bay. The third, Hastings, which is the provincial capital, is situated just to the north-west. There, finally, I found the book which was not in stock at New Zealand's main bookstore chain in Auckland (*In Search of Ancient New Zealand*, Campbell & Hutching (2007)). On the horizon lies the north shore of Hawke's Bay. Beyond is the province of Gisborne I visited on my first tour through New Zealand in 1983. I visited then my cousin Renée and her husband Geoff and despite a drive around Gisborne and its coast, little did I know the area I was on was yet another allochthon: the East Coast Allochthon. I do not know if I knew then much about an allochthon or abduction despite having been involved in Oman on a major rock slope project situated in part of a large abducted slither of the Indian Ocean Plate over the Arabian Plate (Maurenbrecher & James, 2012). The view from Te Mata lookout is a suitable end to part 1 of my post-congress excursion in New Zealand. I have spent more time writing and researching this tour behind my desk then on the actual tour; at Te Mata I had just five days to go before I had to catch my return flight from Auckland to Holland. The remainder of the journey (which will be described in part 2 in a future Newsletter) was by bus from Hastings to visit my cousin Renée and her family who now live in Wellington, followed by a short hop with an Air New Zealand shuttle flight to Nelson to visit my next cousin Paul (elder brother of Renée) at Motueka, before returning to Auckland on a flight from Nelson to meet up again with Noes and Jack. They organised one more excursion for me, to the Manukau peninsula between Manukau Harbour (Auckland's western harbour) and the Tasman Sea. In Holland the steel mills are on dunes at IJmuiden, at Auckland the steel mills derive their ore from dunes along the shores of the peninsula. I intend to end part 2 on a correspondence excursion to Christchurch. In 1983 I had paid a visit to my cousin Alex (brother of Renée and Paul) living in Christchurch. Articles and papers are still being published on the, by now, 2.5 years of earthquake activity since the first earthquake occurred that early Saturday morning of 4 September 2010. I met Ann Williams, convener of the 11th IAEG Congress and who was in 2012 at the ISL/NASL 2012 symposium in Banff (Canada) where she presented a paper on Christchurch earthquake induced rock falls (Williams, Gibson & Gilmer, 2012) as well as participating in the IAEG meeting of country representatives. Though she works in Auckland she said the earthquakes have kept the whole engineering geology community almost totally occupied the last two years. I am compiling a bibliography on the Christchurch quakes and by the time part 2 has been written I may have obtained further information on the experiences of Ann, my cousin Alex, and Charlie Price (Charlie I had met both at a London meeting commemorating 100 years of engineering geology at Imperial College and then later only the first and last of the congress days as he spent the rest of the time at Christchurch dealing with the situation there). His brief appearance on the Friday he spent trying to organise an immediate return flight to Christchurch because his wife was being evicted from their damaged house! I read in a special issue of the Proceedings of the ICE (Hudson, Cormie, Tufton & Inglis, 2012) that 187 people were killed in the February 2011 earthquake in Christchurch.

Epilogue: social functions of the 11th IAEG Congress and going from the 11th to the 12th IAEG Congress

I mentioned about the social functions of the 11th Congress in the last edition of the Ingeokring Newsletter (*Mining & Dredging* edition). We visited Auckland's town hall for the mayor's reception. Almost no coincidence after my presentation on engineering geology and wine in the TU Delft-ITC fieldwork area in Catalonia (*Wines and winelands: Engineering geology fieldwork in Hispania Cisterior*, P.M. Maurenbrecher, D.M. Ngan-Tillard & B. Aline Concha Dimas) we could enjoy a wine tasting experience of wines from the Auckland region, and a buffet/barbecue style conference dinner with even more wine tasting.

The next IAEG Congress will be held in Turin, Italy, in 2014. That should be quite a political venue, by now, as a result of the L'Aquila verdict which has found seismologists and a civil servant guilty of manslaughter. I remember participating in a conference on earthquakes in Crete (Greece), where I presented a paper on damage to buildings of the village of Herkenbosch in the south-east of the Netherlands as a result of the Roermond earthquake in 1992. I was told off by an Italian delegate that I could not use the MM scale (Modified Mercalli scale) to assess the damage of individual buildings. The purpose of the TU Delft research was to assess the damage of individual houses using this scale. I promised her (the Italian delegate) that I would adopt a modified MM scale and as yet see whether the areal distribution of damage had any correlation to the underlying geology and/or the architecture of the buildings. In this way one could get some idea as to the vulnerability of buildings to earthquakes. I still think we (Ard den Outer, David Price, and me) were using the right paradigm. The likelihood of an earthquake should not have been the issue at L'Aquila but what should have been said was: 'if you are in a building which is likely to collapse: move out and only move back in if it has been made safe enough to allow you to escape unhurt should an earthquake occur'. That question was not put and hence the reply was not given.

I am convinced that the relevant authorities purposefully posed the wrong question as the question I assume to be relevant they could have answered too! That question should have been put many times in the past as Italian towns suffer devastating damage each time an earthquake occurs, resulting in casualties, hardship, and costly restoration. The Italian judicial machine, also an authority, to say the least, is by far the more despicable than the trap set by the disaster authorities (politicians) to try and placate the anxious citizens of L'Aquila and then punish them for doing this. It is the question I posed myself with regard to Julie and Tony's rammed-earth house. The answer will be in part 2 of this instalment. By the time I write the second part I should know if the 1931 Hawke's Bay earthquake is New Zealand's worst. At 22 February 2011, just less than six months later than the Darfield earthquake of 4 September 2010 with a magnitude of 7.1 on the Richter scale, a much more violent quake occurred in Christchurch, known as the Lyttelton earthquake. This earthquake had an intensity of IX on the MM scale (violent) and killed 181 people (Gibbons, 2012) or 187 people (Hudson et al., 2012) despite measuring 'only' 6.3 on the Richter scale. Probably with its hypocenter being much shallower it produced a much higher PGA (Peak Ground Acceleration) of 2.2 g compared to Darfield's 1.26 g.

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Lobith
St. Pieter
Water Level (m)
Flooding

Site characterisation in karst and pseudo-karst

Lynn Yuhr, P.G. & Richard Benson, P.G.

Abstract

There are always unknowns associated with a 'site characterisation' and never enough time or money to resolve them. However, the knowledge, tools, and experience to solve the problem of locating, mapping, and characterising geological anomalies and thereby reducing geological uncertainties are readily available. Most geotechnical related accidents, disasters, and failures are not 'acts of God'. If one conducts a thorough and competent investigation, the underlying causes are always identified whether human or natural causes, and in almost every instance the event was recognisable, predictable, and preventable if only good professional judgment had been used. The 'act of God' defence is no longer considered tenable for most geotechnical work impacted by natural disaster (Shuirman & Slosson, 1992). This is also true for environmental work (Freeze & Cherry, 1989). When we have a sufficiently accurate understanding of site conditions, predicting site performance from an engineering and/or hydrogeological point of view will be reasonably straightforward and we can go forward to the next step of construction or remediation with confidence. The authors are a father and daughter team who have worked together since 1978 and represent combined hands-on experience of more than 80 years. They have specialised in site characterisations in karst and pseudo-karst terraines and have worked as project lead or in supporting roles. Their experience is the basis of a new book titled 'Site Characterization in Karst and Pseudo-Karst Terraines: Practical Strategies and Technology for Practicing Engineers, Hydrologists and Geologists' to be published by Springer Publishing in 2013. This book will elaborate on their common sense approach using data examples and case histories from their personal experience.

Introduction

Site characterisation is the process of understanding the geological framework, engineering and hydrological properties, and, if present, the contaminant distribution of a site. It is the cornerstone of all geotechnical and environmental projects. The process is quite similar for evaluating foundations of engineered structures or environmental sites, whether they are large or small projects, varying only by the level of effort. Besides the various technical and non-technical pitfalls that can limit proper site characterisation there are the variable geological regimes in which we work. Site characterisation in areas of karst conditions offers an even more unique and complex setting in which to work. However, the strategy and technologies do exist to carry out an effective and accurate site characterisation. Karst is defined as an array of landforms resulting from the dissolution of underlying soluble rock. The natural dissolution process is a slow one, about 1 inch/1000 years (25 mm/1000 years) and as such is not generally a concern to most engineering or environmental projects. What is of concern are the complex karst conditions which may already exist in the subsurface. The underlying dissolved features may include complex epikarst, heavily weathered zones at the top of rock, dissolution-enlarged joints/bedding planes, cavities, and cave systems, to name just a few. These features are often highly variable within the subsurface and often have no surface expression until subsidence or a collapse feature occurs. There are many other man-made features that result in similar subsidence and collapse. These are referred to as pseudo-karst. Broken sewer and water lines are the most common causes of pseudo-karst. Subsidence over abandoned mines, tunnels, pipelines, or due to groundwater or fluid withdrawal are other types of pseudo-karst.

The problem

The single largest uncertainty in determining the success of site characterisation efforts results from an inability to locate, describe, and quantify the natural geological and hydrological heterogeneity. Heterogeneity is a natural result of the processes that create and modify the geological setting and are sometimes further modified by man's activities. In order to minimise these uncertainties, geologists and engineers are required to assemble and conduct interpretations of geological data. Such data is never complete; hence, different levels of uncertainty arise in both data as assembled and in their interpretations. There is no single, universally applicable philosophy, strategy, method, group of methods, or software that can be used to achieve a complete and accurate site characterisation for all geological site conditions. While a given method or group of methods may be successful in one situation, they may not be in another. There is no silver bullet and likely never will be. So what do we do?

An approach

Our experience has shown that a common sense, broad approach using readily available technologies and sampling methods with a solid team of experts is the best one. This sounds simple and obvious and is certainly not new. Since the early 1900s Terzaghi's observational method and general approach has stressed the need for a common sense get-in-the-field understanding along with critical analysis of geological conditions (Goodman, 1999). This approach is still applicable and important to the site characterisation process today. The starting point for a site characterisation should be based upon what geological conditions you might expect at a particular site and then be prepared for surprises. Develop an understanding of the type, size, and possible variations in the geological conditions. Do your homework before you develop a work plan.

This may include:

- Critical review of regional, local, and site specific geological and hydrological literature and reports.
- On-site observations.
- Aerial photo interpretation.
- Development of an initial conceptual model of site conditions.

A work plan should then be developed which utilises a diversified set of observations, measurements, and sampling, so that data from more than one source supports the interpretation and the conceptual model. There are many tools available to help us characterise a site. We must select an approach using multiple methodologies which are appropriate to the geological setting and to the scale of observation or measurements being made. In all cases, the technical approach to field investigation must be biased to maximise the density and representativeness of spatial data. This may include:

- The use of non-invasive methods such as surface geophysics and borehole geophysics in any existing boreholes, piezometers, or wells.
- The use of minimally invasive methods such as push technology and CPT data.
- The use of invasive methods such as trenching and drilling.
- The use of borehole geophysics in new boreholes, piezometers, or wells.
- A variety of measurements of hydrological and engineering properties appropriate to the project needs.

While this list is not intended to be complete, it provides the basis for a reasonable starting point. The sequence is often modified to fit the project needs and fill gaps in the site specific data. In most site characterisation efforts, there may be two or more iterations of the field work. As the site characterisation process proceeds, one should keep in mind those key aspects of dealing with the assessment of the individual data sets. Each data set should meet the requirement of being appropriate to the site, provide adequate coverage (spatial or temporal) and be accurate. From this point the data can be integrated and used to test the initial conceptual model of site conditions. This is an iterative process, one of building and verifying the conceptual model with each new piece of information. The results of this process may suggest more detail is needed in a particular area or to address a particular area of concern. Most critical to success are the senior experienced hands-on professionals who are sensitive to the issues of geological uncertainty and possess the skill and persistence to pursue them. In addition, the project team needs to know what their technical strengths and weaknesses are. Fill in the gaps and build a solid team specific to the geological and hydrological areas of interest. Maintain continuity in the team throughout the project so that information and understanding is not lost during the process.

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The spatial distribution of arsenic contamination in fluvial sediment of the Ganges River: case study from Bihar, India

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Abstract

Shallow aquifers in the Ganges River channel belt (Bihar, India) have high and spatially variable concentrations of arsenic contamination. The arsenic is of geogenic origin. Hydrated iron-arsenic-oxide coatings on quartz and clay minerals occur in the Ganges River deposits. The arsenic is subsequently released to the groundwater in a redox-controlled environment whereby microbial respiration triggers the reductive dissolution of iron and arsenic. Recent data acquisition in Holocene fluvial deposits of the Ganges River suggests that high arsenic concentrations are associated with sandy point bars in the inner bends of abandoned meandering river bends. Analysis of two 50 m deep cored boreholes shows the lithofacies heterogeneity in the Holocene Ganges River deposits. Stacked point bar deposits and associated clay plugs occur in the first 28 m of the succession. From 28-50 m depth the gravel and coarse grained braided river deposits are the characteristic lithofacies type. In addition, a high resolution time domain electromagnetic survey (TemFast) was performed to visualise the spatial distribution of the fluvial deposits in the shallow subsurface. In both boreholes an anomalously high arsenic concentration (up to 800 ppb) occurs at the boundary between both lithofacies types. Further TemFast data acquisition and analysis should result in the construction of a static 3D geological model which subsequently will be used for flow calculations.

Introduction

Arsenic-contaminated groundwater causes a widespread and serious health risk affecting millions of people worldwide. In the Ganges-Brahmaputra Delta in West Bengal and Bangladesh the contamination has been recognised already twenty years ago (Acharyya, Lahiri, Raymahashay & Bhowmik, 2000) and mitigation projects such as filtration, chemical treatment, and reverse osmosis are currently implemented. However, it was only discovered in 2002 that also further upstream in the Middle Ganges Plain (MGP) of the Ganges Basin in the states of Uttar Pradesh (UP) and Bihar in north-east India, groundwater in Holocene Ganges River deposits is highly arsenic-contaminated (Chakraborti et al., 2003). Arsenic concentrations in Bihar reach 1800 μg/l, far in excess of the World Health Organization guidelines for safe drinking water of 10 μg/l (WHO, 1993). An extensive governmental arsenic inventory campaign in Bihar aims to map the extent and magnitude of the contamination (Saha, 2009). To date, while the inventory is not complete, it is estimated that 25% of the 103.8 million population of Bihar is exposed on a daily basis to arsenic-contaminated drinking and irrigation water.

The arsenic contamination has a geogenic origin. Shah (2010) described pyrite-bearing shale from the Proterozoic Vindhyan Range, arsenic-copper mineralisation in the Bundelkhand Granite in UP, and the gold belt of the Son Valley as potential sources of arsenic. Upon weathering, the arsenic is transported in solid phase by rivers from the provenance to the MGP. Mineralogical studies indicate that arsenic in Holocene sediments of the MGP is associated with hydrated iron-oxide coatings on quartz and clay minerals (Shah, 2008). The arsenic is subsequently released to the groundwater in a redox-controlled environment (Singh et al., 2010). Abundance of organic carbon is a prerequisite for the release of arsenic. Microbial respiration triggers the reductive dissolution of iron and arsenic.

Water wells tapping from Holocene deposits in the affected areas of UP and Bihar show a large horizontal variability in arsenic concentration on scales that extend between tens of meters to kilometres, and in a vertical sense the largest concentrations are found in the upper 50 m of the aquifer domain of Holocene Ganges River deposits (Shah, 2008). Sediments have low arsenic concentrations in areas that are well-flushed by groundwater flow due to a high hydraulic head (Shah, 2010), and concentrations increase in a poorly-flushed subsurface environment. Recent studies by, among others, Shah (2008, 2010) and Saha (2009) indicate a relationship between spatial variability of arsenic concentration, and stratigraphy and sediment type. In this paper we elaborate on this rela-

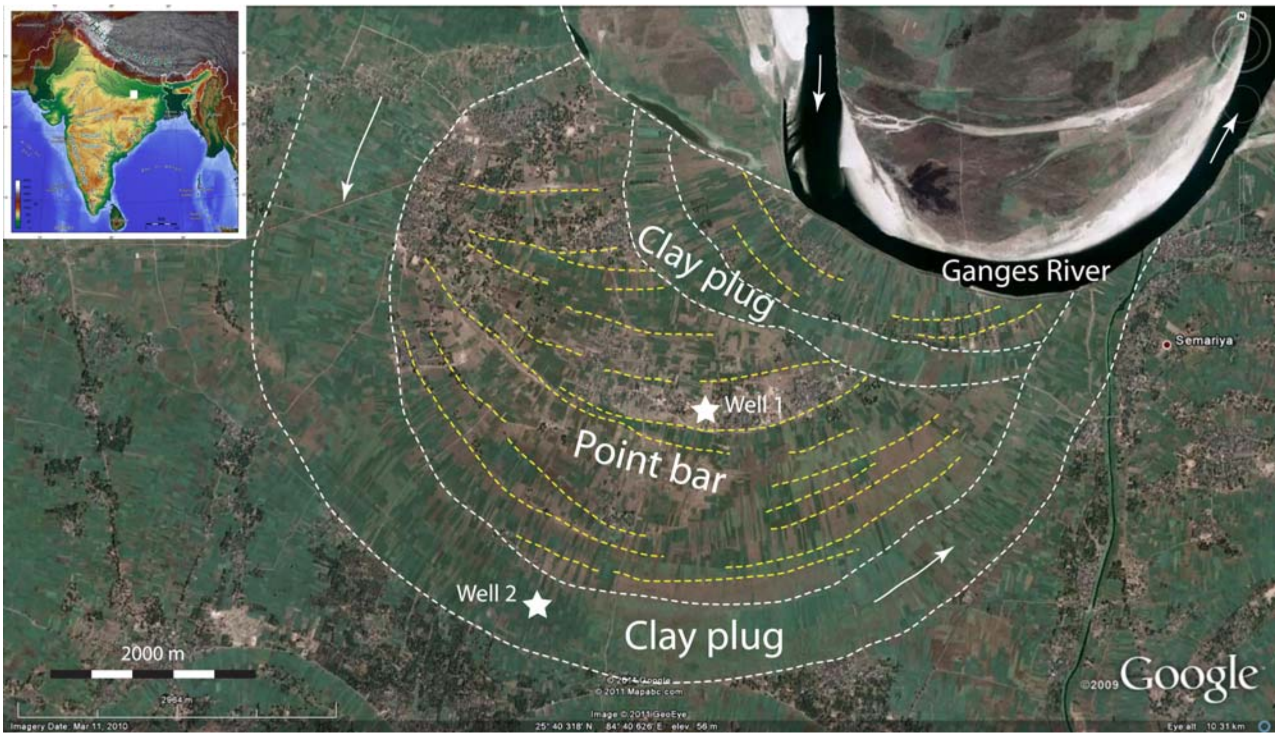

Figure 1 Google Earth image of the study area, with the interpreted morphology of the permeable point bar surrounded on all sides by impermeable oxbow lake (or: clay plug) sediment. White dotted lines mark the outlines of filled-in oxbow lakes. Yellow dotted lines highlight the ridge-and-swale morphology on the point bar surface. Green colours in the Google Earth image represent agriculture plots (i.e., the clay plugs and clay-rich point bar swales); the grey and brown colours are the sandy ridges of the point bar. Villages are located on the higher parts of the point bar (elevation up to 8 m above the surrounding floodplain) for protection against the yearly monsoonal floods. The main source of drinking water comes from multiple, shallow hand pump wells which tap from the permeable point bar sand. Insert: map of India with location of study area (white box).

tionship by highlighting the role of the spatial variability of fluvial lithofacies in the propagation and trapping of the arsenic-contaminated water flux in the subsurface. Focus is on the stratigraphic trapping of arsenic-contaminated water in permeable point bar sediment.

Data and methods

The study is based on the analysis of borehole data and an electromagnetic survey of Holocene Ganges River deposits in Bihar. Two 50 m deep wells were drilled in a fluvial point bar and the fringing, sediment filled abandoned river bend, or oxbow lake (Figure 1), using percussion drilling with piston samples collected in 60 cm long PVC core tubes. Core recovery was about 80% and the cores were accurately depth constrained. In addition, gamma-ray and deep resistivity logs were run in both boreholes. Further, a transient electromagnetic (TEM) survey with a TEM-FAST 48 HPC device was performed in the area between the two wells with the aim to obtain a detailed depth image of the point bar lithofacies distribution in the shallow subsurface. A 12.5 x 12.5 m loop size was used for the TEM survey and a penetration of 50 m was achieved. A 3D time-resistivity image was constructed by repeating the measurements in a horizontal grid. Time-to-depth conversion was obtained by validation of the time section with the resistivity logs in the adjacent boreholes.

Results

Core analysis reveals that the stratigraphic succession in both wells can be subdivided into two sequences with a sharp break at ca. 28 m depth (Figure 2). The lower sequence consists of thinly to thickly bedded gravel layers and coarse grained gravelly sand. Permeability is very high, to the point that the drilling mud (bentonite) completely invaded the core. This sequence is interpreted as formed by shallow braided rivers. The mineralogy suggests that the source area of the rivers was to the south, on the stable Indian Craton. The upper sequence consists of medium to fine grained, laminated sand, silt, and clayey organic matter, organised in three fining upward units with a thickness of 5 to 12 m (Figure 2, Well 01). The units formed by vertical stacking of successive generations of Ganges River point bar sediment. The top of the sequence in Well 02 consists of a 12 m thick succes-

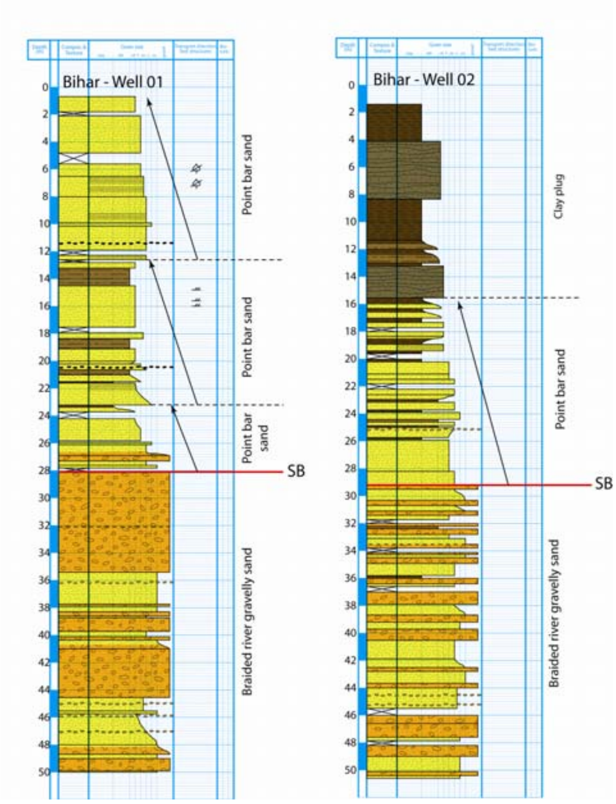

Figure 2 Lithofacies log of the two cored wells. Well spacing is 2.28 km. See Figure 1 for well locations.

sion of silt and black clay, rich in organic carbon. The succession formed as clay plug fill of the oxbow lake that encompasses the point bar sand (Figure 1). The 12 m thickness of the point bar units and clay plug equals the depth of the present day Ganges River just north of the well locations. The sharp break between both sequences is interpreted as a sequence boundary which marks the southward shift of the Ganges River belt to this area, with truncation of the upper part of the underlying braided river deposits.

The sequence boundary shows up in the TEM survey as a sharp change in resistivity, from high resistivity above to low resistivity below. The inclined point bar to clay plug interface has a marked resistivity contrast. Lateral lithofacies changes are detected by gradual changes in resistivity; however, the continuation of the ridge-and-swale topography in the subsurface, which consists of inclined alternating sand and clay layers, is beyond the resolution of the TEM method.

Arsenic concentration measurements in the boreholes and hand pump wells show high but variable concentrations in the stacked point bar sequence. The sequence boundary is characterised by a sharp peak in arsenic concentration, whereas in the lower, braided river sequence the concentrations drop. It is interpreted that a free-moving groundwater flux is present in the highly permeable gravel and gravelly sand below the sequence boundary. The flux effectively flushes the permeable sediment, hence the low arsenic concentration. Arsenic-enriched water that percolates downward from the point bar sand to the sequence boundary accumulates at the top of the free moving groundwater flux; hence the peak in arsenic concentration. The assumption has to be corroborated by further, detailed measurements and tracer tests.

Conclusions

Arsenic contamination in the shallow aquifer domain of Ganges River deposits in the state of Bihar (India) is characterised by a large spatial variability of concentration levels. The arsenic is of geogenic origin and its occurrence in groundwater is the result of dissolution of Fe-As oxides in a redox-controlled environment. The permeability contrast between a low-permeable clay plug and the juxtaposed high-permeable point bar sand creates a stratigraphic trap in the latter in which groundwater with dissolved arsenic accumulates. Core analysis of two 50 m deep boreholes in a point bar and juxtaposed clay plug show superposition of two fluvial sequences separated by a sequence boundary at 28 m depth. The lower sequence consists of stacked, high-permeable braided river gravel and coarse grained gravelly sand; the upper sequence is made up of 5-12 m thick stacked point bar units and associated organic matter-rich clay plug sediment. The spatial continuity of the sequence boundary and the overall shape of the permeable fluvial deposits are observed as resistivity contrasts in a time-domain electromagnetic survey. Measured arsenic concentrations in the boreholes and hand pump wells show high but variable levels in the stacked point bar sequence and low levels in the underlying braided river sequence. A sharp peak in arsenic concentration at the sequence boundary is interpreted by the permeability contrast between the two fluvial sequences.

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