DESIGNING AND BUILDING WITH

COMPRESSED EARTH

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CONTENTS

RESEARCH

DESIGN

RESEARCH

1. INTRODUCTION

"It is a commonly reported fact that around half of all global CO_2 emissions can be attributed to the construction, and more importantly the operation, of buildings." (Hall and Swaney, Stabilised Rammed Earth (SRE) Wall Construction 2005) Global consequences caused by architecture of industrialization and fossil fuel era enforces reconsideration of dominant construction methods and materials with an increasing intensity. More and more often this brings to a resurrection of traditional building practice.

1.1. Rammed Earth – a Definitive Explanation

Rammed earth is longstanding construction technique where natural aggregates – gravel, sand, silt and clay - are compacted into a formwork creating monolith building structure. Among other forms of unbaked earthen construction, such as mud-brick, molded earth and compressed earth blocks, rammed earth is one of the most widespread building forms on the history of our planet. Estimations indicate that nowadays more than one third of the worlds population lives in buildings made of earth. (Rael 2009)

1.2. Historical Background

Earth as a building material has been known for centuries. Historical evidences prove that mud brick as the earliest earth construction method was invented in Russian Turkestan around 8000 – 6000 BC. (Minke 2009) Earth building tradition is represented by many remarkable artefacts: Ziggurat at Ur (4000 BC), the Temple of Ramses II at Gourna, Egypt (1200 BC, fig. 1), the Great wall of China (500 BC), the Sun Pyramid in Teotihuacan, Mexico (300 – 900 AD). Roman architect Vitruvius in his "Ten Books of Architecture" describes various forms of mud brick and their extensive application in city walls, private and public buildings and even royal palaces of the antiquity. (Lee and Ball 2009)
The first application of rammed earth construction technique dates back to 5000 BC when in Assyria and China it was used in foundation and wall construction. Soon after it spread out along dry climatic zones of Africa, Asia and Europe. Initially the formwork was made from wood and ramming done by hand with a ramming pole, as it is still the practice in developing countries with cheap labor. Numerous historical rammed earth buildings in South America, Himalayan regions and Central Europe, but above all entire villages in North Africa and the Middle East supplement the list of worlds architecture treasures. (Auroville Earth Institute 2011)
Nowadays both the design and construction methodology as well as rammed earth building

Fig. 1. Temple of Ramses II at Gourna, Egypt

Fig. 2.-5. Natural rammed earth color and texture variations

distribution areal have undergone notable transformations. Breakthroughs in materials chemical stabilization, structural reinforcement, moisture control, thermal insulation and lots of other aspects have made it technically available to nearly any geographic conditions.

1.3. Rammed Earth Qualities

Application of earth as a building material has numerous advantages.

1.3.1. Sustainability

According to basic building material environmental classification by NIBE, various forms of earthen materials has the lowest environmental cost (fig. 8). Comparing rammed earth to alternative building materials as concrete and brick masonry, its embodied energy is significantly lower (fig. 9).

1.3.2. Microclimate Regulation

Earth has excellent abilities to maintain stabile interior air humidity level and thermal mass potential superior to that of most alternative building materials. More of this is analyzed in chapter 3 and 4.

1.3.3. Soind Insulation

Rammed earth is a good sound insulator. According to the mass law of solid masonry walls, the weighted sound reduction index can be calculated using formula:

$$Rw = 21.65\log 10m - 2.3$$

where *'m'* is the surface mass of the wall (kg/m2). A typical stabilized rammed earth wall with a density of 2100 kg/m3 and thickness of 300 mm has a weighted sound reduction index equal to 58.3 dB that fully satisfies the typical requirements of building codes. (Hall and Swaney, Stabilised Rammed Earth (SRE) Wall Construction 2005) Being a dense and porous material, earth is used as sound insulative material in facilities with increased sound intensity as concert halls and recording studios (fig. 10).

In addition, rammed earth has excellent sound reverberation characteristics. "It does not generate the harsh echoes characteristic of many conventional wall materials." (Downton 2010)

1.3.4. Aesthetics

Visually rammed earth is "true" building material. Its color represents soil characteristics of particular geographical region varying from red to bright orange, yellowish, grey and fawn-colored (fig. 2-5). The horizontal lines on the surface of rammed earth wall reveals its construction method.

Earth can also be adjusted to wide spectrum of visual requirements. A number of color pigments can be added as well as surface texturing may become a field of creative expression (fig. 6, 7).

1.4. Research Problem

Despite of numerous qualities and a potential in addressing sustainability problems of the 21st century architecture, application of rammed earth in contemporary design practice is uncommon. Parallel to subjective issues such as stereotypes among architects and engineers of earth building as existential form of architecture characteristic to developing countries, claims of insufficient scientifically proven information, lack of professional experience in designing and building with earth, there exist several objective aspects (research sub-problems) that hinder rammed earth application nowadays:

- inconsistent materials nature;
- controversial structural properties;
- moisture sensitivity;
- poor thermal performance;
- possible shrinkage and cracking;
- construction may be slow and expensive.

1.5. Research Objective and Structure

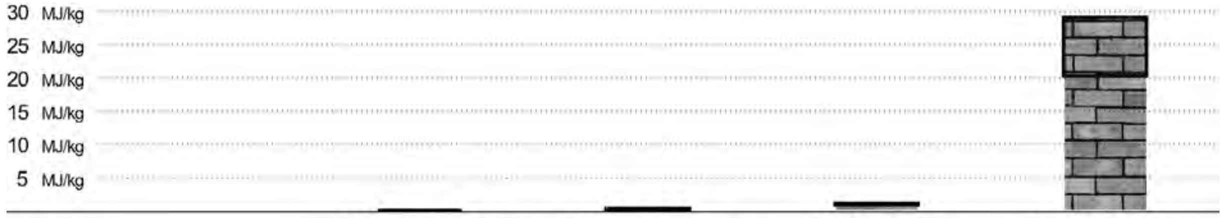
The objective of the research is to provide an overview of rammed earth materialization, design and construction issues with an emphasis on its downsides and possible ways to overcome them. Each of six mentioned sub-problems is analyzed through theoretical perspective and practical examples. Results are interpreted and further developed in context of Scheveningen, the Netherlands in order to gain conclusions for the design proposal to be developed in the further study process.

Finally, it is not the authors intention to prove the superiority of particular building method rather than understand its natural character in context of 21st century design requirements.

Fig. 6, 7. Artificial texturing and color pigments

TOEPASSINGEN	MILIEUKOSTEN (€/m²)
Binnenspouwblad	
leemstenen	2,14
kalkzandsteenelementen	3,20
kalkzandsteenmetselwerk	3,65
beton (0% puingranulaat, gewapend)	8,10
baksteenmetselwerk	17,42
Buitenspouwblad	
logs (gelamineerd, duurzame bosbouw)	1,86
leemsteenmetselwerk	2,13
betonsteenmetselwerk	4,57
kalkzandsteenmetselwerk	4,87
baksteenmetselwerk	17,42
Pleisterwerk (12 mm)	
leemstuc	0,49
cement	1,96
kalkstuc	3,23
rogips	5,76
natuurgips	5,86

Fig. 8. Environmental cost of various building materials (in Dutch)



	Rammed earth	Rammed earth	Concrete	Brick masonry
	unstabilized	stabilized (4 -12% cement)	portland cement	standard
Embodied energy, MJ/kg	~ 0.02	0.14 - 0.42	1 - 1.3	20.5 - 29.3

Fig. 9. Embodied energy of rammed earth compared to concrete and brick

Fig. 10. Professional sound recording studio in Santa Fe, New Mexico with adobe (mud brick) walls

2. SOIL COMPOSITION

Unlike most of manufactured building materials, soil as natural resource is of inconsistent character – when excavated locally, its composition and properties may vary dramatically from one building site to another. Therefore, usually an additional effort is needed to transform soil excavated in the building site into a consistent building material.

2.1. Soil and its Natural Availability

Soil is a cover of the Earths crust. It is the result of transformation of the underlying rock under the influence of a range of physical, chemical and biological processes related to biological and climatic conditions and to animal and plant life. (Auroville Earth Institute 2011) Soil is made up from various finely ground rock particles (sand, silt, clay) and according to their proportion it is common to classify different soil types (fig. 11) that vary both geographically from one region to another as well as in depth of Earths crust (soil horizons; fig. 12). Variable are also properties of individual soil components. While the shape of sand and silt may vary from sharp edged to rounded (fig. 13, 14), clay type depends on its molecular structure.

2.2. Soil for Rammed Earth Application

Earth construction principle in micro-level is based on compacting soil particles of various dimensions in a dense, homogenous mixture, thus largely similar to concrete. Classical understanding of rammed earth composition involves 4 components: gravel, sand, silt and clay with a grain size 2 – 20mm, 0.06 – 2mm, 0.002 – 0.06mm and 0-0.002mm respectively. When the first three can be considered as fillers, clay acts as a binder.

In scientific world various claims have been made for the optimum rammed earth composition. Researchers, however, agree on upper and lower limits for each of the components (fig. 15) (Maniatidis and Walker 2003).

2.3. Methods for Soil Improvement

In rammed earth building practice soil preparation by determining and improving its composition and properties is the primary step to be complete and may include following procedures:

2.3.1. Soil Analysis

Soil patterns are taken from areas of the building site where excavations are intended to be done, and analyzed in terms of homogeneity, grain size distribution, moisture content etc. Rough analysis may be performed manually (sedimentation, ball dropping, ribbon tests) though precise results can only be determined in laboratory conditions. Most often results indicate imperfections and soil

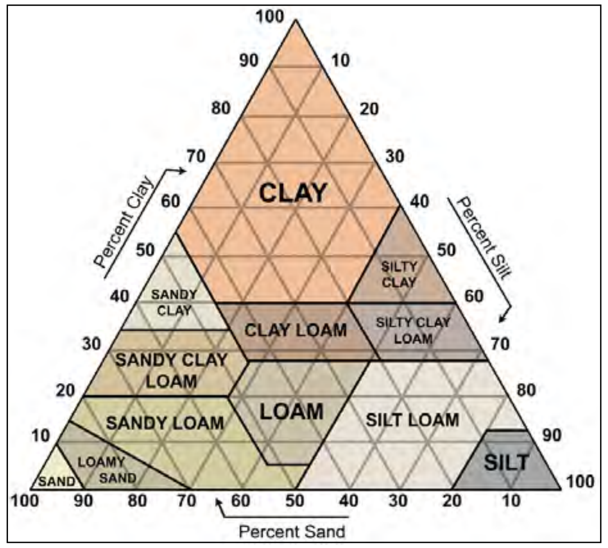


Fig. 11. Soil type pyramid

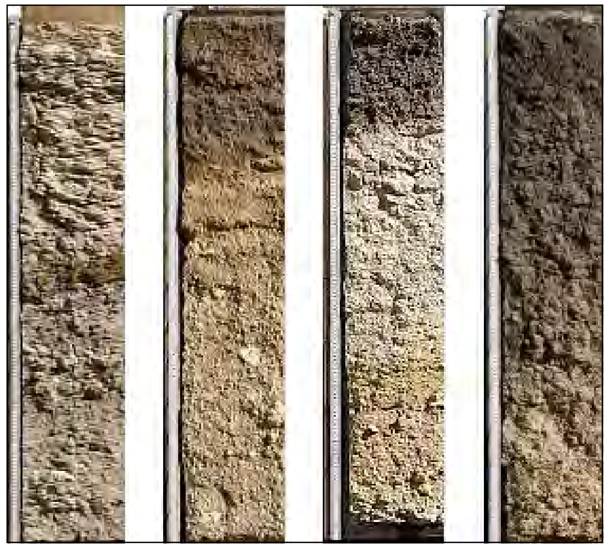


Fig. 12. Soil horizons for various geographic locations

Fig. 13. Clay sand

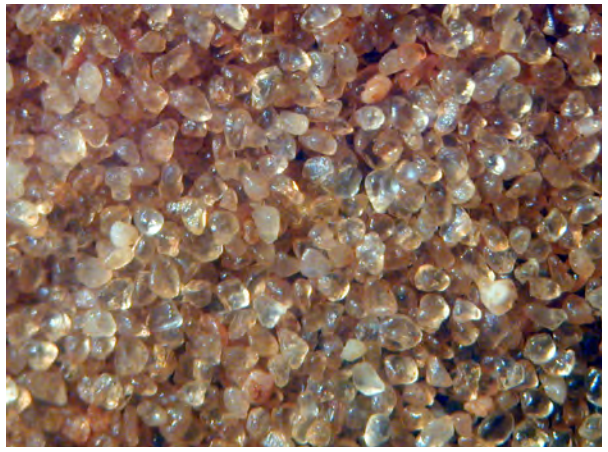


Fig. 14. Dune sand

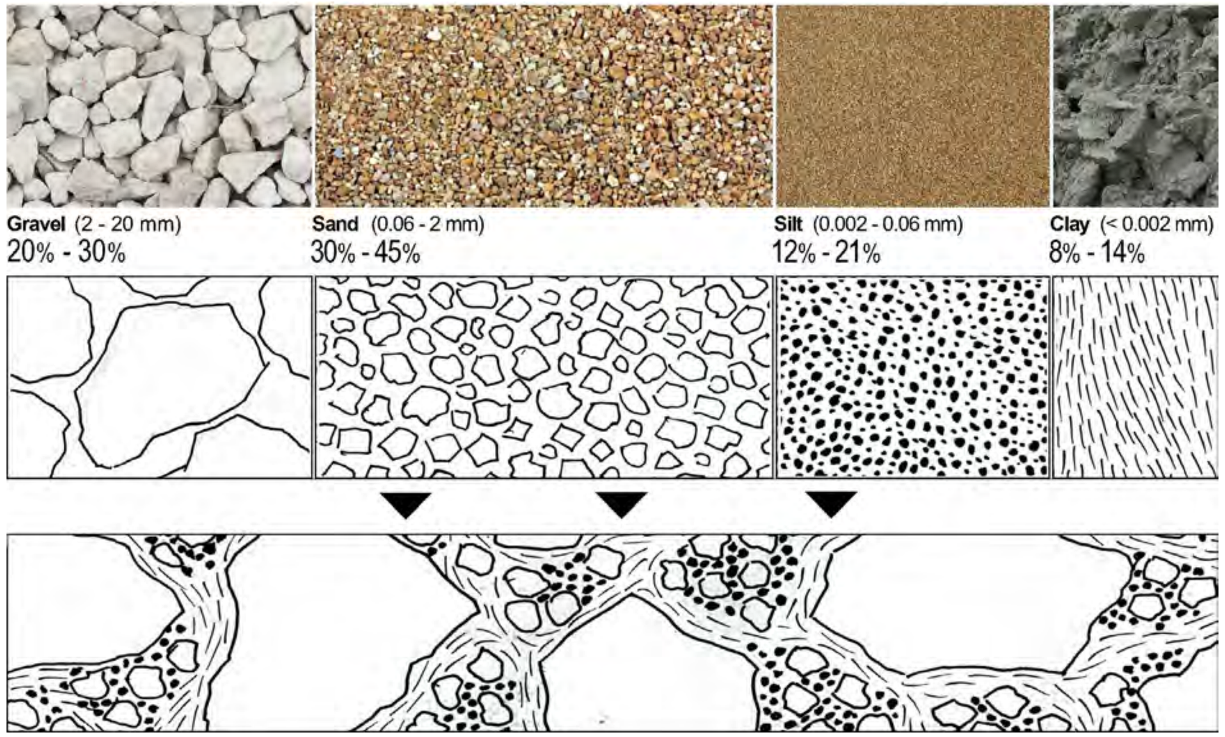


Fig. 15. Proportions of soil components for rammed earth application (top), their structure (middle) and role in final product (bottom)

after excavation must be improved by screening, crushing, mixing, watering/drying or stabilizing.

2.3.2. Screening
Unwanted particles (usually rocks larger than 20mm) are separated from other aggregates by sieving. Nowadays this may be done with advanced movable tools. The most common are vibrating screen (fig. 16) where layers of slightly inclined metal sieves topped one above another may simultaneously separate various aggregate fractions by mechanic vibration, and trommel drum screen (fig. 17) where separation is done by rotating sieve of cylindrical shape.

2.3.3. Crushing
In occasions when excavated soil contains large cohesive aggregations (sand clods, clay clusters) they are fragmented to the level of initial particles to ensure materials looseness. This can be done by a spectrum of various crushers (fig. 18, 19). Most advanced of them apart from soft materials allow crushing of rocks, as well as combine the function of screening.

2.3.4. Mixing
Soil homogeneity is crucial factor determining compaction level and thus materials mechanic properties. Especially when soil excavated on the site is to be supplemented with missing components transported from a remote source, precise grading and mixing of the final material is of utmost importance. Nowadays this can be done on building site by movable soil mixers ensuring high speed and quality (fig. 20, 21).

2.3.5. Watering/drying
Scientific studies prove the existence of an optimum moisture level earth should obtain to reach the highest performance when rammed in a structure. For example, a mixture consisting of 12% clay, 13% silt, 45% sand and 30% gravel has optimum moisture content of 12,5% (Maniatidis and Walker 2003). In material preparation process the actual moisture content can be easily detected by weight tests and decision of whether watering the material or leaving it for natural drying can be made accordingly. Building practice shows that increased binding strength can be obtained by water curing the earth mixture when leaving it rest in a wet state for a period of 12 to 48 hours (Minke 2009). Though by any means the final material consistence during the building process should be mealy rather than sludgy.

2.3.6. Stabilizing
To improve the performance of rammed earth and make it more predictable it is a common practice nowadays to supplement its classical composition with additives. Most often the stabilization is addressed to increase material's strength and durability as well as reduce shrinkage and swell. Usually this is done by adding a little content of cement and/or lime in range between 4 – 12% that both act as binders similar to clay. Moisture ingress can be controlled by 3%-6% content of bitumen based mixture that glues the loam particles during the water evaporation immediately after completing the construction work. Less popular stabilizers are soda waterglass, animal products, plant products (linseed oil, cooked starch, plant juices) and various artificial stabilizers (synthetic resins, paraffins and waxes). (Minke 2009)
Implementation of additives though is a rather sensitive issue since the benefit not always depends on type and amount of stabilizer. It is scientifically proven that various soil mixtures having various properties respond on the stabilization in a different way. Experiments on measuring increase in compressive strength after application of 4% cement and 2% lime especially point out importance of specific linear shrinkage (LS) and plasticity index (PI). "Favourable souls include those with LS<6.0 and PI<15, and those with LS 6.0-11.0 and PI 15-30 and sand content < 64%." (Burroughs 2008) Others have little positive, neutral or even negative effect on stabilizing. British researchers meanwhile characterize the optimum soil for cement stabilization as one with sand content greater than 50% and clay content less than 25%. (Maniatidis and Walker 2003) When successful stabilization may result in remarkable strength increase and improvements in moisture resistance, the actual building practice still indicates necessity of soil stabilization tests in each individual case.

2.4. Scheveningen, the Netherlands
The Netherlands are rich but yet not fully self-supporting for rammed earth aggregates. Map of the surficial occurrence of fine-grained deposits

Fig. 16. Vibrating screen

Fig. 17. Trommel drum screen

Fig. 18. Soil crusher

Fig. 19. Crushing and screening plant

Fig. 20. Small size soil mixer

Fig. 21. Soil mixing plant

Fig. 22. Clay The surficial occurrence of fine-grained deposits in the Netherlands: (1) Quaternary clay, loam and silt, thickness > 1.2 m, clay fraction < 17.5%; (2) Quaternary clay, thickness > 1.2 m, clay fraction > 17.5%; (3) Quaternary clay, thickness < 1.2 m, clay fraction < 17.5%; (4) Quaternary clay and loam, thickness > 1.2 m, clay fraction > 17.5%; (5) Tertiary clay.

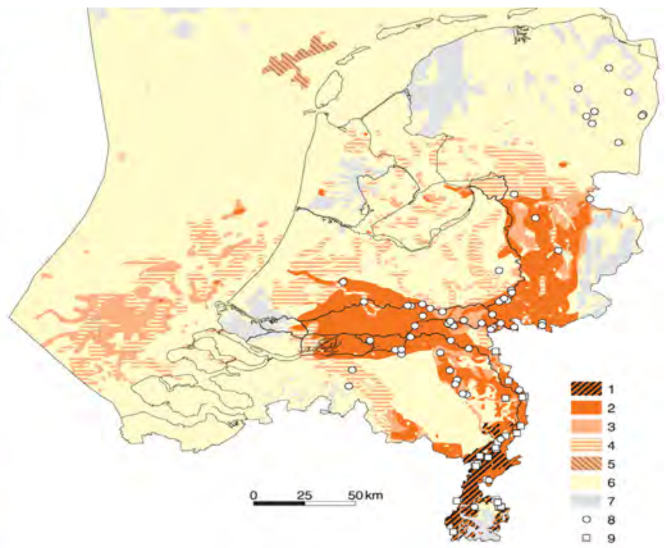


Fig. 23. Main occurrences of aggregates in the shallow Dutch subsurface: (1) gravel; (2) coarse sand (cumulative thickness > 10 m); (3) coarse sand (cumulative thickness 5–10 m); (4) coarse sand and moderately coarse sand (cumulative thickness > 5 m); (5) thin surficial occurrences of coarse sand and gravel in the North Sea (thickness < 2 m); (6) fine sand; (7) no or limited aggregates; (8) extraction site of concrete and mortar sand; (9) gravel extraction site.

in the Netherlands indicates sufficiency with clay and silt. The bulk of the particular aggregate resources is formed by the Holocene peri-marine deposits in the coastal provinces, and Quaternary fluviatile clays, deposited on the floodplains of the Meuse and Rhine, as well as perimarine clays in the province of Groningen. Other exploited resources include deposits in Gelderland, Noord-Brabant, Gelderland and Overijssel, as well as Pleistocene eolian silt deposits in Limburg (fig. 22).
Geological map representing main occurrences of aggregates in the shallow Dutch subsurface (i.e. down to ~30 m below the land surface or sea bottom; fig. 23) indicates also absolute sufficiency of sand resources. Sand deposits are covered across the entire area of the Netherlands, but especially in the southern and eastern parts of the country. When fine sand dominates the central and western part, eastern and southern areas contain coarse sand deposits.
At the same time Netherlands has become dependent on imports of gravel and crushed-rock aggregates. The largest locally available coarse aggregate resources are located in Limburg and relatively minor surficial occurrences of gravel and gravely sand located in the Dutch sector of the North Sea. There is also information about gravel excavations along the basins of river Maas, Waal and Rhine, though most of the gravel is imported from Germany, Belgium and British sector of the North Sea (Broers and van der Meulen n.d.).
During the research basic soil analysis in Scheveningen has been performed with a purpose to determine local soil content and properties thus allowing to evaluate its suitability for application in rammed earth structures. According to the Netherlands soil type map, Scheveningen is laid on fine sand deposits. ISRIC Global Soil Database (a system that summarizes a wide range of soil profile data collected by many soil professionals worldwide) holds no exact information about soil content in Scheveningen, but measurements from Noordwijk coastal area that is located 25 km east from Scheveningen indicate 97% sand, 1% silt and 2% clay content. In order to verify soil composition in exact location of Scheveningen, earth samples were taken from three different areas for sedimentation tests. First two samples were collected from a sand dune and a building site in Duindorp, Scheveningen (fig. 24) and the final one for comparisonal reasons from a building site in Delft (fig. 25).
Sedimentation tests were performed by stirring sand with a lot of water in a glass jar allowing for particle stratificatoin according to their grain size. Results indicate that both soil samples from Scheveningen and Delft consist of sand and presence of other components - clay, silt, and gravel is inconsiderable (fig. 28). This supports the information found in ISRIC database and geological maps of the Netherlands (fig. 26).
Practical tests represented obvious differences in appearance between sand collected from the dune and two other samples. First one is a typical sea sand – lighter and smoother, it contains salt which tends to absorb moisture from atmosphere and brings dampness thus should be avoided in structural construction. While sand excavated from the building site just hundred meters away from the dune area represents typical fine sand qualities identical to one excavated in Delft and thus can be applied in rammed earth building (fig. 27)

2.5. Conclusions

1. Building from rammed earth in Scheveningen requires additional soil supplementation with clay, silt, and gravel. Local sand can be used as long as it is not excavated from direct beach or dune area.

2. Modern soil processing and improvement tools available for in situ implementation are able to ensure materials preparation fast, easy and with high degree of precision, providing consistency of the output close to that of manufactured building materials.

3. Chemical stabilization gives possibilities for materials customization when adjusting earth properties according to site specifics and design requirements. Thus rammed earth as building material is incredibly flexible.

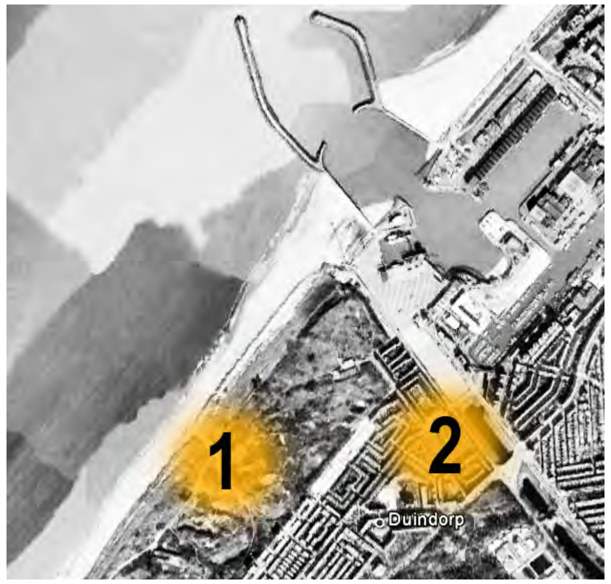


Fig. 24. Excavation site of soil samples Nr. 1 and 2

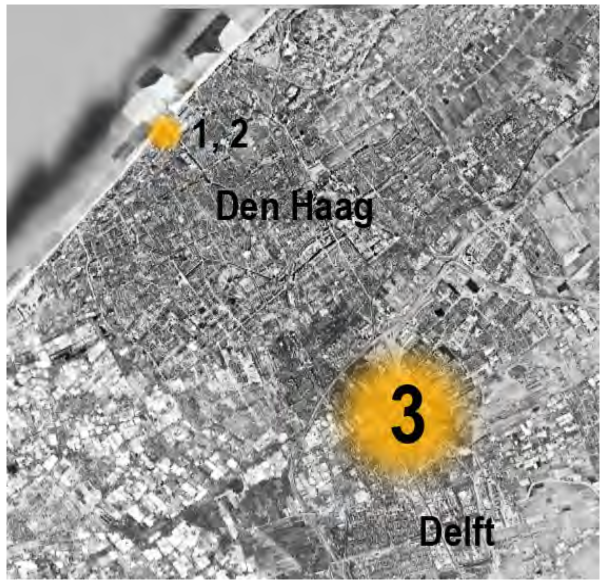


Fig. 25. Excavation site of soil sample Nr. 3

WISE3_ID	HOI	PHK	PHC	ECE	EXC	EXMC	EXN	EXK	EXALU	EXAC	CECS	BS	SAND	SILT	CLA	GRAVEL	BULKI	VMC1	VMC	VMC3
NL0044	2			0,1							4,4		89	8	3					
NL0044	3			0,1							1,4		89	8	3					
NL0044	4			0,1									97	1	2					
NL0045	1			0,1									97	1	2		1,4			
NL0045	2			0,1									97	1	2		1,52			
NL0045	3			0,1									97	1	2		1,51			
NL0045	4								0	0			97	1	2		1,5			

Fig. 26. Fragment from ISRIC soil horizon database. Entry NL0045 represents soil composition ~ 25 km from Scheveningen

Fig. 27. Soil samples

Fig. 28. Sedimentation test with soil sample Nr. 2

3. STRUCTURAL PERFORMANCE

Application of rammed earth is hindered by its structural properties. Relatively mediocre strength and tense constraints set by building codes result in common perception of rammed earth as a construction technique for low-rise buildings, not more than 2 floors high. Obviously this conflicts with nowadays architectural reality of global urbanization and intensification.

3.1. Strength

Mechanical strength of rammed earth is highly inconsistent, defined by various aspects of materials composition, construction technology, and exploitation.

Firstly, mechanical performance depends on properties and proportion of rammed earth components. When clay may differ according to lamellar structure of its minerals, silt, sand and gravel varies in shape starting from sharp-cornered aggregates till completely smooth ones. Even slight changes in soil structure thus will reflect in mechanical performance of the construction.

Secondly, as for porous materials, strength has a linear relation to voids ratio and thus density. It is scientifically proven that each soil mixture has individual optimum moisture content during the compaction process as well as ideal amount of necessary energy to be applied in order to achieve the maximum performance. (Hardin, Merry and Fritz 2007)

Finally, the component of strength of an earth mixture is achieved through matric suction that equals to difference between the pore air pressure and pore water pressure. It increases as soil dries, increasing the particle cohesion and thus strength. (Jaquin, Augarde, et al., The strength of unstabilised rammed earth materials 2009) For that reason materials performance differs according to moisture content during exploitation.

Principally structural performance of rammed earth is similar to that of concrete, though with significantly lower effect. When unstabilized, it works poor in tension but fair in compression. Laboratory tests of typical earth mixture (30% gravel, 45% sand, 13% silt, 12% clay, moisture content between 5-7.5%, dry density between 1700-2100 kg/m3) indicate the ultimate compressive strength in range between 0.6 – 3.0 MPa. (Maniatidis and Walker 2008) Though considering the vast variety of decent mixtures the range can be broadened to 0.5-5 MPa (fig. 29) and modulus of elasticity between 0.6-0.85 MPa. (Minke 2009)

Tests of binding force and eccentric loading prove materials inapplicability for conditions of considerable tension and shear (fig. 30, 31). Usually the critical tensile and shear strength values lie between 25-500 g/cm2 and generally is around 10-13% of compressive strength. (Minke 2009)

Some studies report on phenomenon of earth increasing strength with time. This is, however, an issue requiring more persistent study to take into

	Rammed earth	Rammed earth	Concrete	Brick masonry
	unstabilized	stabilized	portland cement	standard
Compressive strength, MPa	0.5 - 5	3 - 20	13.3 - 30	1.5 - 7.5

Fig. 29. Characteristic compressive strength values of rammed earth, concrete and brick masonry

	Rammed earth	Rammed earth	Concrete	Brick masonry
	unstabilized	stabilized	portland cement	standard
Tensile strength, MPa	0.05 - 0.65	0.3 - 2.6	1.1 - 1.3	0.04 - 0.71

Fig. 30. Characteristic tensile strength values of rammed earth, concrete and brick masonry

	Rammed earth	Rammed earth	Concrete	Brick masonry
	unstabilized	stabilized	portland cement	standard
Shear strength, MPa	0.05 - 0.65	0.3 - 2.6	6.5 - 10.9	0.22 - 1.04

Fig. 31. Characteristic shear strength values of rammed earth, concrete and brick masonry

Fig. 32. Rammed earth building in Weilburg, Germany (1826)

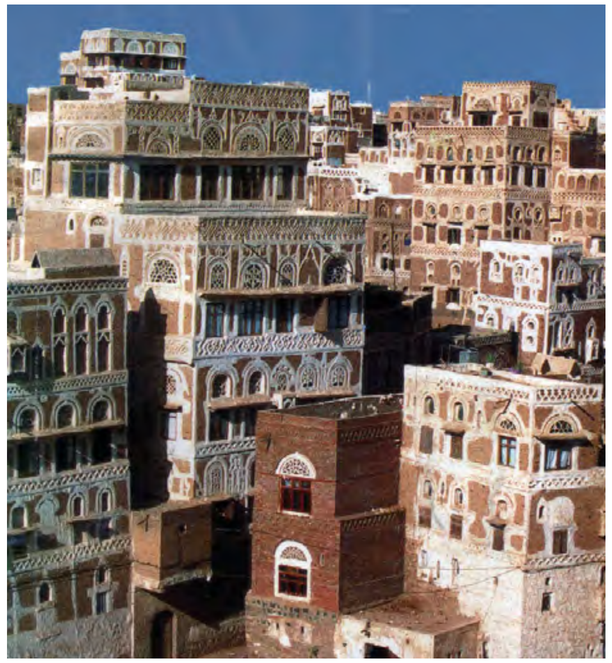


Fig. 33. Earth architecture in Sanaa, Yemen

serious consideration. (Maniatidis and Walker 2008)

3.2. Limitations in Building Codes

Application of rammed earth in countries with remarkable earth building tradition (Australia, USA, New Mexico, Germany, Spain etc.) is controlled by relevant building codes and standards. Generally oriented on setting constructive limitations, most of them represent similar content though might be confusing when compared or viewed in broader context.

Firstly, vast majority of the codes restrict building of rammed earth (and earth in general) any higher than 2 floors. This, however, is confronted by historic examples. For example, the 6 storey high rammed earth residential building in Weilburg, Germany (fig. 32) was constructed in 1826 and is still in use nowadays. (Rammed Earth 2011) So does the impressive 10-12 storey high residential architecture in Yemen (fig. 33) constructed in 19th century, but above all, the highest rammed earth structure in the world – the Pyramid of the Sun in Teotihuacan, Mexico exceeding 60 meters. (Lee and Ball 2009)

Secondly, the existing building codes and standards provide guidelines for minimum wall thickness, maximum wall height as well as wall thickness/height ratio. Some of the values differ significantly and are represented in following table:

Reference	Thickness of Wall	
	Internal	External
Standards Australia (2002)	125mm	200mm
New Mexico Code (Tibbets, 2001)	12"(305mm)	18"(457mm)
New Zealand Code (NZS 4297:1998, 1998)	250mm	
Zimbabwe Code (SAZS 724:2001 2001)	300mm	

Thirdly, rammed earth documentation defines minimum compressive strength. Given values though deviate even more than those for minimum wall thickness. When Standards of Australia and New Zealand set the minimum unconfined strength as 0.4-0.6 N/mm2 and 0.5 N/mm2 respectively, the German Standards DIN 18954 define minimum compressive strength for rammed earth of 2200 kg/m3 density as 4N/mm2. (Minke 2009)

Finally, building codes and standards define maximum load earth structures of fixed binding force may take. Building practice indicate that due to particular limitations "load-bearing rammed earth walls are overdesigned and constructed with safety factor between 3 and 10." (Bui 2009)

3.3. Improving Structural Performance

3.3.1. Stabilization

Significant improvements in material's performance can be achieved with stabilization. Supplementing the typical earth mixture with 5-8% cement (or 8-12% lime) the compressive strength can be increased up to 18 MPa (fig. 34) that is not far from the typical value of 25 MPa for concrete. (Guettala 2006) Theoretically in idealized environment and density of 2000 kg/m3 it would allow to erect a 180 meters high self bearing wall even considering a safety factor of 5. In practice, of course, the potential height would be reduced by loads of floor-slabs and roof, additional loads by exploitation as well as moisture and other environmental impacts. Though obviously stabilization is one of the most promising and commonly implemented method in both increasing materials strength and durability.

3.3.2. Reinforcement

Supplementing rammed earth structures with reinforcing elements has been known for centuries. Initially by simply improving earthen elements with wooden bars, nowadays "rammed earth can be engineered to achieve reasonably high strengths and be reinforced in a similar manner to concrete" (fig. 35, 36). (Downton 2010) Extensive application of reinforcement though can make compaction process technically complicated and result in incomplete densifying of the soil. Eexcessive vertical reinforcement can also cause cracking problems. Due to this reason disposition of reinforcement bars is rather different as in concrete.

Horizontal reinforcement should be placed not closer than after each 450 mm of height, and most recommended under openings, while vertical reinforcement after each meter but also around openings as doors and windows as well as both ends of the rammed earth structure (fig. 37, 38). Eccentric loading tests indicate necessity for more reinforcement in upper part of the load bearing structures. The larger the eccentricity, the higher the cracks usually appear and thus the higher the reinforcement should be applied. (Maniatidis and Walker 2008) Minimum cover to unprotected reinforcement depending on the environmental specifics should be 50 – 100 mm. For tensile stresses the amount of necessary reinforcement can be calculated using formula: $F \leq 0.7fA$ where '*f*' is design tension force acting on cross-section and '*A*' the cross-sectional area of main reinforcement. (Walker, The Australian Earth Building Handbook 2002)

Materials used to reinforce earth walls include

	Different walls treatment							
	Cement (%)		lime (%)		Cement (%) + Lime (%)		Cement (%) + Resin (%)	
	5	8	8	12	5 + 3	8 + 4	5 + 50	8 + 50
Compressive strength in dry state, MPa	15.4	18.4	15.9	17.8	17.5	21.5	17.2	19.5
Compressive strength in wet state, MPa	9	12.7	10.1	11.7	12.3	15.6	11.5	14
Water strength coefficient	0.58	0.69	0.64	0.66	0.63	0.7	0.67	0.72
Capillary absorption, %	2.35	2.2	3.7	2.9	2.3	2	2.3	2.1
Total absorption, %	8.27	7.35	9.8	9.02	8.1	7.9	5.9	5.3
Weight loss (wet–dry), %	1.4	1.25	2.3	2.1	1.2	1.0	0.9	0.9
Weight loss (freezing and thawing), %	2.35	2.23	3.7	2.9	2.3	2.0	2.3	1.8
Hole depth, mm – After spray test	1.0	0.5	2.2	1.0	1.0	0.5	0.25	0.2
Hole depth,[a] mm – Real life exposure	–	–	1.0	0.5	–	–	–	–

[a] Values obtained using a comparator.

Fig. 34. Properties of various stabilized rammed earth mixtures

Fig. 35. Reinforced wall

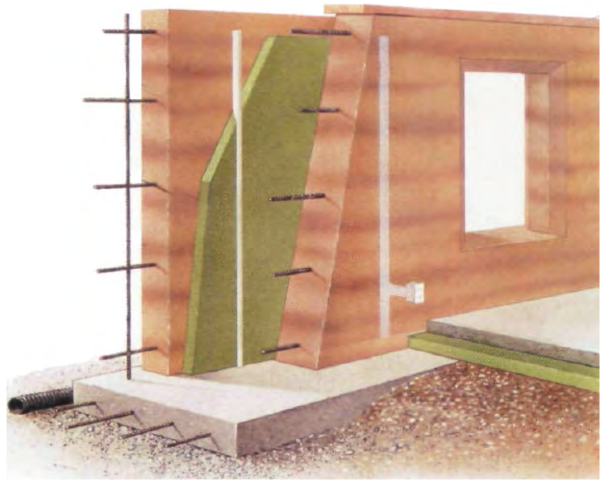


Fig. 36. Reinforced wall and foundation slab

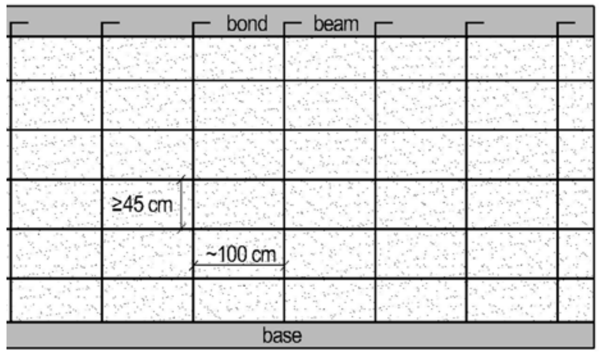


Fig. 37. Reinforcement for plain wall

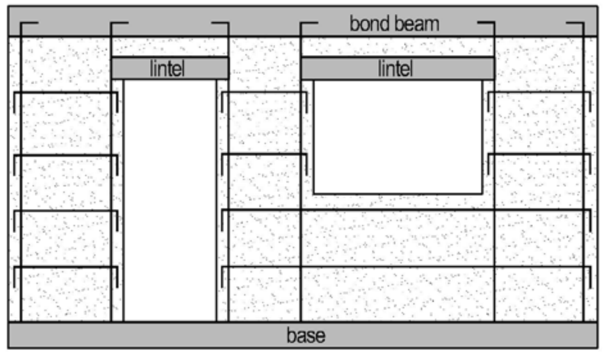


Fig. 38. Reinforcement for a wall with openings

Fig. 39., 40. Rammed earth wall with corner window by "LEEMWERK"

threaded stainless or uncoated or also galvanized carbon steel bar and mesh, steel wire, fiber-reinforced plastic, bamboo, timber, concrete, and polypropylene geotextile grid material. (Walker, et al. 2002; Walker and Dobson, Pullout Tests on Deformed and Plain Rebars in Cement-Stabilized Rammed Earth 2001)
There exist examples when alternative forms of reinforcement have been implemented. Dutch company "LEEMWERK" within a rammed earth wall has integrated a system of metal profiles allowing to buid a corner window without any corner supports (fig. 39, 40).

3.3.3. Lintels and Bond Beams

Rammed earth application requires strict precaution activities to avoid highly stressed areas. Therefore larger openings (usually above 1 meter) must be covered with lintels, similar to that in brickwork (fig. 38, 42).
In order to equalize load distribution by floorslabs (especially in case of wooden beams or trusses) perimetrial bond beams are highly implemented (fig. 37, 38, 41, 42). Usually they are made in concrete, though New Mexico building codes examplify application of plywood as well (fig. 43).

3.3.4. Framework

Applying additional structural system is well known building practice. Centuries ago it was common to combine rammed earth walls with wooden frame taking most of the compressive load. Nowadays constructive frames are made also of metal and concrete. Frame can be designed to take all the load and keep rammed earth only as infill material though it is much more rational to have frame only as a support and therefore make use of compressive potential of earth (fig. 44, 45).

3.3.5. Geometry

Several design aspects should be considered when aiming for maximum performance:

Shape

Tension and shear stresses can be minimized following the theory in structural mechanics of optimum shapes. Several built examples (especially historic ones) reflect variations of cone and pyramid (fig. 46, 47). There exist buildings with mud brick and even rammed earth arch-type roofings (fig. 48). While cupols of famous african earth buildings approximately follow catenary line.

Wall Thickness

In respect to minimum thickness limitations and materials high density that may reach up to 2200

Fig. 41. Concrete bond beams. Chronometry Tower, Zurich

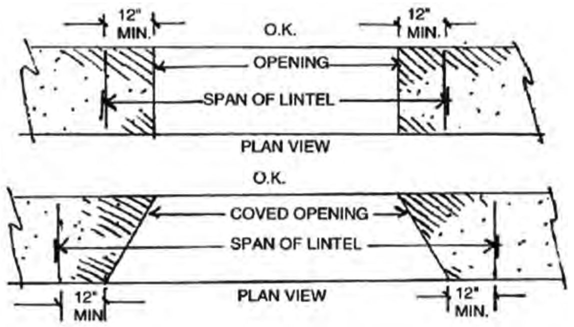


Fig. 42. Permissible lintel dimensions. New Mexico building code

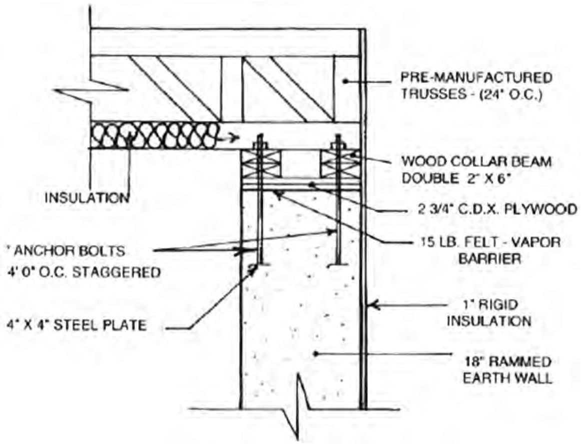


Fig. 43. Light wood bond beam. New Mexico building code

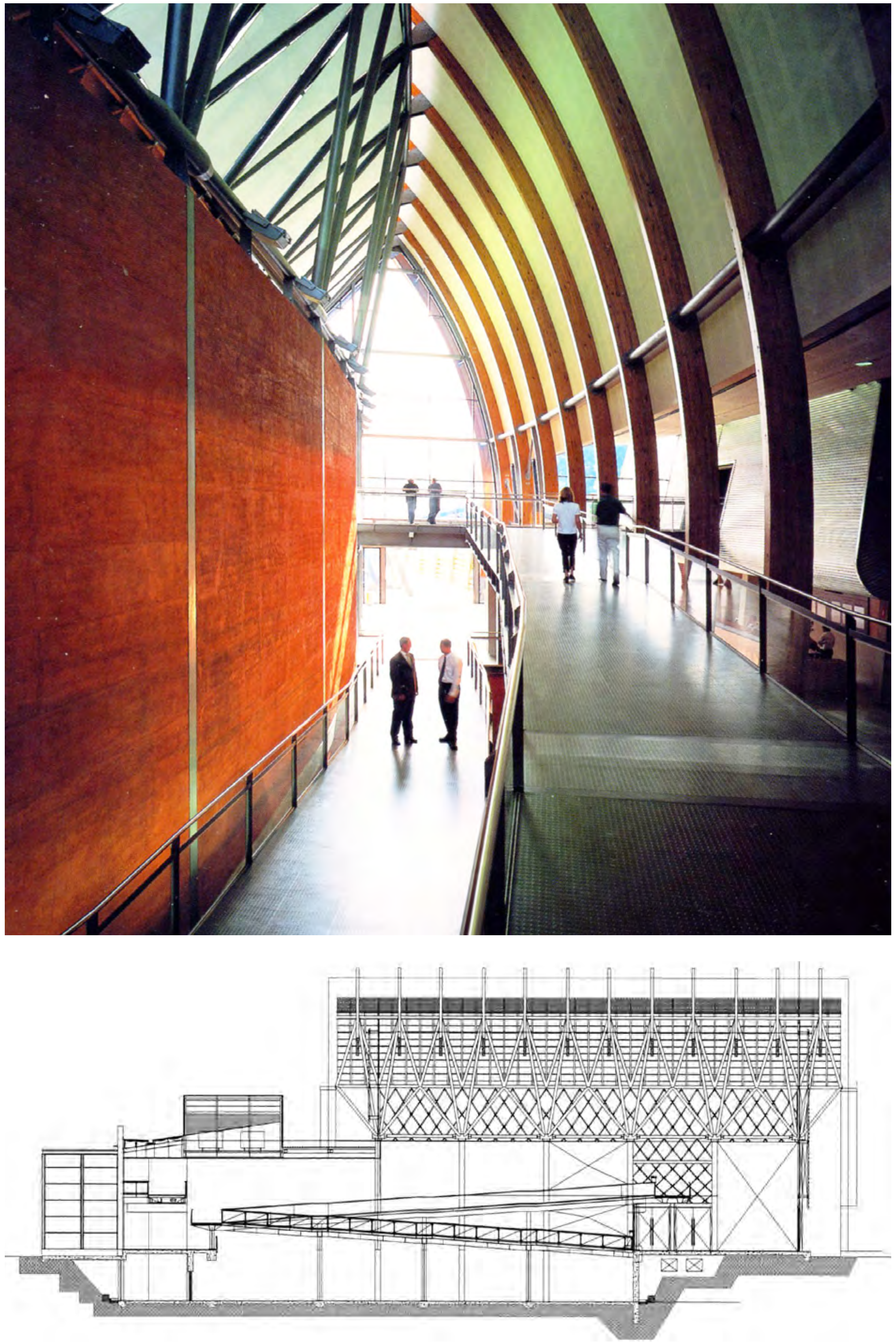


Fig. 44., 45. Metal famework structure within rammed earth walls with integrated diagonal bracing. National Wine Centre, Adelaide

kg/m3, large compression forces are caused by rammed earth dead load. Reducing wall thickness for higher floors (fig. 49) is yet another historically well-known method of optimizing buildings constructive performance applied also for concrete and masonry structures. Previously mentioned 6 storey high rammed earth residential building in Weilburg, Germany (fig. 32) is a good example with wall thickness at the ground floor 0.75 m, reducing by 0.09m each floor up till finally reaching 0.3 m at the top. (Rammed Earth 2011)

Corners

Rammed earth laboratory tests show surprisingly explicit relationship between compressive strength and shape of the tested specimen (fig. 50, 51). With identical soil composition, moisture level and compaction energy, the overall performance of cylinders is more than twice as high as prismatic elements. (Maniatidis and Walker 2008) This can be explained by specifics of compaction process when it is technically rather impossible to achieve perfect compaction in corners with a pneumatic rammer. Differences are not that dramatic for samples of larger dimensions since the amount of poorly compressed areas is constant for depending in rammers diameter. Though corners are usually first to fail anyway and thus are preferably to be rounded or designed in angle of 45˚ (fig. 52, 53).

3.3.6. Building with Alternative Technologies

Alternative rammed earth building technologies ensuring increased strength is application of various prefabricated or semi-prefabricated systems. Interesting example is "Novoram" lightweight manufactured concrete shell blocks where earth is an infill. Manufacturers claim this is cheap and fast construction method not requiring for skilled labor. After blocks of each course are laid in position, gaps are filled with concrete to bind them together and achieve smooth outer finish. Then earth is filled and compacted using a reversible soil compactor. Layers of blocks are finally tied with vertical metal rods.

Tiny concrete shell provides strength of more than 3 N/mm2 and allows a non-insulated, load bearing wall be as thin as 25 cm (alternative block width is 35 cm). Concrete serves also as impact and moisture protective layer increasing materials durability. (McKimmie 2010)

3.3.7. Interventions in Building Codes

This is not the goal of this study to question the validity of the existing building codes and standards. However, examples of construction

Fig. 46. Ice storage made of mud brick in Iran

Fig. 47. Experimental house. Tsukuba, Japan (2005)

Fig. 48. Vaults of compressed earth blocks by Nubian masters

Fig. 49. Differentiated wall thickness. Housing in Bhutan (2005)

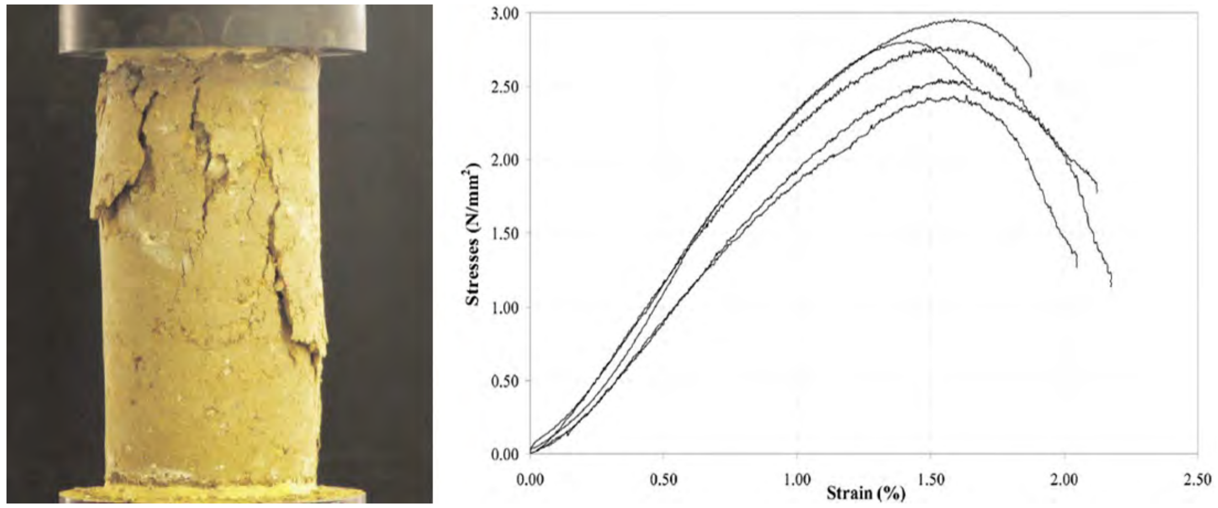


Fig. 50. Compression test results of circular specimens

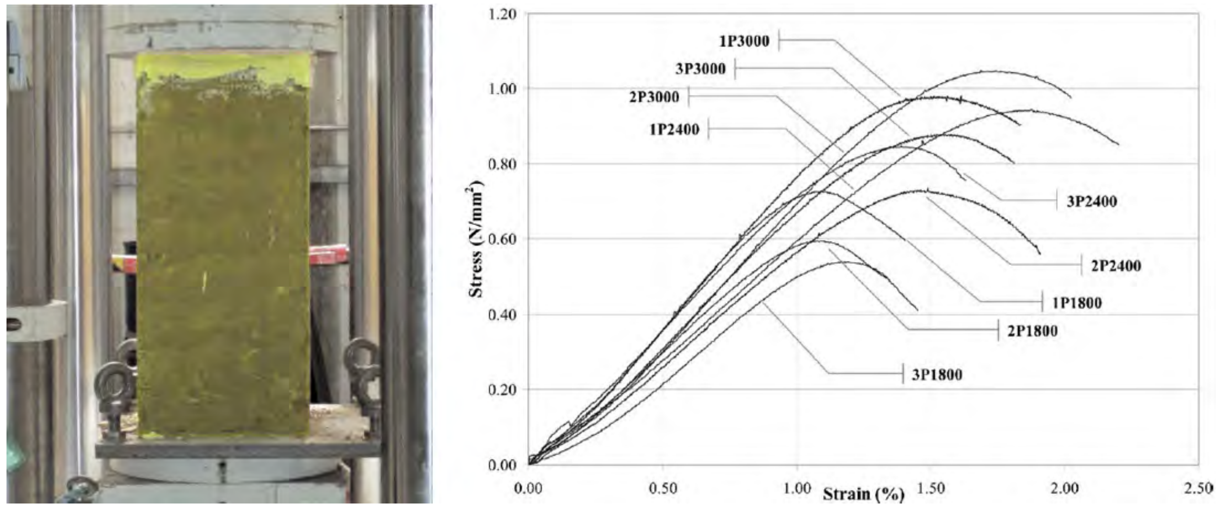


Fig. 51. Compression test results of prismatic specimens

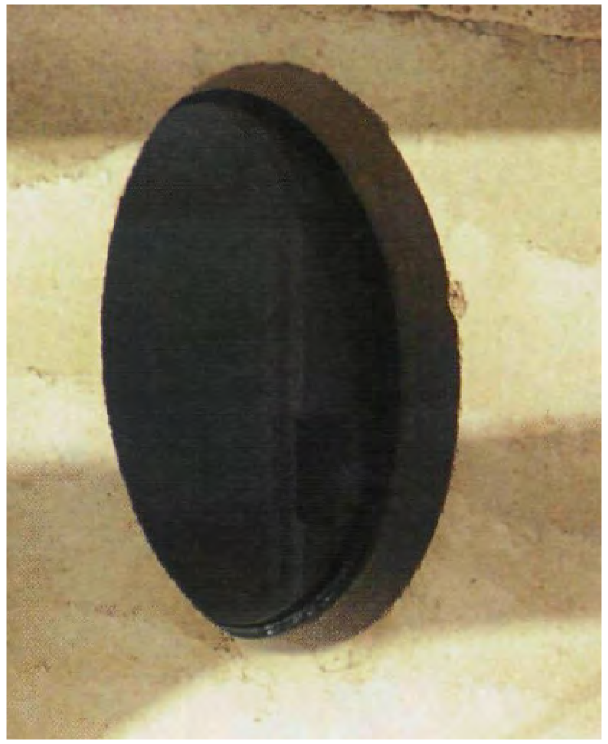


Fig. 52. Critical angle construction method

Fig. 53. Preferable angle construction method

limitations described before imply on necessity apart from structural performance optimization in design and material composition level to reconsider constructive potential of rammed earth also in legislative level. It is highly credible that more detailization and flexibility would have a positive impact on earth building practice.

3.4. Scheveningen, the Netherlands

As a practical input of the research, structural capacity of rammed earth construction with a special reference to environment of the Netherlands has been explored by perfprming computer simulations in Autodesk ROBOT software. A simplified building frame in various heights and optimization stages was tested under the combination of dead load and live load in accordance to Dutch residential building normatives. The main objective of the simulation was to verify rammed earths structural potential and effects of basic optimization methods, some of them represented in the previous paragraph.

The basis for the structural model used for simulations is shown in figure 54. Span of 6 meters was chosen to favor application of both concrete and wooden floor slabs. Initial wall thickness of 40cm was selected as a common average value in rammed earth building practice. Live load of 200 kg/m2 (2 kPa) was chosen as the typical maximum for residential buildings, and loading safety factors applied according to Dutch building code NEN6702. Safety factor of rammed earth structural performance was assumed as high as 4, basing on scientifically measured rammed earth strength reduction caused by moisture ingress and ramming imperfections (more in detail see chapter 4 and 7). Simulations were performed in following steps:

Case 1 (initial state) – typical unstabilized rammed earth walls with compressive strength of 1 MPa, shear and tensile strength of 0.2 MPa and thickness of 400 mm. Concrete froolslabs.

Case 2 (optimization 1) – wall material replaced with cement stabilized rammed earth. Structural properties derived from values prevailing in scientific literature sources.

Case 3 (optimization 2) – concrete floorslabs replaced with 5 times lighter wooden beam construction.

Case 4 (optimization 3) – wall thickness differentiated by reducing from 420 mm at the ground floor level to 300 mm th the top (fig. 55).

The most important simulation results per each step are summarized in figure 56. They reflect large differences in structural behavior between various simulation cases. In tangible results each optimization step allows increasing builing height and amount of floors keeping the maximum compressive, tensile and shear stresses within defined safety renge. (See more of calculation results in appendix).

3.5. Conclusions

1. Results of the simulations verify structural capacity of stabilised rammed earth as sufficient for application in buildings higher than those prevailing in contemporary building practice. Calculations also visualize the most critical parts of the structure containing highest stresses thus implying on the possibilities of further structural optimization by, for example, adding concrete lintels and supports at both ends of the walls (fig. 58, 59).

2. Considering materials poor performance in shear and tension, building higher above the surrounding environment especially in windy regions such as Scheveningen emphasizes a necessity to evaluate the wind impact on the structure. It is highly credible that buildings aerodynamics may become one of design issues.

3. Finally, due to notable weight of rammed earth walls, soil mechanical properties of the building site should be determined.

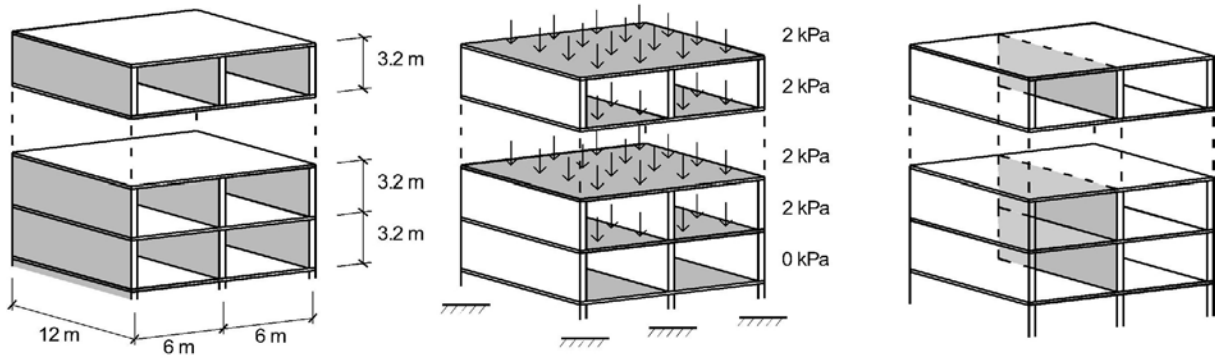
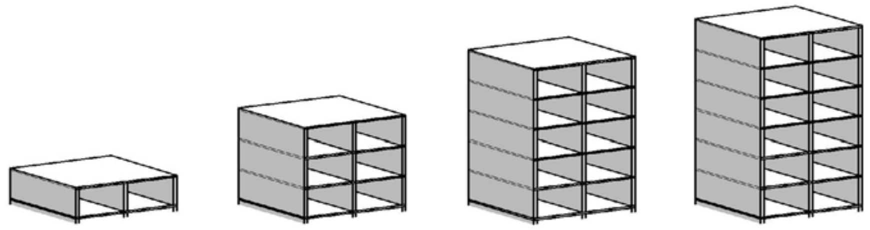


Fig. 54. Geometry of the model (left), loading scheme (middle) and walls calculated (right) in the computer simulations

INPUT DATA		Case 1	Case 2	Case 3	Case 4
		initial state	optimization 1	optimization 2	optimization 3
Walls	- rammed earth type	unstabilized	stabilized (4-5% cement)	stabilized (4-5% cement)	stabilized (4-5% cement)
	- compressive strength (MPa)	1	2	2	2
	- tensile / shear strenght (MPa)	0.2 / 0.2	0.5 / 0.5	0.5 / 0.5	0.5 / 0.5
	- thickness (mm)	400	400	400	300 - 420
Slabs	- material	concrete	concrete	wood	wood
	- weight (kg/m2)	375	375	75	75

Fig. 55. Input data used for each calculation case

RESULTS		Case 1	Case 2	Case 3	Case 4
		initial state	optimization 1	optimization 2	optimization 3



Floors		1	3	5	6
Stresses (safety limit)	- max. compression (MPa)	0.17 (0.25)	0.45 (0.50)	0.43 (0.50)	0.44 (0.50)
	- max. tension (MPa)	0.03 (0.05)	0.07 (0.15)	0.09 (0.15)	0.10 (0.15)
	- max. shear (MPa)	0.05 (0.05)	0.15 (0.15)	0.14 (0.15)	0.15 (0.15)

Fig. 56. Output results

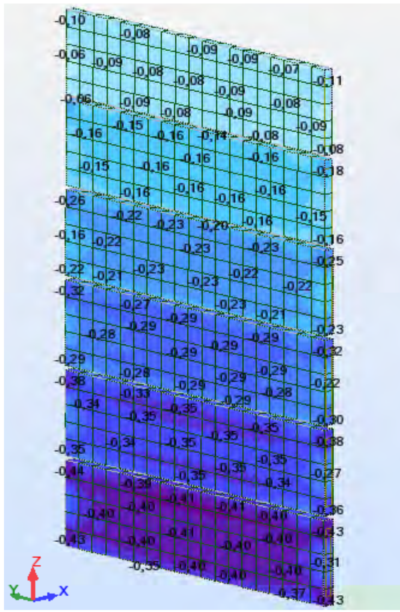


Fig. 57. Compression (zz direction)

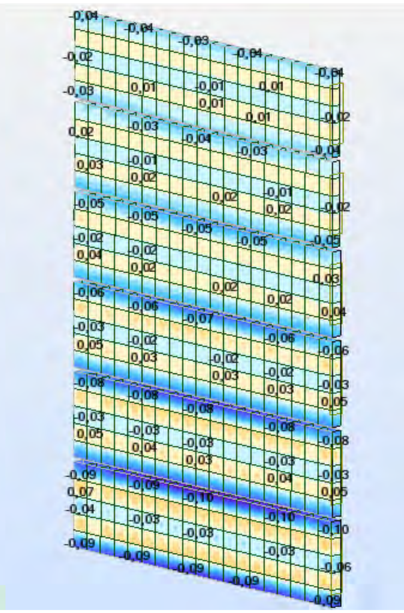


Fig. 58. Tension (xx direction)

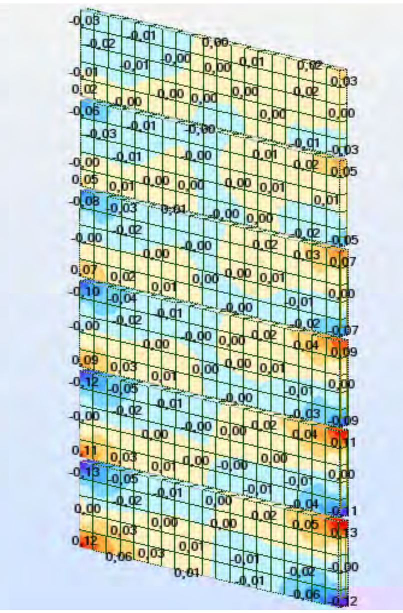


Fig. 59. Shear (yz direction)

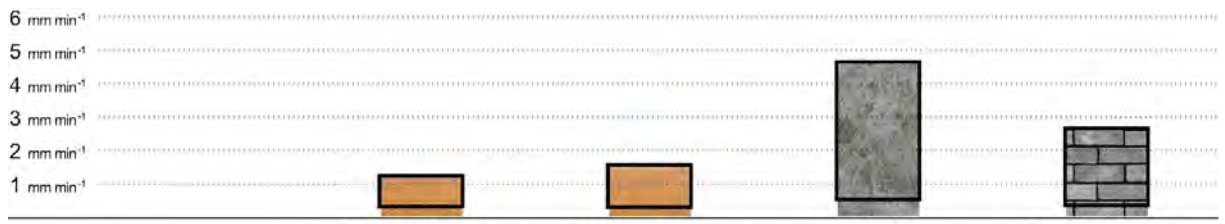
4. MOISTURE INGRESS AND PROTECTION

Unstabilized rammed earth is sensitive to moisture. "Compressive strength of moist material is likely to be at least 50% lower than the final ambient values." (Jaquin, Augarde, et al., The Strength of Unstabilized Rammed Earth Materials 2009) Apart from that water may cause a dozen of other damages as staining, dimensional fluctuation, rotting of timber lintels and frames, surface spalling, decrease in thermal performance, loss of adhesion between binding agents and aggregates etc. (M. Hall, Moisture Ingress in Rammed Earth: Part 2 - The Effect of Soil Particle-size Distribution on the Absorption of Static Pressure-driven Water 2006) Thus distribution of rammed earth buildings mainly within drier climates is not a coincidence, and careful moisture control is of utmost importance.

4.1. Ways of Moisture Ingress

Moisture into earth construction can infiltrate in various ways. Firstly, it is possible due to capillary suction when liquid is transported through pores in materials microstructure caused by intermolecular attraction between water and solid earth particles. (Science Encyclopedia 2011) Sorptivity experiments of unsaturated rammed earth, however, show that quantity of water that can be absorbed over a given period of time is very favorable in comparison to other materials as, for example, various plasters, mortars, natural stone, fired clay brick and especially vibration-compacted C30 concrete (fig. 61). Moreover sorptivity in earth has a linear tendency to decrease in time due to phenomenon of swell that diminishes or completely closes the pore system. Moisture absorption in various earth mixtures depends on clay content - sorptivity level is significantly less for clayey soils than silty and sandy, but above all, concrete stabilized soils. Moisture absorption due to capillary suction depends also on density and surface smoothness. Larger elements as gravel allow for increased "surface tracking" thus pulling water deeper into materials structure, so in order to reduce moisture ingress it is essentially important to provide a smooth outer surface of the structure. Similarly, sorptivity is less a problem in dense earth structures with perfect adhesion between compaction layers. (Hall and Djerbib 2006) Secondly, moisture ingress may occur via condensation. Earth has incredibly high vapor absorption/desorption speed (fig. 62 left) as well as remarkable equilibrium moisture content (the maximum humidity a dry material can absorb; fig. 62 right) that for various earth mixtures may vary between 3% - 7% of materials mass mainly depending on temperature and humidity of ambient air. (Minke 2009) On one hand it determines earth an excellent air humidity regulator being able to maintain a constant interior air humidity level of 50% ± 10%. On the other, however, it causes risk of condensation, therefore, when applied as exterior wall especially in climatic zones with high interior/ exterior temperature differences, special attention must be paid to moisture transport calculations

Fig. 60. Eroded rammed earth wall in China



	Rammed earth	Rammed earth	Concrete	Brick masonry
	unstabilized	stabilized (3 - 9% cement)	portland cement	standard
Sorptivity, mm min^{-1}	0.29 - 1.21	0.25 - 1.63	0.58 - 4.72	0.32 - 2.72

Fig. 61. Characteristic sorptivity values of rammed earth, concrete and brick masonry

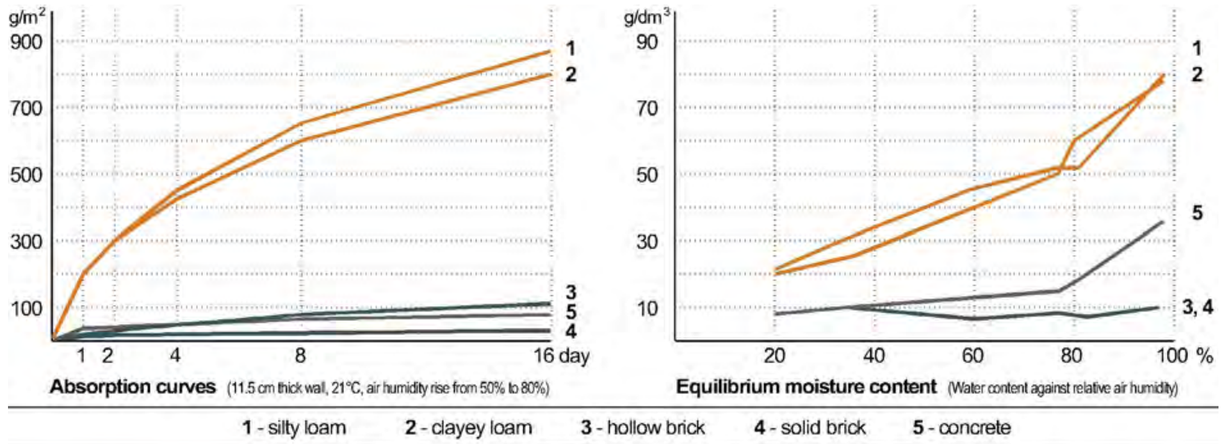


Fig. 62. Moisture absorption curves (left) and equilibrium moisture content curves (fight) for loam, brick and concrete

in order to prevent dew point within the earth construction.
Finally, an impact on flowing water must be considered. Results of scientific experiments, however, indicate that impact of direct rainwater is of secondary importance. High velocity rainfall simulations applying 130 psi spraying water on the rammed earth wall surface show that only a thin layer of material becomes moisture saturated and in case of classical earth content creates an "overcoat" layer that protects further moisture distribution within the structure. "Through testing, no leakage or penetration of liquid water through capillary action was inducible to harmful depth." (M. Hall, Assessing the Environmental Performance of Stabilised Rammed Earth Walls Using a Climatic Simulation Chamber 2007) On the other hand, however, it is proven that long lasting rain may cause deformations or an erosion of materials outer surface. According to durability tests in France where under climatic conditions of 1000 mm annual rainfall rammed earth specimens were exposed for a period of 20 years (fig. 63 - 65), they indicate clear signs of erosion in unprotected areas exceeding 6mm. Being within acceptable range, especially considering remarkable thickness of average rammed earth wall, this is still an undesirable occurrence especially in more humid areas than France. (Bui 2009)

4.2. Moisture Protection

Most common solutions to avoid moisture ingress in rammed earth constructions are design or material oriented. Latest practice all over the highly humid regions, especially the United Kingdom, proves that claims of rammed earth as being applicable only in dry climatic zones is obviously a myth.

4.2.1. Stabilization

"Testing has proven that stabilized rammed earth materials rarely have any problems meeting the requirements of even the most severe durability tests." (Hall and Swaney, Stabilised Rammed Earth (SRE) Wall Construction 2005) The most common rammed earth protection against water impact is by adding cement. A cement gel matrix that binds together the soil particles has not only a positive impact on materials strength and durability in dry state, but unlike clay it maintains strength also in humid state preventing erosion and weakening. (Maniatidis and Walker 2003)
An alternative technique to improve rammed earth water resistance especially for soil mixtures with low clay content is by adding bitumen. "Bitumen is either dissolved in water with an emulsifier such as naphtha, paraffin oil or petroleum." (Minke 2009) After the ramming process is done, earth mixture dries and bitumen evaporates. Being highly adhesive it glues the pores in rammed earth structure. Practice shows that bitumen concentration within earth mixture should be 3-6%.
"Stabilised rammed earth walls need little added protection but are usually coated with a permeable sealer to increase the life of the material." (Downton 2010)

4.2.2. Coating

Widely used coating technique is plastering. According to the New Mexico building code, for example, stabilized rammed earth structures can be left opened to the environment, but if unstabilized must be covered with mud or Portland cement plaster. (Government of New Mexico 2009) More resistant, however, is lime plaster typically consisting of 1 part hydraulic lime and 3 to 4 parts sand. (Minke 2009) Practice shows that plaster is usually applied in 5 – 30 mm thick layer.
Coating might also be done with a paint (fig. 66). Gerinot Minke mentions the importance of micro-pores paint should contain to ensure vapor diffusion. (Minke 2009) While builders from earthen building design and construction company "TERRA FIRMA" emphasizes the need for regular repainting of the surfaces due to environmental impacts and calls rammed earth as material that never needs to be painted. (Terra Firma 2007-2011)
Considering rammed earth aesthetics it is also possible to apply a transparent coating and leave materials texture and color exposed (fig. 67). Company "CROMMELIN", for example, has developed acrylic polymer emulsion coating specially meant for rammed earth surfaces. Material has "excellent UV resistance, weathering ability for external applications as well as moisture and detergent resistance for use in kitchen and bathroom areas." Acrylic coating is a member of larger water repellent family including also various silicones and siliconates. Important that "new water repellent additives that waterproof the walls right through may make rammed earth suitable for very exposed conditions, including retaining walls, but may inhibit the breathability of the material. (Downton 2010)

4.2.3. Avoiding Contact with Moist Surfaces

To prevent capillary suction it is essential to ensure excellent insulation between rammed earth elements and moist building parts as foundation. Earth surfaces should also be separated from moist interiors as shower and kitchen areas. Similar hydro-insulation requirements exist if building with most of other materials as well. Therefore appropriate technological solutions are widely known and not explained further in detail.

Fig. 63., 64., 65. Rammed earth specimens after aging for 20 years. Left – stabilised (5% lime), middle and right – unstabilised

Fig. 66. Painted remmed earth building

Fig. 67. Earth walls covered with transparent acrylic water repellent

Fig. 68. Protective concrete footing

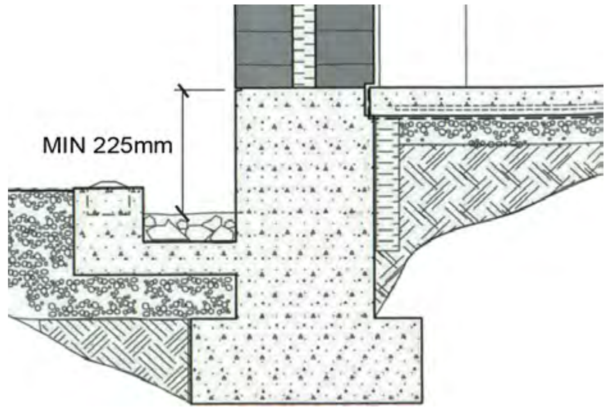


Fig. 69. Typical footing detail

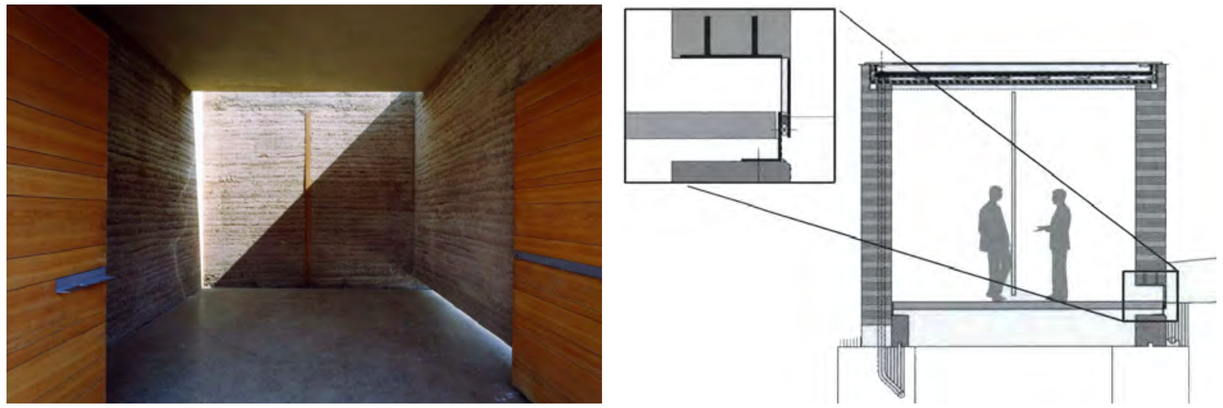


Fig. 70., 71. Uplifted rammed earth wall on a metal beam with double anchorage. Chapel of rest in Vorarlberg, Austria (2001)

4.2.4. Footings and Roof Overhangs

It is essential to maintain protection from direct rainwater and splashing water. In areas, where wind speed is highly predictable (typically dominating from one direction and low from others) large roof overhangs or covered terraces towards the windy side could be enough to protect building from direct rainwater impact (fig. 72).

Splashing water impact can be avoided by a concrete footing (fig. 68, 69). Various sources mention distances in range between 225 - 400 mm as the minimum height of the footing to protect the rammed earth structure. In building practice when using stabilized rammed earth particular design requirement, however, is often ignored.

Especially interesting approach to confront rammed earth heaviness but also protect from splashing water is a mortuary chapel in Vorarlberg, Austria, where one of the walls is lifted from the ground on a steel beam with double anchorage (fig. 70, 71). Here also should be mentioned that the soil used for the building is completely excavated on the building site without any additives (LEHM TON ERDE 2001).

4.2.5. Dew Point

Exterior walls must be designed to avoid dew point occurrence within the rammed earth layer. Scientific measurements indicate that most preferable exterior wall type in cold climates therefore is insulated from outside and optionally with ventilated cavity. Condensate thus appears on either external side of the insulation or within the cavity and is handled without harming rammed earth structure. (Fix and Richman 2009)

4.3. Scheveningen, the Netherlands.

Research of suitable rammed earth moisture protection in Scheveningen conditions was analyzed through the local wind, temperature, and rainfall statistics.

First, the possibility of overhangs and covered terraces was estimated by calculating critical angle of rain incidence and translating it into eventual depth of overhangs. For doing that, the worst-case scenario was determined applying the information from the wind rose of Scheveningen (fig. 73 left) into a mathematical equation:

$$\tan\theta = u/(4.5 \cdot I^{(0.107)})$$

where 'θ' is the angle of rain deflection, 'u' - wind speed (m/sec), 'I' - intensity of rainfall (mm/hr), assumed as 2.5 mm/hr - characteristic for light rain that can be most easily influenced by wind (Ishwar and Bhargava 2005). The maximum wind speed not specified in the wind rose was assumed as a storm that according to Beaufort scale equals to 24,7 m/s (89 km/h; fig. 73 middle).

Results represented in figure 73 (right) show that rainwater angle from western and southern side in case of storm may even deflect by 78,6˚ thus requiring for cantilevers 4.96 times as deep as the height of the building. This is not a feasible architectural solution – cantilevers cannot be the primary rammed earth protection from rainwater in environment of Scheveningen.

Second, the dew point location within two the most typical insulated rammed earth wall types were analyzed: a double leaf earth wall with insulation in the middle (R-value ~2.6; fig. 74, wall type 1), and a single leaf wall with external insulation (R-value ~ 4; fig. 74, wall type 2). Simulations were performed in computer program TRISCO under internal air temperature +25˚C, humidity 50% and external air temperature of -10˚C (as the critical condition derived from climatic statistics of the Netherlands). Results show that double leaf wall is not preferable as the condensation occurs around 11˚C e.i. between insulation and outer earth leaf at any external air temperature below 20˚C. To avoid this problem, a ventilated cavity would be necessary between the two layers, but this is not supported by the construction technology. Second wall type performs well even when external air temperature reaches -15˚C and thus is preferable in terms of moisture protection unless it does not conflict with the design intentions to leave rammed earth exposed to the outside.

4.4. Conclusions

1. High moisture sensitivity specifies rammed earth as preferably applicable in load bearing structures within sealed envelope (internal load bearing walls), especially within climate conditions in Scheveningen where rainwater incidence might be nearly horizontal and uncovered earth external walls might be constantly subjected to condensation.

2. When designed as external wall, rammed earth in Scheveningen conditions must, first, be stabilized and, second, covered with water protective substance (preferably a water repellant) to ensure double safety.

3. Rammed earth could theoretically be successfully applicable in a double skin-system where water protective glass outer layer supplemented with load bearing internal layer out of earth could be a matter of symbiotic and efficient coexistence.

Fig. 72. Moisture protection by overhanging roof. Center of Gravity Foundation Hall in Jemez Springs, New Mexico (2003)

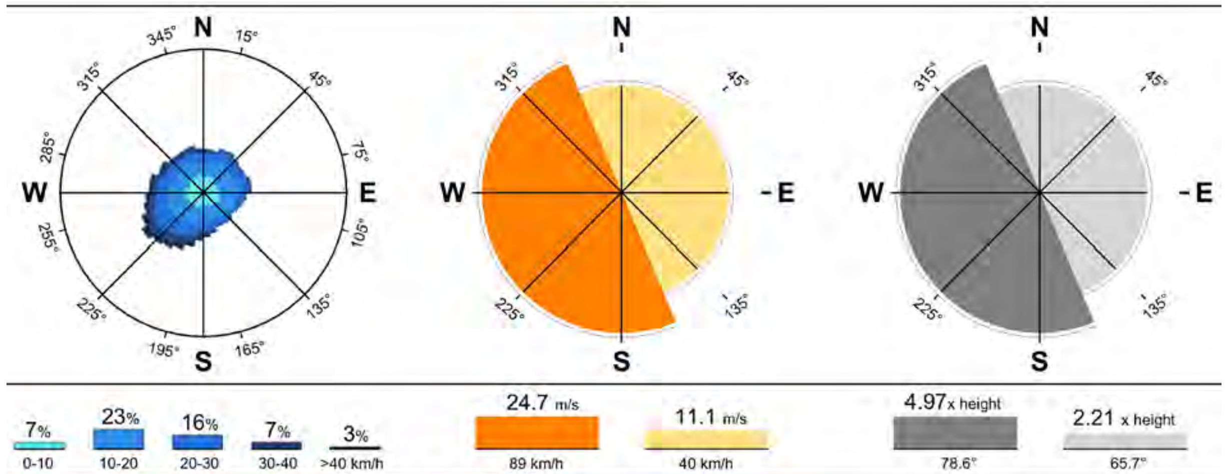


Fig. 73. Wind rose for Scheveningen (left), approximation used for calculations (center), overhang depth and rain deflection angle (right)

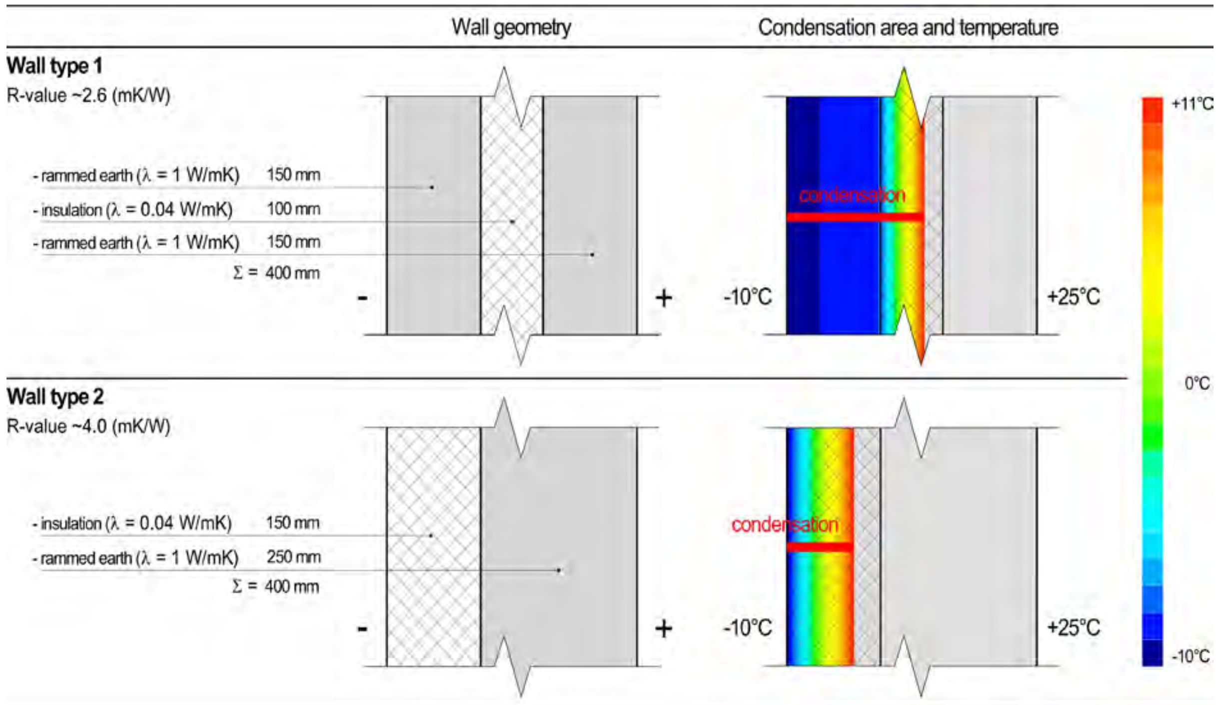


Fig. 74. Dew point calculations for 2 common insulated rammed earth wall types

5. THERMAL PERFORMANCE

Earth materials obtain contradictious thermal qualities. On one hand high density and internal moisture level reflects in large thermal conductivity ratio and thus poor insulation, while on the other - high thermal capacity and heat intake/release velocity provides remarkable thermal mass and natural ability to reduce thermal fluctuations. Historically earth has always been a building material for hotter climates. Nowadays with the development of building technologies and increasing emergence of "green thinking", however, earth application is slightly becoming a worldwide occurence.

5.1. Thermal Properties

Thermal performance of rammed earth largely depends on its density. For unstabilized earth thermal conductivity (k-value) is typically in range between 0.5 - 1.2 W/mK. (Minke 2009, M. Hall, Assessing the Effects of Soil Grading on the Moisture Content-dependent Thermal Conductivity of Stabilised Rammed Earth Materials 2009). For cement stabilized rammed earth thermal resistance can be calculated according to New Zealand building standards, using formula:

$$R = 2.04d + 0.12$$

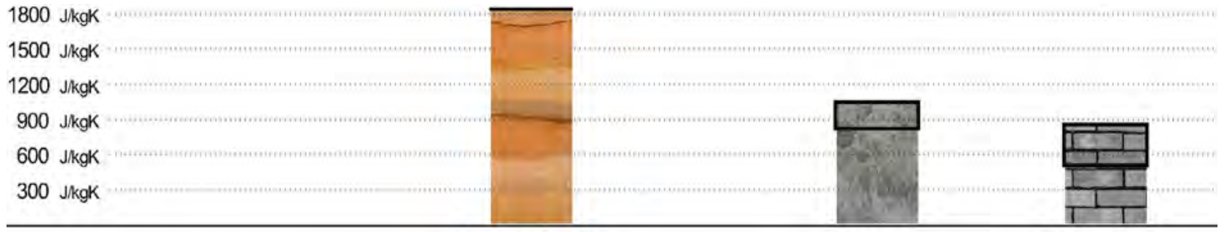
where *'d'* is the cross-sectional thickness of the wall element in meters. (Hall and Swaney, Stabilised Rammed Earth (SRE) Wall Construction 2005) This equals to more optimistic thermal conductivity value of 0.46 W/mK and means that rammed earth is better insulator than concrete and brick. Mentioned values are largely supported by practical experiments indicating thermal resistance of a 200mm thick rammed earth wall slightly below 0.4 mK/W. (CSIRO 2000) This is comparable with the overall thermal resistance of 220 mm bricks with density of 1280 kg/m^3, or 200 mm concrete blocks with density of 2210 kg/m3 and little higher than the resistance of 250 mm concrete wall with density of 2240 kg/m^3. (ASHRAE 1997)

Thermal conductance has a tendency to increase with moisture content. For example, a wall at 60% water saturation has approximately 50% increase in conductivity over the same wall when dry, reaching up to 1.5 W/m^2K. (M. Hall, Assessing the Moisture-content-dependent Parameters of Stabilised Earth Materials Using the Cyclic-response Admittance Method 2008)

Rammed earth can store much energy – its specific heat capacity is typically around 1830 J/m3˚C. (Houben and Guillaud 1994) Parallel it also has high thermal diffusivity allowing for quick heat penetration. Measurements show that the rate of heat transfer through a rammed earth wall is about one inch (i.e. 2.54 cm) per hour. This is approximately six times the heat that passes through an insulated brick veneer wall, and also more than that of concrete. (Hardin, Merry and Fritz 2007, Victoria 2010, Soebarto 2009) Practice shows that use of heavyweight construction materials with high thermal mass can reduce total heating and cooling energy requirements by up to 25%. (Victoria 2010)

	Rammed earth	Concrete	Brick masonry
	unstabilized / stabilized	portland cement	standard
Thermal conductivity, W/mK	0.5 - 1.2	0.7 - 2.6	0.6 - 1.6

Fig. 75. Characteristic thermal conductivity values of rammed earth, concrete and brick masonry



	Rammed earth	Concrete	Brick masonry
	unstabilized / stabilized	portland cement	standard
Specific heat capacity, J/kgK	~ 1830	835 - 1050	500 - 850

Fig. 76. Characteristic specific heat capacity values of rammed earth, concrete and brick masonry

Fig. 77. Straw-loam

Fig. 78. Insulated double leaf wall

Fig. 79. "LIAVER" expanded glass for rammed earth application

Fig. 80. Mixture of straw loam and expanded glass

5.2. Methods to Improve Thermal Performance

A number of material composition, engineering and design oriented techniques exist to optimize thermal performance of an earth building:

5.2.1. Additives

Thermal insulation can be increased by interventions in materials composition when adding porous substances such as straw (fig. 77), reeds and cork, mineral particles as pumice, lava or foamed glass, or waste products as sawdust, wood shavings or husk of grains. (Minke 2009) "LIAVER" – the developer of expanded glass for lightweight loam application (fig. 79, 80) claims that k-value can be reduced as low as 0.11 W/mK. (LIAVER 2010) The insulative effect, however, causes proportional reduction of materials strength.

5.2.2. Thermal Mass Utilization

According to scientific investigations thermal mass effect of a rammed earth wall is determined by its thickness. The maximum effects occurs when a wall is 200 mm thick. Walls with greater thickness have no improvement in thermal mass performance, due to the 24 hour time limit for temperature fluctuations to penetrate more thermal mass, while those thinner than 200 mm are unable to accumulate the potential heat completely. (M. Hall, Assessing the Moisture-content-dependent Parameters of Stabilised Earth Materials Using the Cyclic-response Admittance Method 2008)

5.2.3. Insulation

External walls can be supplemented by rigid insulation (fig. 78). As for nowadays conceptually exist four different insulated wall types each of them offering individual hygrothermal performance and utilization of thermal mass (fig. 85) as well as further variations of vapor barier, cladding, etc (fig. 81 - 84). In hotter climates where the external temperature does not drop below 0˚C insulation is more effective when applied from inside or both sides of the wall ensuring almost constant interior temperature. While in colder climates insulation should be preferably applied from outside as it takes most of the thermal protection load and allows using the maximum thermal mass potential by keeping earth exposed to interior. Here it also works as excellent protective layer against moisture and freeze ensuring high durability of the structure. (Fix and Richman 2009, GREENSPEC 2010)

In colder areas as the United Kingdom and Canada especially popular is the wall type with internal insulation. It has proven to obtain good thermal qualities without compromising aesthetics. Usually both the internal and external leaf thickness is 175 – 200 mm and the insulation between 75 – 100 mm. From the building technology perspective such a system is rather complicated as both leafs must be tied together. This is done by horizontal reinforcement bars applied after each layer of insulation (i.e. usually 30 cm).

5.2.4. Design Issues

Research and built examples point out various design aspects related to window distribution, shading, ventilation, effects on different wall orientations, etc. Largely, however, they are broad and correspond to generally known sustainable design principles and therefore are not further discussed in this paper.

5.3. Scheveningen, the Netherlands

During the research, first, an optimum rammed earth wall type for the Netherlands environment was determined and, second, the relation diagram between wall thickness and its thermal resistance was developed.

Application of uninsulated rammed earth in the Netherlands sets drastic dimensional requirements. To meet the minimum permissible thermal resistance 2.5 m^2K/W determined by the building codes an exterior wall must be 1.25 meters thick even assuming the lowest earth thermal conductivity of 0.5 W/mK. Therefore an additional insulative layer is a must.

The average minimum temperature throughout the year in the Netherlands is above 0˚C (fig. 86). However, there is still high risk of frost in wintertime and during extreme conditions air temperature can drop even below -20.0˚C (e.g. in 1944 the lowest recorded temperature in the Netherlands was -27.40˚C). In order to avoid thaw spalling and ensure materials durability insulation must be applied from outside, thus supporting moisture protection activities discussed in the previous paragraph.

Finally the thickness of insulation is a matter of individual design approach and choice of the material. Built examples demonstrate dominant application of rigid foam with thermal conductivity value close to 0.04 W/mK. Assuming thermal conductivity of rammed earth as 0.5 W/mK, general relations between thickness of an insulated wall and its thermal resistance are represented in figure 87.

5.4. Conclusions

1. Climate specifics of the Netherlands favors rammed earth wall insulation from outside.

2. Minimum insulated rammed earth exterior wall thickness in the Netherlands environment is 300 mm. This corresponds to 200 mm earth layer with thermal conductivity 0.5 W/mK and 100 mm insulation layer with thermal conductivity 0.04 W/mK.

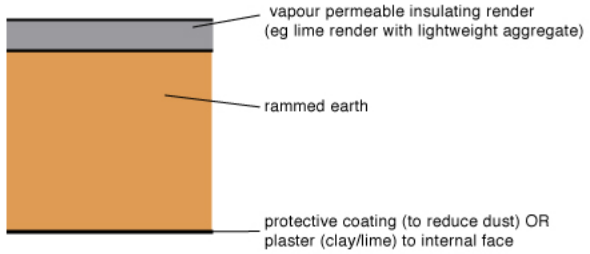


Fig. 81. External insulation

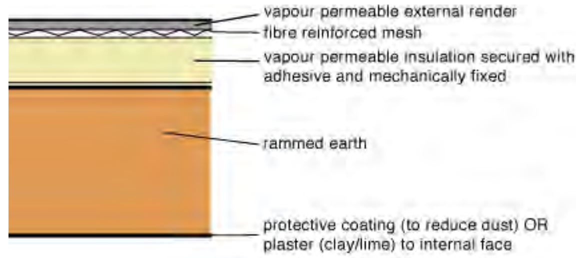


Fig. 82. External insulation

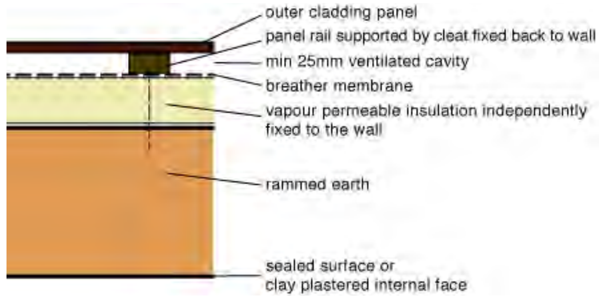


Fig. 83. External insulation with rainscreen cladding

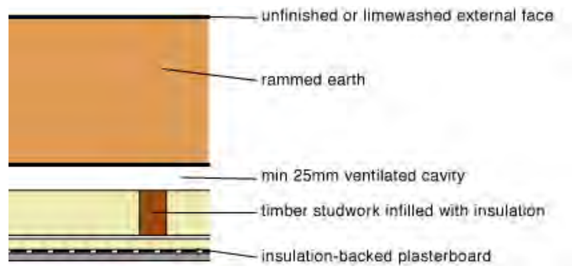


Fig. 84. Internal insulation

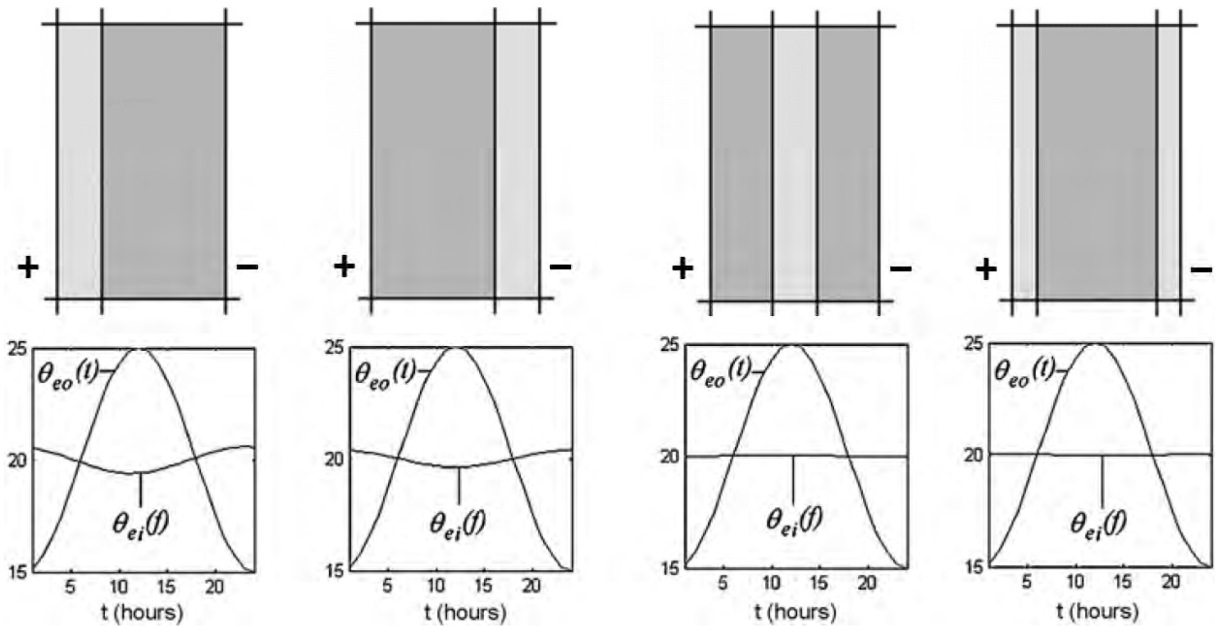


Fig. 85. Typical rammed earth/polystyrene wall types (top) and their respective cyclic indoor temperature response by sinusoidal exterior temperature fluctulation (bottom)

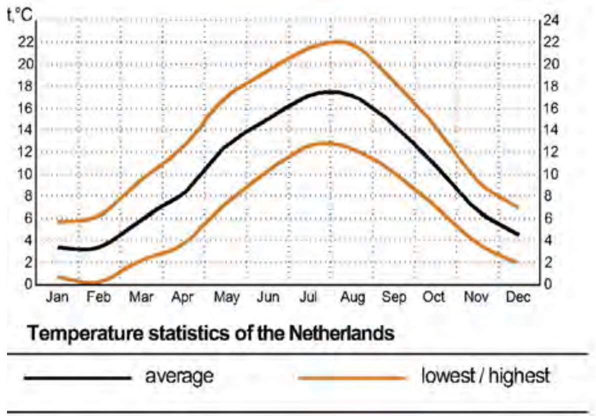


Fig. 86. Temperature statistics in the Netherlands

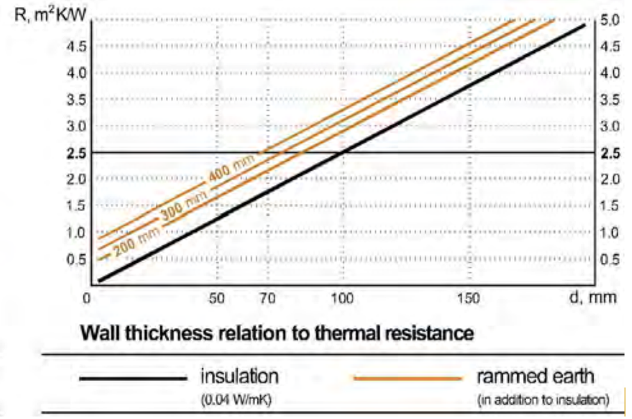


Fig. 87. Wall thickness/thermal resistance relation

6. SHRINKAGE AND CRACKS

Rammed earth elements may shrink and crack. Cracks are especially unwanted occurrence as they may reduce strength of the rammed earth element, cause further permanent damages as, for example, erosion by moisture ingress, and are rather difficult to be fixed.

6.1. Causes of Shrinkage

The highest risk of deformation occurs when material dries or gets in direct contact with humidity. Laboratory experiments prove linear relation between shrinkage and water content of the earth mixture. Earth mixtures with higher water content shrink proportionally more (and thus have higher risk to crack) than drier ones. For example, linear shrinkage for earth mixture consisting of 4% clay, 25% silt and 71% sand at specific environmental conditions equals to 1% at 10% reduction of water content while 2.5% at 25% reduction of water content. (Minke 2009)

Shrinkage also depends on the proportion and type of clay selected. Various clay types in pure form can shrink as little as 4% or as much as 25% (Fromme 1994). For example, mixture of 50% Bentonite and 50% sand has a linear shrinkage 18% when similar mixture with Kaoline shrinks nearly 3 times less. When supplemented by some more sand, silt and gravel this value can be diminished, however, the effect will not be proportionl to reduction of clay content. The most preferable clay minerals in rammed earth application are Kaoline and Illite (Houben and Guillaud, Earth Construction Primer 1984).

Scientific experiments prove that grain size distribution of the aggregates is yet another factor determining shrinkage. Mixtures with coarser aggregates deform less than those with fine ones. Figure 91 reflects the differences in linear shrinkage between similar earth mixtures having different sand grain size distribution. (Minke 2009)

Finally, the temperature and humidity of ambient air is important. Comparing to other materials as baked brick and concrete, rammed earth dries very fast, emphasizing the risk of cracking. Drying time can be slowed down by increasing environmental air humidity and preventing from direct sunshine.

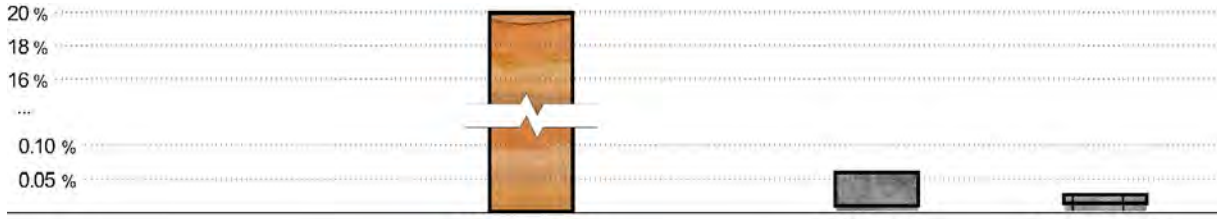
Linear shrinkage of rammed earth in several countries is controlled by relevant building codes. Some characteristic values are given in figure 88. In practical building the shrinkage characteristics of a soil should be examined by laboratory tests and incorporated into the design to satisfy the serviceability requirement of the structure under consideration. (Maniatidis and Walker 2003)

6.2. Precaution Activities

Parallel to considering mentioned direct factors, shrinkage and cracking can be minimized by numerous indirect activities. They might be material composition oriented of design oriented allowing "movements to be controlled or isolated in such a manner that damage to the wall and

	Australia standards 2002	New Zealand standards, 1998	Scotland Scottish Executive, 2001
Maximum permissible linear shrinkage	< 2.5%	0.05%	3%

Fig. 88. Rammed earth linear shrinkage according to various building codes and standards



	Rammed earth unstabilized / stabilized	Concrete portland cement	Brick masonry standard
Linear shrinkage, %	0 - 20	0.01- 0.06	0.016 - 0.028

Fig. 89. Characteristic linear shrinkage of rammed earth, concrete and brick

Fig. 90. Consequences of major shrinkage

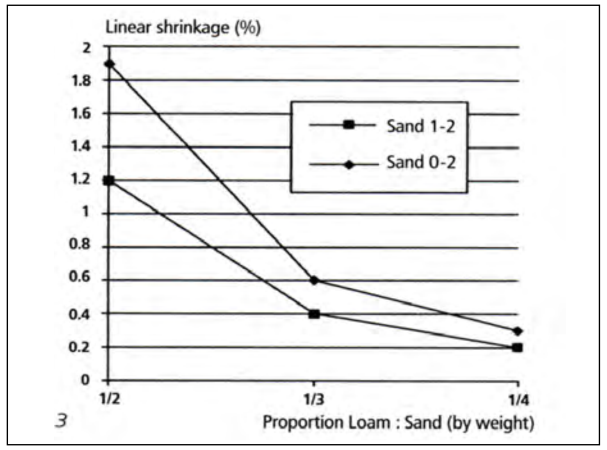


Fig. 91. Shrinkage of earth mixtures with various aggregate sizes

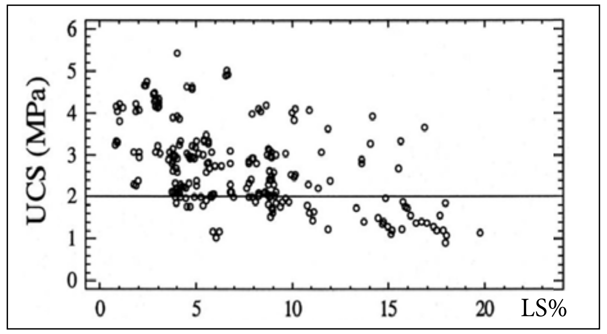


Fig. 92. Shrinkage vs. strength of various stabilized earth mixtures

Fig. 93. Typical rammed earth shrinkage crack

Fig. 94. Clay cracks

the building is avoided and structural and other requirements maintained." (Walker, The Australian Earth Building Handbook 2002)

6.2.1. Additives

As clay is the component responsible for shrinkage, rammed earth deformations can be significantly minimized by reducing clay content and compensating it with stabilizing binder such as cement. Experiments prove that 5% clay replacement with cement can reduce linear shrinkage more than 10 times. It is logical to infer that similar effect would occur if instead of cement adding lime or other stabilizers.

Shrinkage can also be reduced by adding fibers such as straw, wood, and sisal or bamboo fibers. By increasing the binding force they reduce the risk of cracks. According to Australian Standards, the ideal soil for fiber stabilization should have a plasticity index between 15% and 35% with the liquid limit from 30% to 50%.

6.2.2. Control Joints

Material shrinkage without cracking is possible by separating larger rammed earth parts with control joints. Principally this is done in a similar way as for masonry or concrete structures. Typically control joints must be applied after each 2.5 – 5 meters and their width depends on material properties. (Walker, The Australian Earth Building Handbook 2002) For lateral stability vertical control joint in a wall should preferably be made in a tongue-in-groove pattern (corner element with grooves shown in figure 95. Good example for control joint application is the graveyard wall design in Spijk, the Netherlands (by "LEEMWERK") where the 26 meters long structure was actually made out of three separate, 12 meters long parts in order to avoid cracking due to large shear forces (fig. 96).

6.2.3. Elastic Ties and Anchors

Various building parts with diverse shrinkage values usually need to be integrated within a single building system. As for example, rammed earth walls may be connected to additional supporting systems or, more typically, contain doors and windows. In building practice a number of elastic connections exist to avoid gaps or tension between them the various building parts.

New Mexico Standards give several recommended door and window top and jamb joint solutions. A widespread approach is covering the gaps between window and earth walls with a molding trim (fig. 97). More aesthetic solution has been developed for Nk'Mip Desert Interpretive Centre in Canada, where windows are integrated within an insulated double leaf rammed earth wall and rests purely on insulation. Both earth layers thus can freely expand and contract regardless of the window frame avoiding any cracks or gaps (fig. 98)

Interesting method for attaching decorative, self bearing rammed earth wall to supportive concrete wall just behind it has been developed by "LEEMWERK" in the city hall of Coevorden, the Netherlands. Both walls were connected using specially designed sliding anchor system. Vertical u-profiles with a certain distance were attached to the concrete wall acting as a system of rails, while t-shaped anchors with one end attached to the rail were integrated into the earth wall allowing for vertical shrinkage independent from the recessive wall (fig. 99, 100).

6.2.4. Repairing Cracks

"In rammed earth walls unsightly shrinkage cracks can be repaired by pointing or filling with dampened soil of similar characteristics" – color, grading and plasticity. (Maniatidis and Walker 2003) Surfaces of the crack must be moistened to ensure adhesion and the fill mixture have as little linear shrinkage as possible. (Minke 2009)

Structural cracks should be fixed only when the deformation process has stopped. It may require temporary formwork and in occasion also structural support of elements that rest on damaged rammed earth structures. After ramming the new material into place, the exposed surface should be cut back to the original line of the wall (fig. 101, 102). (Red Earth Dreaming 2010)

6.3. Scheveningen, the Netherlands

Relative air humidity of building site may whether stimulate or slow down rammed earth drying process and thus the risk of cracking. Statistical data indicate average air humidity of the Netherlands in range between 67 - 88%. That is notably higher than most other countries in the world with average values around 50 - 60% (Climatetemp 2011).

6.4. Conclusions

1. Shrinkage is largely dependent on material specifics and precaution activities selected for each individual design.

2. What depends on site characteristics, Netherlands and especially the coastal area (including Scheveningen) due to its high relative humidity favours slow rammed earth drying process minimizing the risk of shrinkage cracks.


Fig. 95. Corner element woth tongue-in-groove joints


Fig. 96. Control joint for graveyard wall in Spijk by "LEEMWERK"

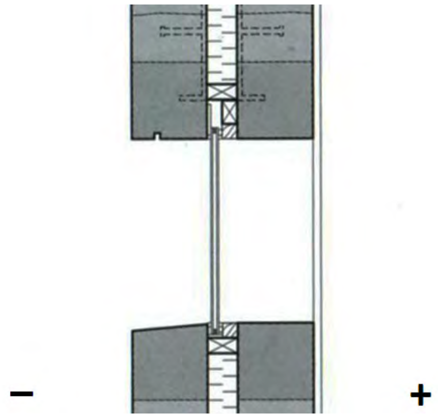


Fig. 97. Window top with a molding trim

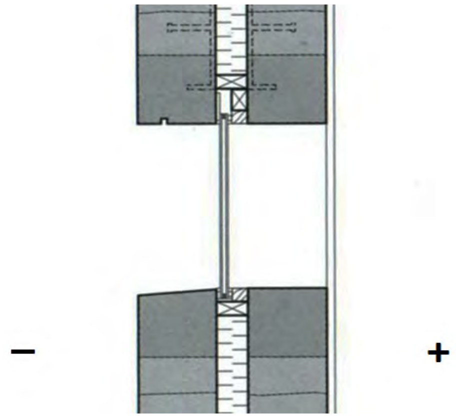


Fig. 98. Window anchorage in insulation cavity


Fig. 99. Sliding anchorage to supportive concrete wall


Fig. 100. Sliding anchors being covered


Fig. 101. Repairing rammed earth element


Fig. 102. Aesthetics of repaired element

7. CONSTRUCTION METHOD, SPEED AND COSTS

One of the main arguments against rammed earth application mentioned by members of building industry is its relatively low construction speed and high costs. Numerous literature sources on the contrary speculate with surprisingly low numbers or claims of progress in rammed earth construction technology representing its application as increasingly affordable. To understand the real picture it requires a deeper look into earth construction technology and factors determining its costs.

7.1. Construction Method

The process of performing rammed earthwork usually consists of four phases: soil preparation, formwork, compaction and post processing. This paragraph gives a deeper analysis of the last three as the first one is analyzed in chapter 2 - Soil Composition.

Formwork is the most time consuming construction phase typically taking up to 50% of whole building process. Principally it is similar as if building with concrete requiring for right choice of formwork system, careful installation and aligning, and finally stripping and cleaning it. (Easton 1996) Most of the formwork systems used for rammed earth are based on in-situ cast concrete formwork systems consisting of sheeting material against which earth is compacted, a system of strengthening and stiffening elements, ties and bolts, and inclined props to ensure overall stability. The exploitation of formwork though is slightly different due to materials properties and specifics of compaction. First, earth in contrast to concrete gains certain stability immediately after ramming thus allowing to remove the formwork soon after the compaction is done. Second, the ramming process itself is gradual and requires construction of formwork in horizontal strips preferably not more than 600mm high (fig. 103, 104) in order to provide comfortable working environment for a person doing the ramming. Building practice, however, show that application of concrete formwork due to its superior availability and flexibility in shaping customization is dominant.

Compaction as the last phase of building process is done gradually in horizontal layers. First, a certain amount of soil is poured into the formwork, then leveled in order to provide even, approximately 15 cm thick layer and, finally, compacted to 8 – 10 cm high solid course (fig. 107, 108, 111). In most of developing countries this is done by a ramming pole using only a human energy (fig. 115). More advanced builders use a pneumatic hand rammer (fig. 116) that increases the compaction energy and speed. There exist also vibrating rammers that can be adjusted for rammed earth application (fig. 117). Measurements show that the ideal compaction energy is around 250 kNm/m3. (Hardin, Merry and Fritz 2007)

When the ramming is done and the formwork removed, earth walls preferably should be brushed to remove loose particles and smoothen the surface. Post-processing may also include treatment with water repellants, painting, finishing or other activities described in previous paragraphs.


Fig. 103. Formwork


Fig. 104. Formwork


Fig. 105. Soil delivery


Fig. 106. Soil delivery


Fig. 107. Ramming


Fig. 108. Ramming


Fig. 109. Removing formwork


Fig. 110. Final result

7.2. Construction Speed

Fluent rammed earthworks typically require as minimum a team of 3 workers, each having an individual role – one responsible for delivering the material, the other leveling uncompacted earth, and the last one performing actual ramming. Simultaneously all of them should also participate in replacement of the formwork and other activities. Building practice shows that in tangible results typical output can be estimated in range between 10 – 15 m² of 300 mm thick solid wall per day per team or 3 - 5 m² per person respectively. (Hall and Swaney, Stabilised Rammed Earth (SRE) Wall Construction 2005, "LEEMWERK") Obviously this is slower than building with concrete and even brick.

7.3. Costs

Speculations of rammed earth building costs is one of the most contradictious issues. Some literature sources mention 200-300 EUR/m². (Hardin, Merry and Fritz 2007), several others claim that rammed earthworks are 5 – 15% more expensive than alternative building (Cruickshank 2005) while there are also claims of difference for more than 2 times. Such opinion discrepancies can largely be explained with geographic and economic aspects for each individual case.

First, natural soil resources of each individual site may vary from perfectly suitable to extreme insufficiency of some rammed earth components. Obviously anything to be imported increases costs, moreover considering that rammed earthworks operate with large material amounts.

Second, the total costs also depend on economic development of the country the building is erected. Considering high labor intensity required for the construction process, workers salaries but also all the potential services as transport, rent of formwork and tools, laboratoric tests etc. is major variable. And this is where a fundamental difference in philosophy of rammed earth application between developing and developed countries occur - when the first ones perceive rammed earth as the most existential form of building an accomodation affordable to anyone, the latter ones represent it as exclusive and expensive design product somewhat overshadowing its inherited qualities.

7.4. Alternative Contruction Methods

Increasing technological development results in emergence of new earth construction techniques promising numerous benefits including higher construction speed, reduced costs and design flexibility.

In order to fasten construction of earth, some companies offer standardized construction solutions as, for example, "Stabilform" formwork system (fig. 114) specifically designed to meet the earth building requirements, or vast variety of prefabricated compressed earth elements (fig. 112, 113) ready for in-situ installation. (Hall and Swaney, Stabilised Rammed Earth (SRE) Wall Construction 2005, Minke 2009)

Many other construction techniques cross the border of rammed earth definitive meaning. For example, the new earth casting method allows avoiding shrinkage and cracking by liquifying earth with special substances and keaping the amount of water to a minimum. The end result makes perfect analogy to concrete.

Especiall promising is earth 3D printing when sand particles are glued together with special inorganic binding ink in nearly any possible shape (fig. 118, 119). Mechanical properties of the output are superior to those of portland cement. Visually the material resembles marble and is cheap and 100% environmentally friendly. For today a 6 x 6 x 1 (w,d,h) meter large 3D earth printer has been designed by Italian inventor Entico Dini. It is possible to take the printer exactly to the building site. And unlike the rammed earth, 3D printing is possible with any kind of sand, dust or gravel (Dini, 2010).

7.5. Scheveningen, the Netherlands

Approximate rammed earth building speed and costs in the Netherlands was determined through interviews of members representing particular field. According to professionals, dominant use of advanced construction tools allow reaching the upper threshold of construction speed ~2m³ uncompacted earth per person per day. Construction costs though are higher then average values found in theoretical study. In the Netherlands rammed earthwork may cost as minimum twice as much as alternative construction in concrete thus adding an exclusivity lable to the material.

Parallel a comparison of materials costs per weight unit between unstabilized and stabilized rammed earth (4 various stabilization mixtures) as well as concrete and brick masonry was made with a reference to dominant material prices in market in 2011 (fig. 120). Information will be used for cost estimates of design to be developed.

7.6. Conclusions

1. Rammed earth building technology need to be reconsidered in a way to increase construction speed and reduce costs.

2. Earthworks in Scheveningen, the Netherlands might be relatively expensive due to insufficiency of building componentes as clay and gravel as well as high labor and material expenses.

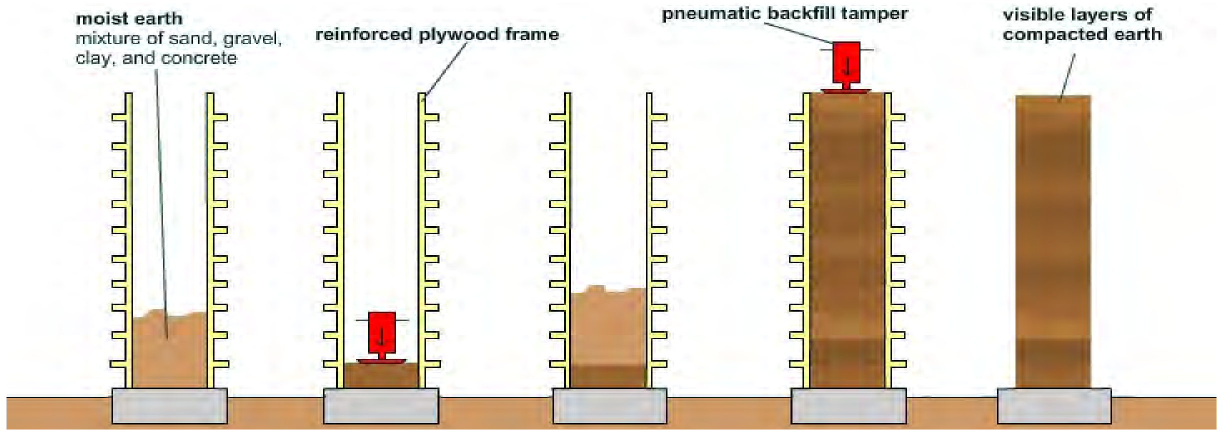


Fig. 111. The schematic sequence of building rammed earth wall

Fig. 112., 113. Prefabricated earth blocks

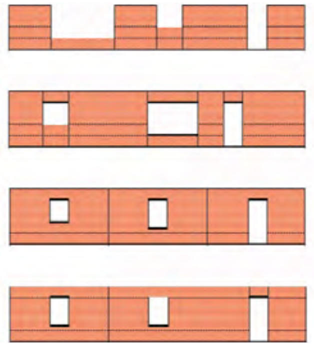


Fig. 114. "STABILFORM" design

Fig. 115. Ramming pole

Fig. 116. Pneumatic hand rammer

Fig. 117. Vibrating rammer

Fig. 118. 3D earth printer in action

Fig. 119. 3D earth printed pavillion model

	Rammed earth	Rammed earth	Concrete	Brick masonry
	unstabilized	stabilized (4 -12% cement)	portland cement	standard
Price, EUR/kg	0 - 0.02	0.005 - 0.033	0.03 - 0.05	0.7 - 3.1

Fig. 120. Characteristic price of rammed earth mixture, concrete and brick (material only)

DESIGN

8. INTRODUCTION

Earth is one of the oldest and most widespread construction materials on our planet. For the past centuries overshadowed by architecture of fossil fuel era, earth construction is slowly regaining its status and becoming integral part of "green thinking". For architects and engineers re-examination of earth construction under 21st century conditions opens new horizon to challenges and innovations.
Second part of this report reflects process of MSC AE graduation studio in after-research phase. It describes theoretical studies performed in order to determine thermal and structural potential of earth constructions, a search for methods to interpret findings in architecture and, finally, the design solutions from architectural engineering point of view.

8.1. Design Focus

Design proposal of a hotel building in Scheveningen represents an alternative way of compressed earth design thinking and compares it with classical one. Design is based on academic research about materials ultimate thermo-structural performance as well as nowadays available technical methods in translating it into architecture.

8.2. Design Methodology

Design process can be formulated as continuous search for answers on numerous "why" and "how" questions:
- "why" earth construction has largely remained the same ever since its origins and "how" can it be changed to reach different, more challenging result?
- "why" most of earth structures are forced against their nature (in other words, "why" we build out of earth as it would be, say, concrete?)and "how" could earth buildings be shaped to reflect materials real structural character?
- "why" earth implementation is largely defined by climatic and typological aspects and "how" can materials incredibly flexible nature be utilized to dissolve these boundaries?

During the study, search for answers on these and many other questions resulted in numerous potential solution scenarios – some of them realistic and less innovative (hybrid earth retailing walls, earth cores as load bearing elements, earth stabilization with cement to increase structural performance), some others – with more questionable feasibility but academically very interesting (heating strategy for tower volume, solutions to avoid "alienated" materials for thermal and moisture protection, "cave" concept and sandbag formworking). Keeping both realistic and innovative side made design and research process from students perspective especially valuable.

Fig. 121. 3D visualization of hotel design proposal. View to the atrium

Fig. 122. 3D visualization of hotel design proposal. View to the retaining wall

9. TECHNICAL DRIVERS OF THE DESIGN

Extensive research mainly based on computer simulations was carried out in addition to theoretical study done in MSc3 phase in order to gain deeper knowledge of materials' properties and use them as technical drivers for design concept.

9.1. Thermal Mass

Apart from aesthetic qualities and low environmental cost earth as a construction material obtains enormous thermal mass. In warm climates this is used for stabilizing day/night thermal fluctuations. The purpose of thermal study was to examine the ultimate potential of earth thermal mass in moderate climates (the Netherlands).

9.1.1. Computer Simulations

Thermal simulations were performed in computer software "CAPSOL". For simulation object a compressed earth wall with specific heat capacity 1830 J/kgK was selected. The wall was aligned to East-West axis in order to provide maximum solar gain on one side and minimum on the other (Figure 123). The purpose of the simulation was to determine yearly temperature fluctuations in the middle of the wall and 5 cm from East and North surfaces while keeping the wall thickness variable. Simulations for 0.4, 1.0, and 5.0 meter thick walls were performed and results are represemted in graphs (Figure 123 - 125).

CONCLUSION: 5 meter thick earth wall under climatic conditions of the Netherlands is able to maintain constant temperature in the middle of it all year long.

This rose a question if temperature in the middle of the wall can be increased by passive means. As a result two methods were found and tested. First, the wall was covered from all sides (except Southern) with 20cm layer of foam insulation with k-value of 0.04 W/mK in order to slow down the heat exchange with ambient air (Figure 126). Second, in addition to insulation a layer of glazing was applied in front of Southern façade thus providing protection from wind and frost as well as creating an air cavity that would heat up due to solar radiation and transfer the heat by conduction further to the earth wall (Figure 127).

CONCLUSION: 5 meter thick insulated earth wall with glass layer and air cavity on Southern side is able to maintain stable temperature of +18˚C in the middle of it all year long.

9.1.2. Thermal Relations

During the research relation between numerous variables involved in thermal behavior formation were determined and conclusions derived:

- Earth wall according to thermal fluctuations should be divided in 2 zones – stable and unstable;
- Increase in wall thickness above 5 meters slightly decreases the unstable area (temperature fluctuations above +/- 2°C), however at certain point thickness increase will have no further effect;

-Openings decrease the thermal stability. In case of

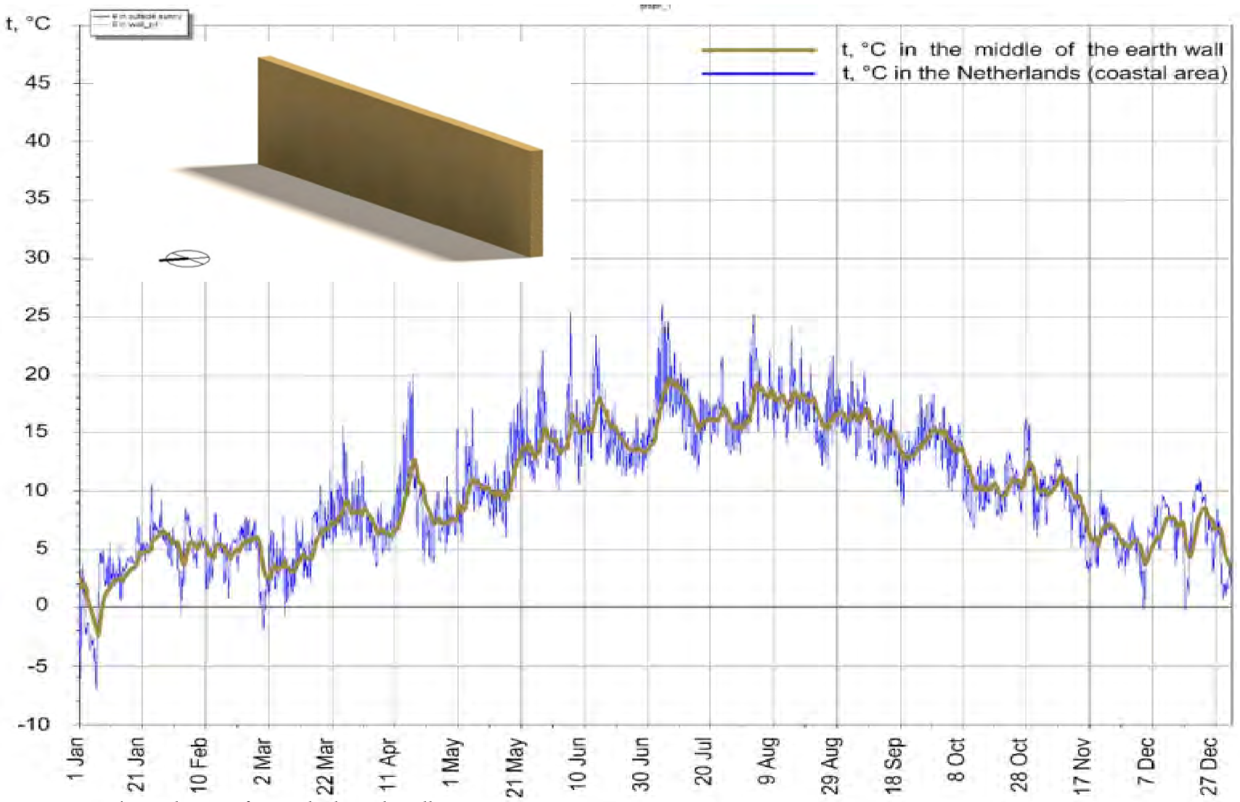


Fig. 123. Thermal mass of 0.4m thick earth wall

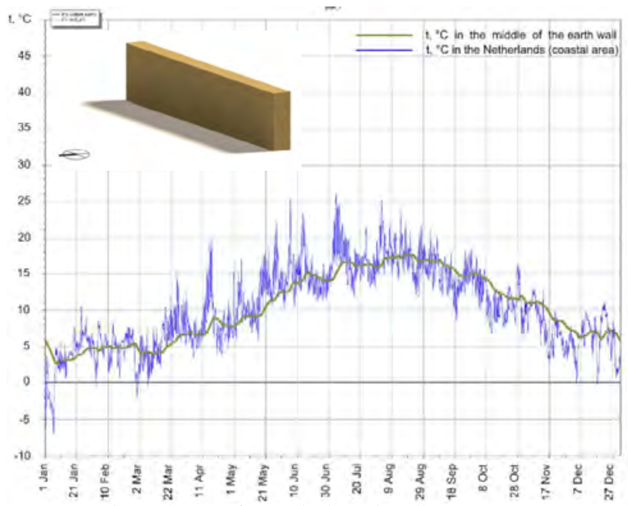


Fig. 124. Thermal mass of 1.0m thick earth wall

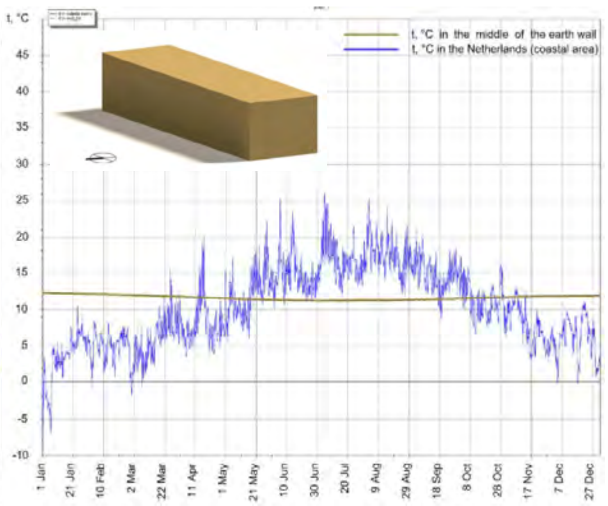


Fig. 125. Thermal mass of 5.0m thick earth wall

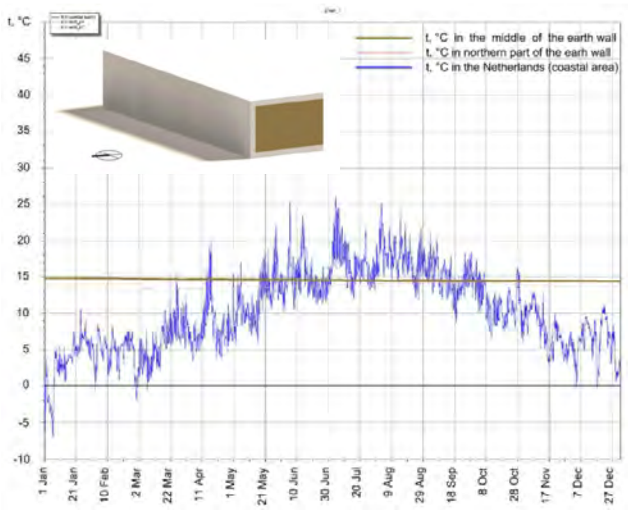


Fig. 126. Thermal mass of 5.0m thick insulated earth wall

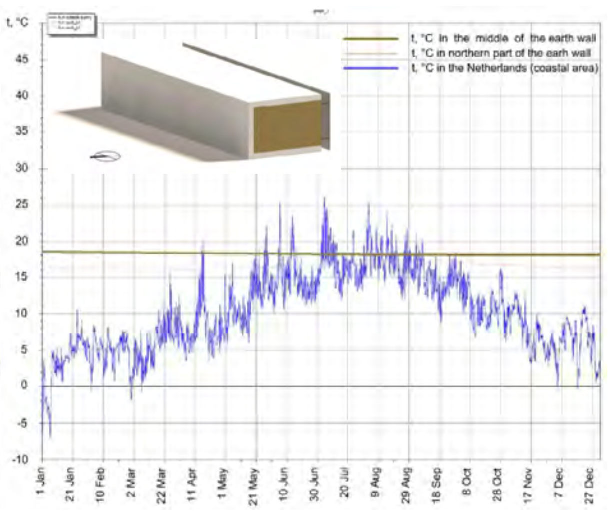


Fig. 127. Thermal mass of 5.0m thick insulated earth wall with glass

openings, each 1m2 southern glass surface needs at least 5m3 rammed earth to maintain reasonable stable area;
- Insulation increases average temperature inside the volume and also minimizes instable temperature area on northern side;
- Glass on southern side slightly increases unstable area, but significantly increases average temperature inside the volume;
- Earth surface contact with warm air rather than exposure to sunlight is critical in heat-up time;
- For 5 meter thick wall thermal saturation occurs after approx. 650 days;
- Openings exchange heat between air and earth. It can be used to stabilize fresh air temperature and heat/cool the wall;
- Stable area (annual temperature +/- 2°C) occurs at 3m thickness. Increasing mass, increases stable area.

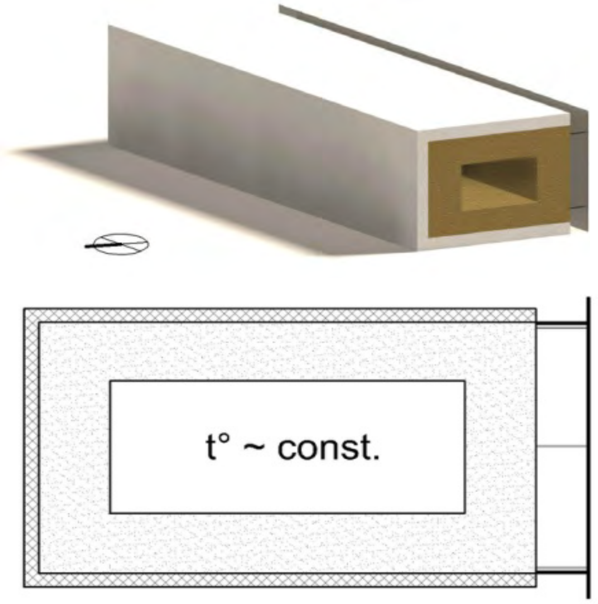


Fig. 128. Thermal concept

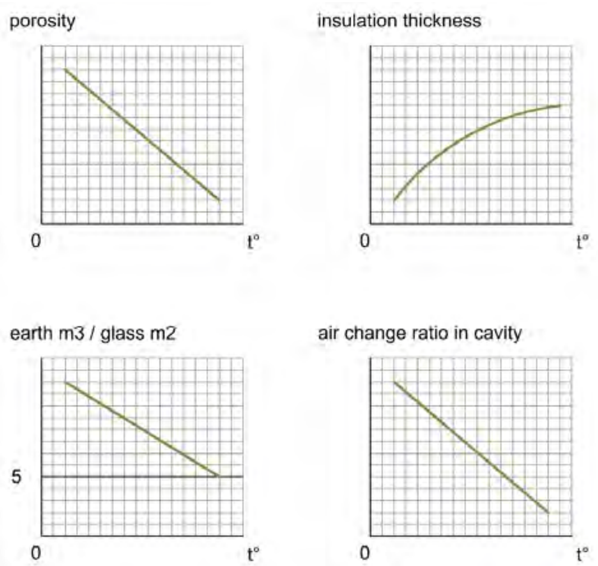


Fig. 129. Relation between thermal design aspects

9.2. Structural Potential

Research of thermal behavior resulted in question if openings can be made in a very thick compressed earth wall from structural point of view. In practice compressed earth is largely being used for construction of walls only. Inconsistent character of materials microstructural composition resulting in high safety factors has always hindered its wider application. And, unlike for most other materials as timber, concrete and steel, there does not exist any rules of thumb for determining necessary dimensions in compressed earth structures.

9.2.1. Computer Simulations

The purpose of structural study was to examine possible shapes and dimensions of openings that can be made in compressed earth structure. Simulations were performed in computer software "AUTODESK ROBOT". Average strength values as input data for simulations were derived from theoretical research carried out during MSc 3 phase (Figure 133).
Initially simulations were performed for 5 x 5 meters large earth block with variable height as this is the maximum size compressed (rammed) earth can be produced in one piece without expansion joints.
First round of simulations were performed to determine the maximum height for cutouts depending on inclination angle and width of supported area. Cutouts were classified as positive, vertical and negative. Then following 2 boundaries have been determined for support thicknesses of 0.4, 0.7 and 1 meter:
- how high can the cutout be not to exceed the maximum permissible compression in outer part of the support;
- how inclined the cutout can be not to exceed the maximum tension in inner part of the support.
Finally the in-between values were calculated by interpolation and summarized in a graph (Figure 135, left column).
Second round of simulations was performed to determine maximum span of an opening depending on the load on top of it (i.e. how many stories are on top). Initially 1.2meter to 3.5meter wide 2-dimensional spans were tested for both the maximum compression on edges as well as maximum tension in the middle. Apart from straight spans also triangular were tested as they are closer to optimum compressive shape – a reverse catenary - but required less computational time. Results were summarized in graph (Figure 135, middle column).
Simulations were continued by testing 3-dimensional openings. For simulation abject a dome-shaped opening has been select and tested in similar way. Results show that expansion joints hinder the utilization of ultimate compressed earth potential as

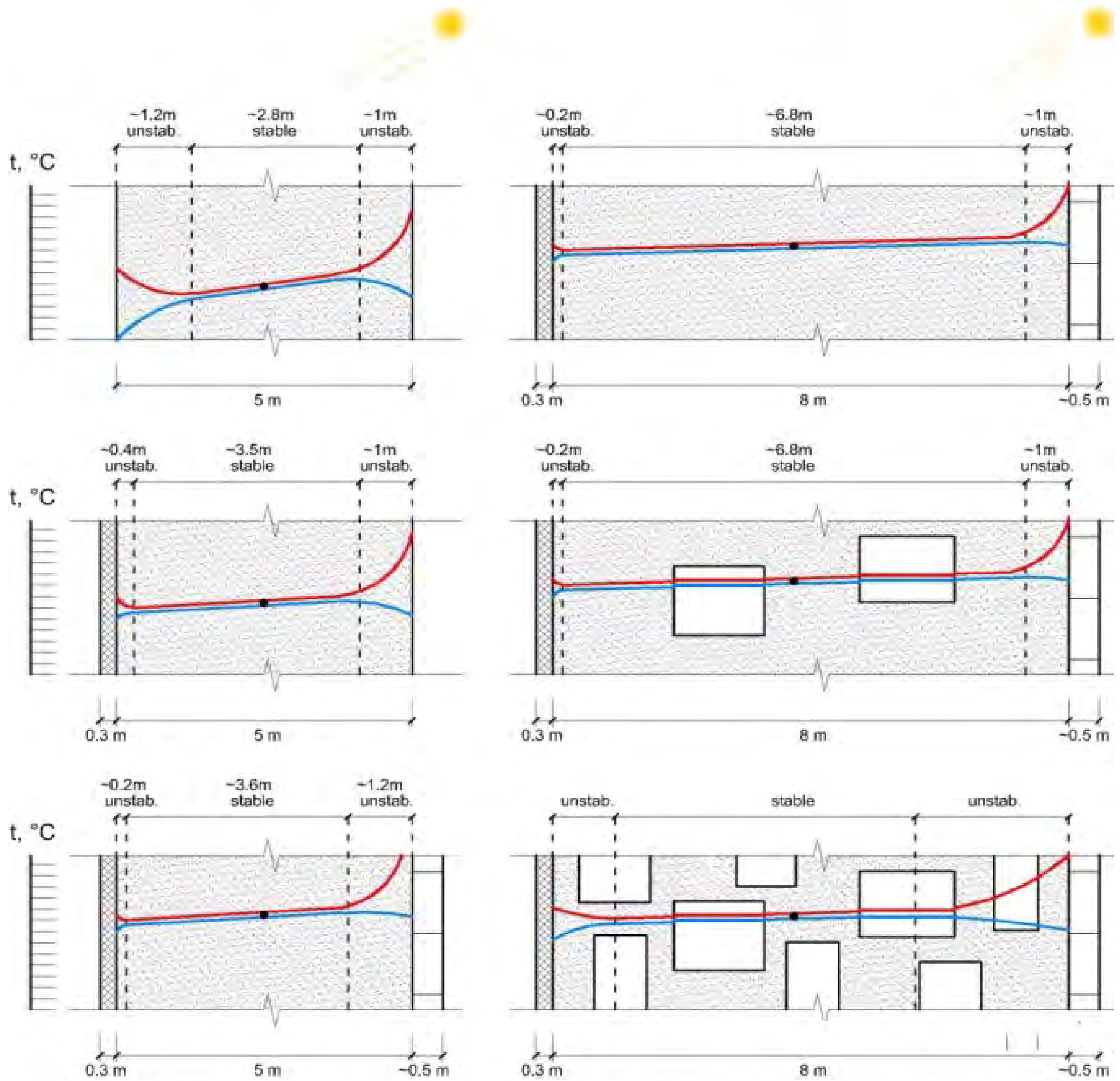


Fig. 130. Stable and unstable thermal zones for various massive earth wall configurations

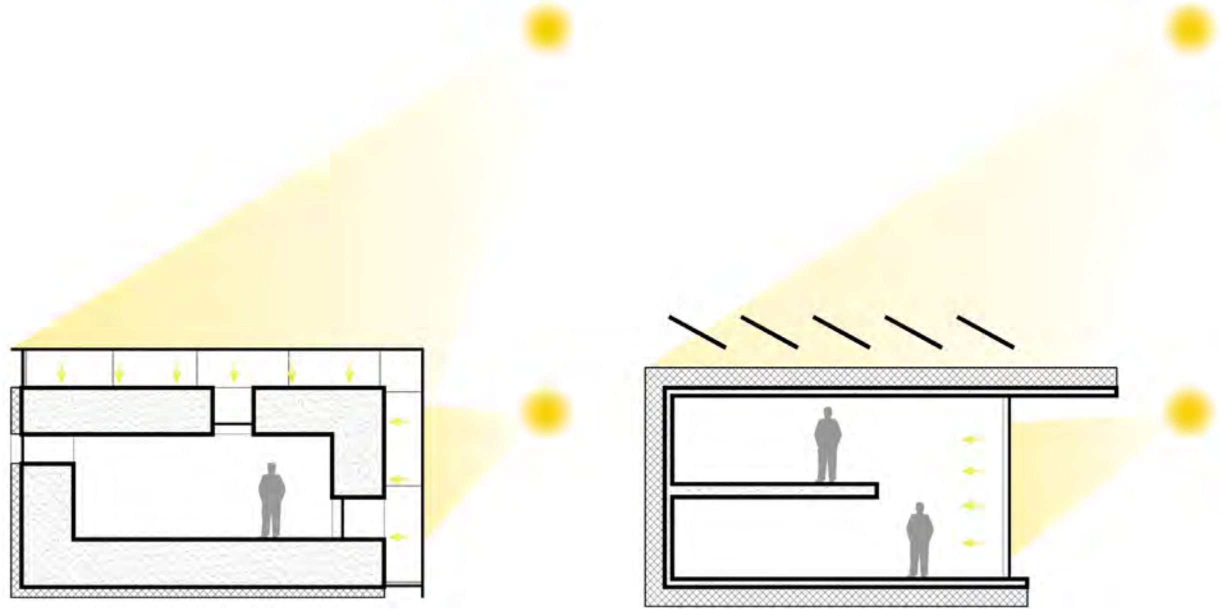


Fig. 131. Summer and winter solar energy utilization in high thermal mass building (left) and typical passive building (right)

the maximum possible span of 5.5 meters exceeds the maximum permissible distance between expansion joints of 5 meters.
Third round of simulations was performed in order to determine minimum necessary wall thickness between two openings. Considering results from previous simulations, spans of neighboring openings were assumed as 1.5, 3 or 5 meters large. Calculations were performed for various loads on top of openings and tested on maximum compression on bottom part of the wall. Results summarized in a graph (Figure 135, right column).

9.2.2. Simulation Results
Neglecting requirements for expansion joints, structural potential of compressed earth is suitable for design challenge – hollowing out massive compressed earth structure in order to facilitate architectural program - spaces with spans up to 5.5 meters. Depending on openings shape, simulation results in very simplified way are represented in figure 136.

9.3. Construction Method

Structural simulations rose a question of construction methods (earth compaction by ramming technique) suitability for design challenge as maximum possible span exceeds the maximum permissible distance between expansion joints. Therefore the analysis of more advanced earth pouring method - a construction technique when earth in liqid form is cast into formwork similar as concrete - was performed.
Pouring technique has following advantages:
- due to higher water content earth shrinkage during evaporation is minimized and does not require expansion joints;
- pouring is much faster than traditional ramming. Using ramming technique 1m3 output needs 6 man hours while using pouring technique from a pump less than 1 man hour (excluding material preparation, formwork installation and dismantling and after treatment of the earth structure). This makes pouring also much cheaper;
- ramming technique normally requires special formwork while pouring can be done in standard concrete formwork. In case of particular design concept decision for choosing pouring technique is especially important as it enables option to use sandbag in-fill formwork that could not provide necessary rigidity in case of ramming;
- pouring does not require special skills as ramming does.
As a result ramming method has been replaced with earth pouring.

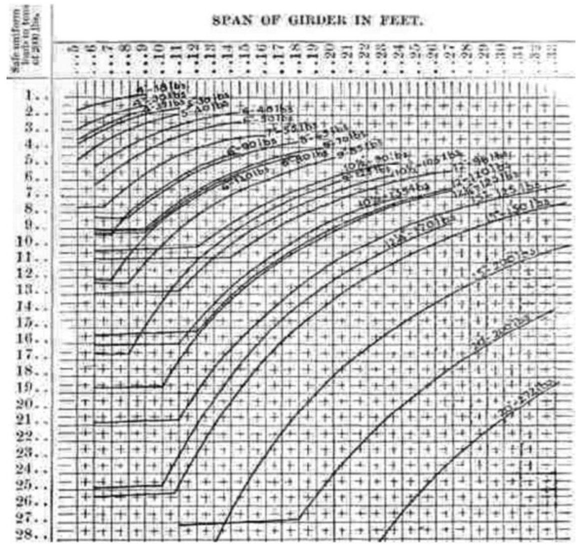


Fig. 132. Cross section and span relation for various timber beams

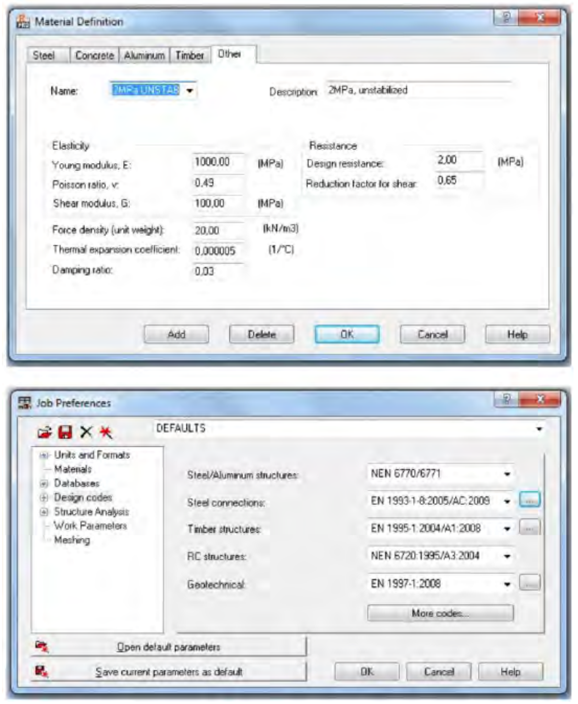


Fig. 133. Calculation settings for structural tests

Fig. 134. "AUTODESK ROBOT" software used for calculations

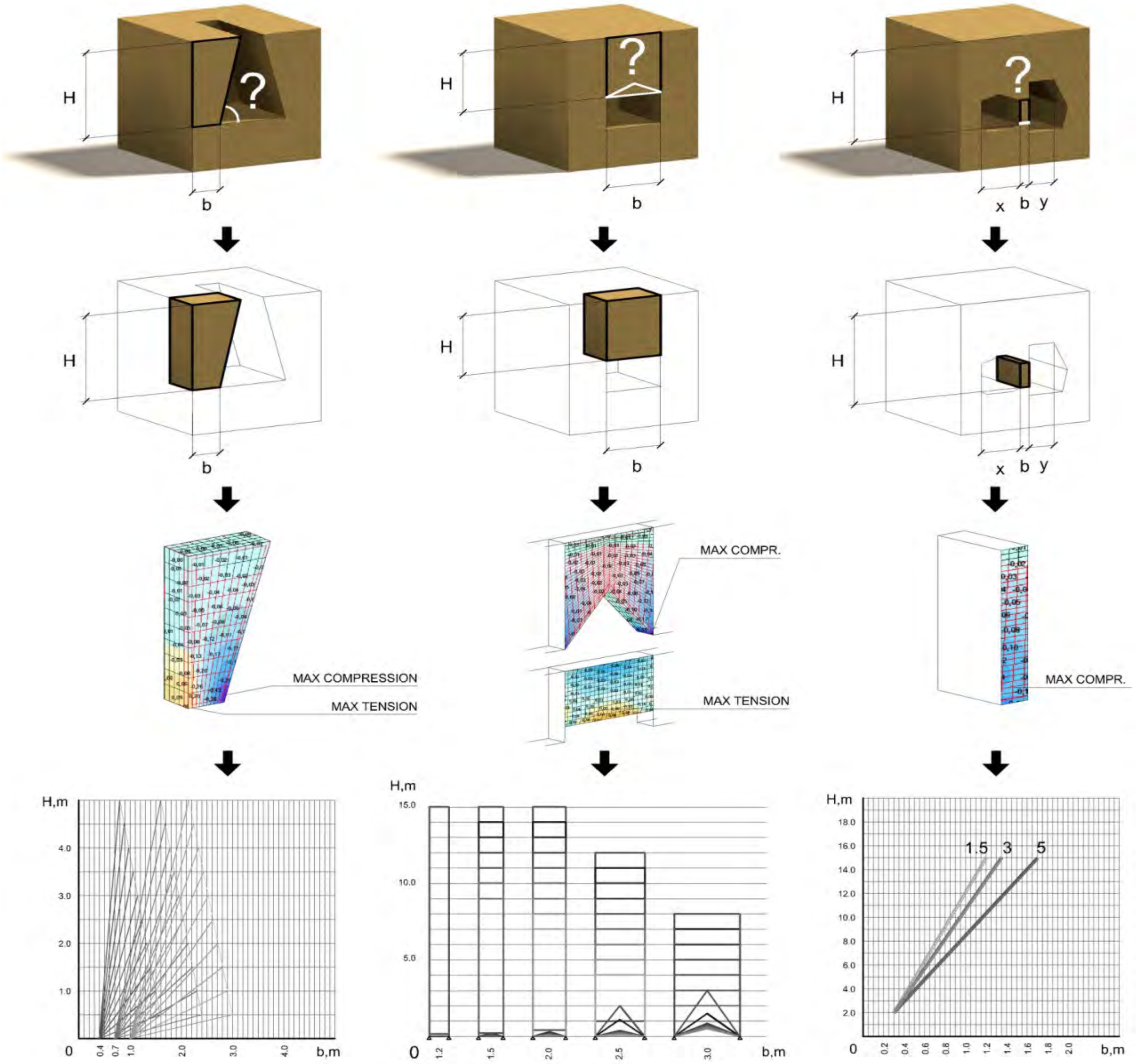


Fig. 135. Structural calculation principle for 2D openings

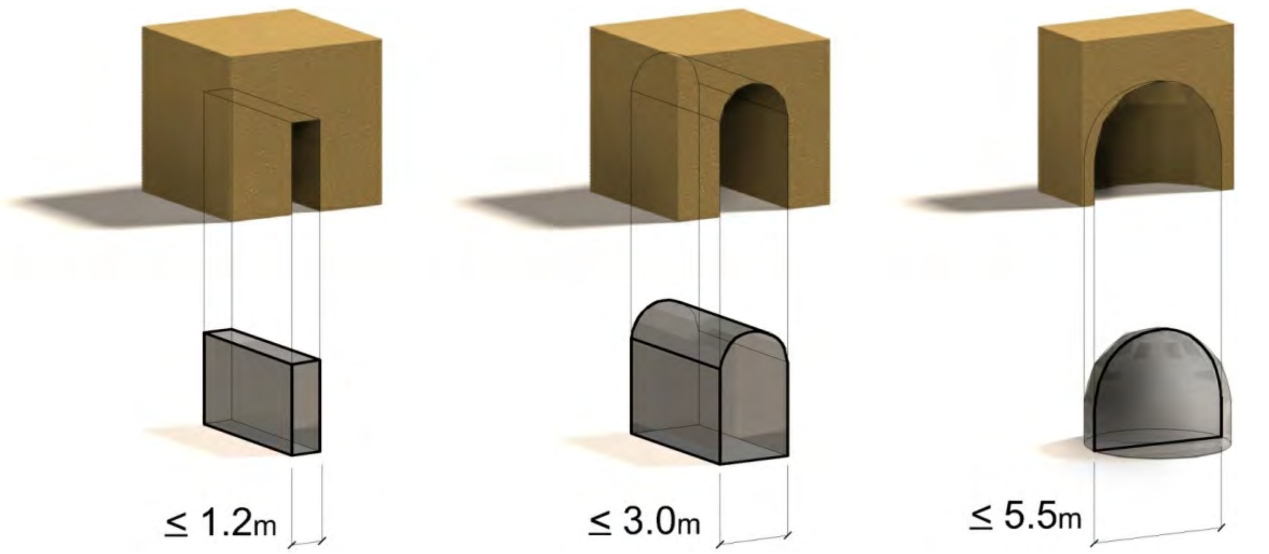


Fig. 136. Simplified representation of calculation results

10. DESIGN CONCEPT

Architectural concept of the building is based on theoretical findings about compressed earth with emphases on its thermo-structural properties. Selection of function, building site, layout configuration and engineering has all been done in a way to support earth and its properties as main design driver.

10.1. Function

Hotel function has been selected because of several reasons:

- structural capacity or compressed earth is suitable for typical hotel room requirements;
- hotel function provides public access allowing to experience material to anyone in both public and more intimate atmosphere. At the same time control of facilities is of utmost importance to protect earth from mechanical damages. Regular room service and collection of personal data during check in phase is way to share the responsibility of facility maintenance between staff and hotel guests;
- limited daylight requirements (sleeping rooms can also be dark) meet with structural limitations to make extensive openings in earth structures;
- being rather unique architectural engineering concept, earth hotel could attract more attention than a regular hotel thus resulting also in commercial indicators;
- it is scientifically proven that due to materials natural origin earth structures ensure better quality of sleep than most others.

10.2. Site

Area at the end of Scheveningen boulevard (Figure 137-139) has been selected as the most suitable for compressed earth hotel building due to following reasons:

- being a transitional space between two opposite worlds – a city and dunes - it has strong relation to earth architecture that unifies both of these worlds in architectural language;
- from urban planning point of view the existing ending of Scheveningen boulevard is abrupt and illogical. It obviously misses a contextual landmark and earth building has all potential to fill this gap;
- several existing hotels right next to the chosen building site supports the selected function. It is proven economical phenomenon that more hotel buildings located not far from each other have symbiotic economical effect on each other.

As a part of design process site analysis was carried out.

10.3. Spatial Division

According to program analysis, standard hotel building requires wide spectrum of facilities. Most

Fig. 137. Site. Areal view and topography

Fig. 138. Site. View from West

Fig. 139. Site. View from East

of them were summarized and divided in 3 groups depending on suitability to earth construction specifics, sell-ability and requirements for climatization. As a result program has been divided in 3 groups (Figure 143):
1) spaces that can be entirely made in earth (hotel rooms);
2) spaces that can not be made entirely in earth due to structural limitations (most of public facilities as well as several staff facilities);
3) spaces that do not "deserve" to be made in earth (parking lots, technical facilities).

10.4. First Concept

Initially the volumetric configuration was solved as organic, ameba-shaped hotel room volume entirely surrounding public facilities that were placed in atriums. Technical and parking spaces were placed in separate underground volume adjacent to the building (Figure 140).
Glass roof covering was intended to have dual function – first, collect the heat and provide it by vertical shafts down into the massive earth volume that according to thermal study would evenly absorb it thus increasing temperature in voids (hotel rooms), and, second, protect earth from rainwater (Figure 141, 142).
This volumetric configuration, however, turned out problematic later in detailization phase when working on methods to solve the roof glazing. Although being light and transparent, glazing required load bearing frame that would be attached to compressed earth and made an impression of alienated structure. Moreover, these were limited possibilities to solve the connection between wall and roof (glazed volume needed to be closed in order to collect the warm air) that forced a reconsideration of volumetric configuration (Figure 146).

10.5. Volumetric Study

Purpose of the study was to analyze possible volumetric configurations and come up with the most effective way to balance architectural, engineering, and aesthetic aspects. Programmatic division between volumes was kept according to initial concept. First, possibilities of using glass for both collecting heat and protecting earth from erosion were examined. Some of results have been visualized and represented below:
1) Earth volume in a glass box:
+ Excellent protection from erosion;
- Perception of earth volume limited by refraction and reflection of glass;
- Space between glass and earth requires powerful climatization in order to facilitate a permanent

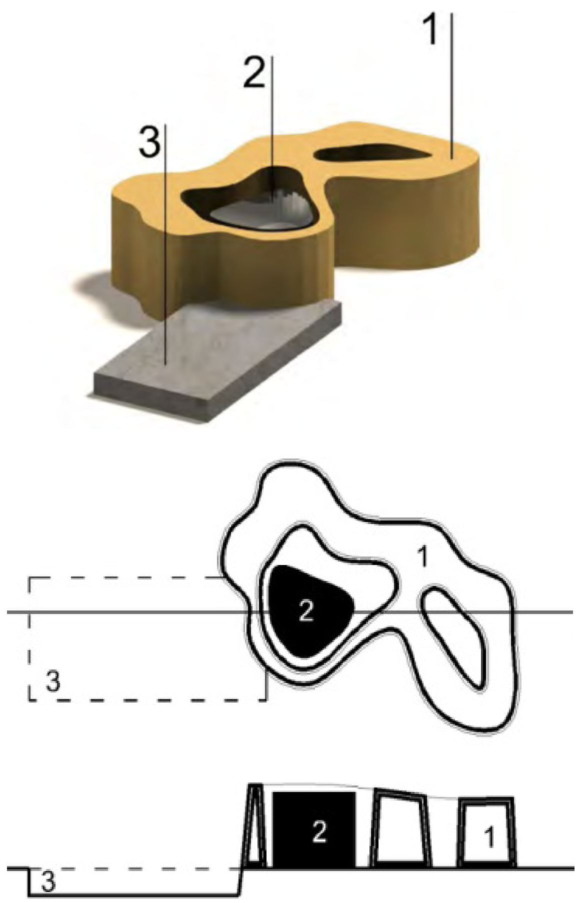


Fig. 140. First concept. Volumetric division

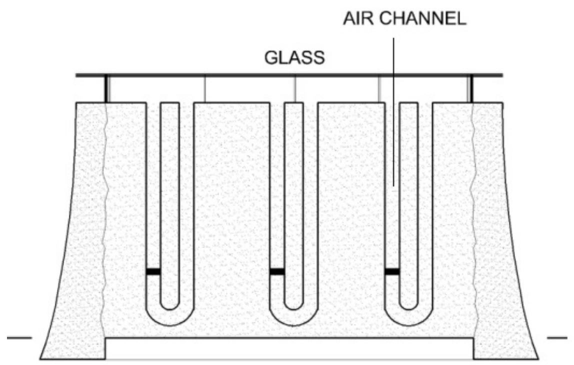


Fig. 141. First concept. Warm air channel system

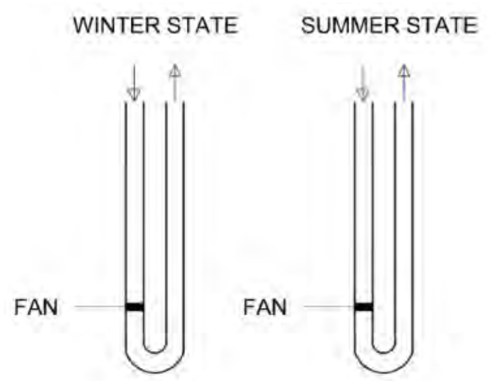


Fig. 142. First concept. Channel working principle

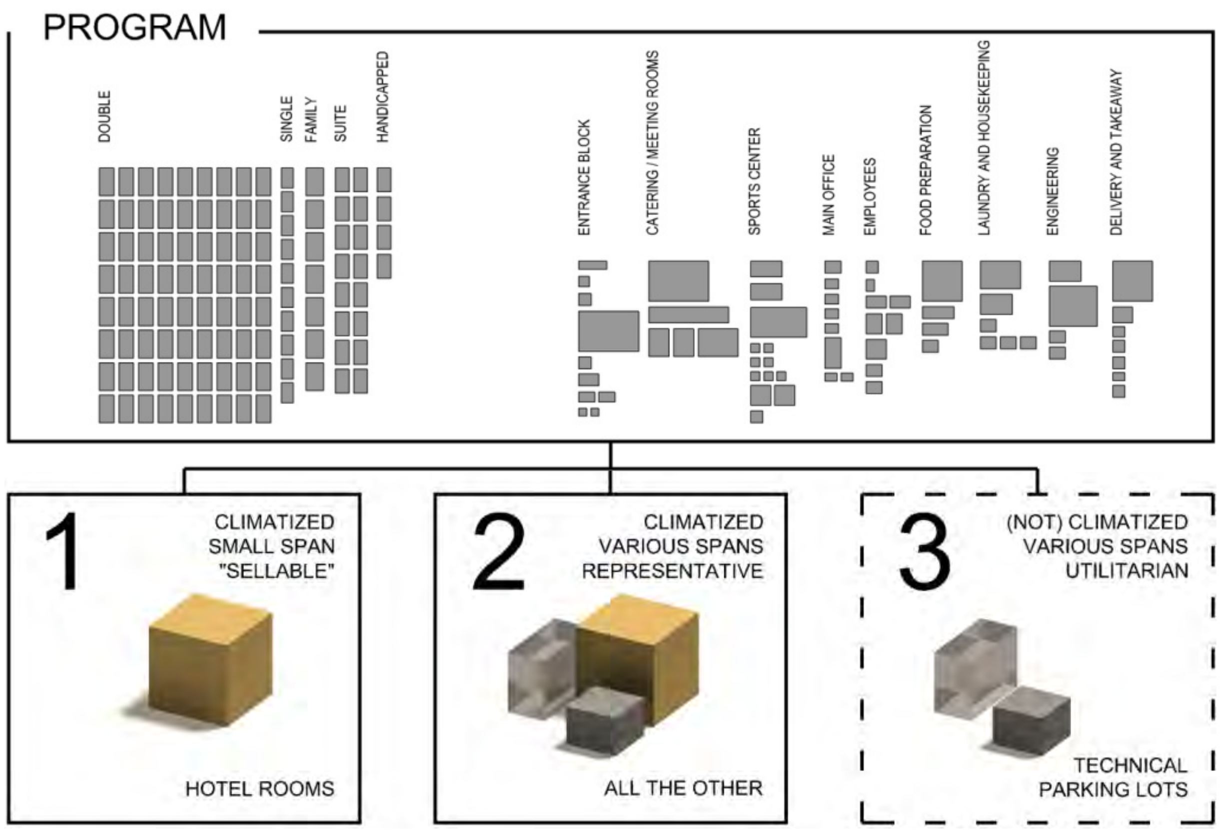


Fig. 143. Conceptual spatial division


Fig. 144. Clay model study

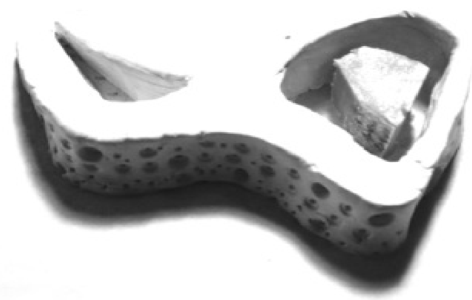


Fig. 145. Clay model study

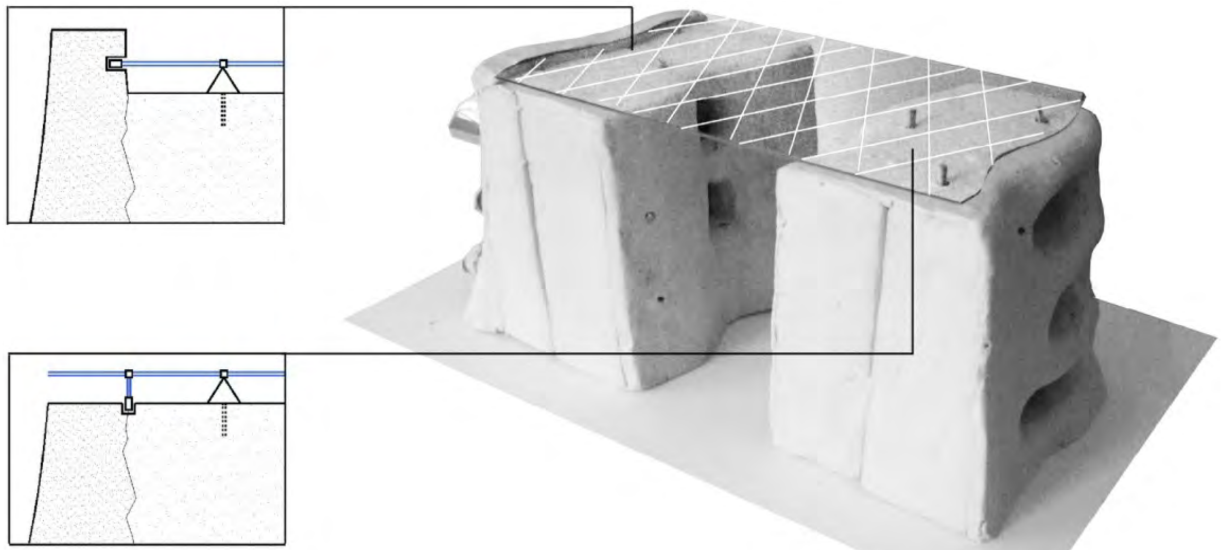


Fig. 146. First concept. Model fragment and schematic parapet solution scenarios

function (Figure 147).
2) Glass roof with individual load bearing structure:
+ Visual differentiation of both volumes;
- Poor connection between warm air glass cavity and earth volume that requires additional insulated channels between both structures (Figure 148).
3) Glass roof on top of several smaller earth volumes:
+ Glass as spatially unifying element with direct contact earth volumes;
- Parapet connection problem as described in previous paragraph (Figure 149).

10.6. Second Concept

As a final solution glass roof has been moved keeping most of earth on top of it (Figure 150). It has numerous advantages over the previous concept:
- aesthetically, earth is finally highlighted as the central design object, and glass surface acts as a setting (a platform for the sculpture);
- architecturally, particular volumetric division is especially suitable for hotel function as the glass roof can cover public and service facilities having good interconnection and accessibility. In site context horizontal volume can be placed underground thus minimizing the blocking effect from important viewpoints (more in detail in the next paragraph);
- from climatology point of view, natural draught effect can be used to pump the warm air from glass roof up into the earth volume. In summertime the warm air collected in cavity between double glazing naturally rises up via channels in earth volume. This cools down the spaces under the glass roof by transferring heat to the massive earth structure. Having enough thermal mass to stabilize yearly temperature fluctuations, earth absorbs the heat and minimized necessity for additional heating system for hotel rooms. In winter the air collected in double glazing is rather cool and will stay in the glass cavity.
- from academic point of view, concept gives an opportunity to examine and compare two different earth construction methods – massive pouring that has been developed as innovative earth construction approach (hotel room volume), and the classical method of implementing earth in construction of walls (volume under the glass roof).

10.7. Context

Building is placed on Scheveningen boulevard axis. Horizontal volume containing public functions is placed:
- underground in order not to block the view to the sea and maintain the contact between promenade and dune park behind the building as well as provide sand as construction material for horizontal volume and serve as a visual setting for the vertical volume.

Fig. 147. Earth volume in glass "box"

Fig. 148. Earth volume covered with glass roof on steel columns

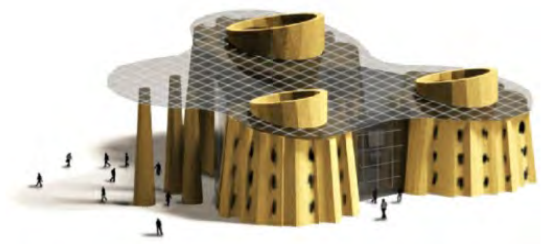


Fig. 149. Defragmented earth volume covered with glass roof

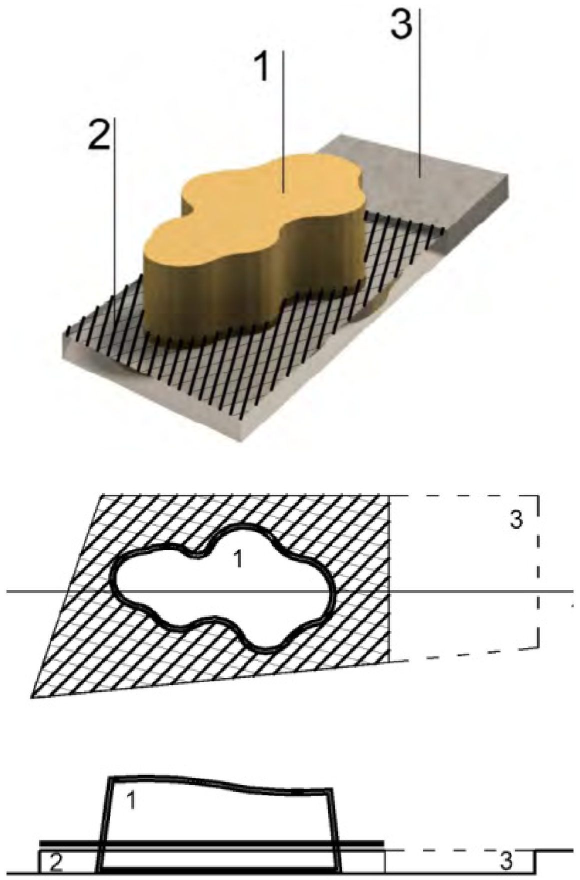


Fig. 150. Second (final) concept

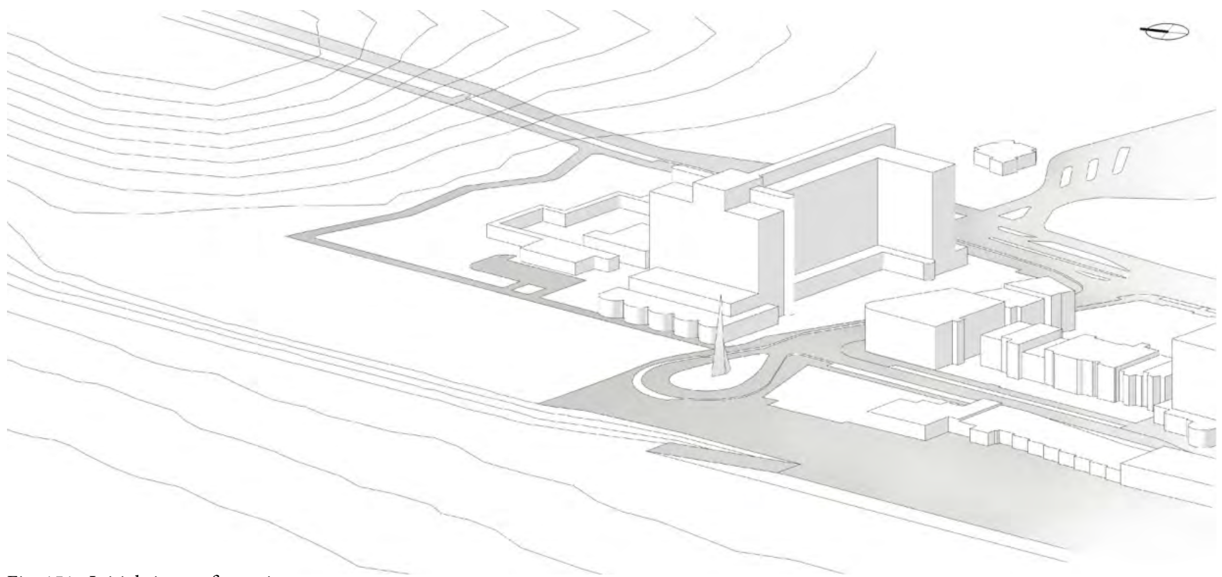


Fig. 151. Initial site configuration

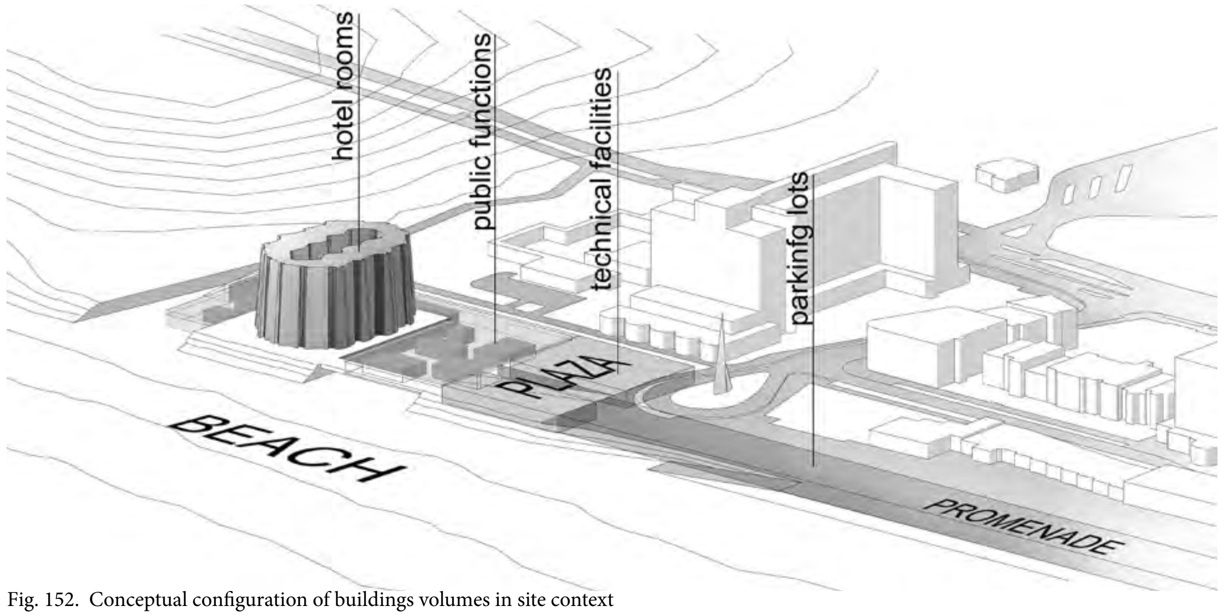


Fig. 152. Conceptual configuration of buildings volumes in site context

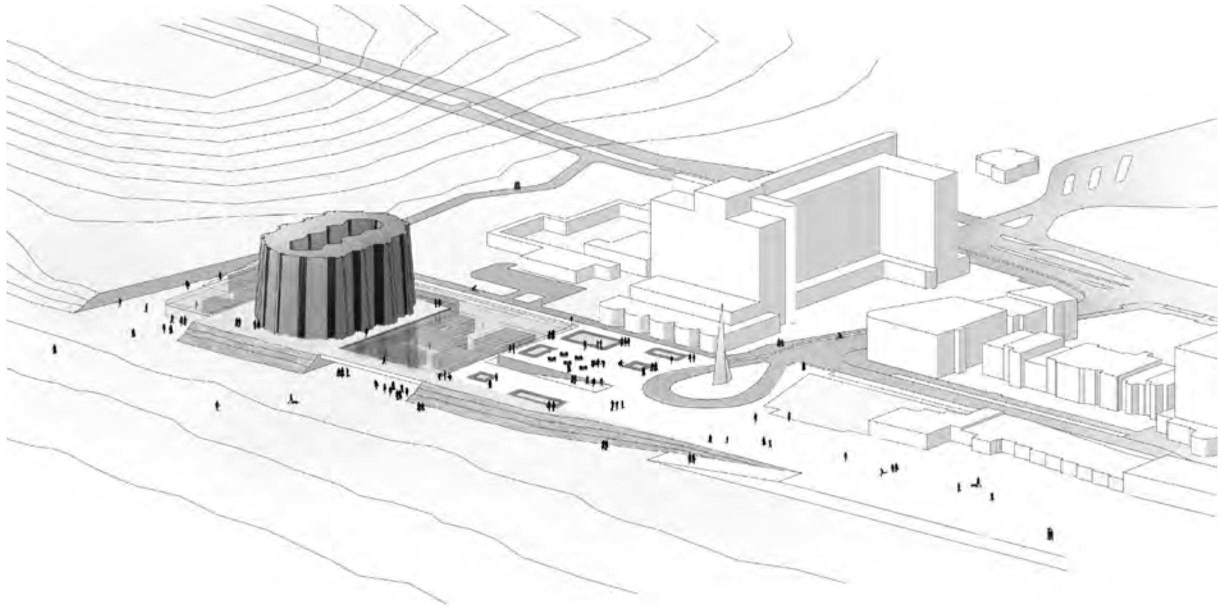


Fig. 153. Schematic representation of buildings integration in site context

At the same time not lower than abs: +7.000 as this has been accepted as flood-safe height after study of tide history (Figure 154);
- in U-shape, with an offset from the promenade in order to avoid shade from surrounding housing and hotel room volume as well as provide free space – plaza at the end of the promenade in front of existing housing. Contact with sea is established by cutouts.
Vertical volume containing sleeping capsules and hotel rooms is placed:
- perpendicular to sea in order to provide view to the water and beach from as many hotel rooms as possible as well as respond on dominant wind direction thus having equal erosion on both sides (Figure 155). Placement on the axes of promenade, but perpendicular to it spatially marks the end of the pedestrian road;
- closer to the sea to avoid casting shade on glass roof;
Technical volume containing staff and tachnical facilities is placed underground in front of the public facilities under the plaza;
Parking lots are placed under the promenade providing good access to staff and maintenance transport. Responding on consequent lack of parking spaces, it is possible to extend the underground construction in South-Western direction to facilitate mixed use parking lots (promenade visitors, hotel guests, local residents).

10.8. Functional Zoning and Accessibility

One of the design requirements was to use the existing infrastructure and avoid creating new one, if possible. For main driveway therefore the only road bordering the site has been selected. The main entrance has been organized from side of pedestiran promenade and driveway. Considering the active pedestrian traffic along the beach as well as pedestrian road along buildings North-Eastern façade, additional entrances from has been designed (Figure 158).
Functional zoning follows the concept defined by buildings volumetric division - most of technical and staff facilities are located in the concrete volume under the plaza while most of publicly accessible facilities are situated under the glass roof. Exceptions are laundry and housekeeping zone that needs direct contact with the hotel volume as well as office block that has strict daylight requirements. Massive earth volume facilitates small sleeping capsules on the ground floor (especially suitable for short-stay during summertime) and larger hotel suites on upper floors(Figure 158-160).
More detailed reflection on buildings architectural aspects from engineering point of view are described in the next paragraph.


Fig. 154. The 1953 North Sea flood (abs: +5.600)


Fig. 155. Wind erosion impact on natural earthen structure

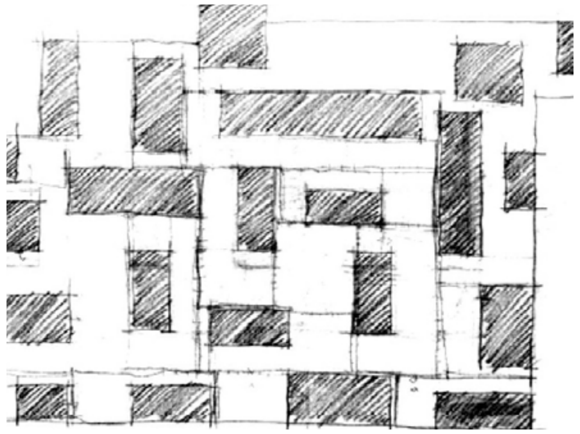


Fig. 156. Therme Vals volumetric concept by Peter Zumthor

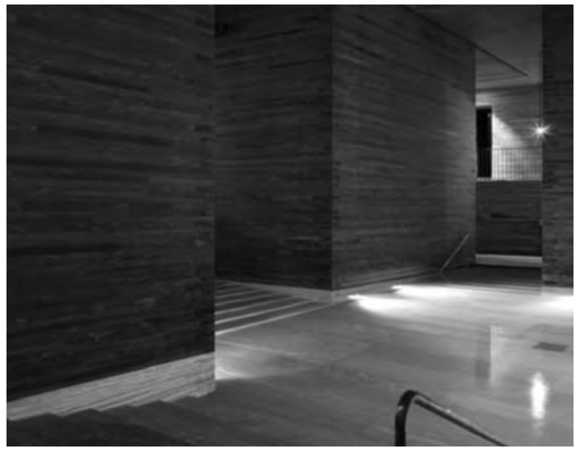


Fig. 157. Therme Vals by Peter Zumthor

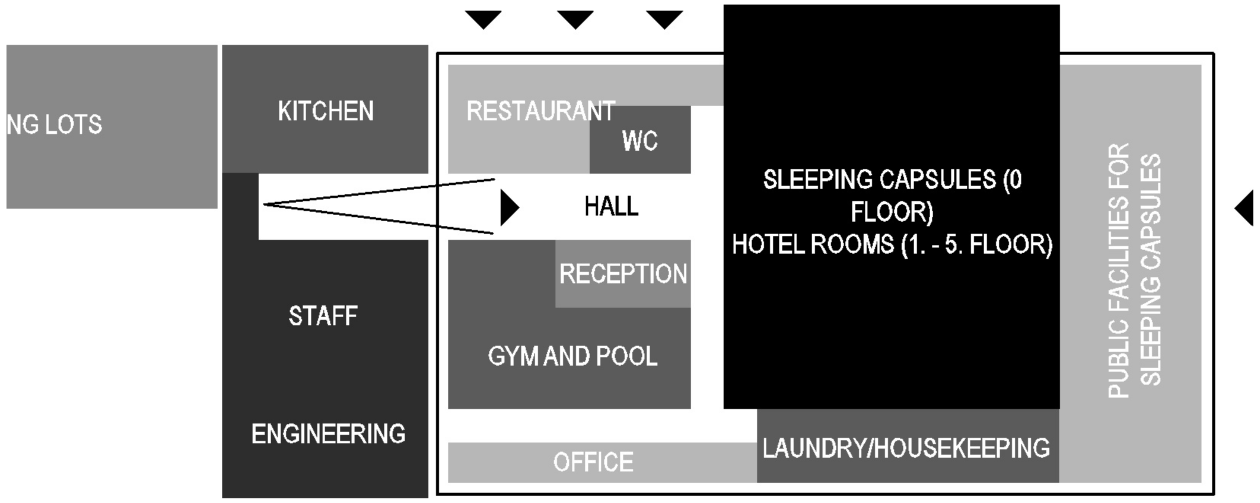


Fig. 158. Ground floor. Functional zoning scheme

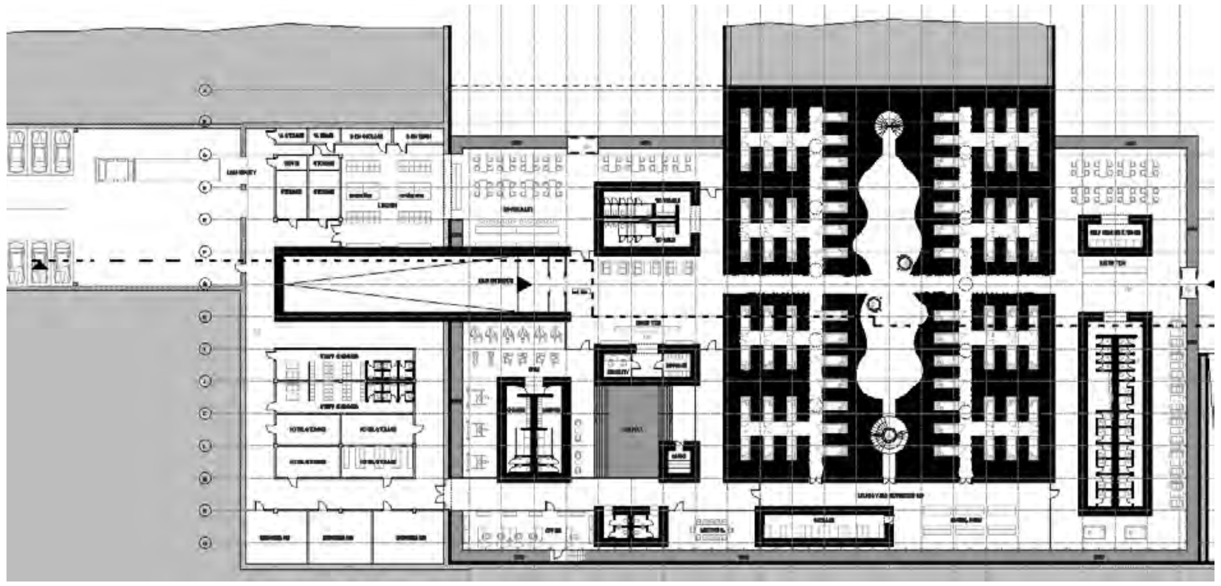


Fig. 159. Ground floor plan

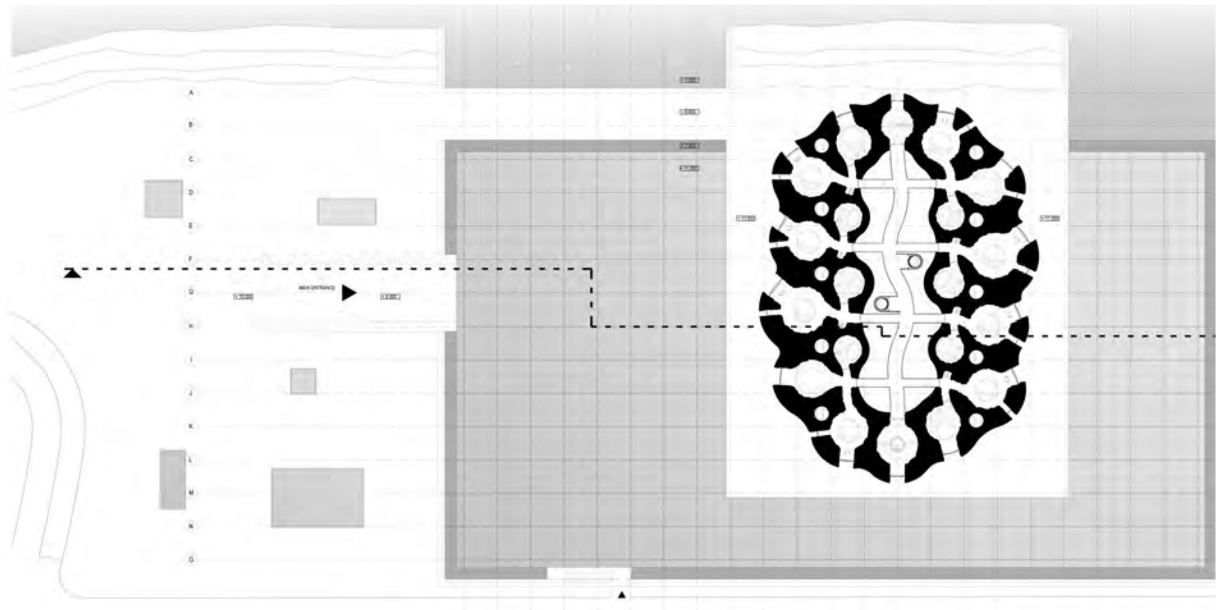


Fig. 160 First floor plan

11. ARCHITECTURAL ENGINEERING ASPECTS

This paragraph reflects main technical and architectural aspects considered during detailed design phase. Project is analysed according to previously established volumetric division: horizontal volume facilitating public functions and vertical volume housing hotel rooms. Technical volume and parking lots are not discussed in this paper as they do not contribute in earth construction.

11.1. Horizontal Volume

Horizontal volume represents classical earth construction method. Its geometrical rectangularity with most of elements strictly following the grid was intended as a contrast to free shaped vertical volume. Main components of horizontal volume are earth cores, hybrid retaining walls, and glass roof (Figure 161).

11.1.1. Earth Cores

Inspiration for earth cores has been derived from Peter Zumthors design methodology especially highlighted in Therme Vals. Earth cores have both architectural and structural purpose as they:

1) organize space by facilitating functions that require privacy;

2) support the roof that otherwise would require individual load bearing system.

Walls of cores are made of unstabilized earth (23% gravel, 45% sand, 20% silt, 12 %clay; compressive strength ~2Mpa). Wall thickness of 1 meter was chosen referring to compressed earth case studies analyzed in Mac3 phase.

Walls have been placed on concrete footing. Thermal bridge avoided by foam insulation on both sides of footing and moisture ingress stopped by layer of bitumen (Figure 164).

Earth walls incorporate power outlets and cables that have been inserted during construction process in especially resistant tubes (Figure 172, 173). All the other engineering communications (especially plumbing that in case of leakage may moisten earth walls thus affecting their strength) are placed in technical shafts to enable easy access for inspection and maintenance (Figure 163).

Similarly also connections between earth walls and any other elements such as toilet seats, shower poles etc. have been avoided due to materials fragility. Connections that could not be avoided have been solved using wooden nailing strips that should be placed inside earth walls already in construction phase (Figure 166, 167).

Openings in earth walls have been solved by using steel lintels in shape of T profile (installed with flat side towards bottom).

11.1.2. Retaining Walls

Underground volume is surrounded by retaining walls. Initially they have been designed entirely out of poured earth (Figure 174). But enormous material use that would be necessary to ensure structural stability (thickness at least 1.5 meters to be able to take shear forces) and precaution activities needed

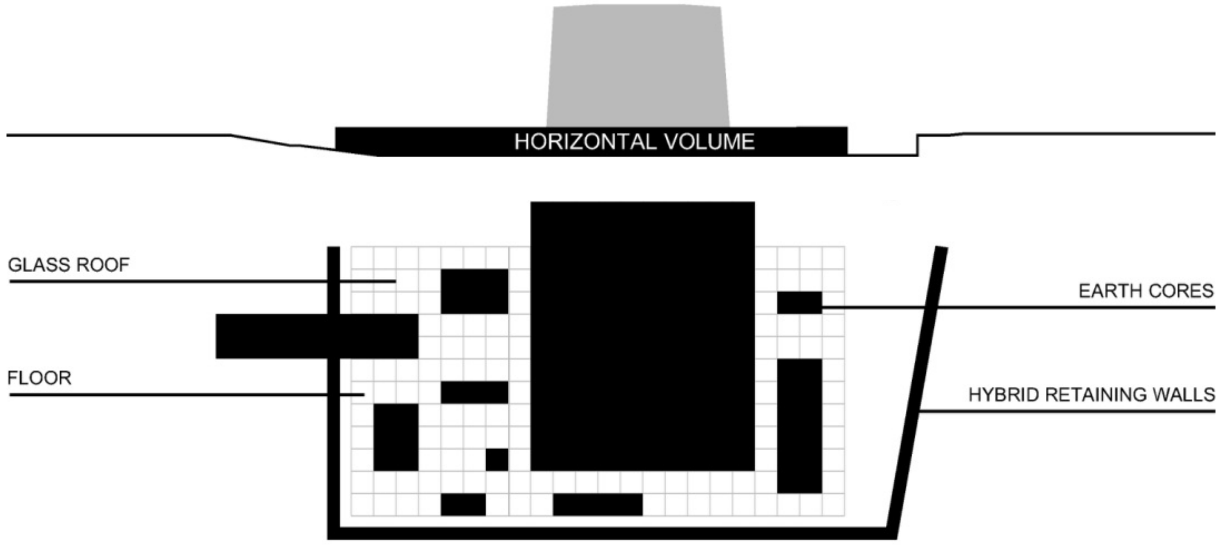


Fig. 161. Schematic representation of main elements in horizontal volume

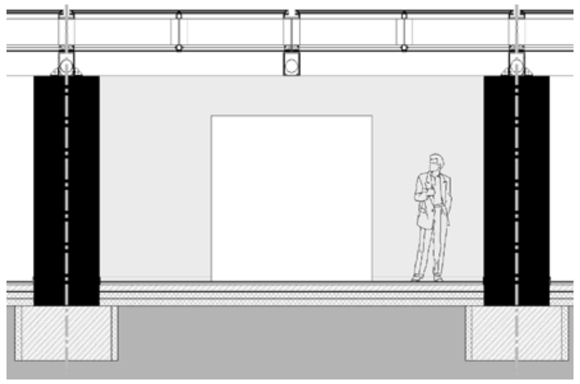


Fig. 162. Section through a typical earth core

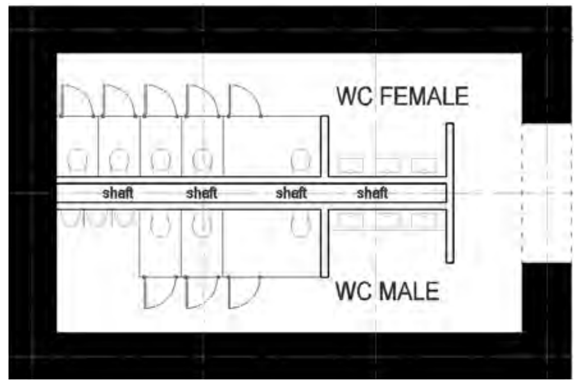


Fig. 163. Plan view of a typical earth core

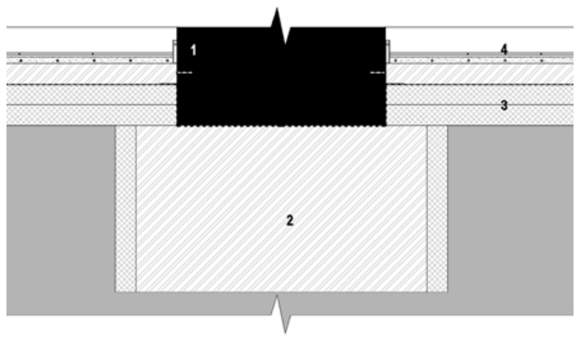


Fig. 164. Footing detail. (1) poured earth; (2) concrete footing; (3) foam insulation; (4) tile flooring on top of self leveling compound with heating cable

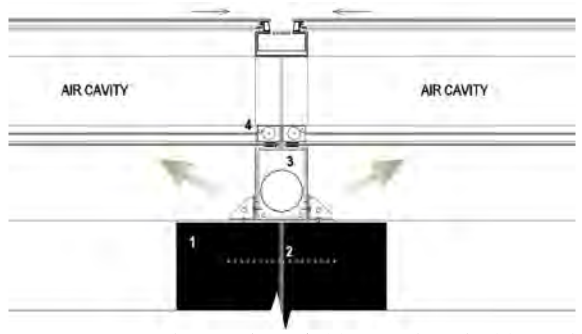


Fig. 165. Connedtion with roof. (1) poured earth; (2) metal T-profile as a bond beam, anchored in earth wall; (3) primary beam with engineering installations; (4) remote controlled shutters

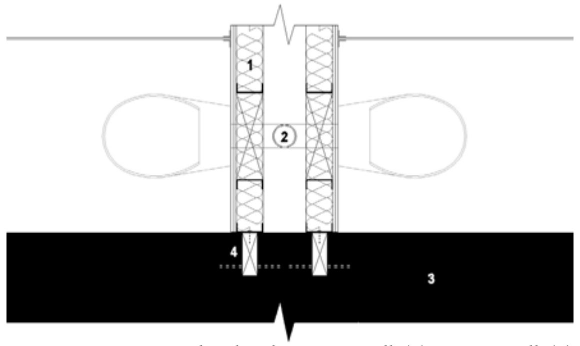


Fig. 166. Connection detail with gypsum wall. (1) gypsum wall; (2) sewer pipe; (3) poured earth wall; (4) nailing strip

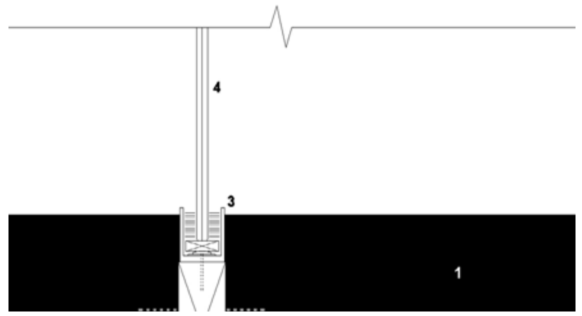


Fig. 167. Connection detail with glass wall. (1) poured earth wall; (2) wooden nailing strip; (3) glazing frame; (4) laminated glass

to protect wall from humidity and erosion did not justify earth application purpose in particular case – only to emphasize visual impression of being underground. Therefore a hybrid wall solution has been chosen instead (Figure 175).
Load bearing part of the retaining wall is made of reinforced concrete while 30cm thick layer of self bearing poured earth is placed in front of it to imitate dune environment. Earth has been attached to concrete by special sliding anchors - metal T-shaped profiles placed into U-shaped rail connected to the concrete wall. This solution ensures structural connection between both walls avoiding cracks that may occur during construction as earth has tendency to shrink (Figure 178, 179).

<u>11.1.3. Roof</u>

Roof solution has been developed responding on findings during thermal study as it is integral player in thermal symbiosis between horizontal and vertical volume. Technical principle of roof was derived from Rodin Museum in Seoul (Figure 168) where load bearing trusses are covered with glass from both top and bottom thus creating in-between cavity. In mentioned example, however, glazing on the bottom part is used to provide translucent light required by buildings function – an art gallery. In hotel building the cavity between both leafs is used for collecting warm air and transferring it to the vertical volume of hotel rooms.
Initially roof construction was based on a modular truss where top and bottom members would also perform as frame for glazing (Figure 180, 186). This solution, however, turned out to have considerable problems:
1) the visual contrast between roof and earth blocks was too disturbing;
2) roof structure did not allow integrating engineering communications (light, ventilation, water mist system).
As a result additional research was done in order to examine roof structures of existing compressed earth buildings that highlighted necessity for more massive-looking construction.
The final roof proposal is a metal beam system that consists of massive primary beams and relatively slender windowframe-based truss system on top that forms the warm air cavity (Figure 181, 187). Derived from examples by "Foster + Partners" and "Licht Kunst Licht" primary beams contain ventilation and electricity installations as well as lighting (Figure 169).
Diagonal bracing for windowframe truss construction is avoided by cross-shaped metal connectors. Between internal windowframes remote


Fig. 168. Double glass roof system. Rodin museum in Seoul (KPF)


Fig. 169. Beams with integrated ventilation (Licht Kunst Licht)


Fig. 170. Loadbearing steel beam in relation with earth wall


Fig. 171. Glass roof system in relation with earth walls


Fig. 172. Power outlets in earth wall


Fig. 173. High compression resistance power outlets

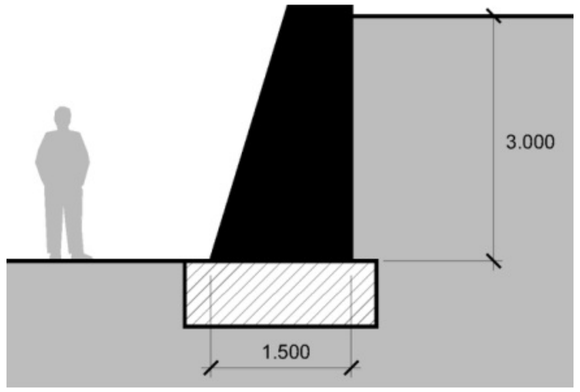


Fig. 174. Earth retaining wall. Initial concept

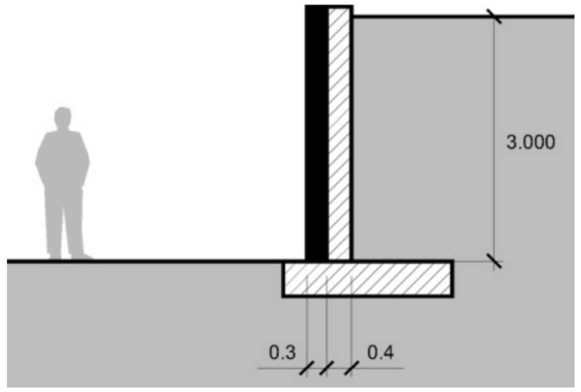


Fig. 175. Hybrid retailing wall. Final concept

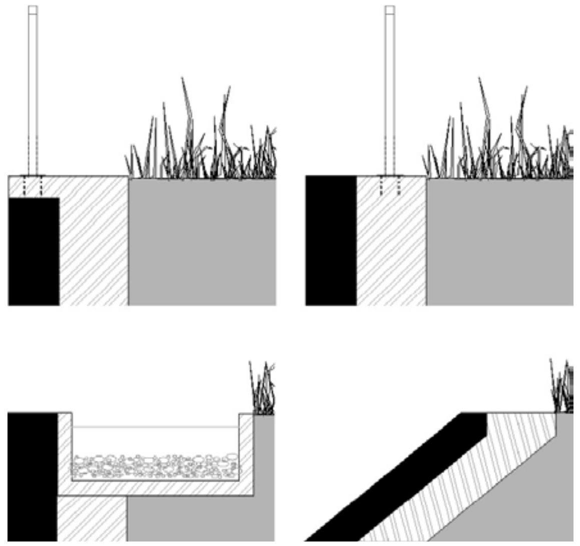


Fig. 176. Retaining wall top part study

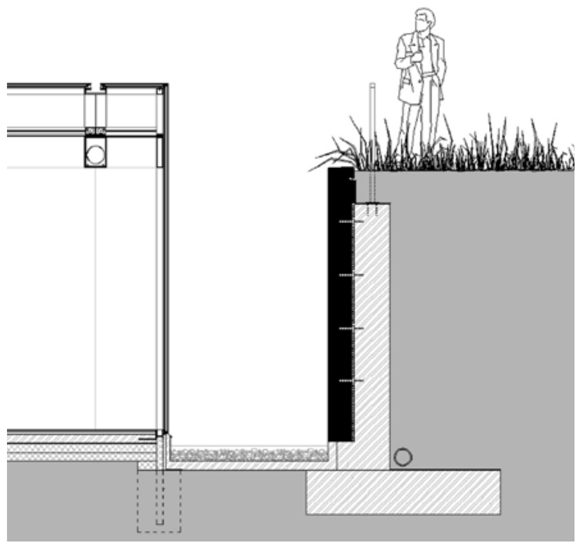


Fig. 177. Retaining wall in detail

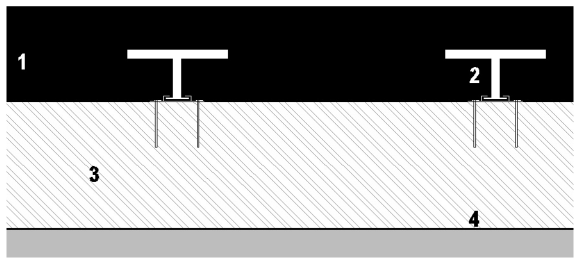


Fig. 178. Sliding anchors. Horizontal section. (1) poured earth; (2) sliding anchor; (3) load bearing concrete wall; (4) bitumen

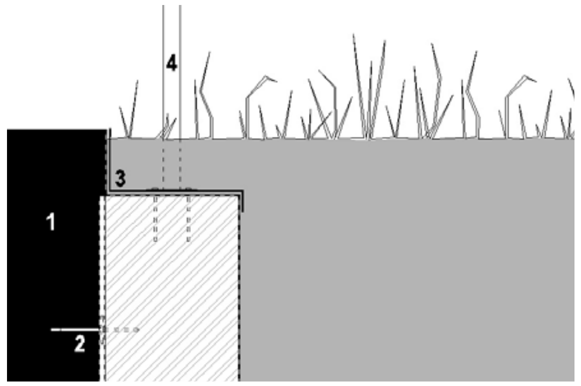


Fig. 179. Sliding anchors. Vertical section. (1) poured earth; (2) sliding anchor; (3) metal flashing on top of bitumen; (4) handrail

controlled shutter system should be installed in order to keep the solar radiation within air cavity (Figure 42).
Due to poor compressive strength of earth constructions, primary beam can not be placed directly on top of earth cores but needs bond beam that transfer the load from roof to earth walls as uniformly as possible. Bond beam has been solved as metal T profile inserted in earth wall during the pouring process (Figure 165).
One of the most questionable aspects of the design is maintenance of tha glass roof. Therefore as a part of study main problems and potential solution scenarios have been analyzed.
1) Dirt and sand. Considering location as well as dominant wind directions and their force, it is expected that roof glazing will get regularly covered with sand particles. Problem can partly be solved by application of nano-coating with self-cleaning effect as offered by, for example, "Pilkington". According to manufacturers information, result is a unique self-cleaning glass, which breaks down dirt naturally through a photocatalytic process. Rain water then sheets off, thanks to the hydrophilic properties of the glass, taking the dirt with it and leaving a clearer view, and reduced streaks. Dirt washing away requires special filters to be inserted in rain gutters with manual cleaning option.
2) Birds. Similar as in airports, birds can be kept away using sonic cannons that emit disturbing frequencies. These sounds can not be heard by human being and do not harm neither birds nor humans.
3) Impacts. Top layer of glass roof should be laminated.

11.1.4. Floor

Although implementation of unstabilized or cement stabilized compressed earth floors is an existing practice (Figure 183), floor material for the horizontal volume was selected considering specific exploitation conditions of hotel buildings public facilities. Regular impacts by sharp heels, walking sticks, wheels of suitcases as well as risk of dirt and moisture ingress may damage even stabilized earth floor. Moreover, earth floors are not suitable for floor heating (the most suitable heating system for particular building) for following reasons:
1) electric heating cables may get damaged during construction;
2) water based floor heating may affect stability of the floor in case of leakage;
3) enormous thermal mass of earth floor would make the response time of heating system extremely long.
Therefore, as more suitable flooring material tiles have been chosen (Figure 184).

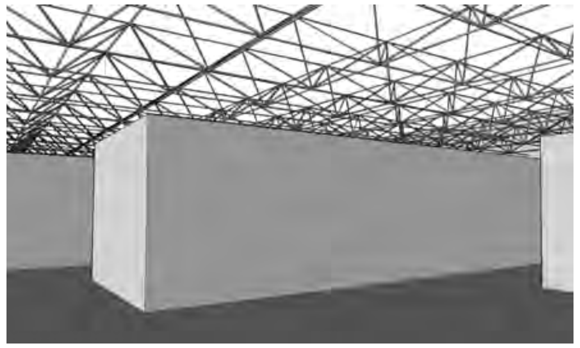


Fig. 180. Roof structural solution. Initial concept

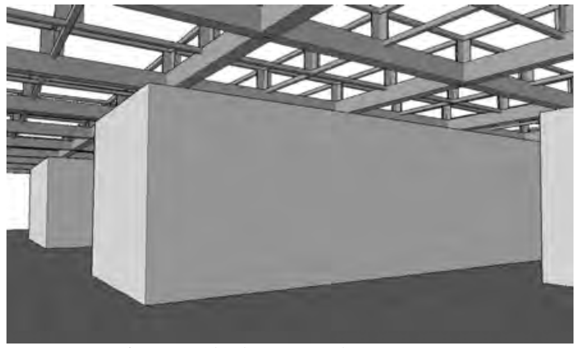


Fig. 181. Roof structural solution. Final concept

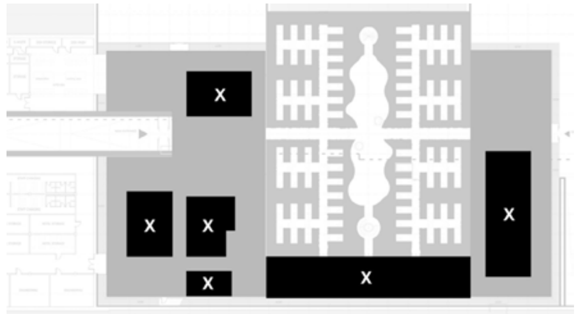


Fig. 182. Unsuitable areas for earth floor application

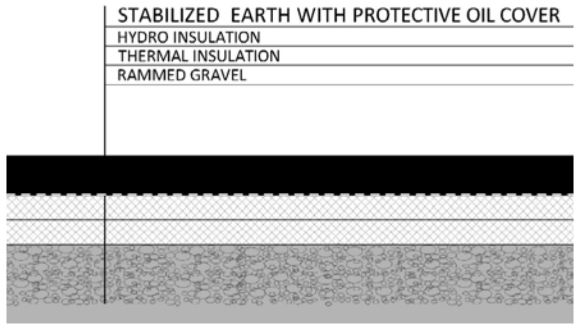


Fig. 183. Initial floor solution

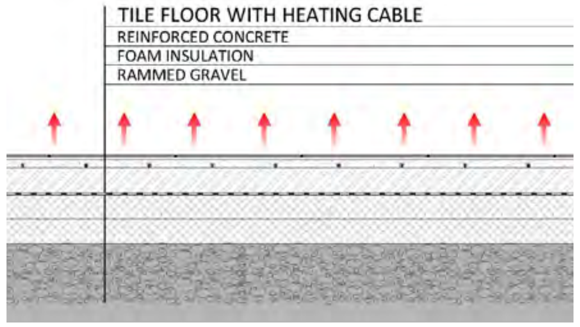


Fig. 184. Final floor solution


Fig. 185. Final roof solution. 3D visualization

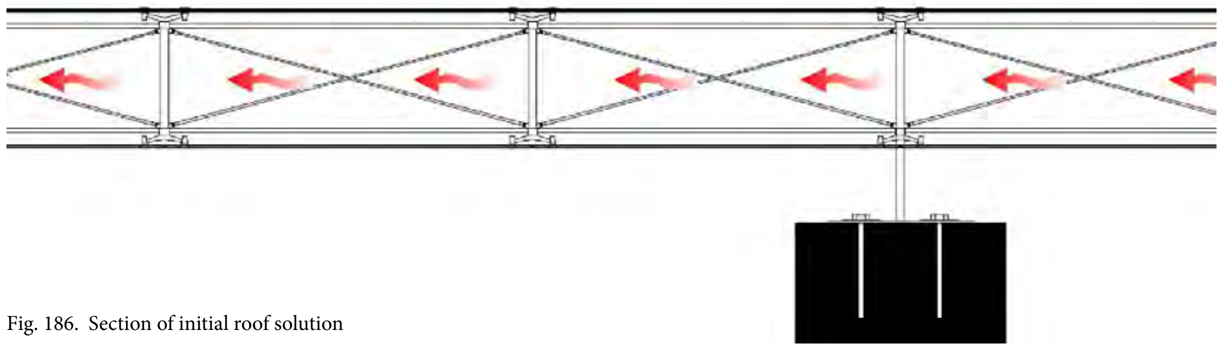


Fig. 186. Section of initial roof solution

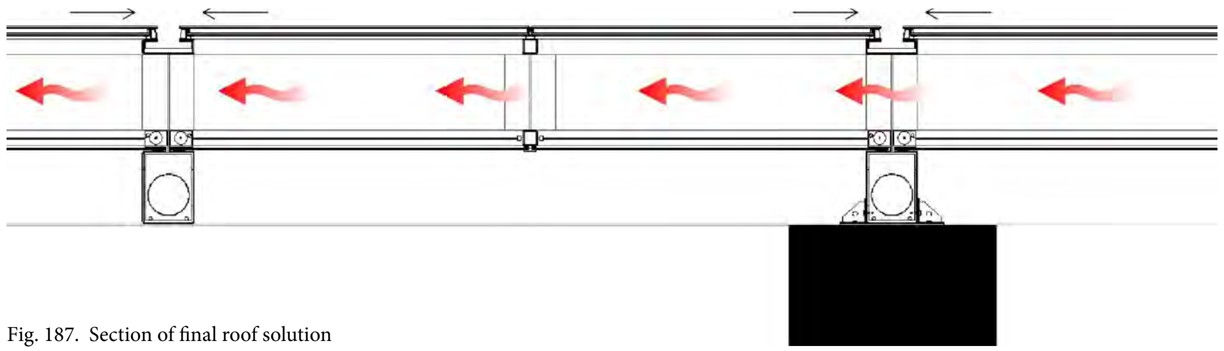


Fig. 187. Section of final roof solution

11.2. Vertical Volume

Hotel room volume represents an alternative compressed earth design thinking - perceiving volume as enormous earth mass and facilities as voids.

Earth volume has been divided in two parts:

1) base – the part under the glass roof that serves as a foundation and represents qualities of both earth cores and volume on top;

2) tower – the part above the glass roof that embodies findings of structural study. This is organic focal point of the entire building (Figure 188).

Differentiation between top and bottom parts has no architectural or programmatic rather than engineering explanation. Initially perimeter of the vertical volume was intended to be constant throughout. But thermal transfer between glass roof and vertical volume required their thermal connectivity. As a result 3 options to provide this were found and analyzed (Figure 188):

1) Platform separate from tower.

+ no physical connection between volumes needed;

- thermal transfer from glass roof to tower via extensive and complicated network of insulated ducts;

2) Platform “cutting through”.

+ thermal transfer solution between volumes simple and efficient;

- connection detail between glass and curved tower technically very complicated;

- aesthetical factor;

3) Tower with rectangular base.

+ Relatively simple both thermal transfer and connection solution;

+ base serves as structural foundation;

+ being rectangular, base spatially fits among earth cores.

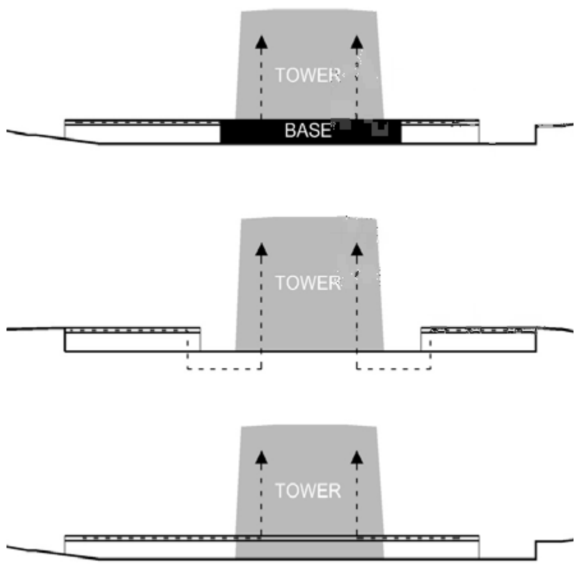


Fig. 188. Platform and tower connection scenarios

11.2.1. Base

Constructive purpose of the base is to transfer load from tower to ground under the building. Leaving such a massive volume empty would be irrational while facilitating normal hotel rooms would not provide uniform distribution of the load towards the bottom. Therefore a decision to facilitate spaces with minimum spans was made.

Programmatic inspiration – sleeping capsules – has been derived from alternative hotel architecture in Japan. A sleeping capsule does not require more than 1.2meter span and its height allows placing another capsule on top thereby significantly increasing accommodation amount and compensating relatively high area-requiring hotel rooms on the higher floors (Figure 190).

During the study relevant structural calculations have been performed to determine necessary horizontal and vertical dimensions between sleeping capsule openings considering the load from the tower volume (Figure 189). Results are interpreted in capsule layout plan (Figure 190).

Being a reception-free sleeping area sleeping capsules are more subjected to potential damages, even vandalism, and therefore have their own frame made of thin sandwich- type panels. To improve thermal comfort panels are insulated. At the back of each capsule is a gap for engineering communications – fresh air inlet and suction, as well as electricity. Beds are mounted on rail systems allowing their partial ejection. This provides easier access for regular maintenance and bed linen change (Figure 190).

Base is made of unstabilized compressed earth with 1.2 meter high insulated, stabilized and bitumen impregnated solid earth layer underneath (23% expanded glass, 43% sand, 20% silt, 7 %clay, 2%bitumen, 5%cement). This layer is necessary to ensure thermal insulation from underground.

11.2.2. Tower

Free form shaped tower is an architectural translation of structural study explained in second chapter. Considering maximum dimensions for voids possible in unstabilized earth block, hotel rooms have been made of several interconnected volumes. Design strategy can be represented by following images:

To ensure structural stability, stacking of voids was done according to developed algorithm.

Horizontal stacking. According to structural study, each void depending on its shape, span and load on top needs a certain minimum area around it. This area was determined by additional calculations where straight and dome shaped voids were tested in

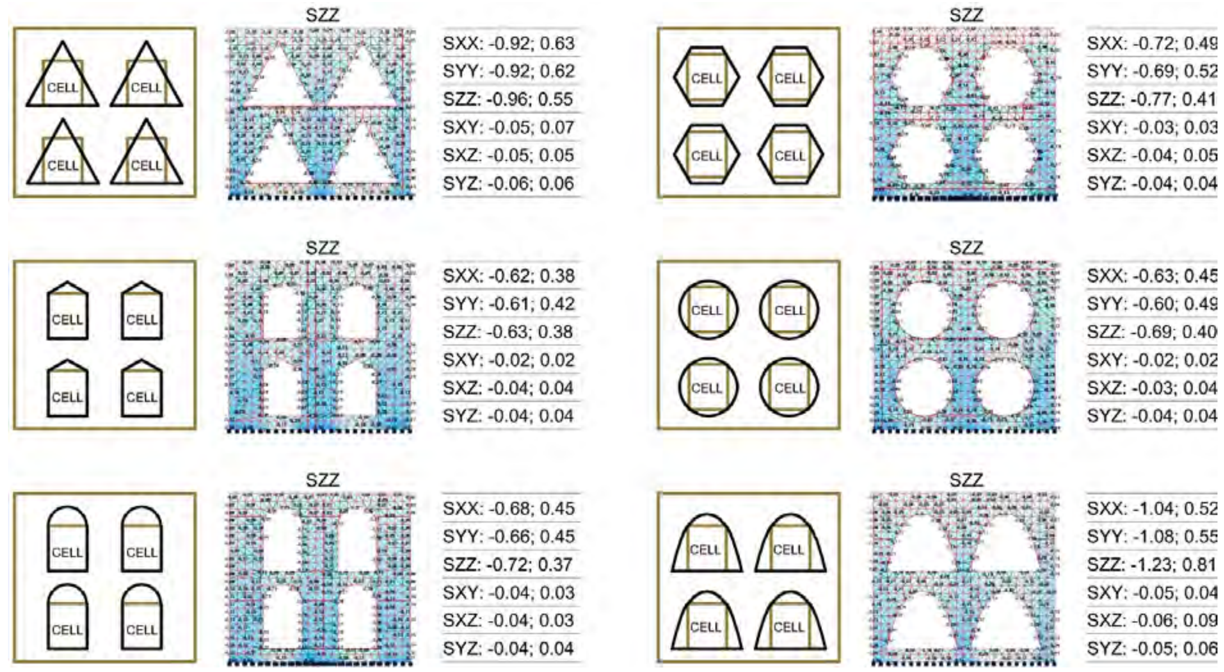


Fig. 189. Structural analysis for various opening configurations

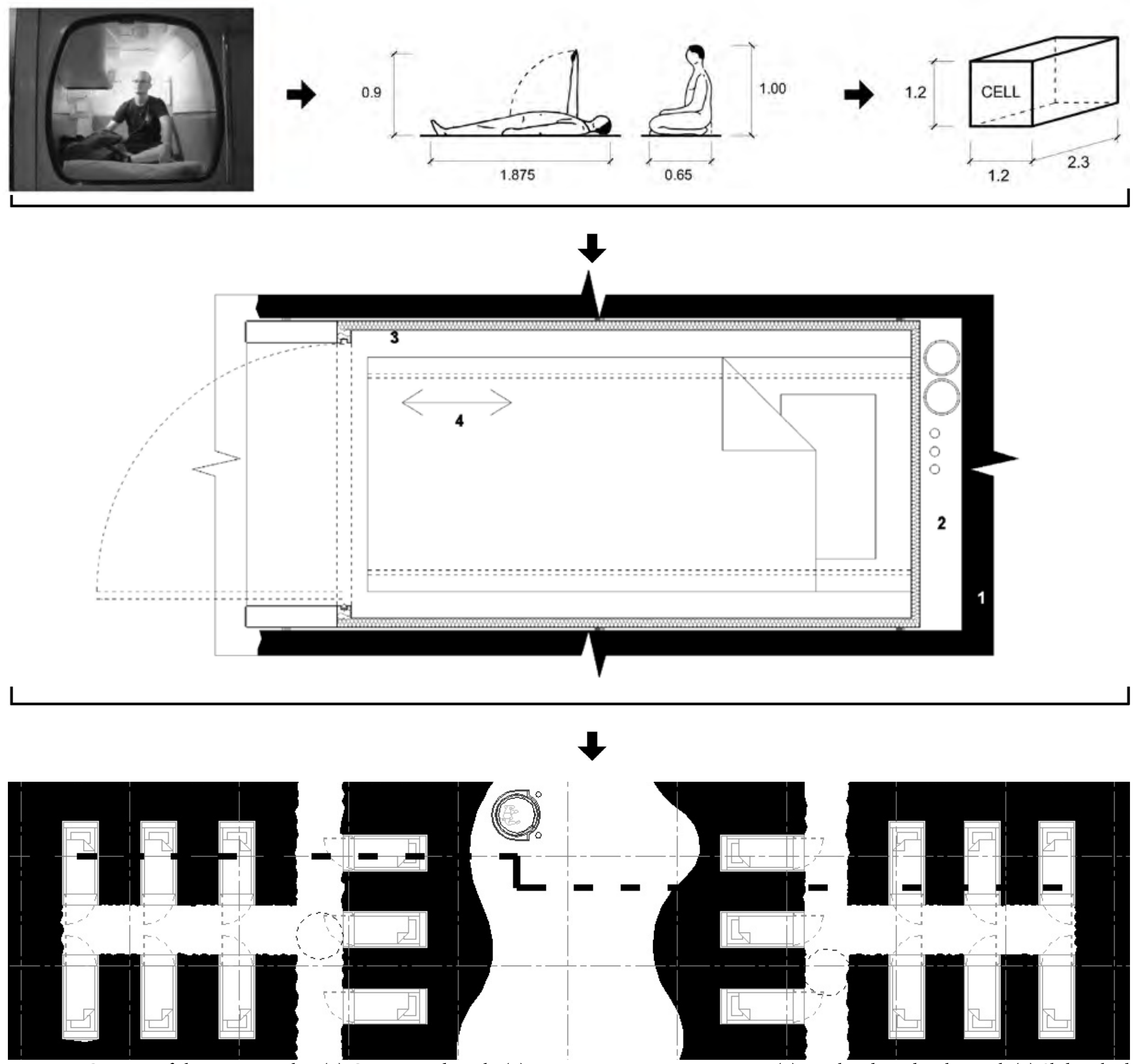


Fig. 190. Concept of sleeping capsules. (1) Compressed earth; (2) Engineering communications; (3) Insulated sandwich panel; (4) Sliding bed

various positions in a massive earth block and results summarized in graphs (end values calculated and in-between values extrapolated. Figure nr. 50).
When connecting the voids, their security areas interfere with security areas of other voids or even voids themselves. To compensate the loss of necessary support area, security radius in such cases has been increased approximately according to the interfered area. Although this is very simplified way of ensuring the necessary support area that neglects lateral forces, all critical parts (especially tensile parts of interconnections) can be reinforced by steel bars. Besides, safety factor of 4 provides a considerable reserve as well.
Free spaces between circles have been used for warm air channels that act as chimneys making earth absorb the heat coming from glass roof. Air channels have also combined shaft functions containing ventilation, plumbing and electricity (Figure 197-199).

Vertical stacking. Although architectural and artistic translation of caves into compressed earth volume would spatially benefit from irregular disposition of voids, all the hotel rooms with larger spans have been placed on top of each other. This has been done to minimize lateral forces causing much tension and requiring to increase vertical distance between floors (Figure 195).

Materialization and engineering. Among all surfaces (except windows and doors) only bathroom floor has been done in other material than earth. And even though earth could be impregnated with bitumen and surface covered with protective oil, decision for alternative material was made as the protective layer may wear out by time and surface might become vulnerable to ingress of smell and color via liquids (cosmetics, urine, etc.). Double flooring system selected for bathrooms enables also under-floor space for plumbing (water and sewer pipes) that has been connected to communication shaft (Figure 200).
There is no suspended ceiling for ventilation or lighting. Suction and fresh air inlets/outlets have been placed in walls and connected to main ducts inside shafts (Figure 201).
A study of possible window and door solutions was performed and 3 most feasible options analyzed. As a result the method of metal frame inserted between unstabilized and insulated earth layers was chosen (Figure 57, left) as it was least visible from both inside and outside. Frame must be inserted during construction while glazing placed after the pouring is done. Similar method has been chosen for door

Fig. 191. Hotel room formation. Primary spatial units

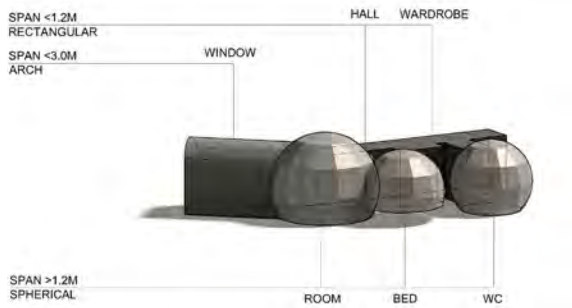


Fig. 192. Hotel room formation. Primary spatial units merged

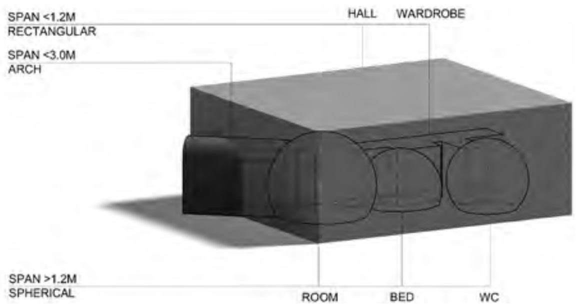


Fig. 193. Hotel room formation. Covering with earth

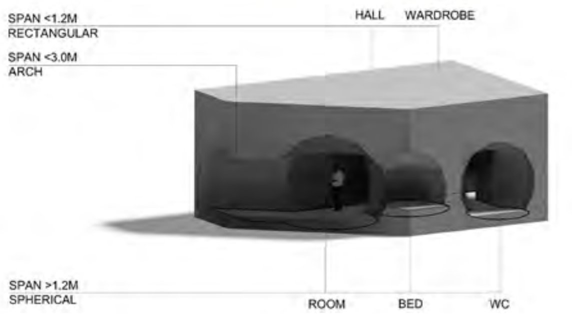


Fig. 194. Hotel room formation. Final result

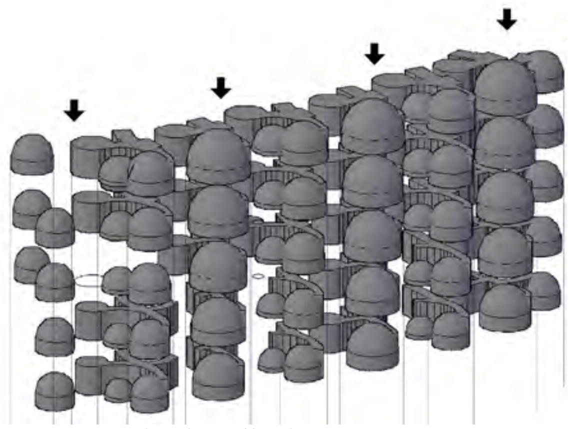


Fig. 195. Vertical stacking of hotel rooms


Fig. 196. Typical hotel room. 3D visualization

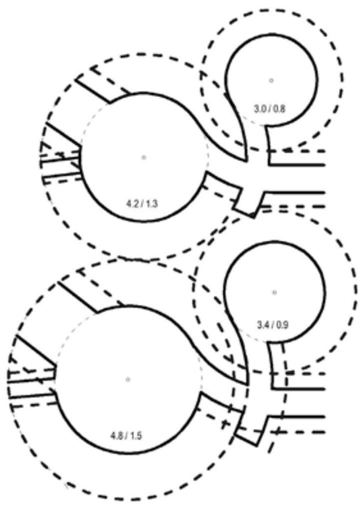


Fig. 197. Horizontal stacking of spaces

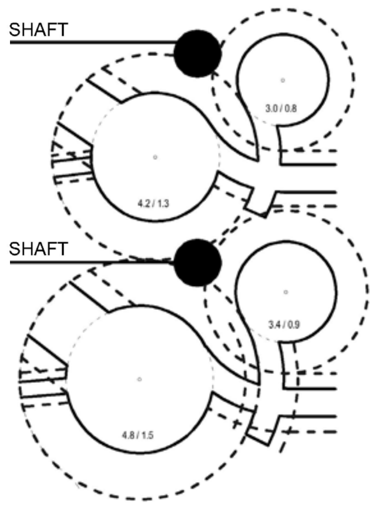


Fig. 198. Warm air/engineering channels

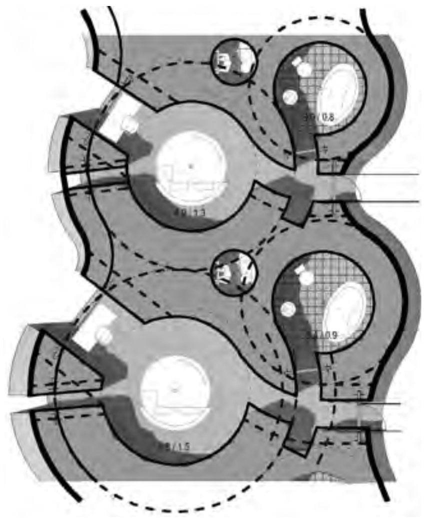


Fig. 199. Floorplan fragment of hotel rooms

frames (Figure 202).
There is high risk that air temperature in hotel rooms will be lower than 18.5˚C as estimated in thermal study due to fact that there will be no direct solar radiation on earth surfaces inside shafts (radiation component on earth wall forms approx. 20% of total heat gain that makes approx. 1˚C temperature increase therefore estimated temperature in hotel rooms is between 16.5 and 17.5˚C). To compensate this and give hotel guests an option to adjust temperature according to their needs each suite is equipped with a fireplace. Architecturally this is used as a contextual reference to ancient cave-man lifestyle turned into thematic hotel attraction where guests have to collect firewood in reception and make their own fire (Figure 202).

<u>Furnishing.</u> Maximum exposure of earth surfaces set special requirements on room equipment. Design strategy is to avoid placing furniture or other elements along walls providing only the most necessary equipment. The main element – bed – has been placed in center of the room and it combines other functions as light, TV, etc. Bed can rotate around its axis thus allowing guests to choose their desired viewpoint. A power cable from shaft to bed needs to be provided in a special pressure resistant tube as described in paragraph 4.1.1. This is done during pouring process.

<u>Construction method.</u> Concept of voids is largely based on extensive research about existing formworking methods and analysis of relevant case studies.
Initially voids were intended to be 2-dimensional. But after examination of various existing 2D formwork systems and the potential outcome decision to focus on 3D formwork was made (Figure 204).
Turning point in formwork study was examination or “Truffle” house in Spain by “Ensamble Studio” that was made using straw infill formwork. After the construction straw was removed leaving interesting interior surface texture (Figure 205, 206).
Infill formwork concept has been adapted to site specifics of Scheveningen by replacing straw with sandbags. In order to examine potential formworking process and end result a light concrete mockup was built. First, 5 bags were filled with sand and earth mixture (soil type available on site), densified and placed as shown in figure 209. Half of sandbags were covered with construction foil while others left wxposed in order to gain various textures. Second, a simple rectangular formwork was created and then concrete poured in. After few days formwork was removed. Sandbag on the top was

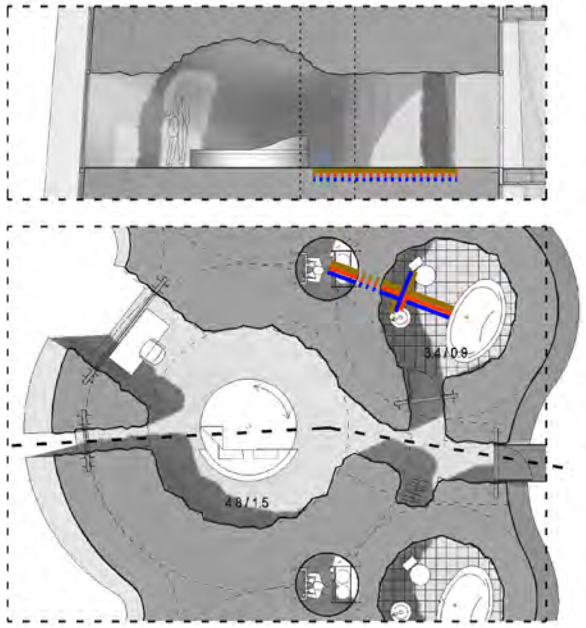


Fig. 200. Plumbing solution. Floorplan and section

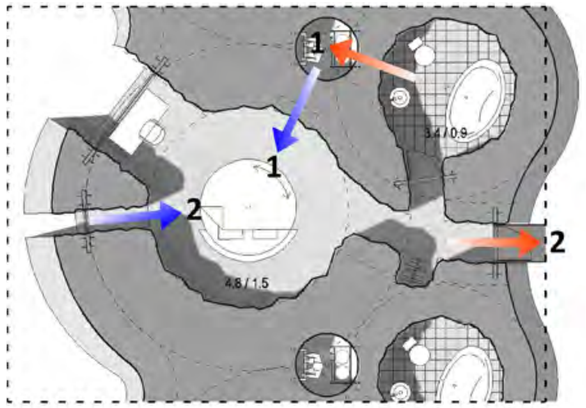


Fig. 201. Ventilation solution. (1) natural; (2) forced

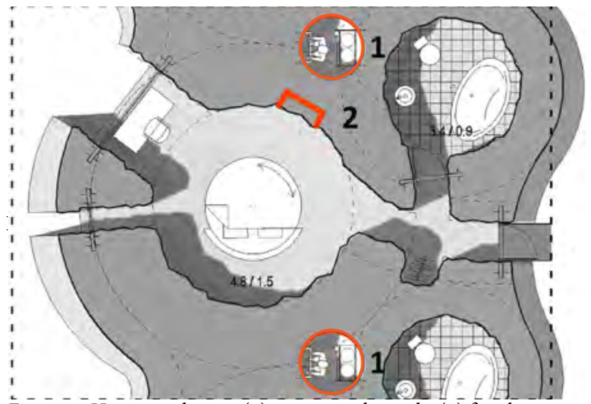


Fig. 202. Heating solution. (1) warm air channels; (2) fireplace

Fig. 203. Window solution scenarios

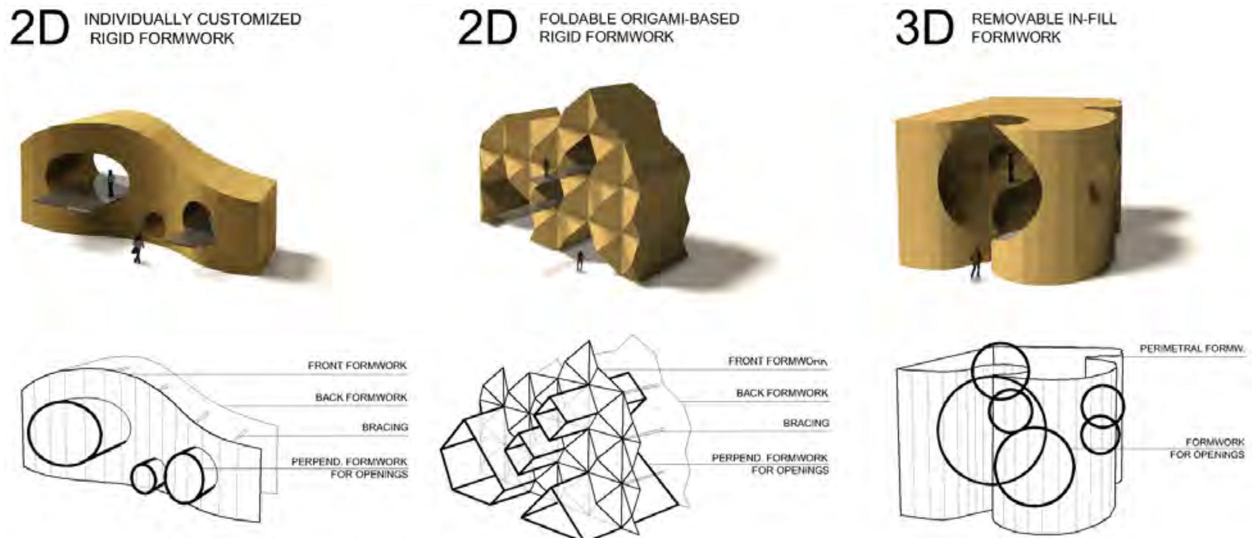


Fig. 204. Formwork study in relation with earth aesthetics


Fig. 205. “Truffle” house in Spain by “Ensamble Studio”. Exterior


Fig. 206. “Truffle” house in Spain by “Ensamble Studio”. Interior


Fig. 207. Existing and potential 3D formwork systems and elements

Fig. 208. Main case studies examined during concept development stage


Fig. 209. Step 1. Placing sandbags


Fig. 210. Step 2. Construction of formwork


Fig. 211. Step 3. Pouring light concrete and removing formwork


Fig. 212. Opening top sandbag and removing sand


Fig. 213. Step 5. Removing other sandbags without opening them


Fig. 214. Final result

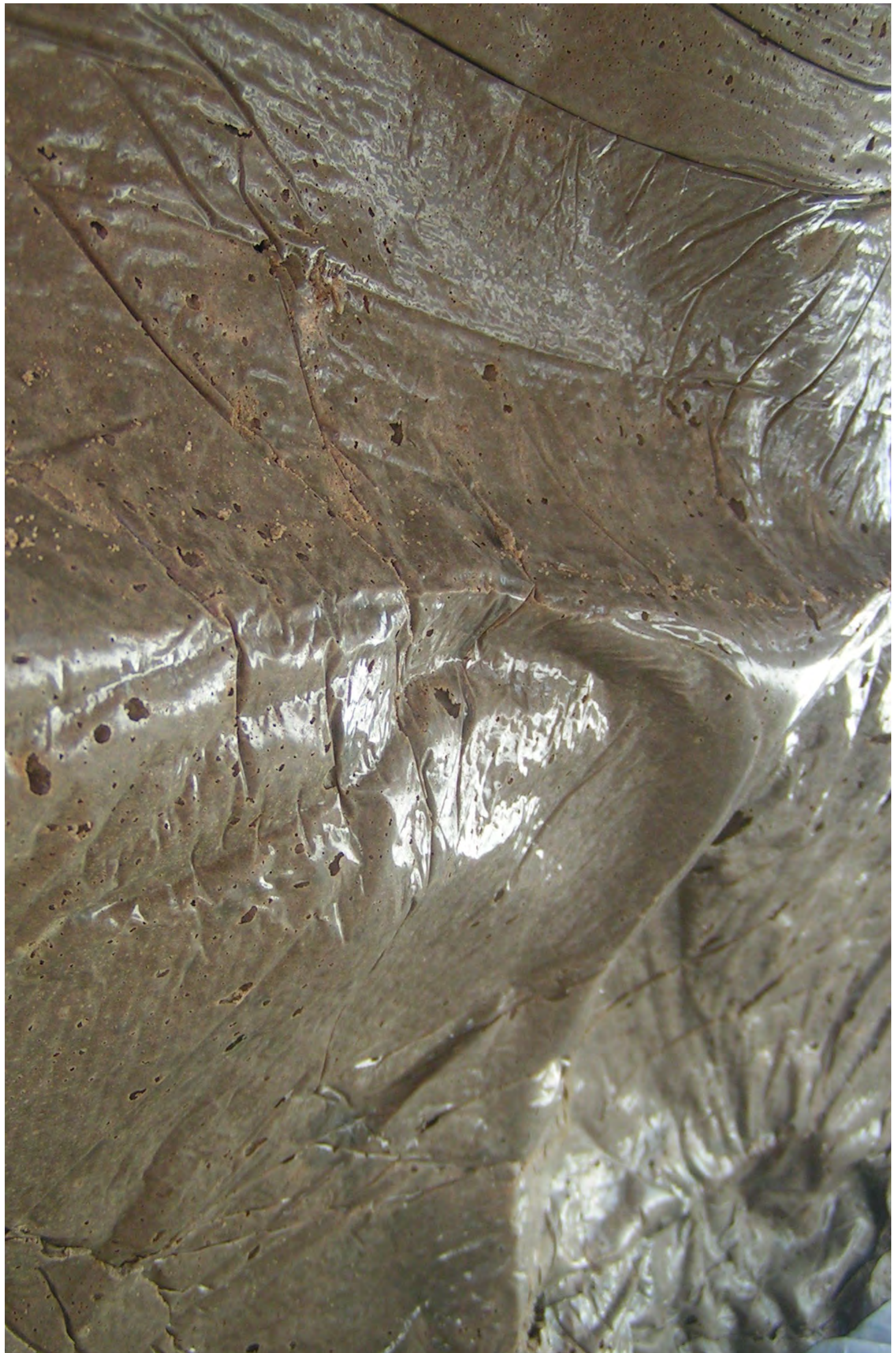


Fig. 215. Final texture

opened and earth taken away in order to loosen the whole infill formwork system. Then other sandbags were removed without need to be opened. Following conclusions were made:

- Texture created by sandbags covered with construction membrane is suitable for earth application and gives visual impression that fits the design concept - creating a cave impression;
- First sandbag should be opened before removal. Others can be removed rather easy without opening
- Voids made entirely of sandbags, however, is too time consuming, physically difficult and expensive for developed countries as the Netherlands.

As a result combined method of individually customized hollow formwork system in combination with sandbags have been selected as preferable construction method. Larger spaces are made by dome-shaped hollow aluminum formwork systems with one layer of sandbag cover while halls and window openings are made entirely from stacked sandbags that are removed after pouring process is done. Dome-shaped formwork can be reused from floor to floor while sandbags ensure unique surface texture in each hotel room. In order to avoid sharp edges that might be caused by gaps between sandbags as well as minimize adhesion between sandbag and earth mixture, a membrane should be covered on top of sandbags before pouring and removed after the process in done.

11.2.3. Atrium

Atrium spatially connects base with tower, provides light and contains horizontal and vertical communications. From engineering point of view atrium is interesting for its technical details of walkways and their connection to earth volume as well as skylight solution.

Analyzing pros and cons between suspended, cantilevered and columns-based bridges, first option was chosen as the load from all bridges via steel beams and concrete bond beams can be transferred to earth in a uniformly distributed manner (Figure 218). Main load bearing elements (steel tension rods)are hardly visible and their connections with earth volumes (at room entrances) do not require complex bearing system and can only be connected to integrated doorframes (Figure 217).

Bridges are designed to provide maximum transparency (hand rails entire out of laminated glass) but also feeling of safety (rather thick and heavy looking walking surface with integrated engineering installations; Figure 201).

11.3. Earth Types to Be Used

Hotel building represents versatile character of earth as a construction material that can be reached by using different additives. 5 different earth types have been used:

1) unstabilized earth (23% gravel, 45% sand, 20% silt, 12 %clay; compressive strength ~2Mpa (used for calculations));
2) impregnated earth (23% gravel, 43% sand, 20% silt, 12 %clay, 2%bitumen); Highly waterproof. Bitumen is either dissolved in water with an emulsifier such as naphtha, paraffin oil or petroleum. After pouring is done, earth mixture dries and bitumen evaporates. Being highly adhesive it glues the pores in rammed earth structure;
3) impregnated and insulated earth (23% expanded glass, 43% sand, 20% silt, 12 %clay, 2%bitumen). Manufacturer “LIAVER” claims that such admixture has k-value ~0.11W/mK – it means only ~4 times less efficient than foam or wool insulation;
4) impregnated, insulated, stabilized earth (23% expanded glass, 43% sand, 20% silt, 7 %clay, 2%bitumen, 5%cement).
5) earth surface treatment with oil – for floors in tower volume in order to protect from moisture and dirt ingress.

Fig. 216. Inspiration for atrium design

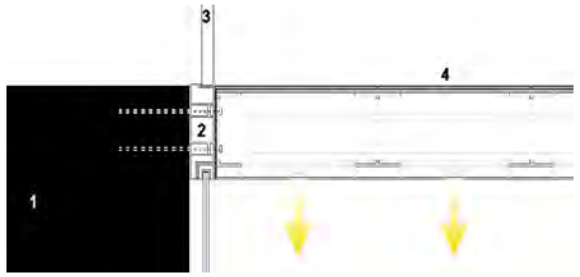


Fig. 217. Catwalk and earth volume connection. (1) Unstabilized poured earth; (2) Internal door frame system; (3) Hotel room entrance doors; (4) Catwalk

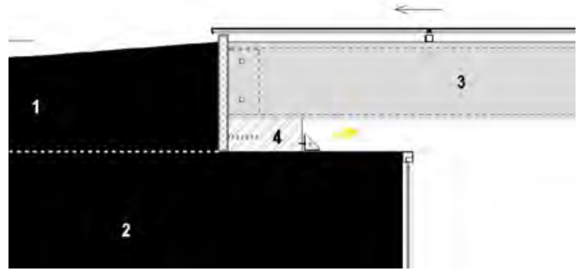


Fig. 218. Skylight and earth volume connection. (1) Insulated, bitumen impregnated earth; (2) Unstabilized poured earth; (3)Steel beams; (4) Concrete bond beam

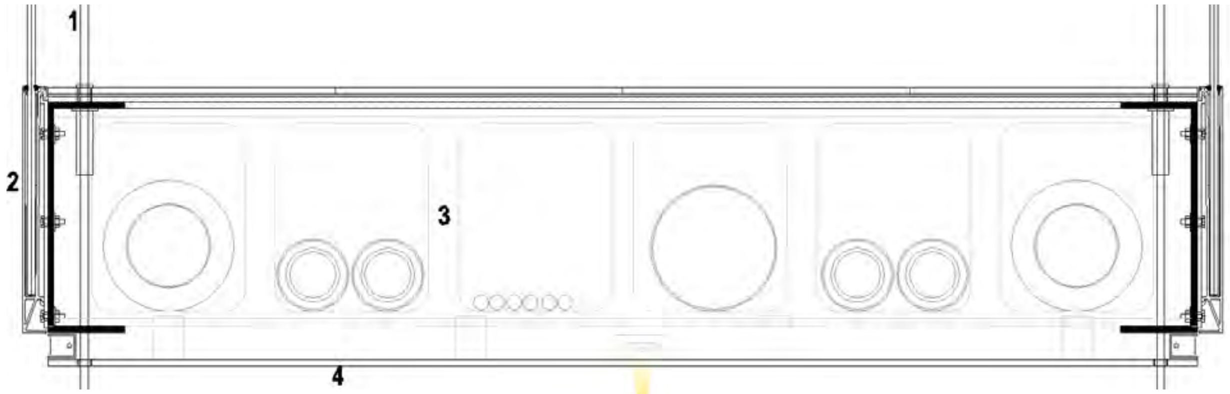


Fig. 219. Catwalk solution. (1) Tension rod; (2) “Easy fix” glass handrail system; (3)Steel beams with openings; (4) Suspended ceiling

Fig. 220. Catwalk concept. Macro Museo d’Arte Contemporanea, Roma

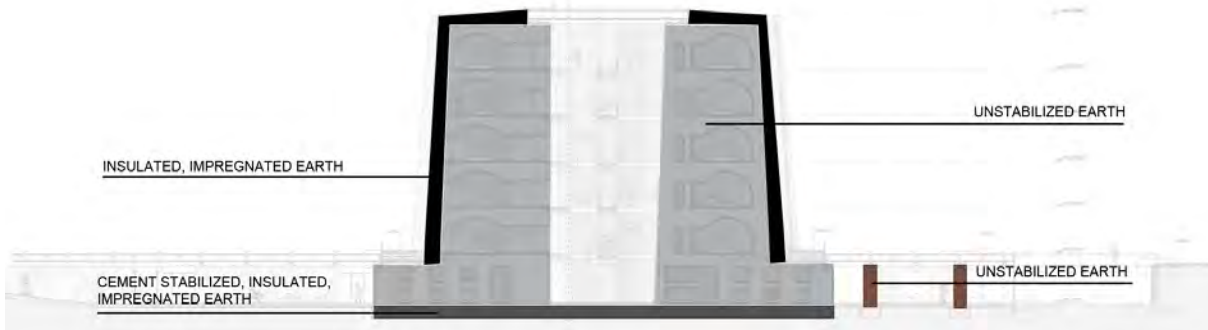


Fig. 221. Earth types used in hotel design

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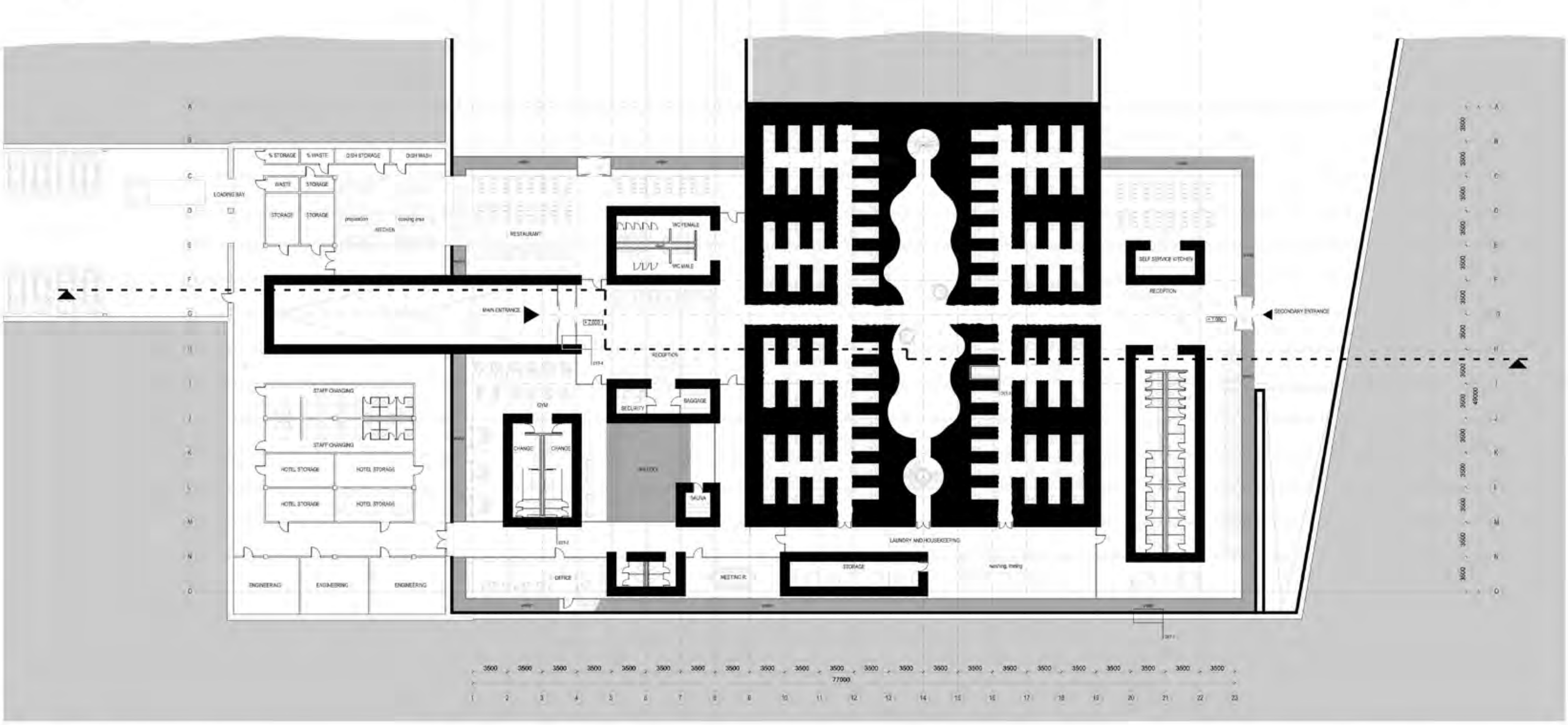
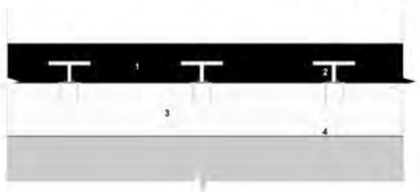
GROUND FLOOR PLAN
1:200



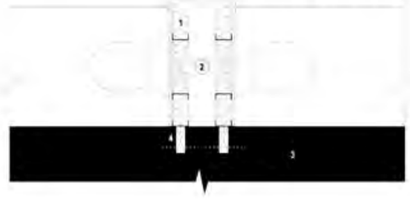
DET-9 RETAINING WALL ANCHORING
1:10

BITUMEN IMPREGNATED POURED EARTH 1
"T"-SHAPED ANCHOR PLACED IN "U"-SHAPED RAIL 2
REINFORCED CONCRETE 3
HYDRO INSULATION 4



DET-10 COMMUNICATION SHAFT CONNECTION
1:10

DOUBLE GYPSUM WALL ON ALUMINUM FRAME 1
SEWER PIPE 2
UNSTABILIZED POURED EARTH 3
WOODEN NAILING STRIPS WITH ANCHORS 4

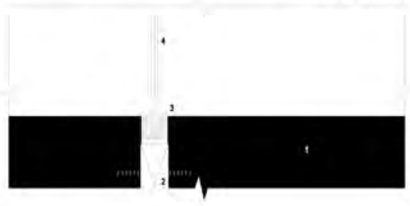


DET-11 SLEEPING CAPSULE
1:10

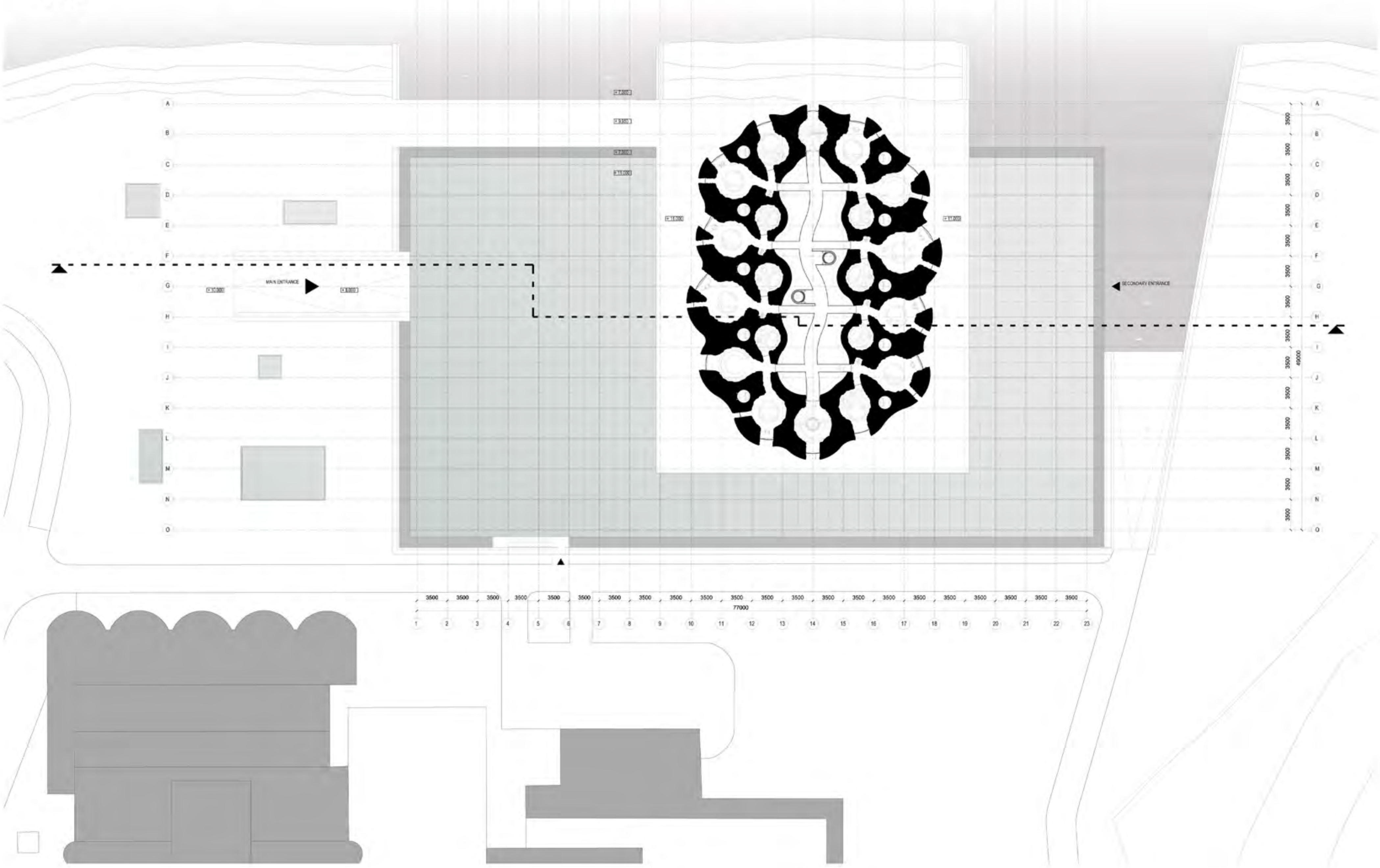
UNSTABILIZED POURED EARTH 1
SPACE FOR ENGINEERING INSTALLATIONS 2
SANDWICH TYPE METAL FRAME WITH 3CM THERMAL INSULATION 3
BED ON RAILS FOR EASIER MAINTENANCE 4

DET-12 GLASS WALL CONNECTION
1:2

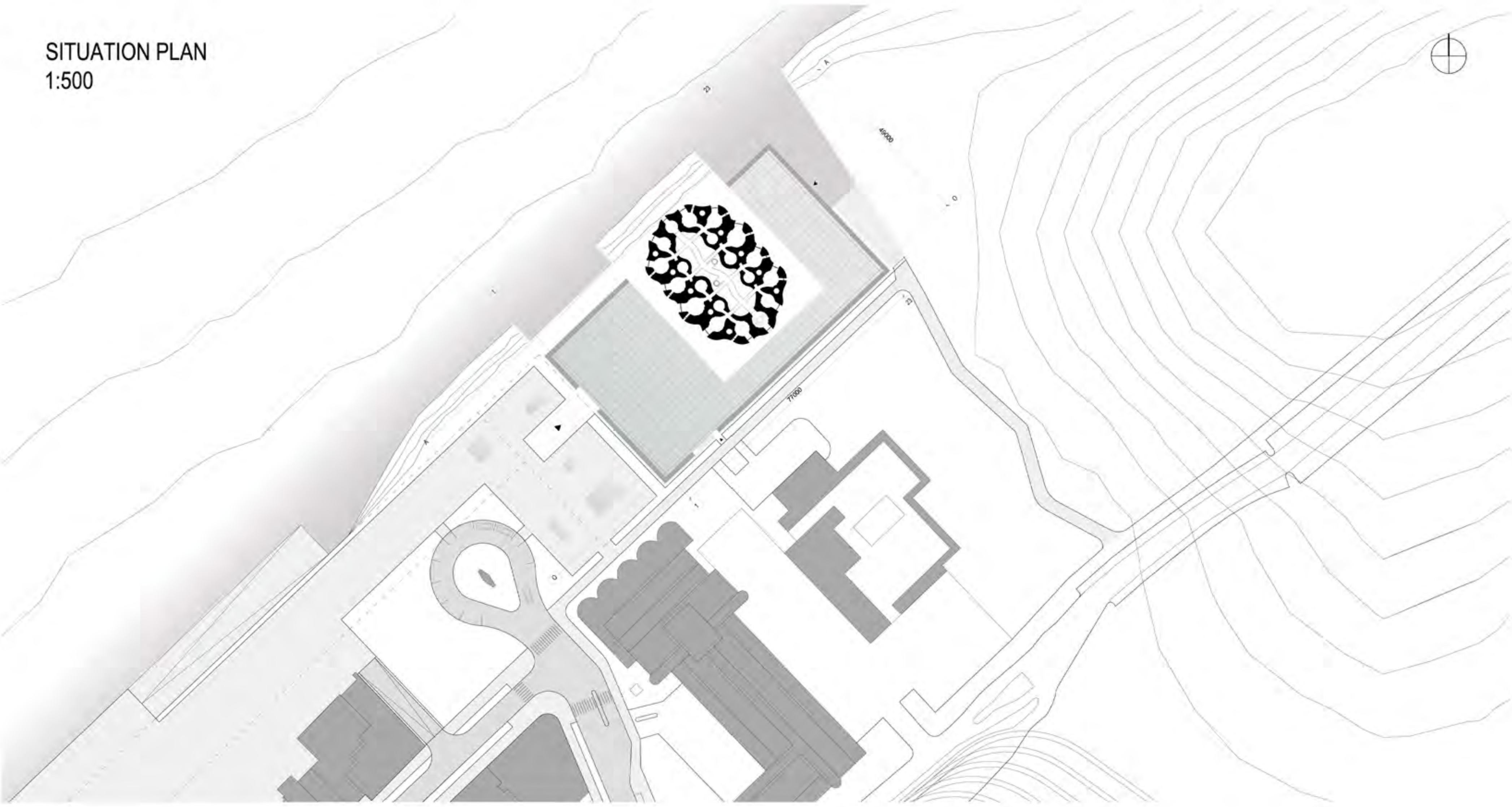
CEMENT STABILIZED POURED EARTH WITH 20% EXPANDED GLASS CONTENT 1
WOODEN NAILING STRIPS WITH ANCHORS 2
ALUMINUM WINDOW FRAME 3
LAMINATED GLASS 4



FIRST FLOOR PLAN
1:200

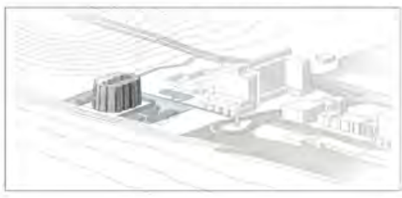


SITUATION PLAN
1:500



5. EARTH TOWER

FACILITATES HOTEL ROOMS
MADE OUT OF UNSTABILIZED POURED EARTH
OUTER LAYER - INSULATED, IMPREGNATED EARTH



6. RAMPS AND CUTOUTS

MAIN ENTRANCE 1
SECONDARY ENTRANCE 2
ENTRANCE TO RESTAURANT 3

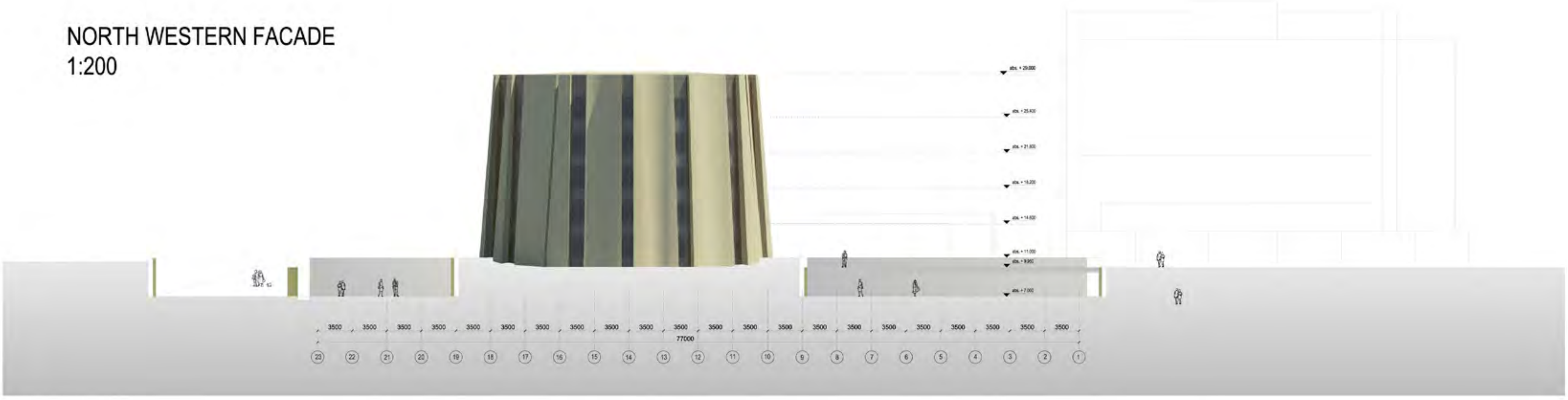
7. TECHNICAL FACILITIES

STAFF, LOADING BAY, KITCHEN, ENGINEERING
MADE AS CONCRETE STRUCTURE

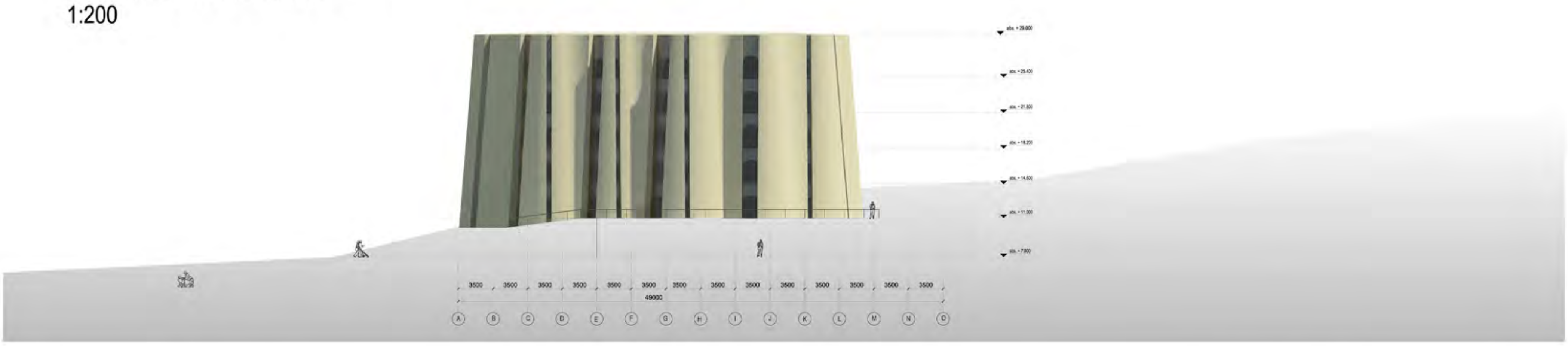
8. PARKING LOTS

ENTRANCE RAMP 1
STAFF PARKING LOTS AND LOADING BAY 2
PUBLIC PARKING LOTS 3

NORTH WESTERN FACADE
1:200



SOUTH-WESTERN FACADE
1:200



1. EXISTING SITUATION

SCHEVENINGEN PROMENADE 1
HOTEL BUILDING 2
OXBOUW BEACH CLUB 3
DUNE PARK 4

2. CUTOUT IN DUNES

CUTOUT:
DIMENSIONS = 80M X 45M X 3M
SAND USED AS CONSTRUCTION MATERIAL

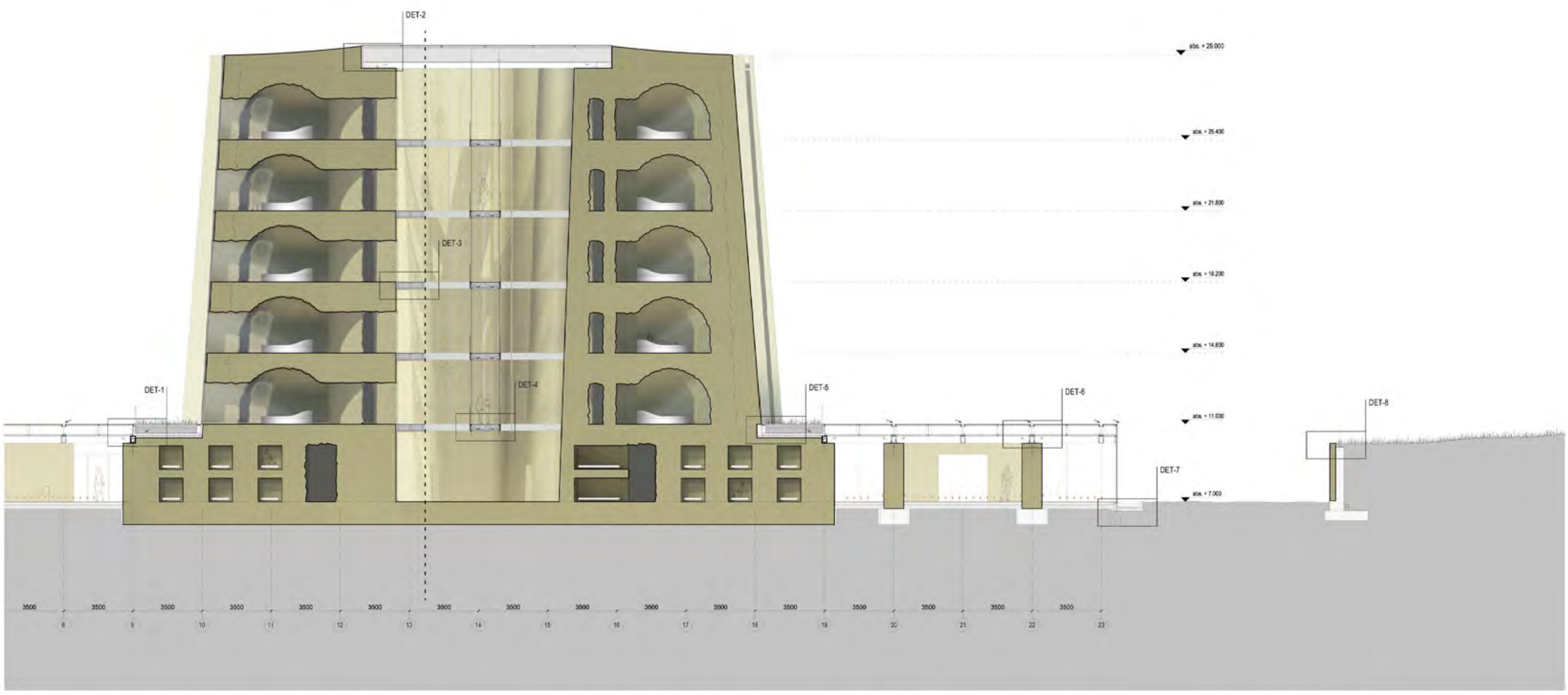
3. EARTH CORES

SLEEPING CAPSULES 1
TOILETS, CHANGING ROOMS, WASHING FACILITIES 2
RECEPTION 3
SELF SERVICE KITCHEN 4

4. GLASS COVER

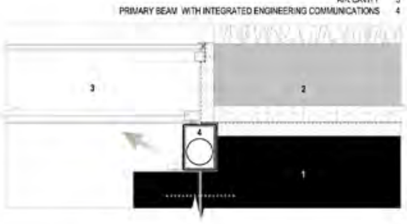
PROTECTS EARTH CORES FROM ENVIRONMENTAL IMPACTS
COLLECTS WARM AIR TO HEAT UP EARTH TOWER
SURFACE - DOUBLE LAMINATED GLASS COVERED WITH DIRT PROTECTING COATING

CROSS SECTION
1:100



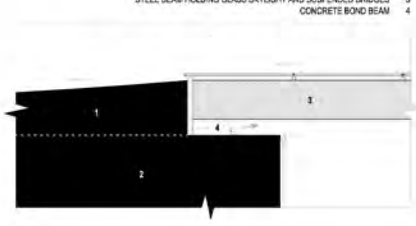
DET-1 GLASS ROOF CONNECTION 1
1:20

UNSTABILIZED POURED EARTH 1
SOIL 2
AIR CAVITY 3
PRIMARY BEAM WITH INTEGRATED ENGINEERING COMMUNICATIONS 4



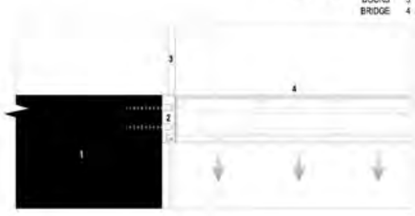
DET-2 GLASS ROOF CONNECTION 2
1:50

BITUMEN IMPREGNATED POURED EARTH WITH 20% EXPANDED GLASS CONTENT 1
UNSTABILIZED POURED EARTH 2
STEEL BEAM HOLDING GLASS SKYLIGHT AND SUSPENDED BRIDGES 3
CONCRETE BOND BEAM 4



DET-3 SUSPENDED BRIDGE AND WALL CONNECTION
1:20

UNSTABILIZED POURED EARTH 1
INTERNAL FACADE FRAME 2
DOORS 3
BRIDGE 4

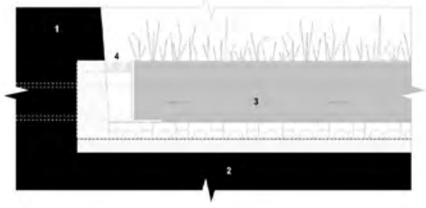


DET-4 SUSPENDED BRIDGE
1:10

TENSION ROD CONNECTED TO LOAD BEARING "C" PROFILE 1
"EASY GLASS" RAILING SYSTEM 2
STEEL BEAMS WITH OPENINGS FOR ENGINEERING COMMUNICATIONS 3
SUSPENDED METAL CEILING 4

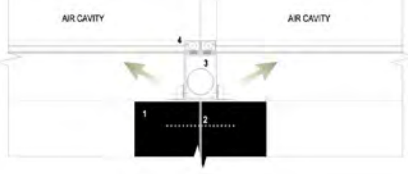
DET-5 GREEN ROOF CONNECTION
1:20

BITUMEN IMPREGNATED POURED EARTH 1
UNSTABILIZED PORED EARTH 2
INSULATED WARM AIR DUCT 3
GULLY 4



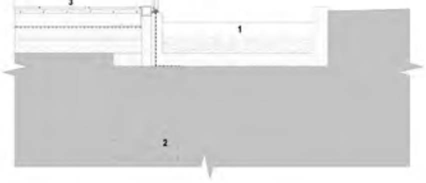
DET-6 GLASS ROOF AND EARTH WALL CONNECTION
1:20

UNSTABILIZED POURED EARTH 1
STEEL PROFILE BOND BEAM ANCHORED IN EARTH WALL 2
PRIMARY BEAM WITH INTEGRATED ENGINEERING INSTALLATIONS 3
REMOTE CONTROLLED LOUVER SYSTEM 4



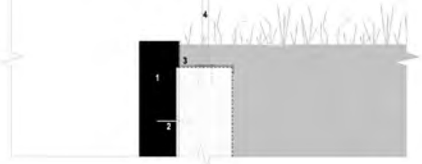
DET-7 RAINWATER COLLECTOR
1:20

RAINWATER COLLECTOR WITH PEBBLES 1
FOUNDATION FOR SELF-BEARING FACADE FRAME 2
TILE FLOOR WITH HEATING CABLE 3



DET-8 TOP OF RETAINING WALL
1:20

BITUMEN IMPREGNATED POURED EARTH 1
SLIDING ANCHOR 2
FLASHING METAL 3
HANDRAIL 4



FIRST FLOOR FRAGMENT
1:100