SUBTERRESTRIAL CHAMBERS OF HAGA

an exploration into sustainable concrete alternatives and underground construction technics

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Department of Architecture & Civil Engineering
Spring 2024

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Thank you

Family & friends

Erica Hörteborn
Jonas Lundberg
Tabita & Peter

Abstract

The construction industry has an undeniable share in the global CO2 footprint and according to the UN Environmental Programme the industry is drawing further away from the 2050 decarbonisation pathway while its emissions reached a new peak by exceeding the pre-pandemic numbers of 2019 (UNEP, Nov 9 2022). With concrete being one of the predominant construction materials, it contributes to this share massively. Furthermore not only the production of concrete but also extraction of its components from the planet is accelerating in a warning rate and causing unrepairable environmental damage.

Especially Nordic countries have high environmental awareness and there are many examples of sustainable buildings responding to current needs. Nevertheless the large scale underground structures are still built with concrete due to their higher requirements.

The study aims to explore the properties of carbon neutral or even carbon negative substitutes in combination with alternative building methods and design approaches. The replaced materials jointly with a supporting design process and construction method aim to minimise the environmental impacts.

As location for the thesis Haga station of Västlänken project (eng.: West Link), a part of an ongoing infrastructural project of Gothenburg, is chosen, which is situated in one of the oldest districts of the city surrounded by historical landmarks. In addition to its touristic appeal, according to the urban development project the commuter traffic in the area will increase. The thesis proposes an exhibition area in the first underground level of the station dedicated to showcase these explorations and further researches to raise awareness, while connecting two entrances to the station and forming an alternative path for the commuters. The space is designed with focus on efficiency of material use and inspired by traditional but mostly abandoned building technics.

Keywords
sustainable concrete; cement substitutes; recycled aggregates; architectural design

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According to Robert Courland,
author of „Concrete Planet“,
there is approximately

40.000
kilograms

of concrete for each person
alive and we’re adding ca. 500
kilograms per person each year.

Introduction

Problem statement

Reducing CO_2 emissions is essential to itigate the adverse effects of climate change. Continues CO_2 emissions will lead to increased global temperatures, exacerbating extreme weather events and sea-level rise (IPCC, 2021). Furthermore, studies have shown that reducing CO_2 emissions improves air quality and public health by decreasing pollutants associated with fossil fuel combustion (Anenberg et al., 2019). Transitioning to low-carbon energy sources is critical for sustainable development and innovation (IRENA, 2020).

To fight the Covid 19 pandemic, many preventive measures were taken in the first quarter of 2020 and which had a strong impact on construction production and the recovery continued throughout summer (Eurostat, 2022). Even in the early weeks of pandemic restrictions and almost a full stop of many industries including construction, nature started to restore itself from human destruction in a rapid speed (Arora et al. 2020). But with the lifting of the restrictions most people went back to their lives as before pandemic, if not with more consumption.

The construction sector is responsible for over 34% of global energy demand and has a critical impact on achieving the sustainability goals. According to the UN Environmental Programme construction industry's CO_2 emissions reached a new all-time high by exceeding the pre-pandemic numbers of 2019 and drawing away from the 2050 decarbonisation pathway (UNEP, Nov 9 2022). Cement, one of the primary construction materials and one of the main ingredients of concrete, is alone accounted for 5% of total CO_2 emissions (Basyigit et al. 2021) and sand, another main ingredient of concrete, is one of the most mined material on the planet with 68% of all (UNEP, 2014) while it stated in the same article "formed by erosive processes over thousands of years, they [sand and gravel] are now being extracted at a rate far greater than their renewal".

Aim & Purpose

This thesis project aims to investigate alternative design approaches in development of underground concrete structures and their potentials through material, form and method explorations. Although with the awakening in the construction industry the interest in building with a broader assortment of materials is growing, it is important to draw attention that concrete is still mainly preferred for large-scale underground structures.

Thesis Questions

When investigating sustainable alternatives for concrete blends, researchers tend to look for changing the mix so that the construction can stay exactly the same. But new combinations might work better with other methods.

- What changes appear in architectural expression when modifying concrete blend?
- What architectural design approaches can be applied to create an underground structure that takes advantage of these potentials and deals with pressure of surrounding soil in the example of Västlänken's Haga station in Gothenburg?
- How do these modifications affect the space and its physical features? What design approaches can take advantage of building underground that would be impractical above ground?

Method

Literature Studies

Relevant literature covering books, publications and articles are examined in order to understand the roles of the materials and building methods and their possible utilisation.

Case Studies

A critical analysis of relevant built references are carried out to gain insight regarding building techniques in combination with the material studies.

Interviews

Interviews with researchers and professionals are conducted. Their valuable inputs gave new insights during the research. A visit to C-Lab gave a first hand experience how material observations and tests are carried out.

Material & Spatial Explorations

Suitable materials and forms are identified through a background research. Various material explorations are carried out for a hands-on material experience and their properties are analysed with both qualitative and quantitative approaches.

The explorations' physical properties such as visible differences, tactility and texture are catalogued for later potential use for user experience and spatial design.

Delimitations

In the heart of the thesis lies the material and design explorations on a quest to mainly investigate architectural qualities of the modified concrete blends and a design approach for building underground.

The materials were chosen through the months leading to this thesis according to their accessibility.

All materials are mixed and cured in a home lab. The physical features are inspected and compared to each other but no mechanical tests are conducted due to accessibility issues to facilities. Chemical and sustainability properties, economical viability or material availability for widespread use are not included.

The final design is not tested in any mechanical way nor is its structural, fire protection or thermal properties are calculated.

Case Studies

„Concrete is an artificial stone, and like stone, it does not want to be a straight beam, it wants to be a masonry arch.“ Philippe Block (Block Research Group)

Pantheon

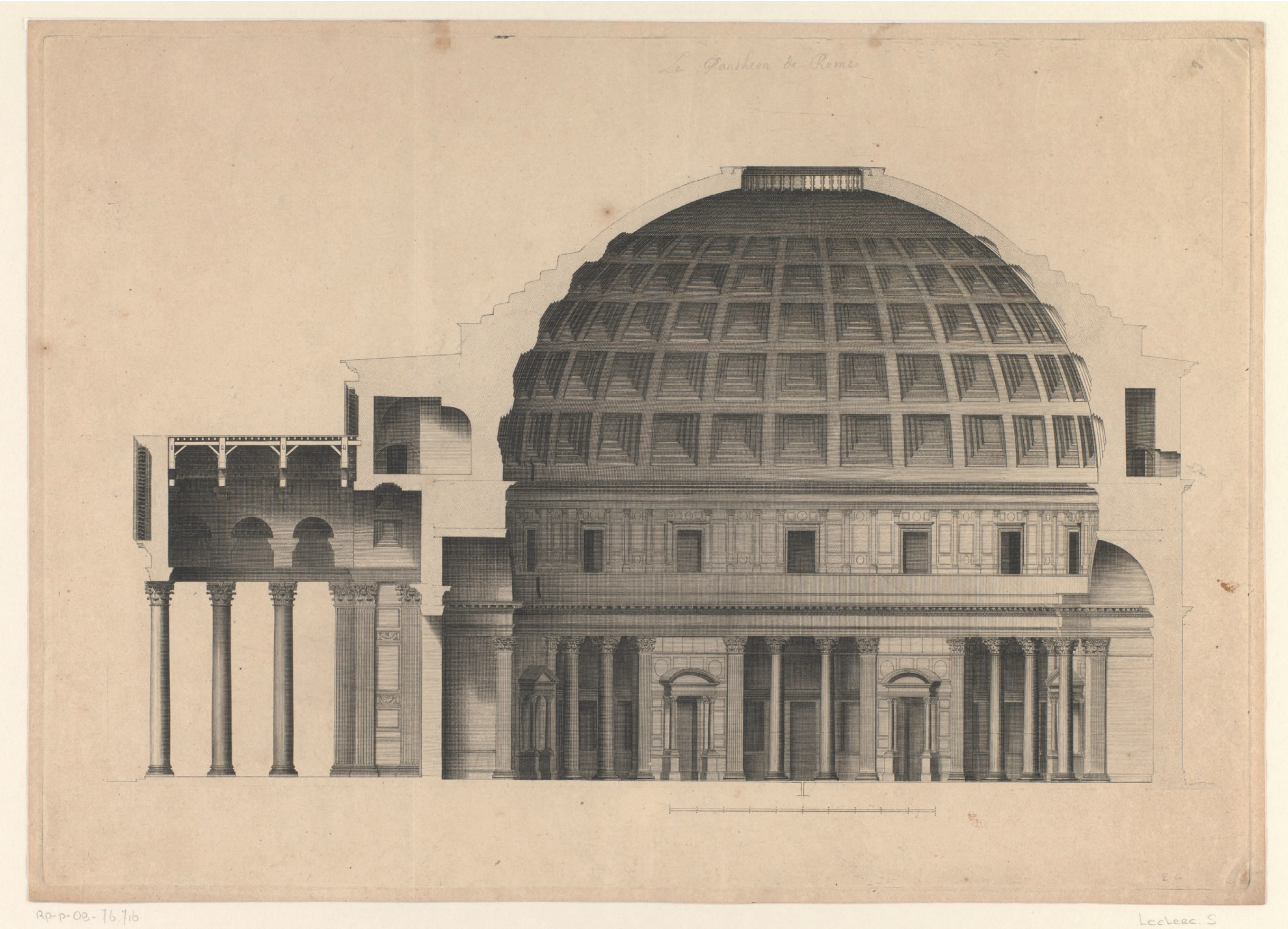
Santa Maria del Fiore

St. Peter‘s Basilica

Ex-Soviet Metro Stations

Striatus Bridge

Underground Cities of Turkey



Dome of Pantheon

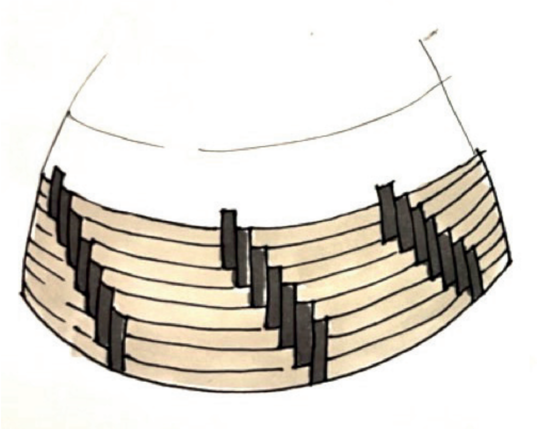
Pantheon was built 2nd century AD in Rome, Italy. The rotunda has an inner diameter of 43m. And although finished almost two millenia ago, it is still the world‘s largest unreinforced concrete dome and can serve as an inspiration for its advanced engineering and methods.

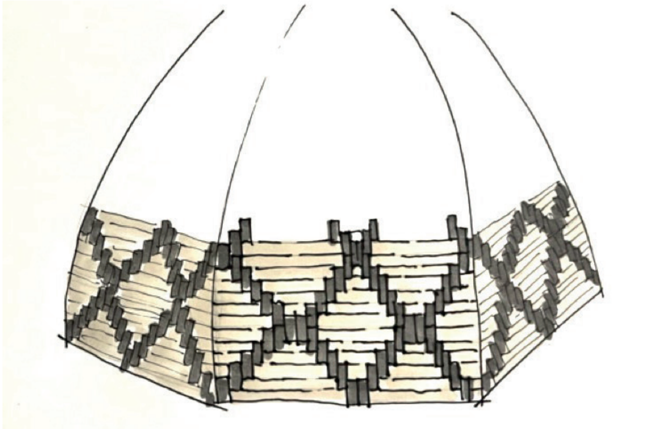
Massive walls supporting Pantheon’s dome is acting as foundation so the dome isn’t pushed outward under its own weight. The dome was constructed probably with a temporary wooden centering and in layers of a fairly dry Roman concrete for it to cure rapidly, since it was not possible to cast on site in the densely built central Rome.

The dome has a lighter concrete than the walls with volcanic sand and light tuff, and they become thinner upwards. Lower parts were built with basalt mixed concrete meanwhile the top was pumice mixed concrete.The ceiling has recessed panels to reduce unnecessary material while maintaining structural integrity (Mark, 1993). The oculus is the source of natural light and acts as a compression ring and eliminates the stress of concrete at the dome’s weakest point (MacDonald, 2002).

Fig. 01: Cross section of the Pantheon in Rome. Source: Leclerc, S.I, Desgodetz A., Coignard, J.II, (1682)

on next page top to bottom:
Fig.02: Pantheon‘s dome and oculus. Source: Ganji, M., (2018)
Fig.03: Pantheon. Source: van der Werf, P. (2022)





Dome of Santa Maria del Fiore

The dome of Santa Maria del Fiore in Florence was designed by Brunelleschi and constructed in 14th century without a temporary centring formwork, as by the time the dome was being built the cathedral was already in use (Maccaferri, 2014).

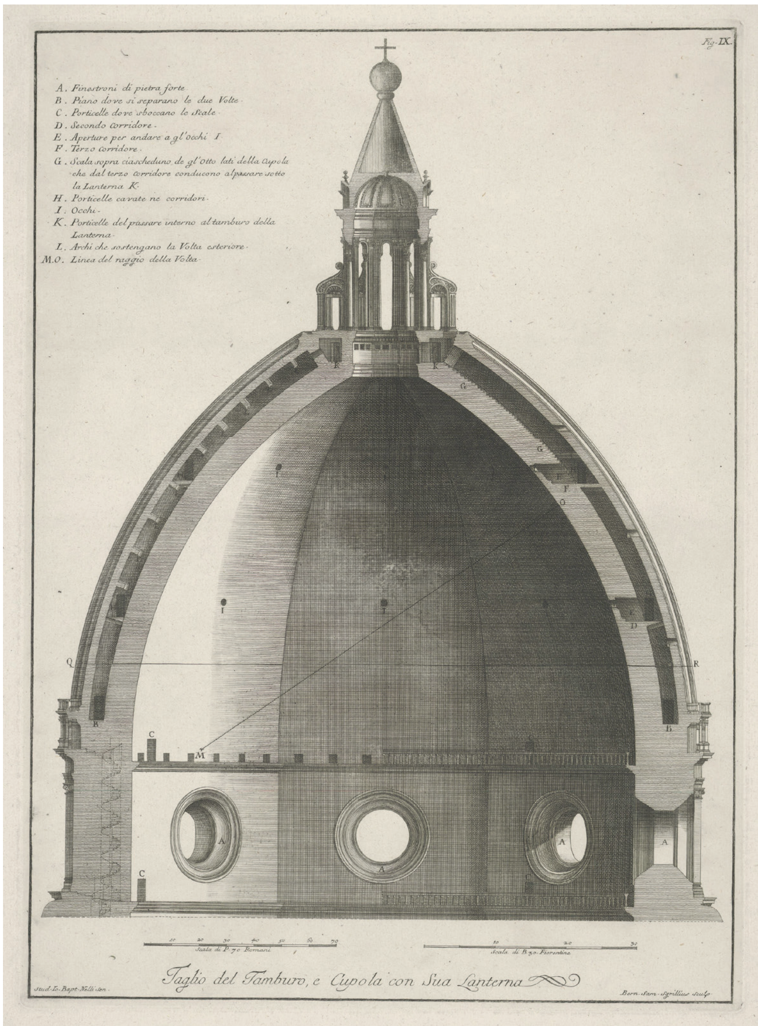
This dome was constructed with bricks to take advantage of their lighter weight than stone and concrete. The dome is formed by herringbone technic and is a double shelled dome (King, 2000). The oculus at the top is open like the Pantheon to bring light inside.

Dome of St. Peter‘s Basilica

The dome of St. Peter‘s Basilica is supported by four piers and is designed as a double-shell masonry structure with an inner and outer dome connected by ribs (Designing Buildings, 2022). Massive chains embedded within the masonry to stabilise the dome without needing extensive external buttressing (Martines, 2003).

Both of these buildings are great examples of integration of aesthetic and functions and how historic technics can be combined with modern applications.

Fig. 04: Florence cathedral. Source: Nguyen, M. (2012)
Fig. 05: Sketch of method. Image by the Author.
Fig. 06: St. Peter‘s Basilica. Source: Harris, J. (2018)
Fig. 07: Sketch of method. Image by the Author.



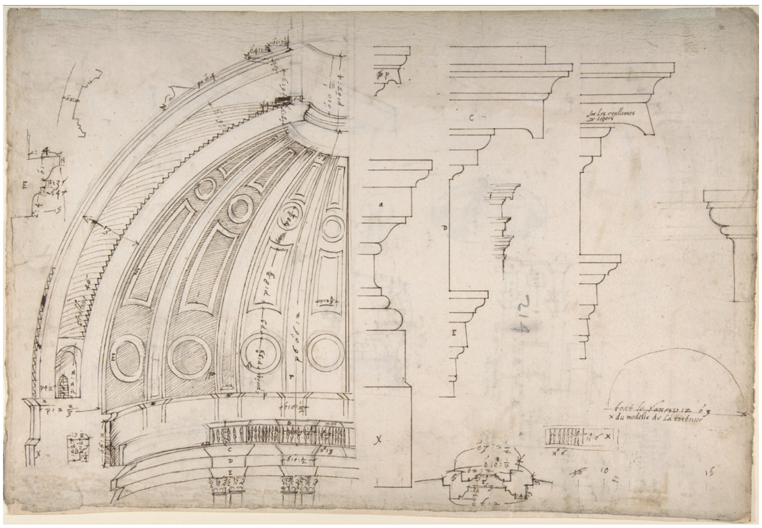


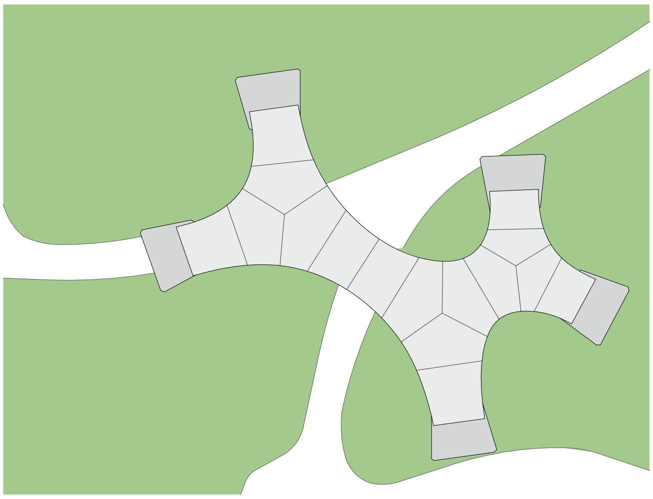
Fig. 08: Cross section of the dome of Santa Maria del Fiore in Florence. Source: Sgrilli B., Nelli G. (1755)
Fig. 09: St. Peter‘s dome and drum. Source: DuPérac, E., (n.d.)

Ex-Soviet Metro Stations

Frank Herfort's CCCP Underground displays several metro stations from over 17 post-soviet countries (Herfort, 2019). With this collection he documented the artistic and architectural richness of this era. Each metro station is designed individually and showcase handcrafted elements.

Spaces can resonate with their users through embedded cultural narratives into their design and the ambiance of a public space can be elevated by ornate detailing.

Fig. 10: Kirovsky Zavod station, St Petersburg. Source: Tofani, F. (2015)
Fig. 11: Kryvyi Rih- Prospekt Metalurhiv station. Source: Monto, T. (2013)
Fig. 12: Kievskaya metro station, Kharkiv. Source: Timon91 (2017)



Striatus Bridge

The project by Zaha Hadid Architects and The Block Research Group, displayed at Venice Architecture Biennale 2021, aims to demonstrate the potentials of unreinforced concrete and computational design.

The bridge has an arched form divided in parts following the historic masonry construction principles and consists of 3D-printed hollow concrete blocks that were dry assembled without use of any steel or mortar. The 3D-printed parts were not only produced with a low carbon concrete, but the printing process also optimised the use of material.

Strength is created through geometry, rather than an inefficient accumulation of materials as in conventional concrete beams and flat floor slabs.

The seamless blend of advanced technology with aesthetic appeal can serve as an inspiration on how a design can be both beautiful and functional.

Underground Cities

Underground cities in Turkey's Cappadocia region were built about 2000 years ago. The region is covered in soft volcanic ash, also famous for its fairy chimneys (Fig.14). The locals dug their own holes into the stone ground (tuff) for storage and temples, later developing into underground cities with ability to house up to 20.000 people and animals, for the purpose of refuge under attack. These cities are inspirational for natural ventilation shafts providing fresh air and how the rooms are organised in an underground space according to needs.

Fig. 13: sketch of Striatus Bridge. Image by the Author.
Fig.14: Cappadocia's fairy chimneys. Image by the Author.

Design Research

Design Research

Material Investigations

Material Explorations

Chain Models

Molding & Texture

Site

Site Analysis & Plans

Design Proposal

Exhibition space

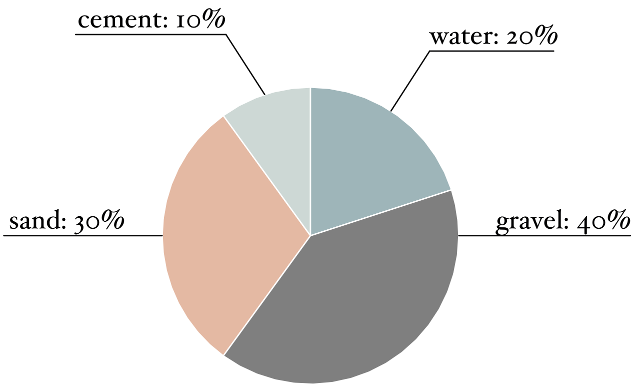
A Journey through Exhibition space

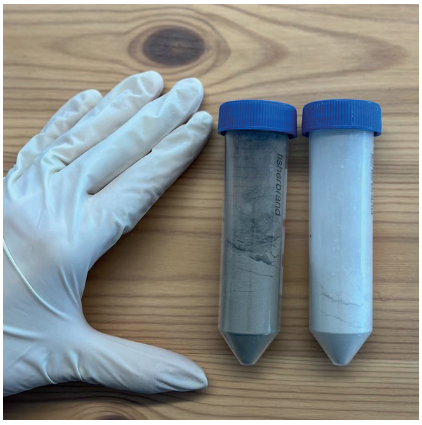
Main Gallery

Physical Model

Material Investigations

There are numerous companies which specialise in concrete with cement or sand replacements and even more research on substitution materials. The list below doesn't cover all of them but mainly focuses on industrial by-products that are readily tested and already in-use.





General info on concrete composition

Concrete has been in use as construction material since ancient times and is preferred due to its strength, durability and workability.

In its most basic form, concrete is a blend of paste and aggregates. The paste is usually a mixture of Portland cement and water, meanwhile aggregates are the granular materials such as sand, gravel, crushed stones and recycled concrete.

Cement acts as the binding material and is a powder made mainly of limestone, clay, and other minerals. When in contact with water, cement undergoes a chemical process called hydration and hardens over time.

1. Cement Substitutes

1.1 GGBS

Ground Granulated Blast Furnace Slag is a by-product of steel and iron industry. It is typically combined with Portland cement between 20% and 80%. It has a longer setting time, resulting in concrete to remain workable longer and creates a reduced risk of cold joints, which is particularly useful in warm weather (CSMA, 2022). GGBS reduces carbon footprint of concrete not only by using an industrial waste but also by reducing the need for clinker production.

1.2 Coal Fly Ash (PFA)

Fly ash is a by-product of coal industry. It can create a stronger, longer-lasting and an environmentally friendly alternative to Portland cement, when mixed with borate, bottom ash and a chlorine compound. In comparison to traditional concrete, Ashcrete has more resistance to acid, fire, extreme temperatures and corrosion. Although fly ash is significantly cheaper than standard cement, its production may not be economically feasible in long-term due to planned reduction of the use of coal in the future.

Figures on both pages:
Fig. 15: Composition of concrete. Image by the Author.
Fig.16 Fly ash powder on the left and GGBS on the right. Image by the Author.
Fig.17: Treated fly ash in solid form. Image by the Author.
Fig.18: Pumice stone and powders. Image by the Author.

1.3 Waste Fly Ash

Waste incineration is an efficient and climate-sound way of producing district heat and electricity and at the same time a solution for waste that can‘t be recycled. Unfortunately, incineration of waste generates flue gas waste; hazardous fly ash and a contaminated acid. Today thiss fly ash is transported to specific landfill sites, especially in closed mines. With a unique and sustainable process that recovers salts and metals from untreated and heavy metal containing fly ash, it is possible to return harmless and usable material to the economy.

1.4 Ferrock

Ferrock is a recycled construction material produced mainly from waste steel dust and silica from ground-up glass. Utilising waste materials which would land otherwise in landfill, ferrock is a carbon negative alternative to traditional cement. Concrete made with ferrock has a five times higher strength than made with ordinary Portland cement and is also more flexible thus endures higher compression stresses due to seismic forces. Since it is composed of industrial by-products and can have limited production, it is less accessible in larger scale.

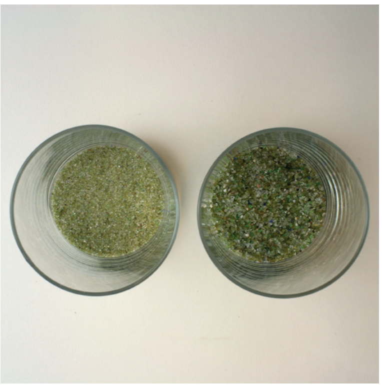
1.5 Pumice

Pumice is an igneous rock which is formed by a sudden decompression and cooling down of magma or lava after an explosive volcanic eruption (both continental and submarine). The molten lava or magma originating from Earth’s interior loses heat abruptly when it reaches Earth’s surface. This leads the previously dissolved gases within magma to escape and resulting pumice’s foamy appearance. Even though it frequently has a light color because of high silica and low iron and magnesium content, its colour can vary depending on the composition. Due to its high porousness, pumice is significantly light weight and can even float on water, thus potentially forming floating islands.

Most typically pumice has a silica-rich composition and can be found everywhere, although the composition can vary from place to place due to differences in magmatic composition, geological and crystallisation settings, characteristics of the volcanic activity and so forth. According to US Geological Survey leading pumice producers worldwide in 2022 were locate in Italy, Turkey, Russia, United States, Iceland and Greece.

Pumice or ground pumice is used widely in everyday life, for instance as skin exfoliants, production of stone-washed jeans, toothpaste, horticulture etc. Ground pumice was mixed by Romans as binder in concrete blend and many of its examples such as Pantheon in Rome are

2. Sand Substitutes



2.1 Sheet Glass (crushed glass)

Glass is produced in different variations of shapes and forms from containers and sheets to bulbs and has a wide of utilisations. Although all these have comparatively short life spans and need to be recycled and reused to avoid possible environmental damage by their disposal in landfills (Park et al., 2004). Glass is a material which can be recycled completely and continuously without any quality loss. Replacing sand with glass powder in concrete improves concrete's workability and 10 to 30% sand replacement with glass waste powder increases strength by 20% (Jagan et al., 2023).

2.2 Quarry Dust

Quarry dust is a by-product resulting during cutting and crushing process of stone and can be used as fine aggregates. Typically this dust is seen as useless and waste while part contributes to air pollution due to its fine particles. It can be used as a replacement to sand partially or even entirely without compromising the quality of concrete, hence it presents an opportunity to be used for construction as building material with lower costs (Prakash & Rao, 2017).

2.3 Demolition Waste

Demolition waste consists of waste materials such as dead mortar, concrete, stones, which are non-biodegradable and chemically inactive substances. Replacing river sand up to 25-50% with these materials in concrete blend increases compressive strength up to a certain percentage and advantages the environment, since these materials typically end up in landfills and are heavy and bulky with high density.

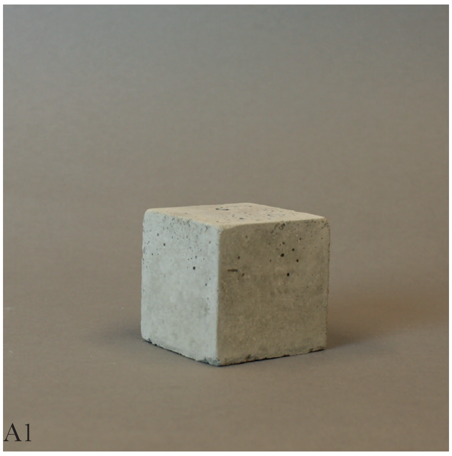
Fig. 19: Crushed glass in two grain sizes. Image by the Author.
Fig.20: Demolition waste. Source: Pixabay (2016)

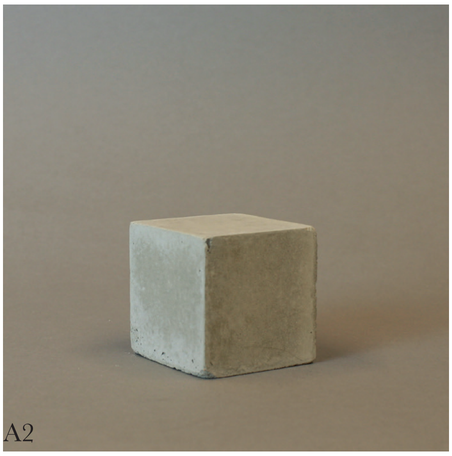
Figures on the right:
Fig.21-26: cement, Iceland pumice, Greece pumice. on right: Norm sand, crushed glass 1,5mm, crushed glass 0,5mm.Images by the Author.






Material Explorations


A1


A2


A3


A4


A5

Figures 27-31: Material explorations A1-5, images by the Author.


B1


B2


B3


B4


B5

Figures 32-36: Material explorations B1-5, images by the Author.

To have more hands-on experience and understand the materials better, explorations were done.

Iteration A

The first iteration was done in october 2023. In this iteration, following mixes and materials were used (Fig.27-31):

A1: typical pre-mixed concrete blend, as main comparison

A2: A1 with added 10% glass powder. Powder produced by crushing several glass bottles manually by the author.

A3: A1 with added fly ash.

A4: A1 with added GGBS.

A5: sand replaced by demolition waste. Demolition waste produced by author with crushed previously made A1.

A2 has visibly more shiny surface in comparison to A1, meanwhile A3 and A4 look almost identical. A3 is slightly heavier than A1 and A4 has slightly lighter colour.

Iteration B

The second iteration was done in january 2024, after producers and researchers were contacted and material was collected (Fig.32-36).

B1: sand replaced 100% by crushed glass mix.

B2: cement replaced by pumice from Greece (50/50) and sand replaced by glass mix.

B3: cement is replaced by pumice from Iceland (50/50) and sand replaced by glass mix.

B4: cement replaced by pumice from Iceland and Greece (all 1/3) and sand replaced by glass mix.

B5: cement replaced by pumice from Iceland and Greece (all 1/3) and norm sand is used.

Crushed glass mix is a 50/50 mix of two grain sizes recycled glass from a producer. Replacing glass worked with pumice mixes better than only cement. B1 has a grainy texture, meanwhile B2 and B3 are visible easiest to differenciate.

Iteration C

The third attempt, done in february 2024 focused on local gravel granodiorit, gray-red coloured and forming texture with bubble wrap. Gravel floated into the mix and is mostly not visible at the end.

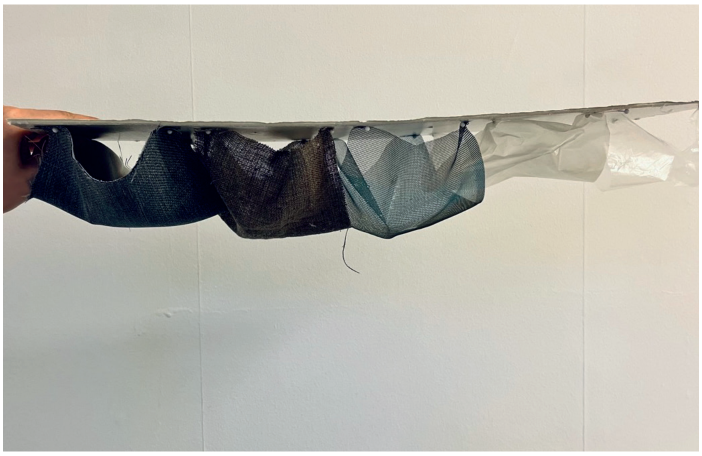
C1: A1 mix with gravel (Fig. 37-40).

C2: a mix of B2 and B3, creating a colour gradient.

C3: plaster in bubble wrap for comparison.

C4: B2 and B3 divided by a gravel layer.

Figures 37-40: Material explorations C1-4, images by the Author.



Hanging Chain Models

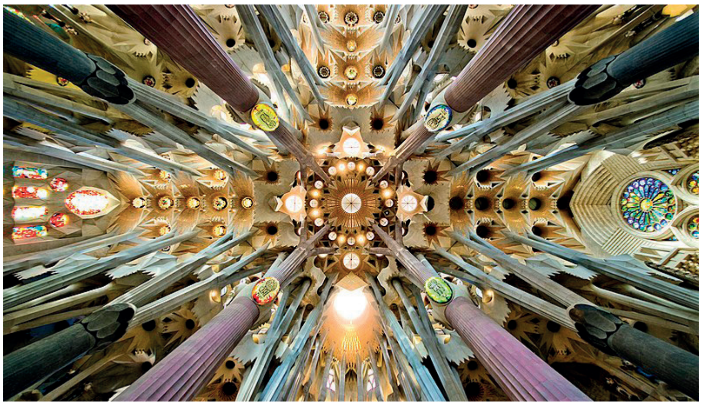
Hanging chain models have been used for centuries to define arches. Because when suspended from both ends, chains form catenary curves, that distribute the static load evenly.

Antoni Gaudi, a catalan architect best known for his design for Barcelona‘s Sagrada Familia, was using models instead of drawings during his design process. He studied nature to find elegant, aesthheticly pleasing yet structurally self sufficient forms. So he used chain models to create and study his ideas. What he did inventively was, to hang chains on chains asymmetrically, to form his signature design elements (Gomze-Moriana, 2012). Chains react and adapt to changes in loads instantly allowing to see direct results overall. With this working models he was actually using parametric design before computers existed. Today we are using various softwares to do the same, study alternatives and compare design strategies.

An example of his technique is visible in the design of Sagrada Familia, of which the working chain models are still in showcase in Barcelona. Another well known name for using working models for form finding is Heinz Isler, a Swiss designer-engineer, who is known for his thin shell concrete structures. He developed high efficiency and low environmental impact structures by exploring various formwork: molded earth, inflated rubber membranes, and draped fabrics (Build LLC, 2009).

On the left top to bottom:
Fig.41: Gaudi‘s hanging chain model. Source: Enking, L. (2010)
Fig.42: Chain working model by the author
Fig.43: Textile working model by the author

On the right top to bottom:
Fig.44: Sagrada Familia Source:Gagnon, B.(2009)
Fig.45: Sagrada Familia nave roof detail. Source: SBA73 (2011)
Fig.46: Casa Batllo Source: Flori, L.(2017)
Fig.47: Facade detail of Casa Mila by the author

Molding & Texture

The impression of concrete is mostly grey, cold and with sharp edges. But it should not be forgotten, it starts irs journey as a powder, than forms a more fluid and workable state before finding its forever form.

Usually concrete walls are covered and painted for the user unless it is especially mixed and casted as an exposed concrete. The visibly different alternatives could be left exposed in order to draw attention to their variety and use of diverse materials.

On the following pages, exploration process of various molding methods are shown.

The first (Fig.48-50) and second explorations (Fig.51-53) are made with gypsum instead of concrete to simplify the material and concentrate on the form. The gypsum is poured into balloons with the help of a water bottle and later filled balloons are put in a rectangular form to keep them in the right place. These attempts formed irregular and individual block, showing the shape of the outer mold and can stay together without support.

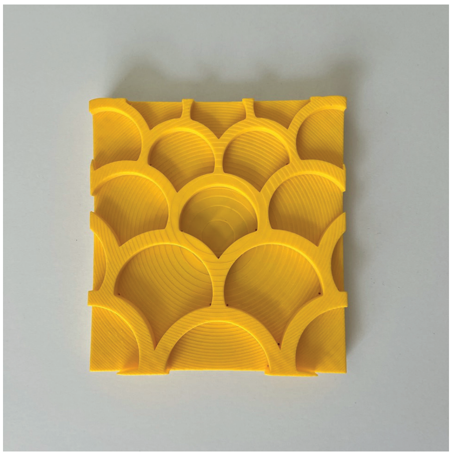
Figures 48-53: Molding and texture explorations. Attempts 1 and 2. Images by the Author.

Third attempt was to use natural elements such as pine needles and a tree trunk to create textured surface (Fig. 54-59). For this the pre-mix concrete blend (A1 from material explorations) was used.

The outcomes are not as initially wanted. The pine needles mostly floated into concrete blend and were not visible at the end, meanwhile the tree trunk actually worked, but seemed very weak and breakable, as well as not aesthetically pleasing. It looked more like accidental then intended.

After the third attempt, exploration phase stopped to use the collected information and experience on the design proposal. Next attempt was after details for the proposal were set.

Figures 54-59: Molding and texture explorations. Attempts 3. Images by the Author.



Figures 60-63: Molding and texture explorations. Images by the Author.

The fourth attempt was led in a later stage to create desired surface pattern for the interior design in scale 1:10. Initially a piece of the surface is 3d-printed, than two different molds are formed using this initial block: one with a plastic sheet and the other with silicon (Fig. 60-71).

Plastic sheet was formed into desired shape by placing the 3d print in to a machine, which heats the plastic sheet and later vacuum shape it (Fig. 62). For this mold, the 3d-print was perforated, so the vacuum can form an exact shape. The process takes about a minute. Unfortunately, with the small detailing of the form, the dried concrete was stuck to plastic sheet and couldn‘t be taken off without breaking.

The silicon mold is formed with mixing silicon hardener and base, both in hardness shore 20, in 1:1 ratio and later pouring into a box, where the 3d-printed block was limidiately placed on the top. The 3-d printed block is kept in place, so it doesn‘t float and move, with the help of some weights. The silicon needed different drying times for each piece, probably due to differences in depth, open surface area etc. Some air bubbles occured during drying of silicon and was filled with more silicone afterwards. Taking the 3d-prints off of the silicone was fairly easy and uneventful, as a soft and flexible silicon was used. Afterwards, individual concrete blends are poured into the silicon molds. One of the mixes was destroyed during its curing period by outer forces (Fig.63), but the other 2 could be taken off of silicon easily.

The mixes used for this stage are overlapping with the design proposal. All mixes have partial replacement of sand by crushed recycled glass. Strongest mix with icelandic pumice is used for tree trunk inspired part. This mix is visibly darker than the other mixes. The pine needle inspired pieces is made with a mix of icelandic and greek pumice, meanwhile pine cone inspired one is the lightest in colour and weakest with the greek pumice.

Figures 64-71: Molding and texture explorations. Images by the Author.

Site

Fig. 72: simplified map of Gothenburg

Gothenburg is home to the largest port in Scandinavia, located on the west coast of Sweden, under 500km far from three capital cities: Stockholm, Copenhagen and Oslo.

It was founded in the early 1600s as a trade city and has currently about 600.000 inhabitants (World Population Review, 2024), making it the second largest city in Sweden and fifth largest city in Scandinavia.

In spite of its northerly latitude, the city has mild temperatures throughout the year due to influence of the Gulf Stream (Linden, 2013). Although the midnight sun is not experienced in Gothenburg, in summer the daylight reach up to 18 hours.

In winter, the days get as short as 6,5 hours and the sun doesn‘t go high above the horizon, forming long shadows and golden light.

Fig.73-75; left to right: Statue of Gustaf Adolf | view of Vasaplatsen | long shadows in winter at noon. Images by the Author.

Fig.76: Location of Haga with major places

Haga District

Haga is the oldest suburb of Gothenburg situated south of Rosenlund canal with its history going back to 17th century. It was originally a working class district and consisted of one storey wooden houses (fig.80). After the industrialisation of the city, with the rapid population growth, some of the houses were rebuilt in Landshövdingehus style; typically with a stone ground floor and two wooden floors (figures 76,78,79,81).
In addition to its touristic appeal, according to the urban development project the commuter traffic in the area will increase. The ongoing major infrastructural project Västlänken will have one station situated near Hagakyrkan. This area is currently under construction.

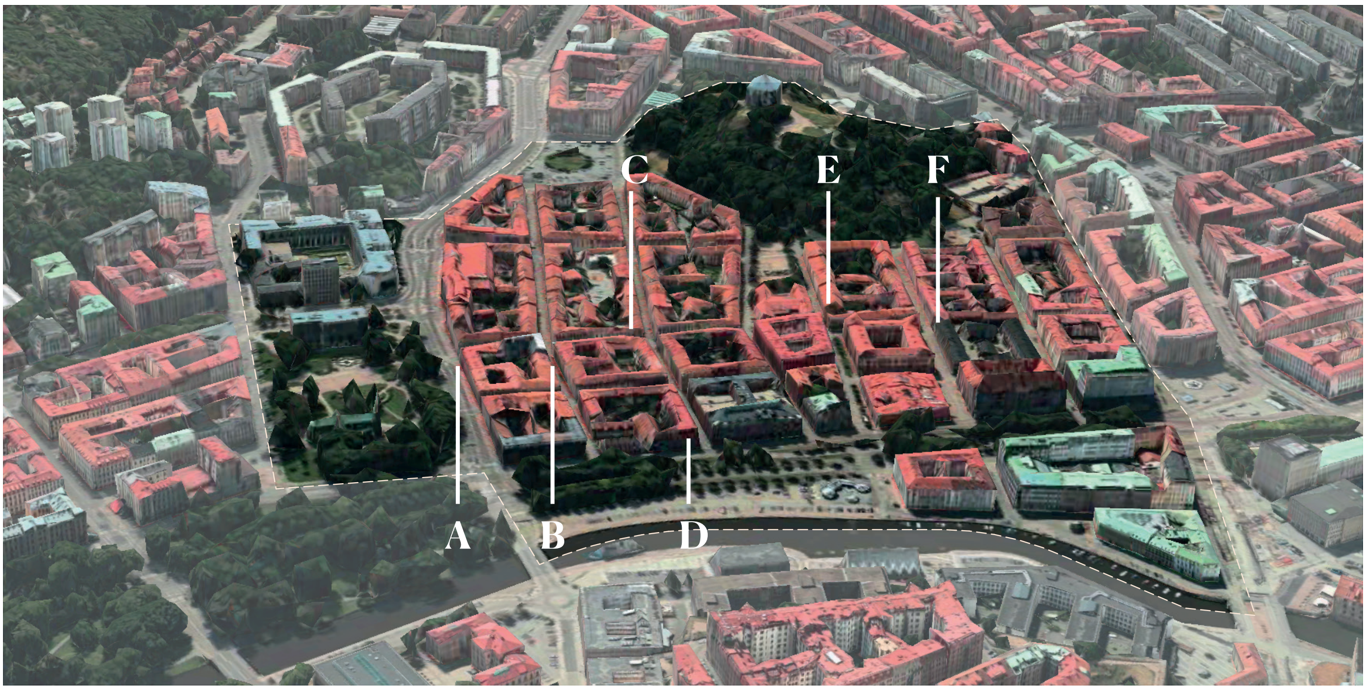


Fig.77: Aerial view of Haga, Apple Maps

Fig.78-83: Views A-F from Haga district, approximate locations where the pictures are taken are marked Figure 77. Images by the Author.

Fig. 84: overview of Västlänken stations. Image by the Author.

Västlänken Project

Västlänken (the West Link) is a major infrastructral project n Gothenburg, which is relevant to the thesis's topic with its 8 km long double track railway, including a 6 km tunnel underneath central Gothenburg to provide the city with uninterrupted commuter and regional train connections.Three underground stations in the city are planned as seen in the map (Fig. 84):

- Central Station
- Haga
- Korsvägen

Haga station is the main interest of the thesis, as the ground where the station is being build is a clay soil, in contrast the most of project is located in a rocky grounds of the city. Construction of Haga Station started in 2017 and estimated traffic start is 2026.

The design for Haga Station of Västlänken was chosen by a jury through a competition in 2019, to which 5 architectural offices took part. The jury decided for „Gläntan" proposal by Gottlieb Paludan Architects based in Copenhagen, Denmark.

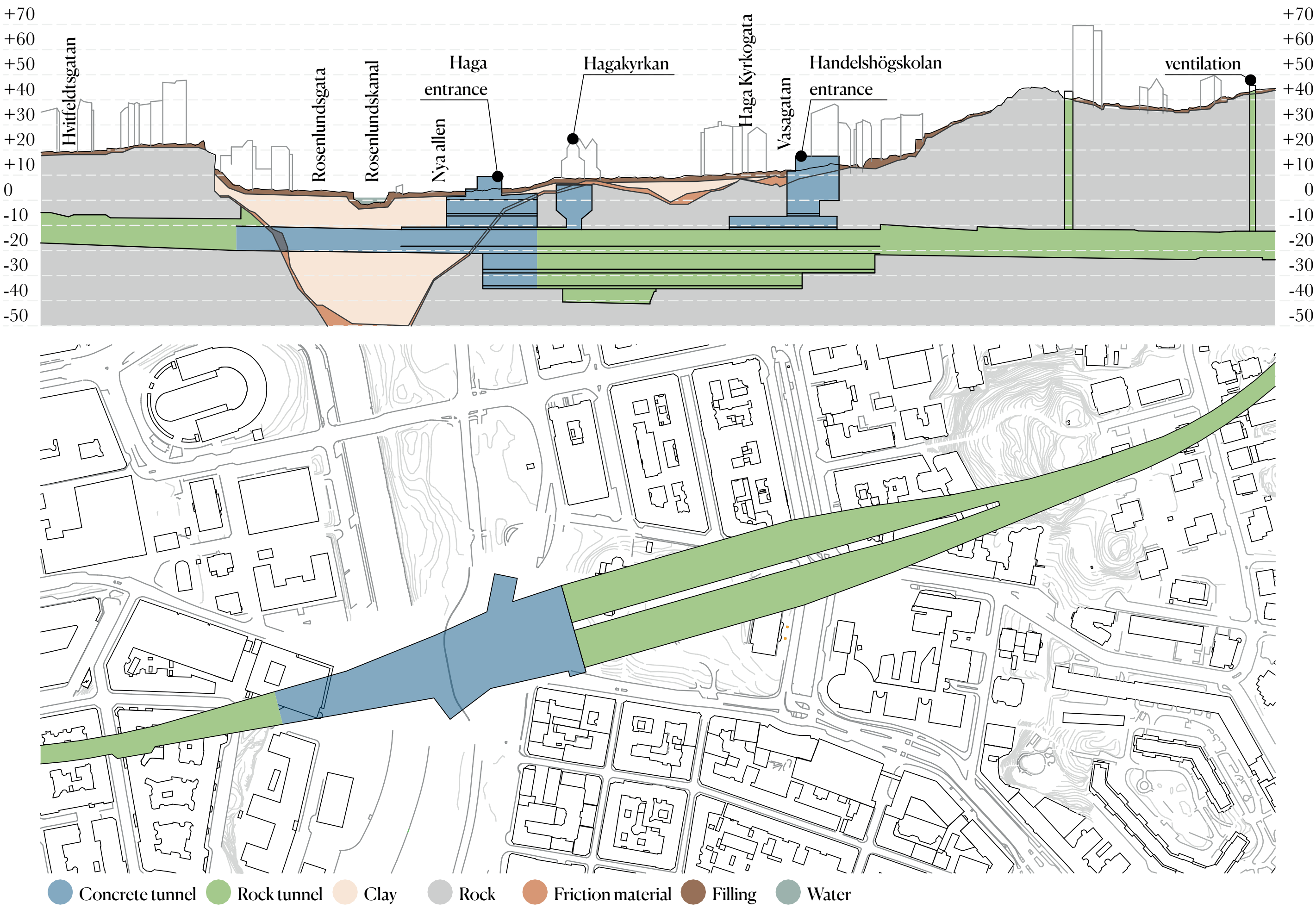


Fig. 85: overview of Haga station. Image by the Author.

Haga Station consists of 1,7km tunnel of which 250m are concrete tunnel in clay soil. The rest is situated in rock and is built through „drill and blast“ method. The station is situated around 10m under surface.
The geotechnical conditions at the station entrances‘ locations are dominated by clay soil. Near Rosenlund Canal the clay soil reaches as deep as approximately 55m. This part of the station will be a concrete tunnel with load bearing capacities, built as an open shaft within rigid stamped support structures. The shaft goes up to 25m under the surface (Fig.85) and is between 30 to 80m wide. The concrete tunnel is founded with piles to the rock and tension anchored to avoid lifting. The shafts past the Rosenlund Canal are carried out within rigid stamped support structures, for example slot walls as outer walls and with transverse slot walls under the bottom of the shaft. Taking into account the great mud depth, the walls of the support structures do not reach the rock, but are carried out as a „floating“ construction.
The platforms will be located with the top of the rail (RÖK) at -18.45 m. The ground level is located at +2 to +11 m, meaning that the tracks are about 21 to 30 meters below surface.

Site

The project is an additional underground exhibition space to the Västlänken's Haga Station, located between Haga and Pustervik entrance and the Rosenlundcanal, close to Feskekôrka and Haga, the landmarks in proximity (view A,D,I).

The station will be a transportation hub where the existing tram and bus lines (View B,C) are connected to the underground railway.

The exhibition space is aimed to stay over the planned railway tunnel to minimise its impact on the park, blue lined building in Figure 101 and respects existing trees' root areas (View E,F). The exhibition space will allow visitors unusual views of Kungsparken.

The trees in this area are moved during the construction work in the area. As of spring 2024, the area is under heavy construction, the parts of park is not accessible (View G,H).

Fig. 86: Sun path study and main wind directions on site. Markings of views on next page. Source: Apple Maps.

Fig.87-95: Views A-I, approximate locations where the pictures are taken are marked on the aerial view fig.91. Images by the Author.

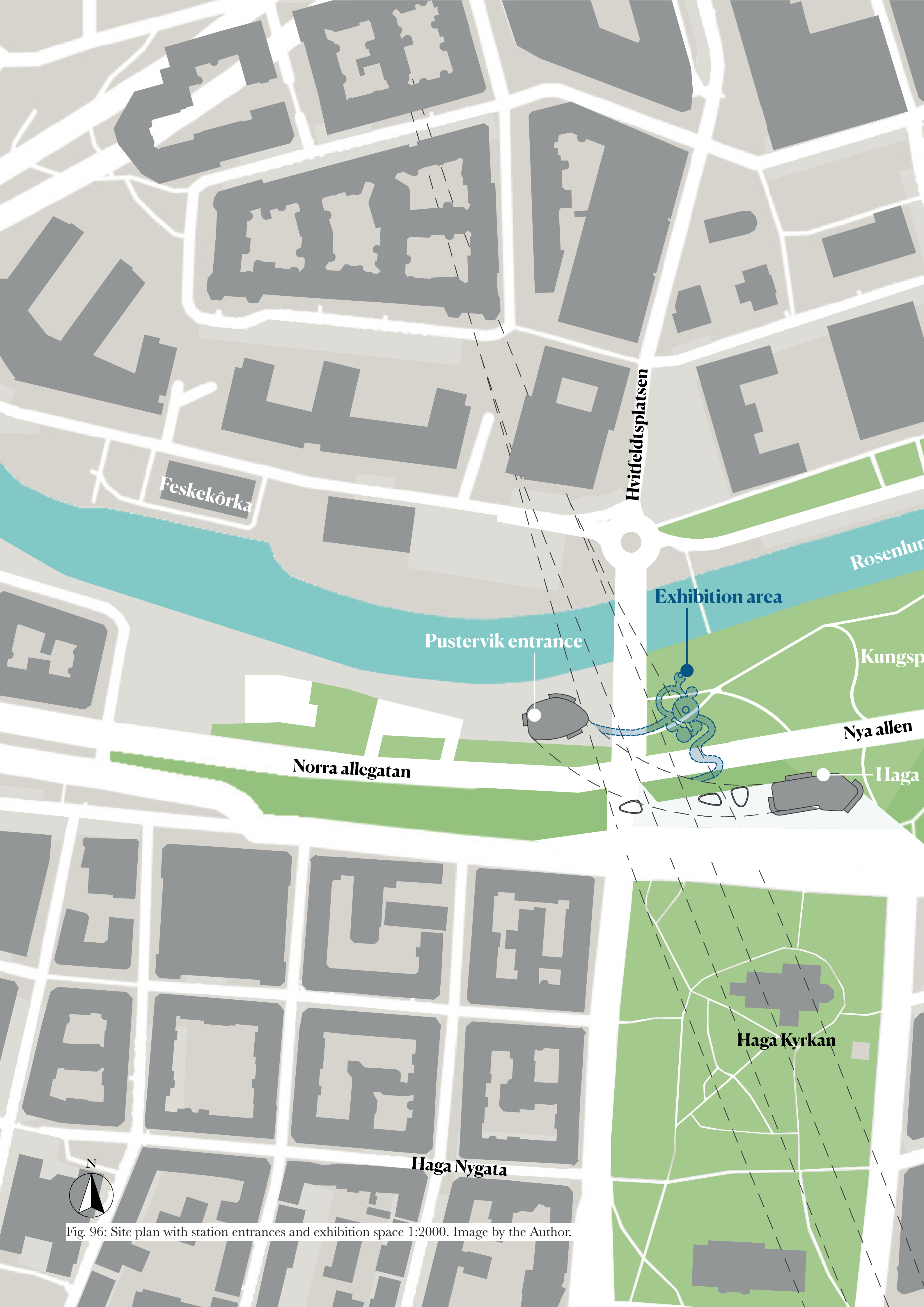


Fig. 96: Site plan with station entrances and exhibition space 1:2000. Image by the Author.


Pedagogiska
bibliotheket
Raoul Wallenbergs gata
nd canal
parken
entrance
Parkgatan
Vasagatan

Design Proposal

Exhibiton space

The exhibition space is mainly connected to the first and second underground levels of the planned station. Floor -1 could be used as a passageway while changing vehicles by travellers as well as by pedestrians in the area instead of crossing multiple busy streets. The exhibition area serves in this scenario as an alternative pathway, but could also become a destination for many travellers.
Several paths connect to station to the Gallery of Inspirations. Floor -1 and -2 of the station and floor -1 and -2 of exhibition complex is even, enabling a shorter path between the areas meanwhile the top level (floor 0) of exhibition space will be connected via ramps and a lift. Various tunnels allow the visitors not to take various paths, not repeating the same way to enter and to exit the exhibition. In the end, the entrance and the exit are not clearly drawn as the area can be entered and exited both ways, creating different experiences (fig.98-101).

The exhibition area consists of 3 types of spaces (fig.95):

- main gallery
- smaller spaces
- tunnels

Spiriling tunnels are connecting rooms to eachother, while they are also evolving on the way, creating sequences of spaces. They get wider in the middle to let the visitor take a breath but get back smaller closer to an opening.

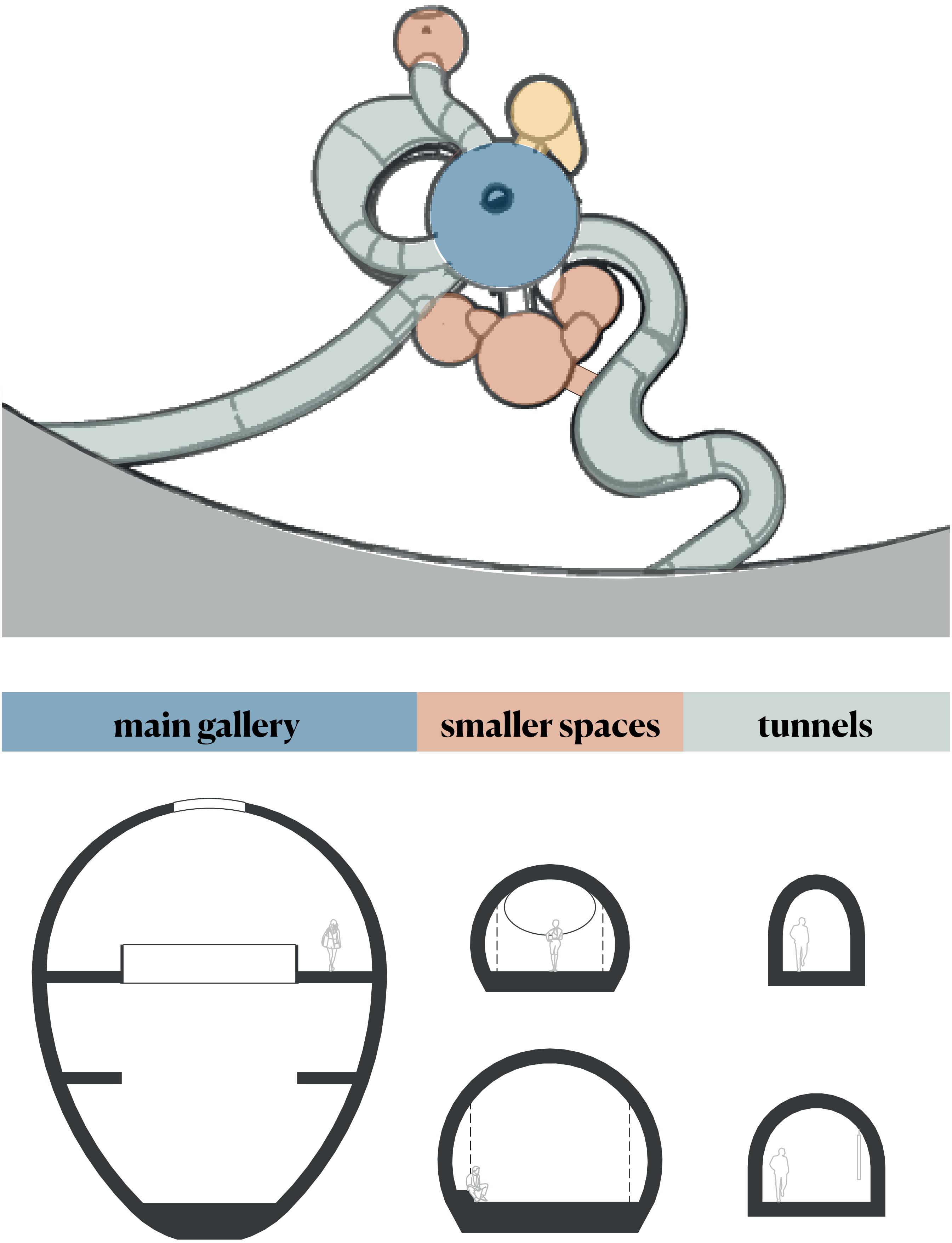


Fig. 97: Geometry typology of exhibition area. Image by the Author.

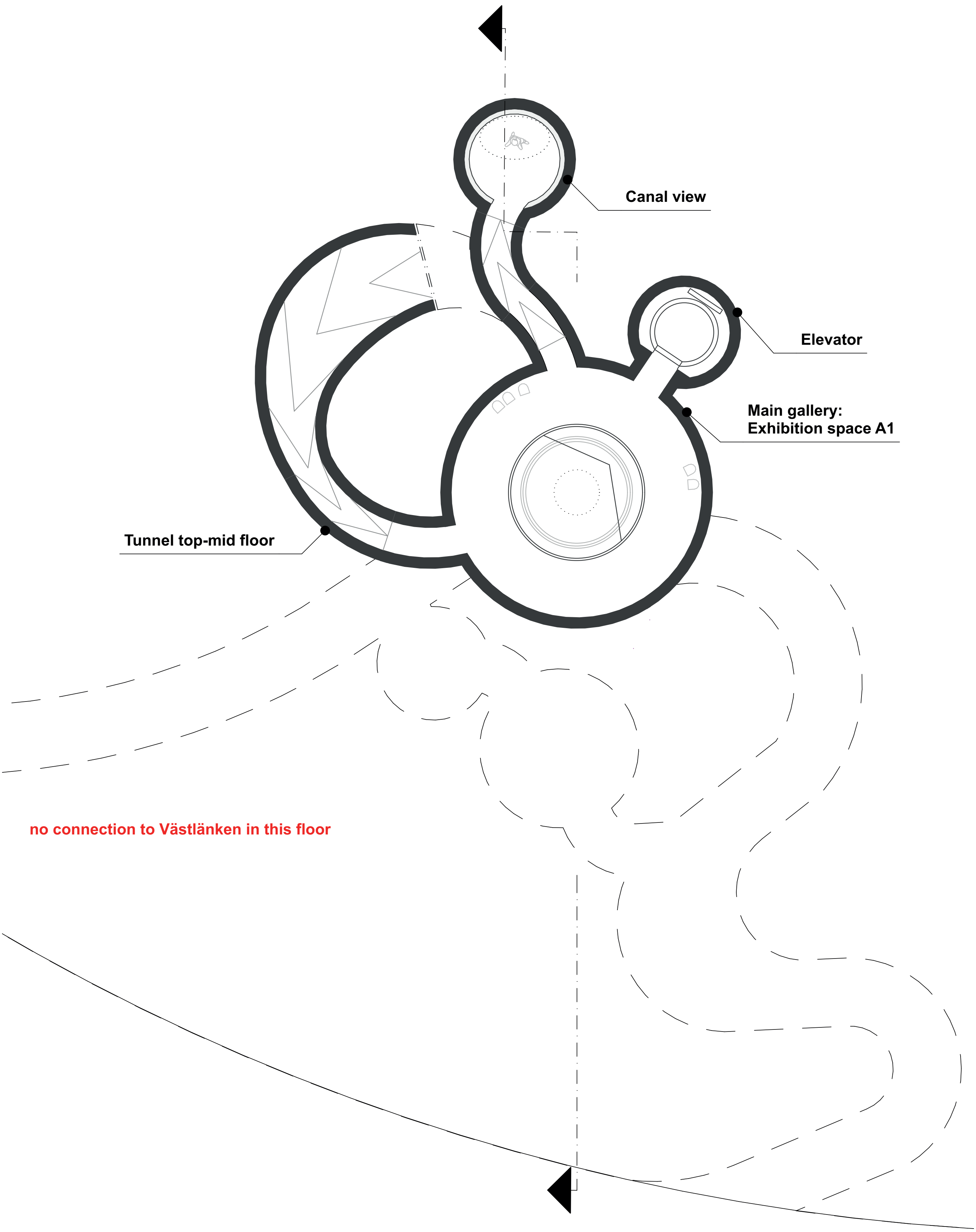


Fig. 98: Floor plan, Level 0. Image by the Author.

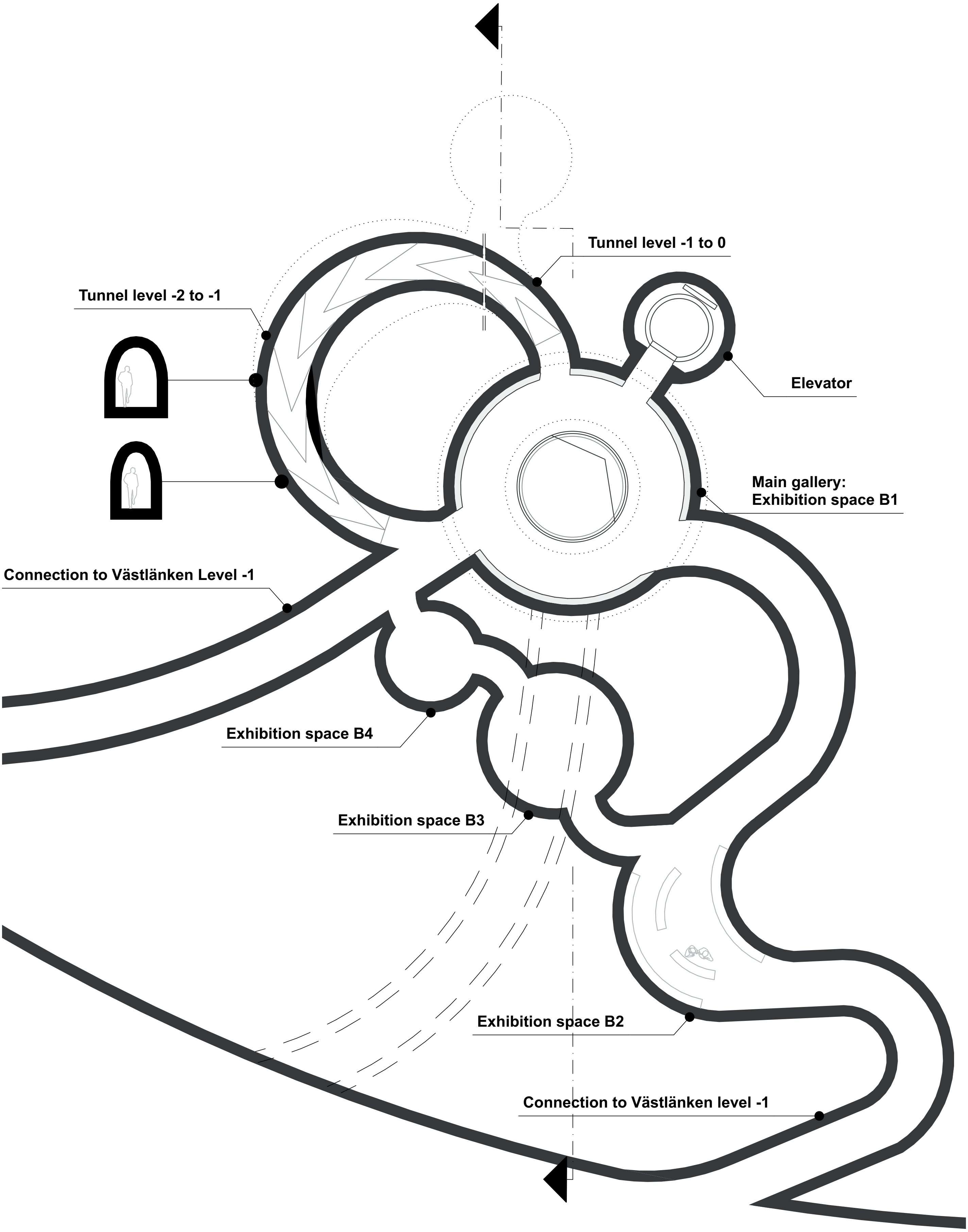


Fig. 99: Floor plan, Level -1. Image by the Author.

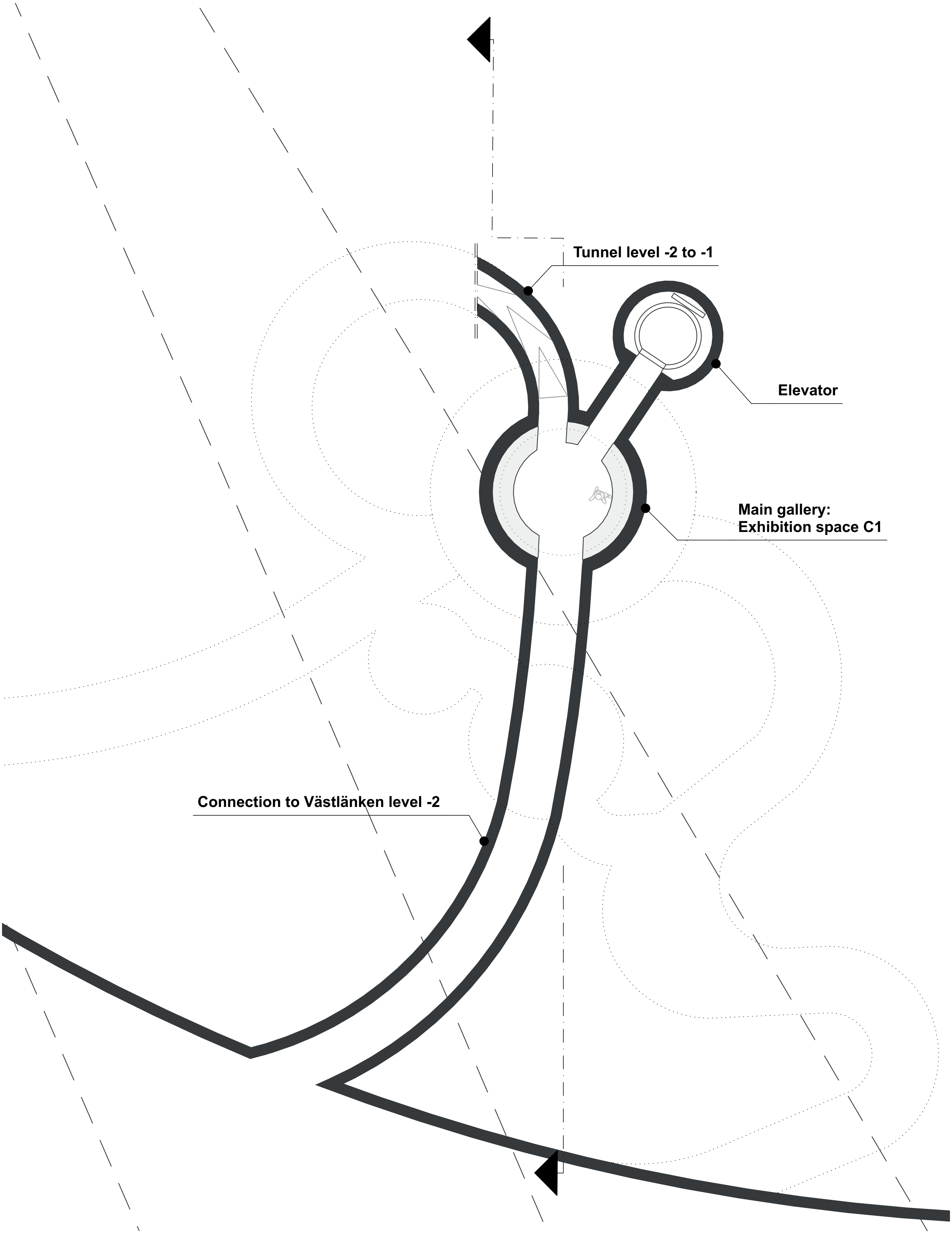
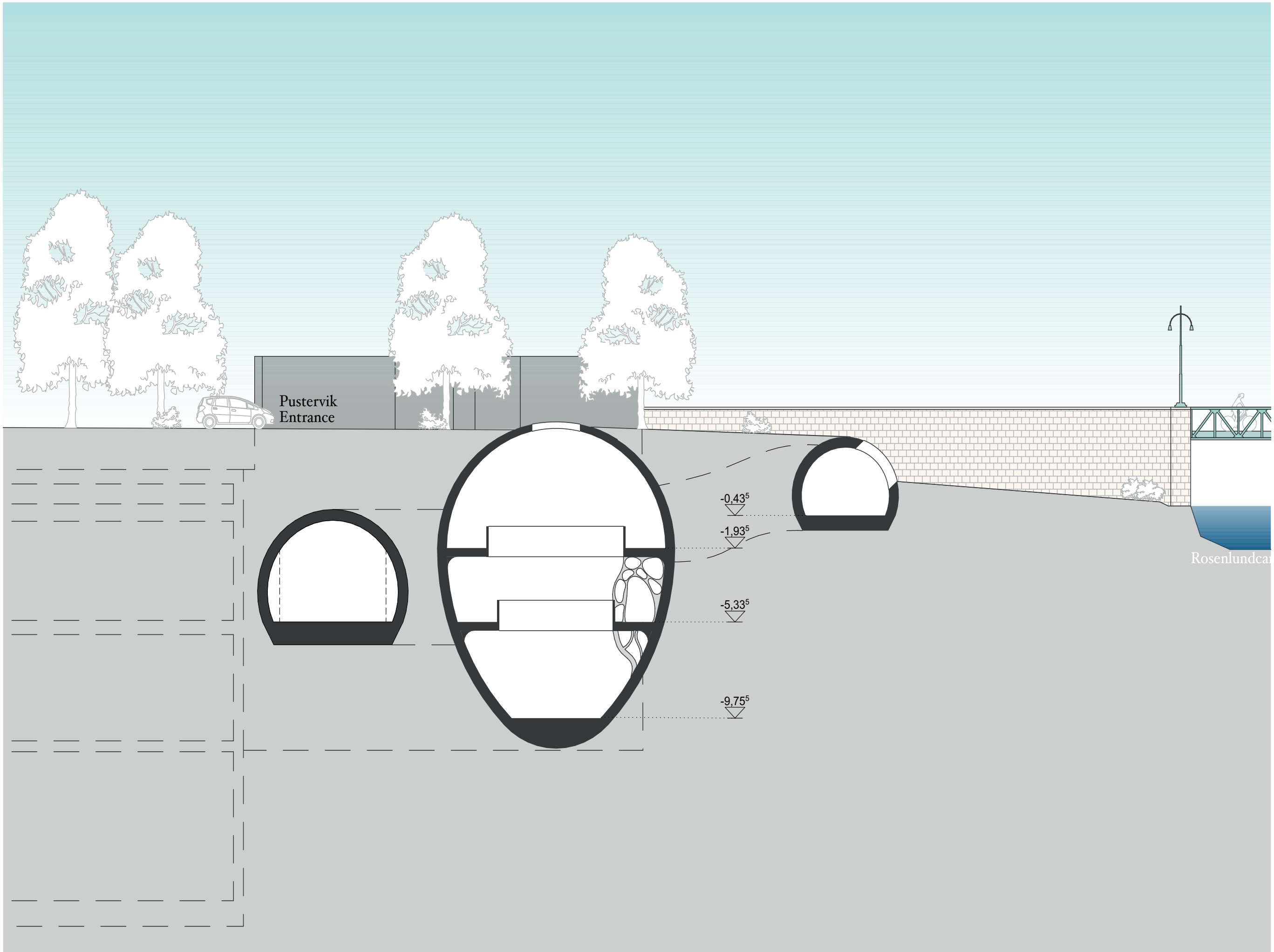


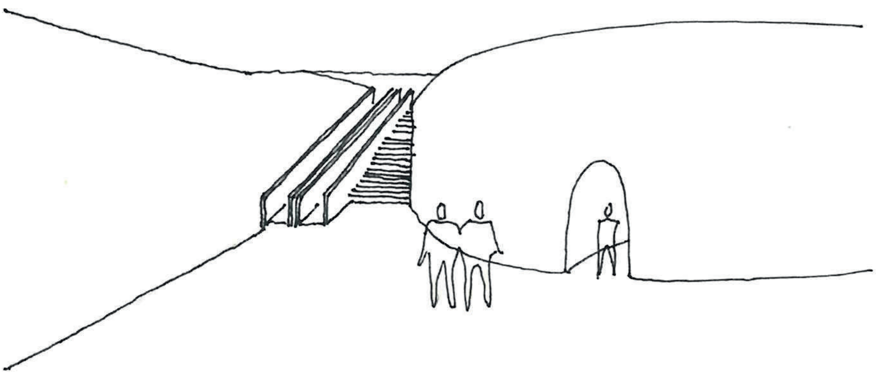
Fig. 100: Floor plan, Level -2. Image by the Author.

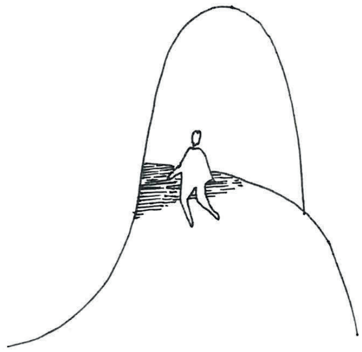


The main gallery has an oculus letting natural light in and allowing visitor to a view of the sky and trees from below.
A tunnel leading from main gallery in level 0 to a special room, „canal view“ is where a big double curved window is located. Here the visitor is just below the surface and has a direct view of the canal. This view can also allow a new perspective, for example in summer when the grass outgrows, the visitor has a view of the canal through the grass.

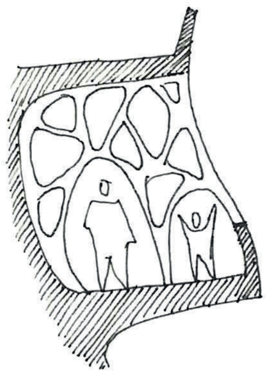
Fig. 101: Section A-A. Image by the Author.

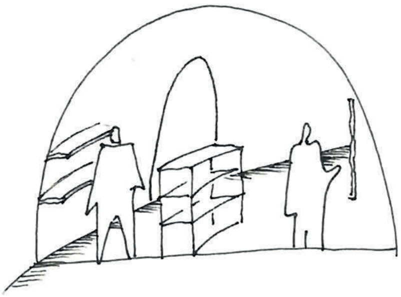
A Journey through exhibition space

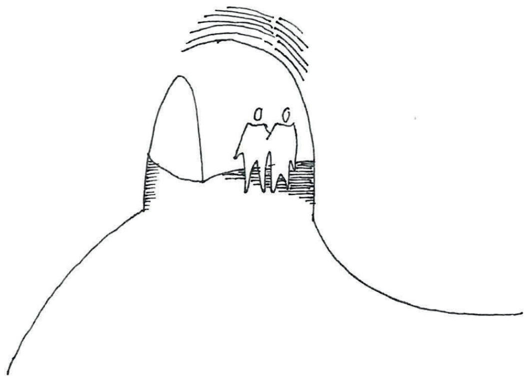




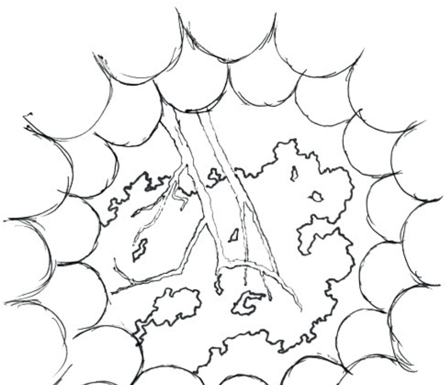
Coming from the station, tunnels are visible. The tunnel bends and leads

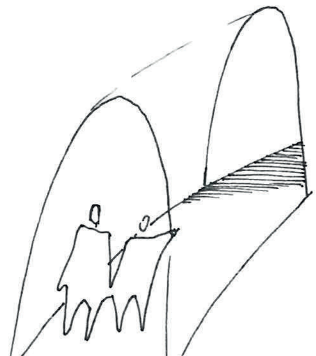


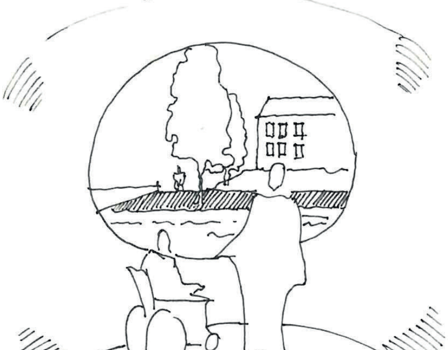




Walls with unusual openings. Another tunnel opens up to bigger space. And while it bends, other spaces become visible.



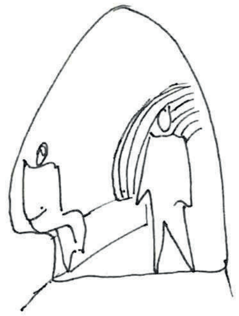




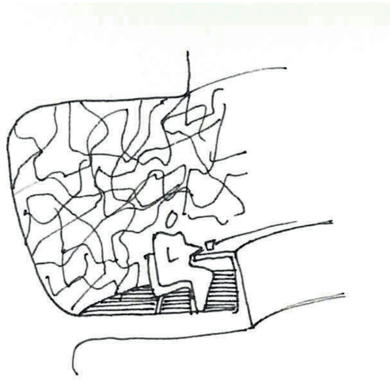
Looking up, patterns form a frame around oculus. Another tunnel bends and leads up, here a smaller dome has a view of the canal.

Fig. 102: Sketches of sequences of the spaces. Image by the Author.

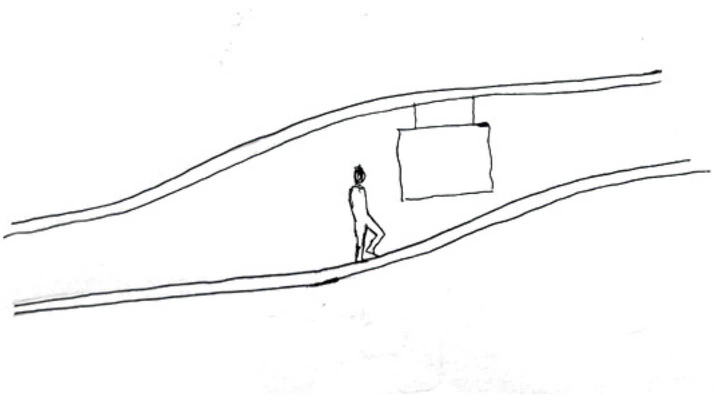
Tunnel opens up to the main gallery level -2.



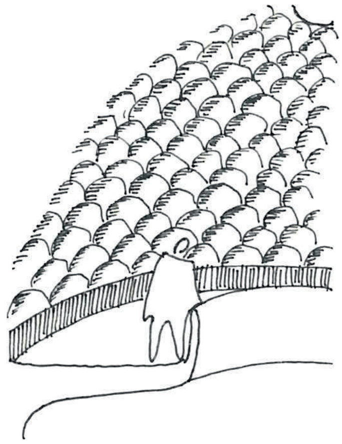
From there another tunnel leads up.



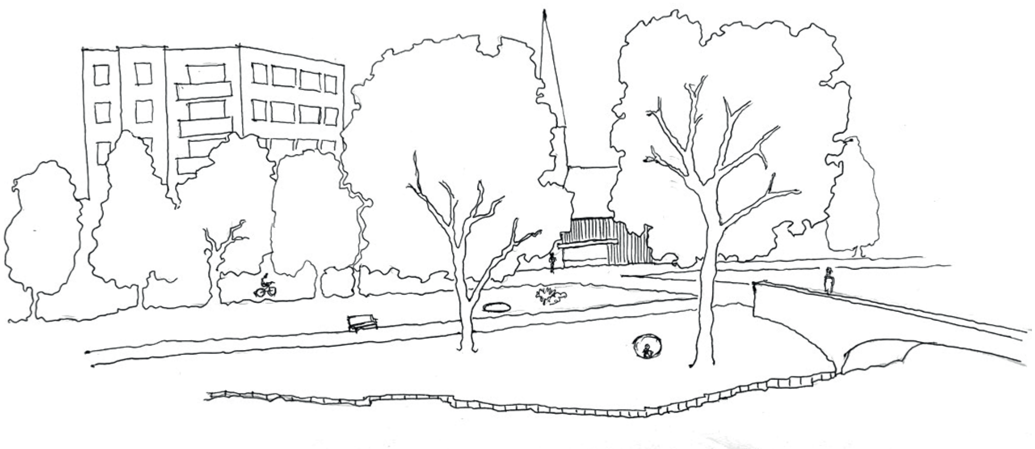
And arrives to level -1.



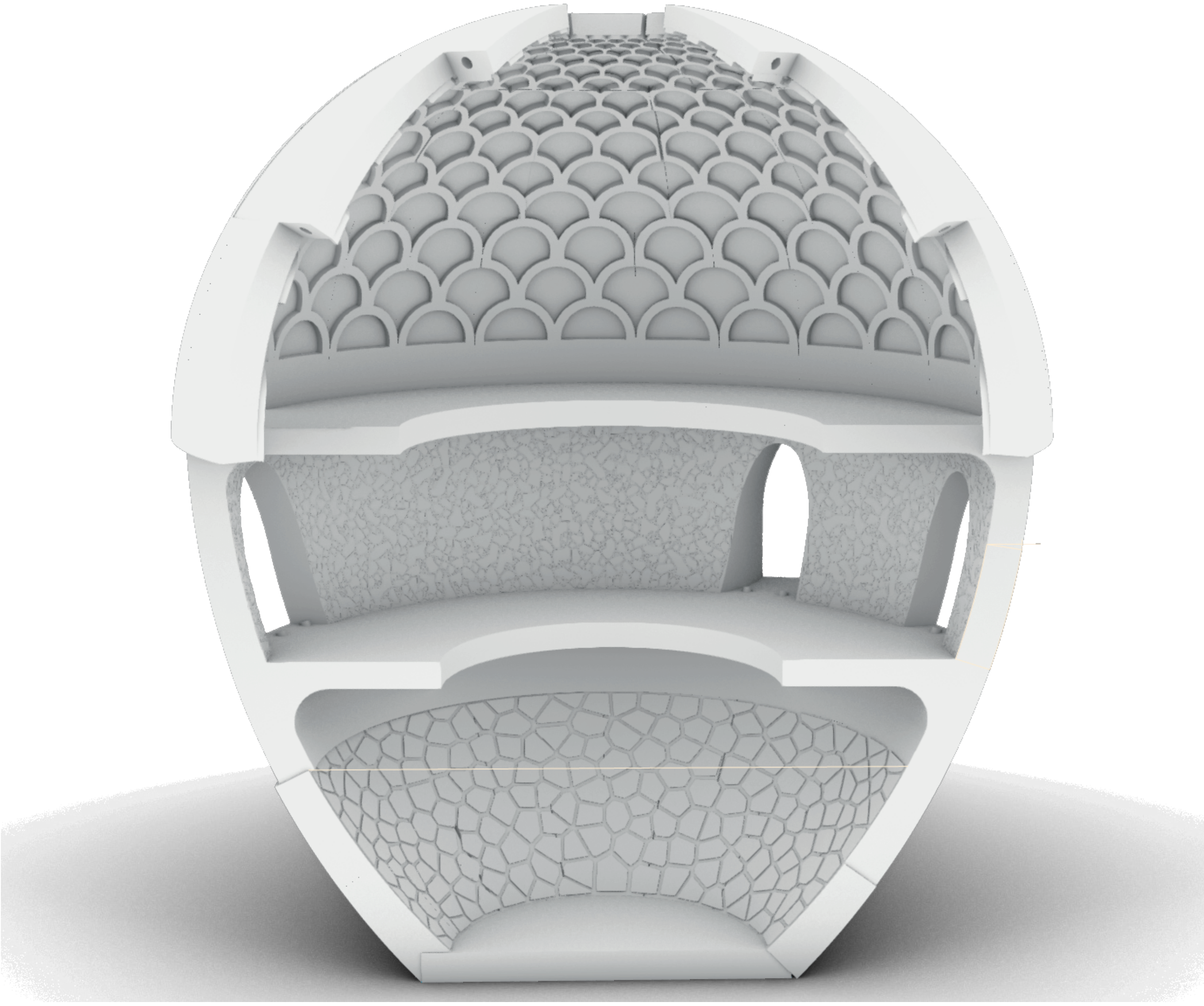
Tunnel leads further up..



..to the top level of the main gallery



The exhibition space and its openings become a part of topography.



Main Gallery

The main gallery, named the Gallery of Inspirations hosts a permanent exhibition of alternative concrete blends and materials.

It has three floors, each with patterned walls, inspired of pine trees (fig.100,101). The floors are inspired, from top to bottom by (fig.102):

- pine cones (Part A)
- pine needles (Part B)
- tree trunk (Part C)

The walls' patterns have abstract design (fig. 109). As a previous material exploration, the pine needles and tree trunk was used to form textured surface, but the outcome wasn't as desired.

The gallery is built with pre-cast double curved blocks and assembled on site with help of a temporary centring. Each floor has an individual concrete mix, adapted to its conditions, getting stronger and thicker downwards.

The floor slabs are supported by pillars and wall elements.

The overall geometry is inspired by Pantheon and has an oculus, allowing visitors to see the tree standing next to it from a new perspective. The oculus is glassed with a strong glass melts into the topography, so people in Kungsparken can walk on and wonder what is laying underneath. The glass oculus also prevents vandalism or natural disturbances such as heavy rain.

Fig. 103: Section perspective of main gallery. Image by the Author.

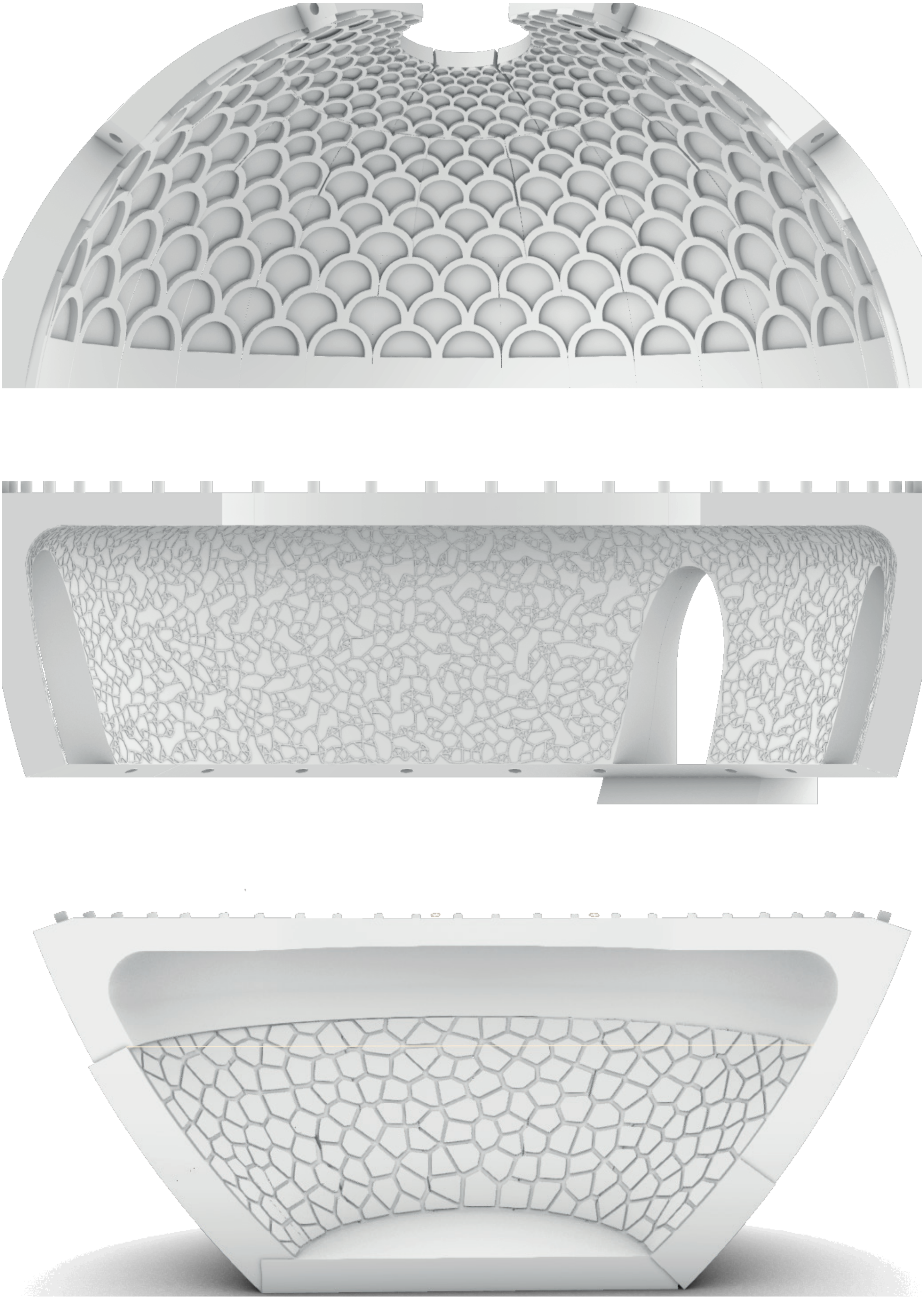
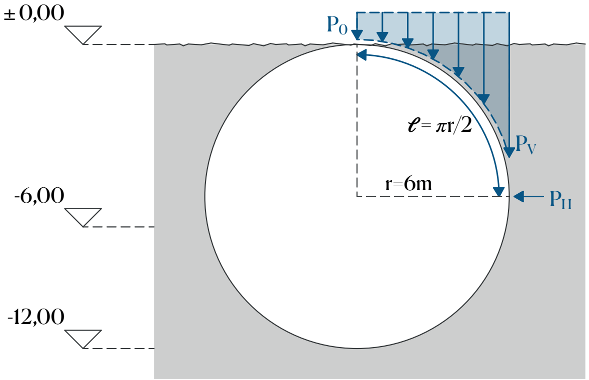


Fig. 104: Close up of levels of main gallery. Image by the Author.

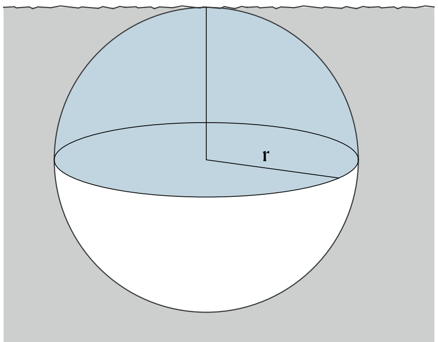
The form of the main gallery is chosen after a comparison: does a sphere or an eggshape/ ovoid perform better under the pressure of the surrounding soil?
A rough calculation for different possible shape's load distribution showed that in comparison a spherical dome work more efficient than an egg shape (fig.103). To optimise the sum of loads and useful space height, an over head egg shape is chosen as main gallery. This way the vertical loads of the surrounding soil is optimised while the height takes advantage of the ellipsoid shape.

Fig. 105: Parts A,B,C details, inspirations and interpretations.. Image by the Author.

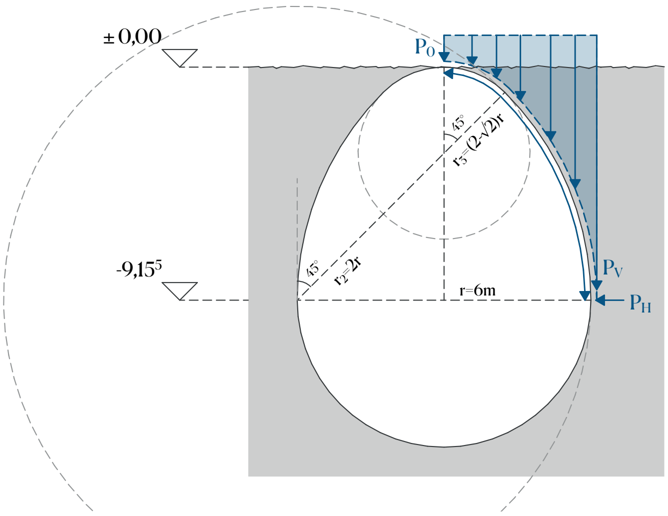


Σ_{PV}= ($P_0.P_V$)+($4r^2$-πr^2)
if π=3,14, r=6m and P0=0 because top of the sphere is at ± 0,00;
Σ_{PV}=P.(0,86.r)
= P.(0,86.6,00)≅5,16.P

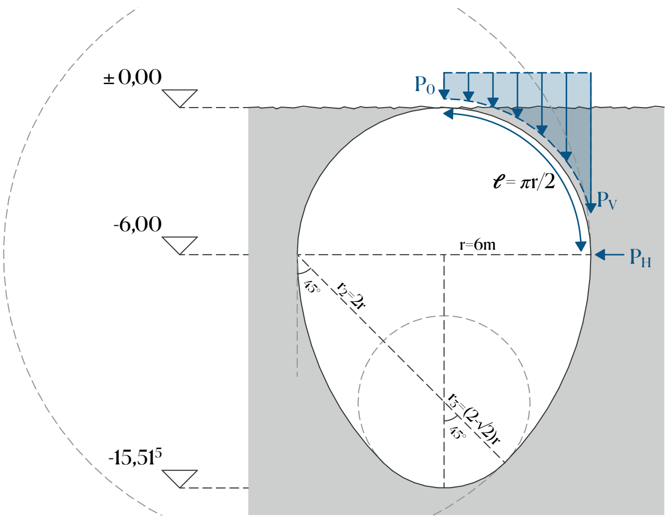
$P_H = P_V.K$
K_{clay}=0,1
P_{Hsum}≅0,516.P



Surface area sphere= $4\pi r^2$
only upper half= $2\pi r^2$
$\Sigma^{2\pi}{}_0=(\pi r/2).2\pi=\pi^2 r$
if π=3,14 & r=6; π^2≅9,86
P_{Vsum}≅59,16P

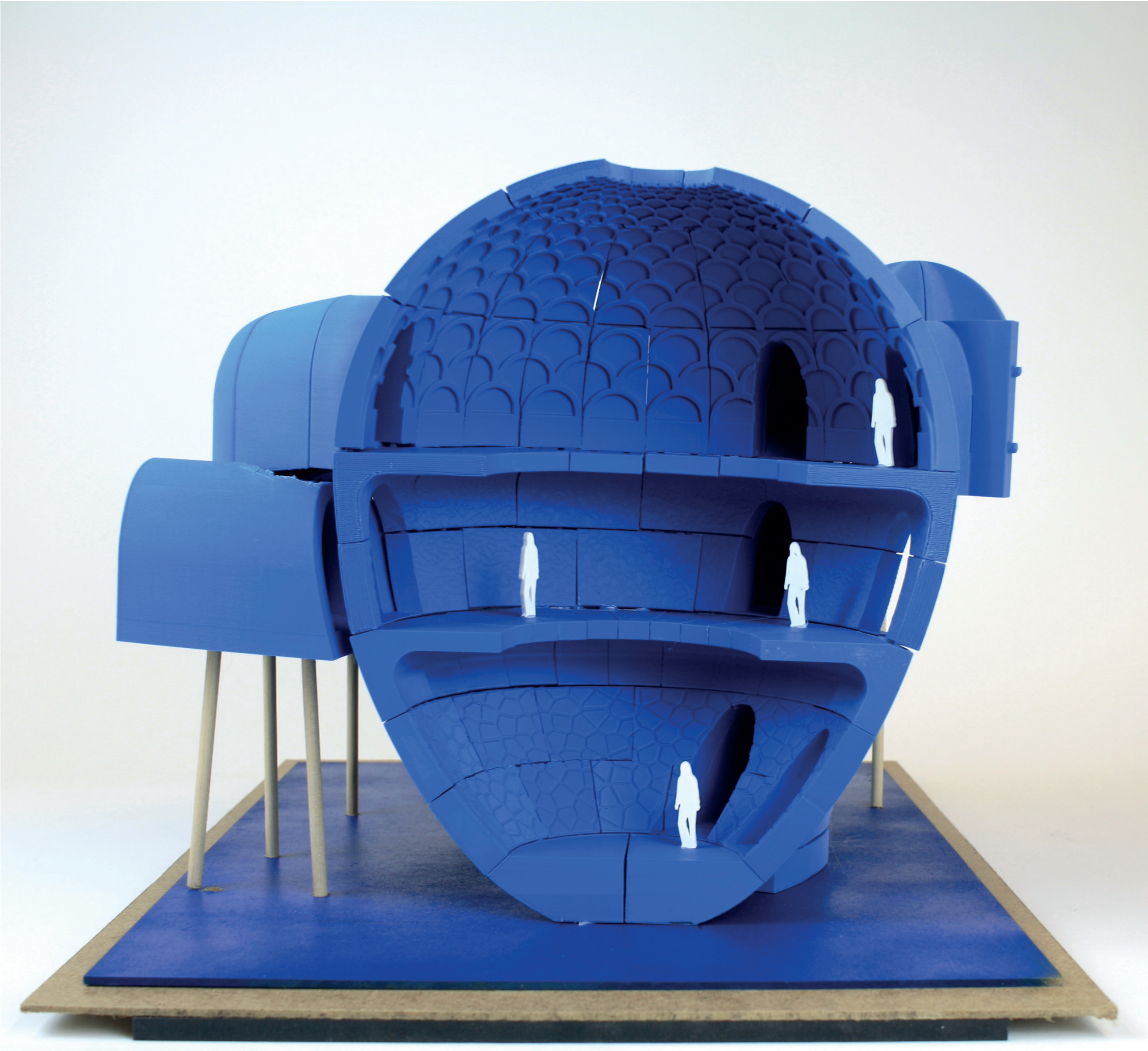


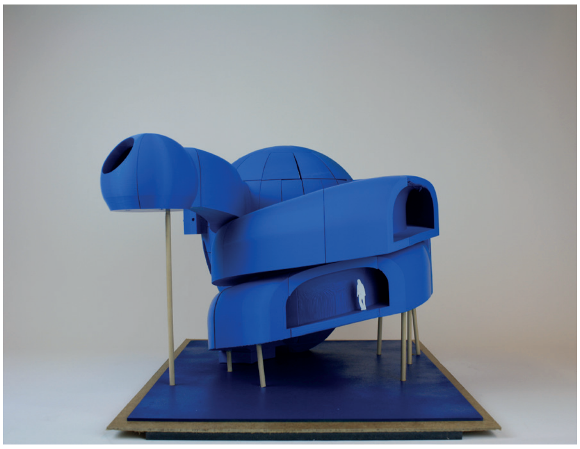
Σ_{PV}=P. [(3r-√2r).r]-[((π(2r)²/8)-(r²/2))-(π.(2r-√2r)²/8)]
=(3r²-√2r²)-[(π4r²-4r²)+(π(4r²-4√2r²+2r²)]/8
= (24r²-8√2r²-4πr2+4r2-6πr2+4√2πr²)/8
if π=3,14, √2=1,41 and r=6m
P0=0 because top of the sphere is at ± 0,00;
Σ_{PV}=P.r².(3,03/8)
≅5,43.P
linear forces Pv %5 more than sphere with same radius
$P_H = P_V.K$
K_{clay}=0,1
P_{Hsum}≅0,543.P



Σ_{PV}= ($P_0.P_V$)+($4r^2$-πr^2)
if π=3,14, r=6m and P0=0 because top of the sphere is at ± 0,00;
Σ_{PV}=P.(0,86.r)
= P.(0,86.6,00)≅5,16.P
By turning the eggshape, the form takes advantage of smaller forces from surrounding soil and achieves a greater depth.
$P_H = P_V.K$
K_{clay}=0,1
P_{Hsum}≅0,516.P

Fig. 106: Rough calculations of load distribution on various geometries. Image by the Author.



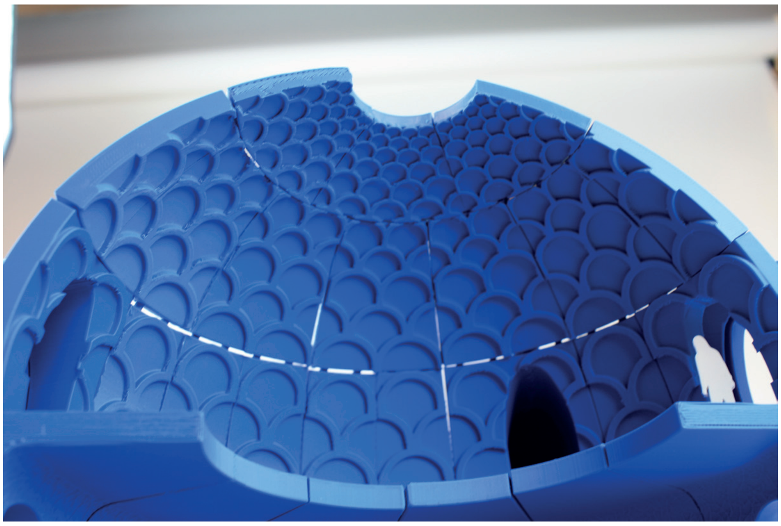
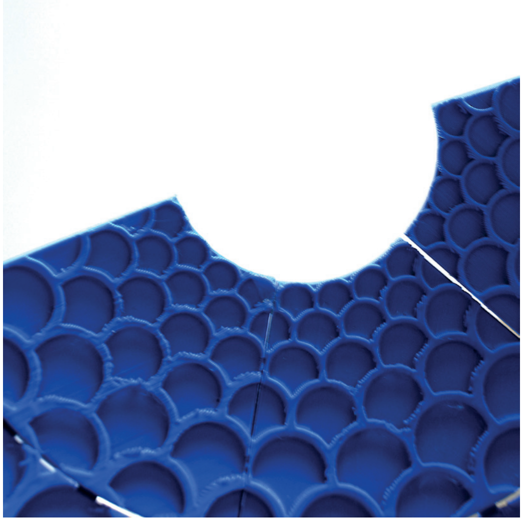
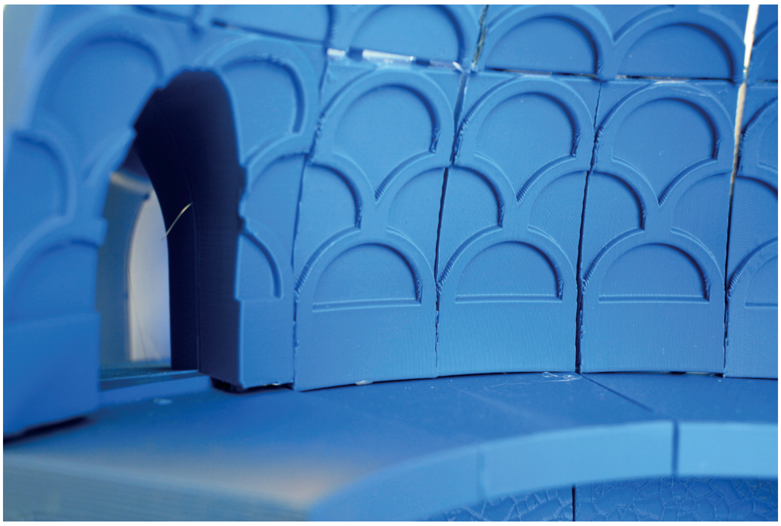
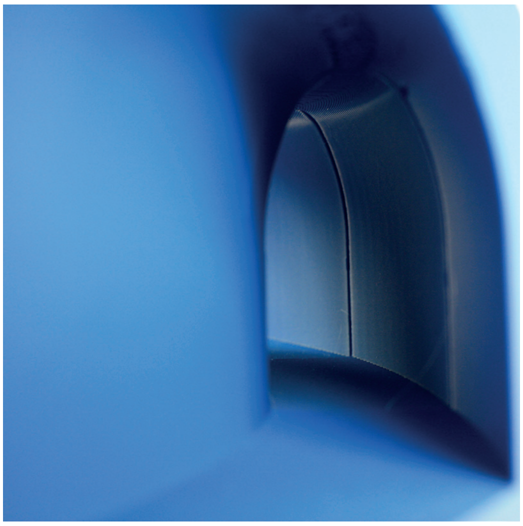
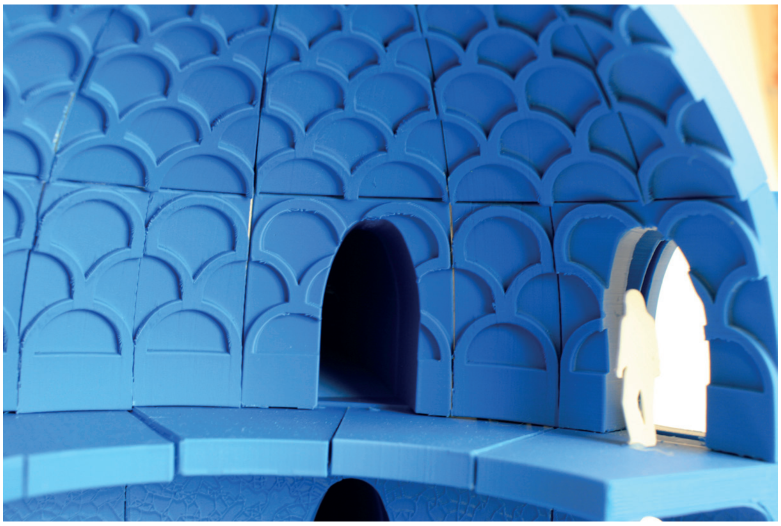
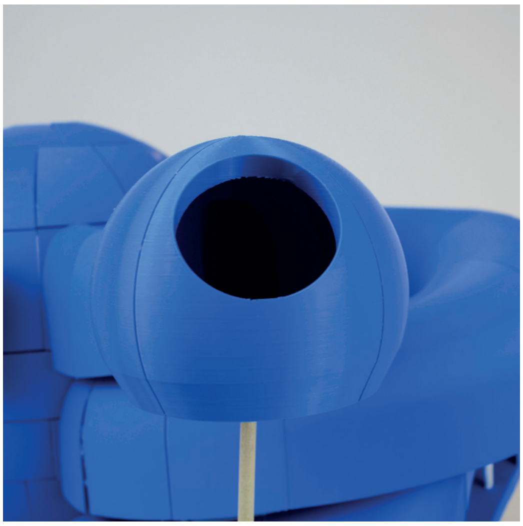


Physical Model

The model is built with 3d printed parts in 1:50 scale. Each piece has dimensions accordingly, so that could be precasted and transported in a real construction scenario. The 3d-printed pieces have clipses so the model could be put together mostly without glue.

The main gallery and the spiriling tunnels are cut open for visibility purposes of the model.
The tunnels and the smaller dome is supported by wooden sticks in model, in reality the sticks would not be needed underground.

Fig. 107-117: On left and right pages. Views of physical model 1:50. Images by the Author.

Conclusion

This thesis aimed to explore sustainable concrete mixtures, some of which are still under research, as well as an alterative design approach that can be used for building underground. This has been achieved through studies of materials' components, interviews with researchers, material explorations and historically relevant and newer case and method studies, which resulted in the design of an extension for Haga Station in Gothenburg, Sweden.

• What changes appear in architectural expression when modifying concrete blend?

Material explorations showed that changes in concrete mixtures are usually not visible, although slight differences can be noticed. For instance, recycled glass results in concrete to be shiny, while GGBS gives a brighter colour. Biggest differences are noticable with pumice of various origins and these are also clearly with finer grains.

Usually concrete walls are covered and painted for the user unless it is especially mixed and casted as an exposed concrete. The visibly different alternatives could be left exposed in order to draw attention to their variety and use of diverse materials.

• What design approaches can be applied to create an underground structure that takes advantage of these potentials and deals with pressure of surrounding soil in the example of Västlänken's Haga station in Gothenburg?

Different concrete blends can have various properties. The blend with weaker strength and less weight can be used for building closer to the surface, as the loads to carry are less on the top. Stronger blends can be used in deeper layers. The strength of the material can be optimised by planning accordingly. In historical examples it is usually visible that underground spaces, such as basements, cisterns and tunnels, have arched or bent ceilings, although built by bricks, they follow the same principle of distributing loads efficiently.

• How do these modifications affect the space and its physical features? What design approaches can take advantage of building underground that would be impractical above ground?

While designing an underground space, the biggest challenge in comparison to above the ground is, to keep the connection to outside. A building that raises above the ground can have windows for ventilation, lighting and connection almost on every outer wall, but this is not the case underground. To achieve this connection, the top of the outer shell needs to follow the surface level to an extend. In a topographically challenging area this may result in various levels in the same floor. At the same time it also creates potentials for the architect to focus on the main interior experience, as the building and how its rooms are situated and connected to each other will not be visible from outside, because it is underground and is surrounded by soil.

Final Reflection

The reason on why I chose this topic is, that in the years I worked as an architect, I realised that in the day to day life, while making decisions sustainable consciousness can be forgotten. In construction industry the scientific or technological developments are adapted far later than in other industries and this responsibility shouldn‘t be put solely on planers. However, in the rush of a project, architects and engineers use the same materials they are familiar with repetitively, to save time or use that time and energy to focus on the design or challenges on the way. And eventhough we try to be sustainable, it is difficult to adapt and follow new developments and it takes our precious time. I wanted this project to be a starting point of a guideline to follow in my future.

My initial approach was to investigate alternative materials and use their outcomes to create an outline for what they are capable of and how to use it. In the early stages it became clear that concrete mixture is a very wide topic and even considering alone the curing time of concrete, it can‘t be passed over quickly in a period of a few months.This resulted in a stopping point and a new approach in my progress. So I focused on case studies for building methods and design approaches. Due to organic shapes of the design and 3d printing I learned new softwares and working hands-on with material also gained me experience and familiarity with the material.

In my opinion the design process was rather smooth, I tried different paths and when felt stuck, the case studies and other reference projects helped to see other perspectives to deal with the same challenges or, rather to see it as an opportunity.

Additionally I believe that this thesis will be of helpful to others, giving a catalogue of material and methods to achieve a more conscious material choice and underground architectural design approach.

Student Background

educational background

2022-2024 M.Sc. Architecture and Urban Design
Chalmers University of Technology

2013-2018 B.A. Architecture | Technical University of Munich

2015-2016 School of Architecture | Politecnico di Milano
one year International Exchange program Erasmus

2008-2013 Cagaloglu Anatolian High School, Istanbul

work experience

2020-2022 Architect (HOAI phases 1-5)
Landau + Kindelbacher Architekten | Munich

2018-2020 Architect (HOAI phases 4-8)
Binnberg Architekturentwicklung | Munich

2017-2018 Internship (HOAI phases 1-4)
LMT3 Architekten | Munich

2016 Internship (lightning planing)
3lpi Lichtplaner | Munich

Sources

Images

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