DOWN TO EARTH.

CIRCULAR MATERIAL FLOWS // RESOURCE SALVATION

- exploring the use of excavated earth material from Västlänken, focusing on Rammed Earth techniques in a Nordic urban context.

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Down to Earth: circular material flows & resource salvation

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ABSTRACT

DOWN TO EARTH
– Circular Materials Flows & Resource Salvation

Architects around the world have finally declared a climate and biodiversity emergency as the most serious issue of our time. This is no longer an abstract threat; it is real. From now on, our buildings, cities and infrastructure must become self-sustaining systems. And this all begins with our use of material.

Future architects bear the responsibility to study the evidence relating to natural bio-based fossil free materials and techniques that can be incorporated in circular flows. Radical tectonics must be explored, where waste is considered as a material resource.

Massive amounts of earth from excavations can be found in urban areas, from the construction of infrastructure projects (tunnels, metros, parking garages etc.). Earth, the clay-mixed material beneath our feet, has already been shaped into buildings lasting hundreds of years.

This master's thesis will focus on the potential use of Construction Demolition Waste (CDW) material; specifically local earth masses excavated from the Västlänken metro in Gothenburg. The scalability of the rammed earth techniques in colder climates will be examined, making a case for clay as a future circular building material in a Nordic urban context.

The design section of the thesis will be a proposal for one of the stations for the new metro. The methodology will involve using the case study as an example of a design-for-material approach. It is important to showcase the potential of local waste material in the urban environment.

Compacted earth, like stone, is heavy and slow to change with the passage of time. It might not be renewable, but is completely recyclable and with a minimal CO^2 footprint. Like concrete, earth can be controlled to respond to a variety of sites and desired forms – in other words, it might well be an architect's dream material. The aesthetics of rammed earth are striking, but the story behind the material is even more powerful.

Clay – the most important component in rammed earth
Image of Kaolinite Clay – Scanning Electron Microscope
(© 2004 PetroTech Associates)

“*Every day in some form or another, I touch earth. I don't mean I walk on it, everybody does that. I mean the earth that you pick up and touch, it's all different, you know. Some of it's granular and coarse, and some of it's silky and soft. It comes in all these different colors, it can be gold, red, brown, grey. It has an aroma. You can build things with it, you can grow things in it. It's remarkable stuff, and it's everywhere. If I were blind, I would still feel the earth.”*

Bick, Z.R. (2016). p. 95

AUTHOR

VERA MATSDOTTER

- in search of the seriously sustainable

I was born in the United States but I have lived in Sweden for most of my childhood, and have been raised in a family where the state of our planet has often been discussed, a decade before climate change was defined by most as a real threat. This has and will continue to shape my work as a designer, critically reflecting upon the layers of sustainability – and always with an optimistic mindset where nature and people are stakeholders.

Searching for sustainable materials and tectonics has been a focus during my studies, where nearly all projects have been timber structures. As a nature lover, I truly believe that architects have the power and responsibility to make a change. My dream is to shift a building's negative impact on the environment into a positive one.

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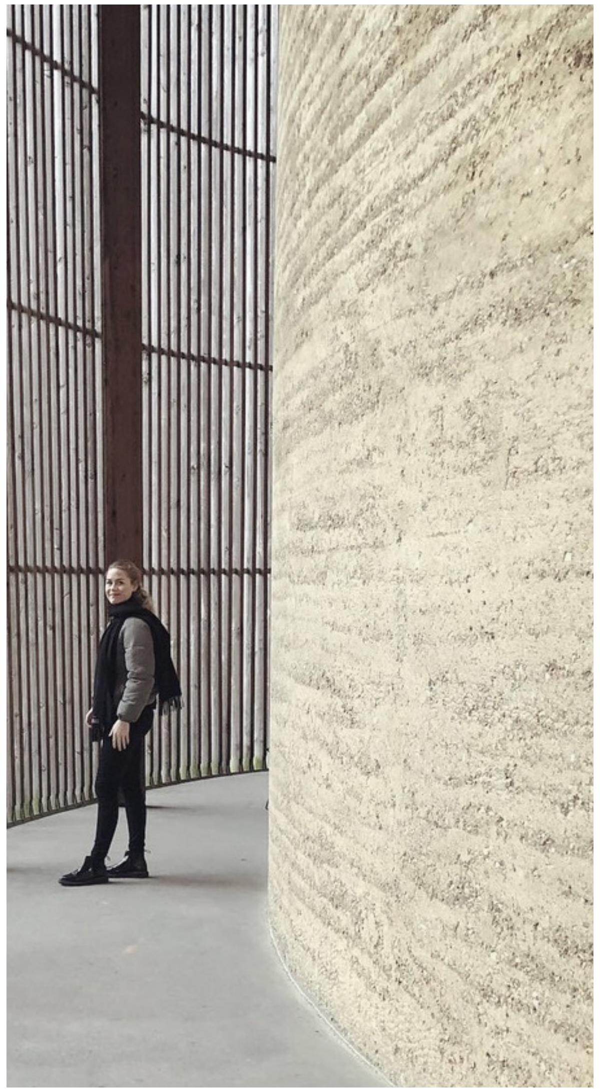

Chapel of Reconciliation, Berlin 2020
Image of my first real-life rammed earth experience

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2

DESIGN FOR MATERIAL // THE CIRCULAR PROCESS

This chapter introduces the idea of Design for Material as a toolbox for sustainable architecture. Starting with Earth Basics, identifying challenges and opportunities with rammed earth construction. Design strategies are presented for the Nordic context, followed by material testing with local clay.

3

URBAN EARTH STRUCTURES // DESIGN PROPOSAL

Introducing the design object and the context for the project location. A condensed climate and site analysis exploring the design for earth in a Nordic urban context. Application of the Design for Material toolbox in the Haga Station. A material celebration, tectonics highlighting the rammed earth structure.

4

DISCUSSION // SCALABILITY

Summary and reflection on how the thesis question has been answered. The potential of scalability for using earth masses in the built environment will be illustrated in a potential roadmap. The discussion will examine the contribution of the thesis to the development of the research topic of circular material flows.

DOWN TO EARTH – GLOSSARY

CDW
- construction demolition waste, such as excavated earth masses

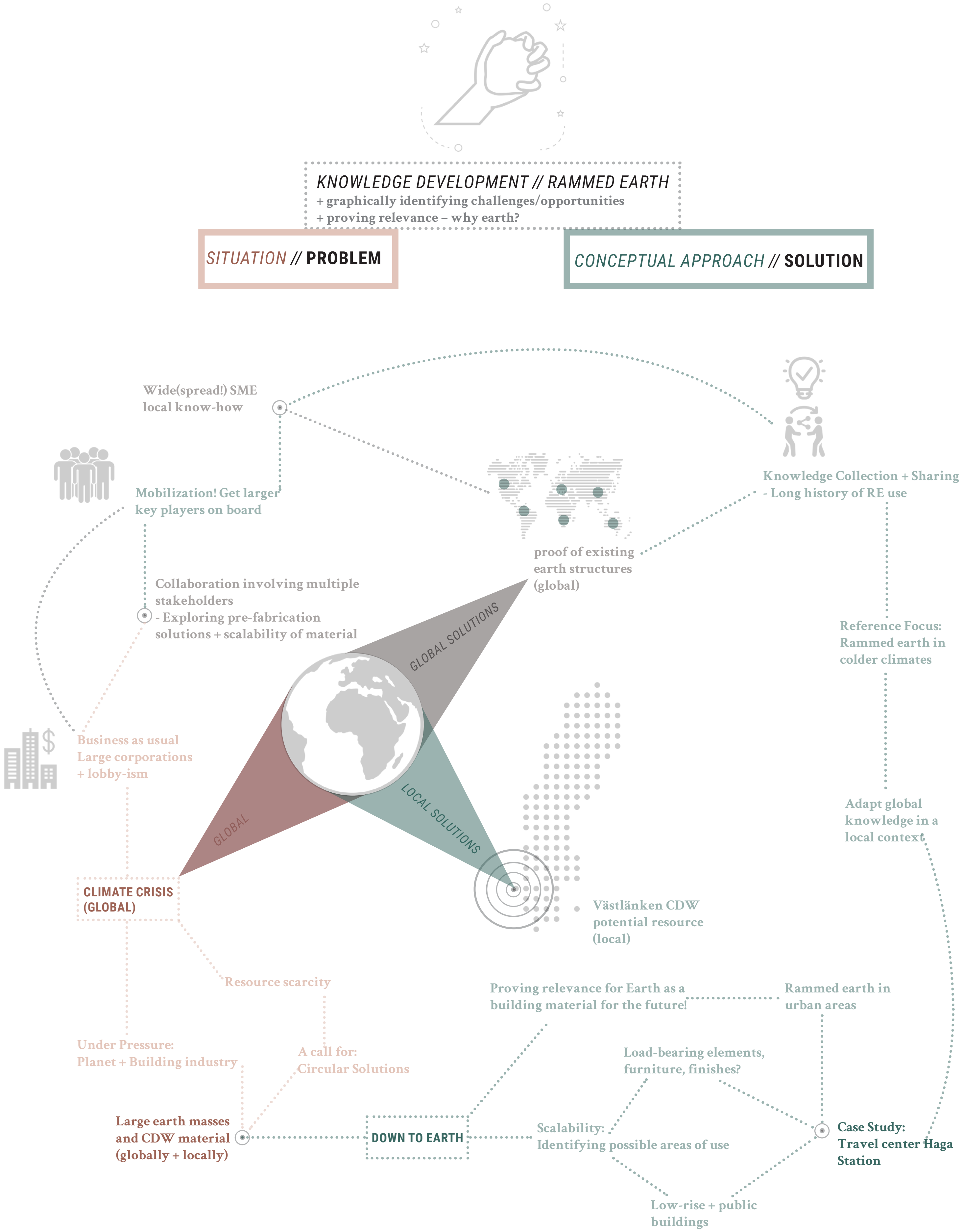
RE (UNSTABILIZED RAMMED EARTH)
- a mixture of sand, loam, clay, and other ingredients. Rammed earth walls are constructed by the compacting (ramming) of moistened subsoil into place between temporary formwork panels. When dried, the result is a dense, hard monolithic wall with the earth layers exposed. This is the most common way of building rammed earth structures in Germany.

SRE (STABILIZED RAMMED EARTH)
- the same building technique as RE, with the addition of lime or cement (5-7%) into the mix. This improves the strength and durability over time. However, by mixing the raw earth material with cement (high embodied energy), the recyclability of the material is compromised. SRE is most common in Australia and Canada, where the earth building codes require these additives.

THERMAL MASS
- a material's ability to absorb heat, providing stagnation against temperature fluctuation, typically over 24 hours. Materials with high density (RE, bricks, concrete) can store more heat and have a high thermal mass, whereas wood (low density) has a poor thermal mass.

CIRULAR MATERIAL
- materials that are a part of a closed-loop system eliminating the creation of waste, carbon emmissions and pollution. Earthmasses is an example of a circular material that can be recycled in a circular way.

RENEWABLE MATERIAL
- materials are sources from living, grown by the sun, and biodegradable. Timber, Reed, Hemp are renewable materials and can be considered as carbon sinks, absorbing CO^2 from the atmosphere.



Down to Earth - Graphical Manifesto

PART 1.

INTRODUCTION // WHY EARTH?

- presenting the chosen research field and the subject discourse

MATERIAL MATTERS

THE CHALLENGE – embodied energy & resource scarcity

There is a growing body of evidence that material matters. The construction industry is responsible for roughly 40% of global material and energy consumption. Meanwhile, CO^2 emissions from the chosen materials in buildings account for 28% of the buildings' related annual CO^2 emissions. Cement and steel manufacturing have the highest carbon footprint and the materials are used in large quantities. Efforts are made globally to reduce direct and indirect emissions by replacing fossil fuel combustion in buildings with renewables. However, the embodied energy from the construction of buildings, the extraction of materials, and production remains out of the spotlight. The global carbon footprint of our buildings therefore continues to increase (World Green Building Council, 2018).

The 2018 Global Status Report; *Towards a zero-emission, efficient and resilient buildings and construction sector* highlights the fact that a building's embodied carbon is primarily based on material demand and trends. There has been an annual increase in steel and cement due to rapid economic growth in developing countries. China has set the trend for a growing construction market and accounts for close to 40% of current building material use. Shifting the focus to embodied energy from material is therefore a crucial piece of the puzzle in order to reduce emissions in the building industry (World Green Building Council, 2018).

CIRCULAR MATERIAL FLOW – from waste to resource

Today our buildings have a lifespan of 20-40 years. Recycling and recovery rates for materials are low due to the existing building stock not being designed for dissasembly. The European Waste Framework Directive has a goal to decrease Construction Demolition Waste (CDW) through reuse and recycling, where member states are required to recover 70% of materials by 2020. One example is the EU funded RE^4 project (REuse and REcycling of CDW materials and structures in energy-efficient pREfabricated elements for building REfurbishment and construc- tion), in which new pre-fabricated materials from CDW have been developed. Excavated earth material is one part of the research project, focusing on non-load-bearing indoor applications. The idea is to develop reversible construction elements for new buildings and refurbishment, promoting circular construction. Focusing on earth and minerals from CDW represents one of the main waste streams in Europe (Klinge et al., 2019).

> *"It is but timely that earthen constructions are revisited for their potential to meet the growing demand for modern housing, relieve the increasing burden of urbanisation, and as an alternative material which is environmentally benign, renewable, globally accessible and affordable."*
>
> B. V. Venkatarama et al., (2019) p.7.

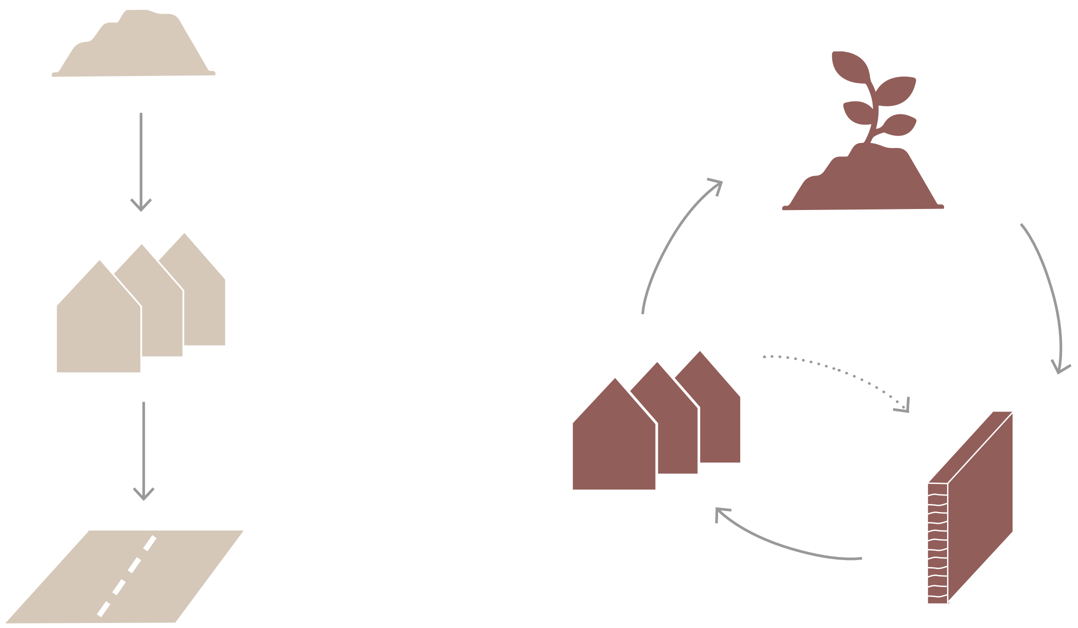


Figure 1. **Future proofing material resources – Comparing cycles of concrete and earth material construction**
Earth remains in the biological cycle and concrete enters a technical cycle of material degradation, compromising future recyclability.

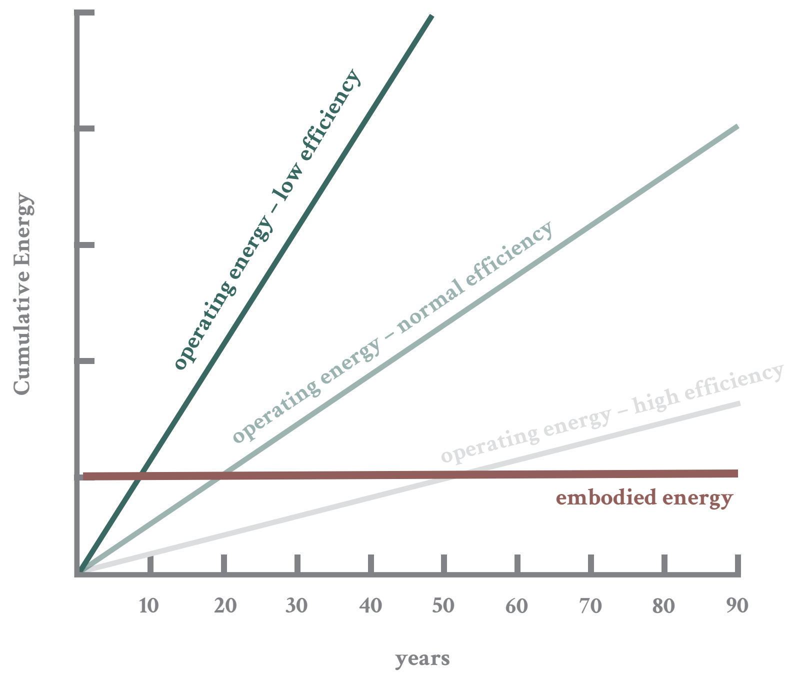


Figure 2. **The changing relationship between embodied and operating energy consumption over time, proving that material matters.**
Retrieved from: Stauffer, N (2009) *MIT Energy Initiative*

MATERIALS*	kg CO^2/m^3	kg CO^2/tonne
Bricks (fired)	**1 895**	**972**
Concrete (precast)(1)	**328**	**137**
Gravel	19	10
Rammed earth (2)	**19**	**10**
Sand	19	10
Steel	**25 870 - 54 497**	**3 455 - 6 987**
Straw Bale	4	-
Wood	147	104

1.) with reinforcement

2.) without formwork

***values account for the raw material – not transportation or production, as the energy source could vary**

Figure 3. **Comparing embodied CO^2 energy in materials**
Retrieved from: Martínez Escobar, (2014)

> “The word Earth has many interpretations; as a planet that sustains all life and ecosystems, terrestrially it is the land mass we live on; as a material resource, it represents the complex mixture of clay, sand, minerals and nutrients that sustains agriculture, subterranean biodiversity and human civilisations; and spiritually, it goes full circle to establish our primal oneness with the planet. To all native civilisations, the earth is all encompassing and revered spiritually; to all modern civilisations, the earth supports all the ecosystem services that drives development, industrialisation and economic growth. Through millennia, the earth has served to house civilisations across the world, in nearly all climates and terrains, and has sustained the ravages of time as a durable and sustainable building material. In modern interpretations, the earth carries a nearly zero-carbon footprint, negligible life-cycle impact and complete recyclability with no end of life (disposal). It is accessible in its diversity to nearly all civilisations across the world, where unique construction techniques have evolved from cob wall, wattle and daub, to modern rammed earth building technologies.”

B. V. Venkatarama et al., (2019) p.7.

RELEVANCE

SUSTAINABILITY – Resource Salvation

If we focus on the issue of CO^2 emissions and resource scarcity, the building industry is one of the villains – but also one of the key players, and part of the solution (Beim et al., 2019).

The building sector accounts for a third of the total waste generated in Europe. Due to buildings not being designed for disassembly, elements are hard to recover and often end up in landfills. The waste material recovered is predominately used for low-grade applications such as road fill. The focus during demolition is on cost and time efficiency rather than recovering material. This results in material resources and energy being wasted (Klinge et al., 2019).

The solution to this problem can be found in the concept for the circular economy, transforming waste into a resource. This requires leaving the linear “take-make-waste” model behind and thinking of material waste streams as “closed loops”, where a product is a part of a technical or biological cycle. This entails retaining both the material qualities and the embodied energy used in processing (Ellen Macarthur Foundation, 2020).

This is where earth/clay-based structures have great potential, as the material can be recycled indefinitely without degradation. And since this material is being excavated as a by-product from the construction industry, such use would help close the loop (Klinge et al., 2019).

PROFESSION - the Future Architect

Due to resource scarcity and increasing material costs, it is reasonable to imagine that future architects will not have the luxury to choose the material after the design. Instead, the design must follow the material and its availability. As architects, we should use our skills in communicating totality not only in a design project but in relation to our choices of materials, and should push for more circular solutions.

Once we realize that material matters, a change of mindset in the architectural design process is crucial. The choice of materials needs to enter the discussion at an earlier stage in terms of critically reflecting on extraction, renewability, recyclability, and locality.

Architects do have power – and it is crucial for us to take a lead and be actively critical of the materials we design our buildings with. But innovation towards more circular materials is already out there. We simply need to be bold enough to test their potential and put them into practice. Architects must start taking on these challenges and dig deeper into circular waste or bio-based materials, with the conviction that part of the solution may lie beneath our feet.

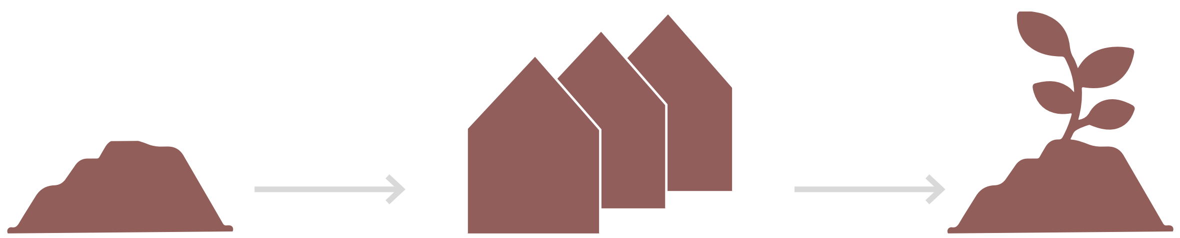


Figure 4. **Earth is a circular & completely recyclable building material** - future proofing resources for generations to come

BACKGROUND

THESIS CONTEXT - Västlänken

The city of Gothenburg has the largest city development plan in Scandinavia, with 12 000 housing units planned in the coming decade. Meanwhile, since 2018, millions of tons of Construction Demolition Waste (CDW), a potential building material (earth) have been excavated as part of the Västlänken tunnel project (Business Region Gothenburg, 2019).

The Västlänken project is a controversial project; a symbol fueling distrust in local politicians. Large numbers of citizens have protested against it, even since construction has begun. It is described as a national infrastructure project where the people of Gothenburg are paying the cost. There are obvious long-term sustainability benefits from the project, yet large CO^2 emissions are inevitable. By making use of the excavated waste materials, there is a possibility for the project to give back more to the city beyond the functions of underground transportation.

This thesis is intended to support a selection of local research projects into clay based building materials. ReCirculate is a government funded research project starting in January 2020 (see stakeholder diagram p.??). The project intends to explore the possibility of re-using waste material from demolished buildings and waste clay, both by researching innovative sustainable clay products and by developing a system for re-use of demolished and disassembled building products.

The design section of this thesis will be a proposal for one of the travel centers for the metro. The idea is to showcase the possibility of building with the local excavated 'waste material' (earth) from the tunnels. Clay and rock (gravel) are the key ingredients for the rammed earth mixture, enabling a local opportunity for upscaling this technique.

PURPOSE – Design for Material

The overall purpose of this thesis is to prove to architects and builders that earth is a viable material for the future, by lifting examples of different applications of the material. Rammed earth is not only a material suitable for private homes in rural areas in the southern hemisphere, but also for buildings in colder climates in an urban context.

This thesis will not necessarily generate new knowledge in terms of technical development of the rammed earth (RE) technique. Existing evidence based examples will be collected, and strategies will be identified for a successful earth-based structure in a Nordic context.

Beyond the earthen material itself, this thesis underpins the concept of Design for Material, exploring what this implies in the architectural process – critically reflecting on the choice of material and understanding material properties for every project in order to guide the design to enable more resilient and circular structures.

CASE STUDY – Haga Station

The aim of the case study is to showcase the actual material excavated in a potential design object. The design proposal will not be a detailed proposal for the station that solves all aspects. Instead, the focus is on revealing the challenges and opportunities presented by building with rammed earth in the Nordic context.

With the conviction that the million tons of earth excavated from tunnels can be integrated as part of a circular material flow in the future built environment, the aim is to make clay/earth-based structures accessible and visible in an urban context. To prove the potential of local 'waste' materials is key – and to display this in a public building.

"*Earth architecture today remains a do-it-your-self technique because there is an absence of these buildings in urban cities. What is urban could be another discussion, but the lack of earth building constructions in city centers and modern developments is what is important to point out.*

Buildings with natural materials are usually designed to be placed in the countryside. If we, as architects, design and evidence that is possible to build with earth, people will start to notice, and we would be able to see these kind of constructions more and more in our urban areas."

Martínez Escobar, (2014)

Figure 5. **Mapping of where (on) earth rammed earth building techniques have developed, and are standardized and regulated by building codes**

WHY EARTH?

SUBJECT– Material Background

Clay as a construction material has a very large potential for sustainable construction and circular economy, among other things. Earth has the potential to tackle CO^2 emissions and is an example of a material with low embodied energy. It is an alternative to very high CO^2-emitting materials such as cement and hydraulic lime mortar. Earth is not a renewable resource but it is circular – the raw material is almost inexhaustible. This means that when kept in its raw form, without adding any cement or burning it, earth can be recycled to its original composition indefinitely (Nielsen, 2018).

One half of the worlds population live or work in earth buildings and they represent some of the oldest strucutures in the world (Naidoo, 2010). There are many reasons why earth has been used for thousands of years. In terms of architectural qualities, the aesthetics of rammed earth (RE) are striking; however, the story behind the material is even more powerful. Earth has earned supporters due to its local accessibility, eliminating transportation and CO^2 emissions, and the fact that it is completely recyclable and with an architectural plasticity. Other recognizable properties are that RE is a non-flammable, non-toxic material proven to regulate humidity and increase thermal comfort (Martínez Escobar, (2013).

Yet the increasing interest in the building method is limited by a number of drawbacks. One of these is the lack of scientific basis, regulations and standardization applicable to other conventional construction materials. Building with earth is also labor intensive, resulting in longer lead times and making it less competitive in commercial projects (Bernata, Gila and Escrig, 2016).

Today rammed earth (RE) buildings are gaining ground on a global scale, with regulations most highly developed in New Zealand and Germany. Examples of high-end contemporary architecture can be found in Australia, South Africa, Central Europe, South and North America. RE-passive houses are also being developed in Canada, where the cold climate is even more extreme than in the Nordic countries.

The world's most famous earth building master, Martin Rauch, is based in Austria. He has over 30 years of experience of earth buildings and his firm Lehm ton Erde have consulted on many rammed earth projects in central Europe. Rauch has developed several RE buildings from both pre-fab elements and on-site construction. These buildings perform in climactic conditions not so different from those in Nordic countries. Rauch's work is based on working with local earth as close to the project site as possible.

Designing with local materials is not a new concept. However many traditional building techniques have largely fallen into the shadow of industrialized building with steel and concrete. The result is that less attention and research have been devoted to the potential of earthen construction (Bernata, Gila and Escrig, 2016).

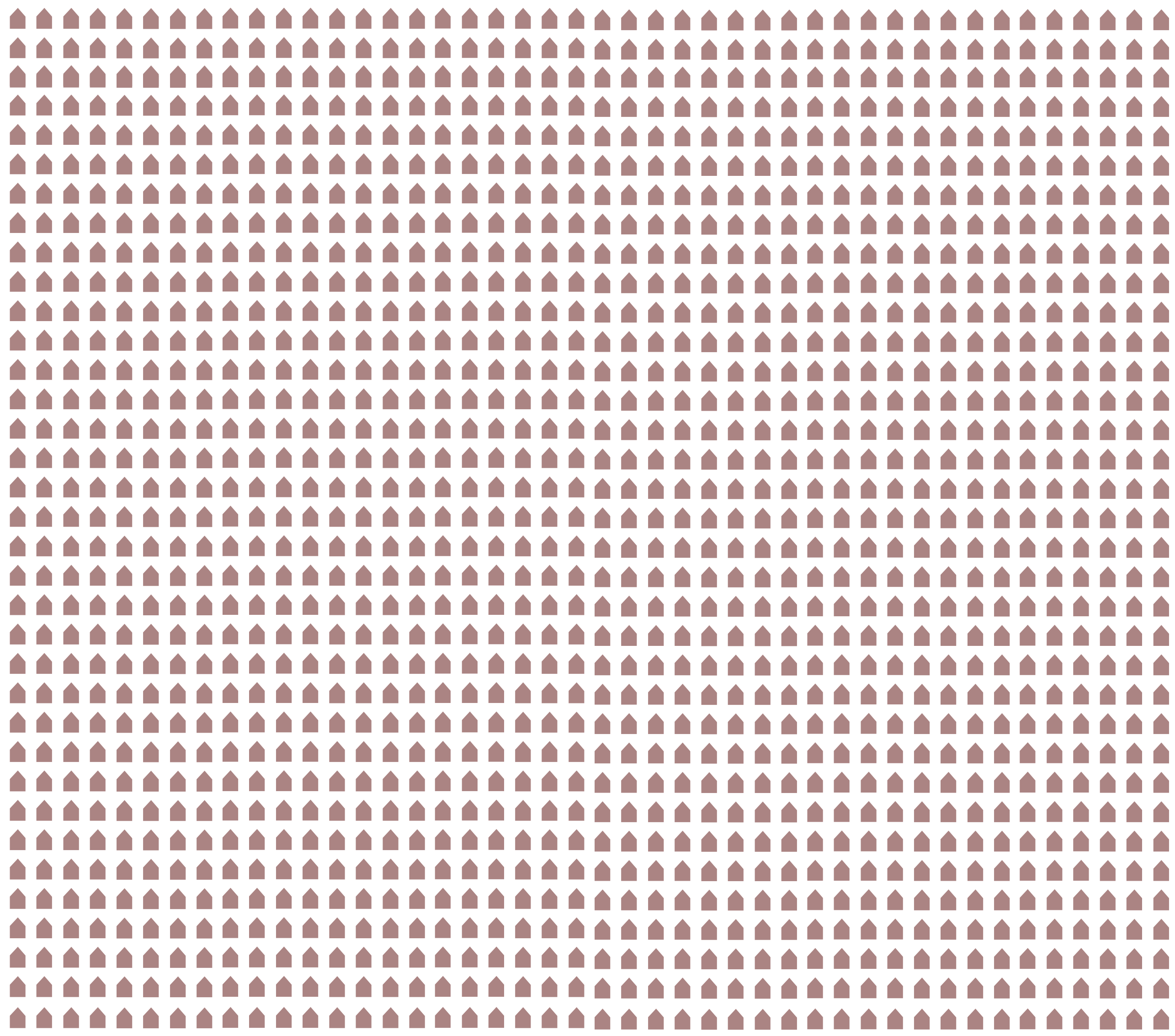
Identifying both the opportunities and challenges of working with earth is crucial – this material is not a universal solution. But materials that are ultimately a part of securing resources for future generations must be investigated to their fullest potential.

Figure 5. **Rammed-earth tower by De Gouden Liniaal Architecten overlooks the Maas river by the Belgian- Dutch Border (Dujardin, 2017).**

RESEARCH QUESTION

- What is the potential for using local excavated earth* as a circular material resource, generating rammed earth structures in a Nordic urban context?

*earth masses from construction demolition waste



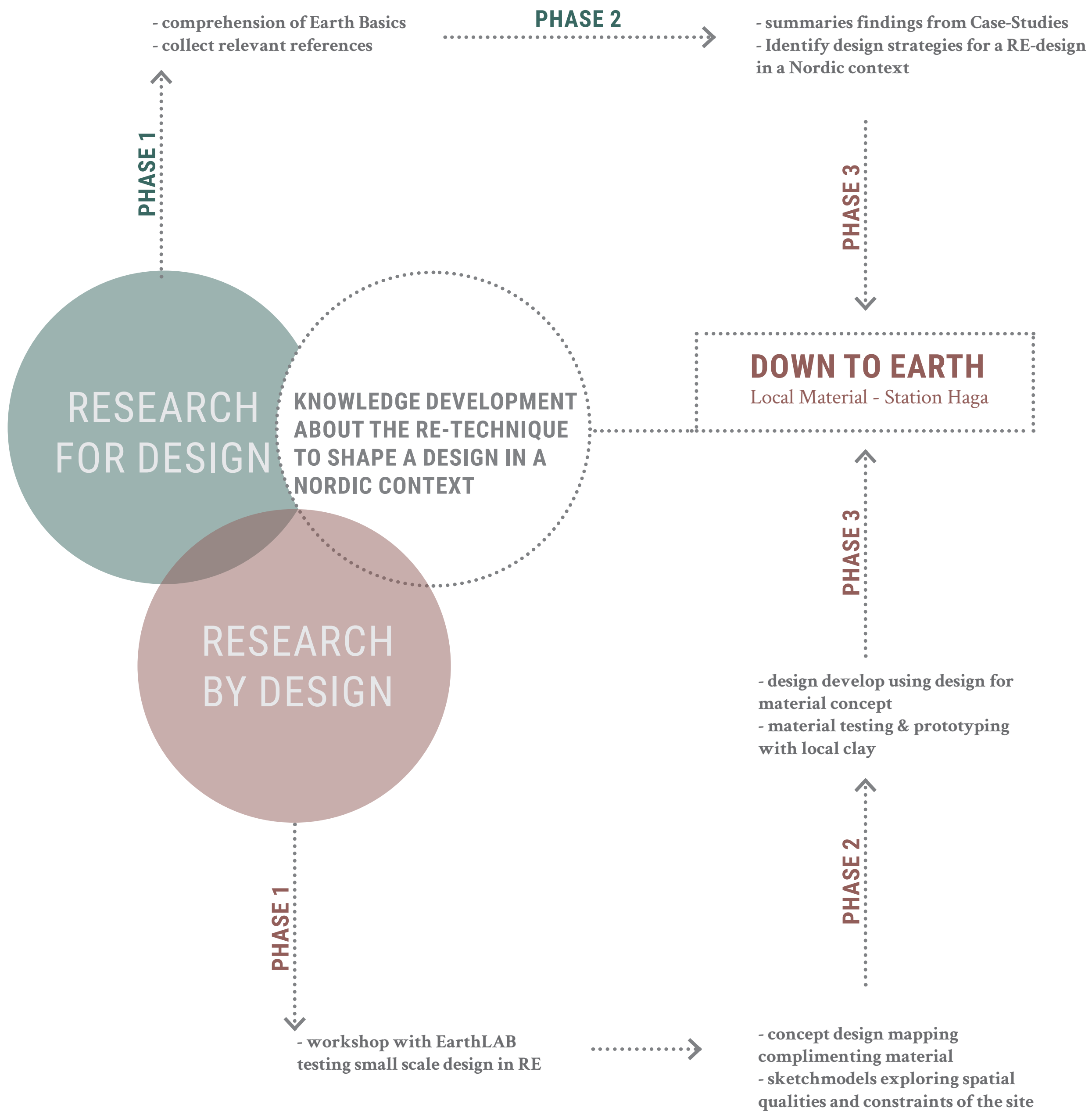
The Västlänken tunnel project in Gothenburg will yield 1 500 000 m^3 earth and clay masses.

METHOD(S)

THEORY // INITIAL CONCEPT

+ intended to be explored in the thesis

+ practical & theoretical



DELIMITATION // FOCUS AND SCOPE OF ACTION;

+ the aim is an exploration of the architectural process of circular material flow

+ identifying and understanding material qualities' contribution to shaping the design

Defining what the thesis: **WILL DO**

PROVE THE RELEVANCE OF EARTH AS A BUILDING MATERIAL for the future
- with a focus on the Nordic urban context

RAMMED EARTH IN COLD CLIMATES
- Collection of existing knowledge (global + local)

Example of **DESIGN FOLLOWS MATERIAL**
- identifying challenges and opportunities with rammed earth to shape the design

VÄSTLÄNKEN CLAY AS A LOCAL RESOURCE
- Physical models/prototypes - local earth
- Scalability of the material

Example of **A CIRCULAR MATERIAL RESOURCE** from CDW (construction demolition waste)
- cradle to cradle design

RAMMED EARTH IN PUBLIC BUILDINGS
- showcasing the importance + potential of earth as a building material

HEALTH BENEFITS OF EARTH STRUCTURES
- indoor climate and benefits of thermal mass

SELF-BUILDING WITH RAMMED EARTH
- social sustainability aspects and scalability

REGULATIONS AND LAWS for earth buildings

A study of the **DIVERSITY OF CLAY MATERIAL AND THE GLOBAL POTENTIAL** of building techniques

GENERATE NEW KNOWLEDGE FOR TECHNICAL PERFORMANCE and building physics for earth structures

RAMMED EARTH IN WARM CLIMATES
- global application of design solutions

THE UNIVERSAL SOLUTION

WILL NOT DO

MANIFESTO

Planet Earth is endangered and **UNDER PRESSURE.** And for as far as we know **THERE IS NO PLANET B**. Children are striking, forests are burning and the sea is rising. We no longer talk about climate change as an abstract future threat. **THE CLIMATE CRISIS IS NOW** – architects and builders must take action.

The construction industry is also under pressure. **WE HAVE THE POWER** to shift this negative development and impact on our environment into a positive one. This crisis **DEMANDS SELF-EXAMINATION** within the building industry, and a change of mind-set. It involves **RESOURCE SALVATION (MATERIALS)** and designing buildings as active and re-generative resources for the future.

In our search for **"SERIOUSLY SUSTAINABLE"** architecture, a radical shift and action have to happen – fast. It involves **MERGING LOW-TECH MATERIALS** with high-tech solutions, making them efficient, competitive and recyclable not only for 10 but for 100+ years ahead.

...SO WHAT ABOUT EARTH, UNDER PRESSURE? Not the planet, but the material beneath our feet? Compacted earth, like stone, is heavy and slow to change with the passage of time. It might not be renewable, but it is completely **CIRCULAR AND PLANET EARTH FRIENDLY**. It is a democratic material, with a long history of use all over the globe. Like concrete, **EARTH CAN BE CONTROLLED** to respond to a variety of sites and desired forms. It **MIGHT WELL BE AN ARCHITECT'S DREAM** material**...**

We **DON'T KNOW FOR SURE** what the future looks like. Whether our houses will be built with **PLASTIC, ROBOTS, 3D PRINTERS** or whether the **CRAFT** building traditions will return. What we do know is that the **SCARCITY OF RESOURCES** and **INCREASED EMISSIONS** caused by the building industry are a real threat. **EARTH IS ONLY ONE** part of this library of potential building materials. From now on, we must **LEAVE OUR DESTRUCTIVE PATH BEHIND,** to become and explore what it could be like, if everything was...

DOWN TO EARTH.

PART 2.

DESIGN FOR MATERIAL // RAMMED EXAMPLES

- developing the design strategies for the Nordic context

DESIGN FOR MATERIAL

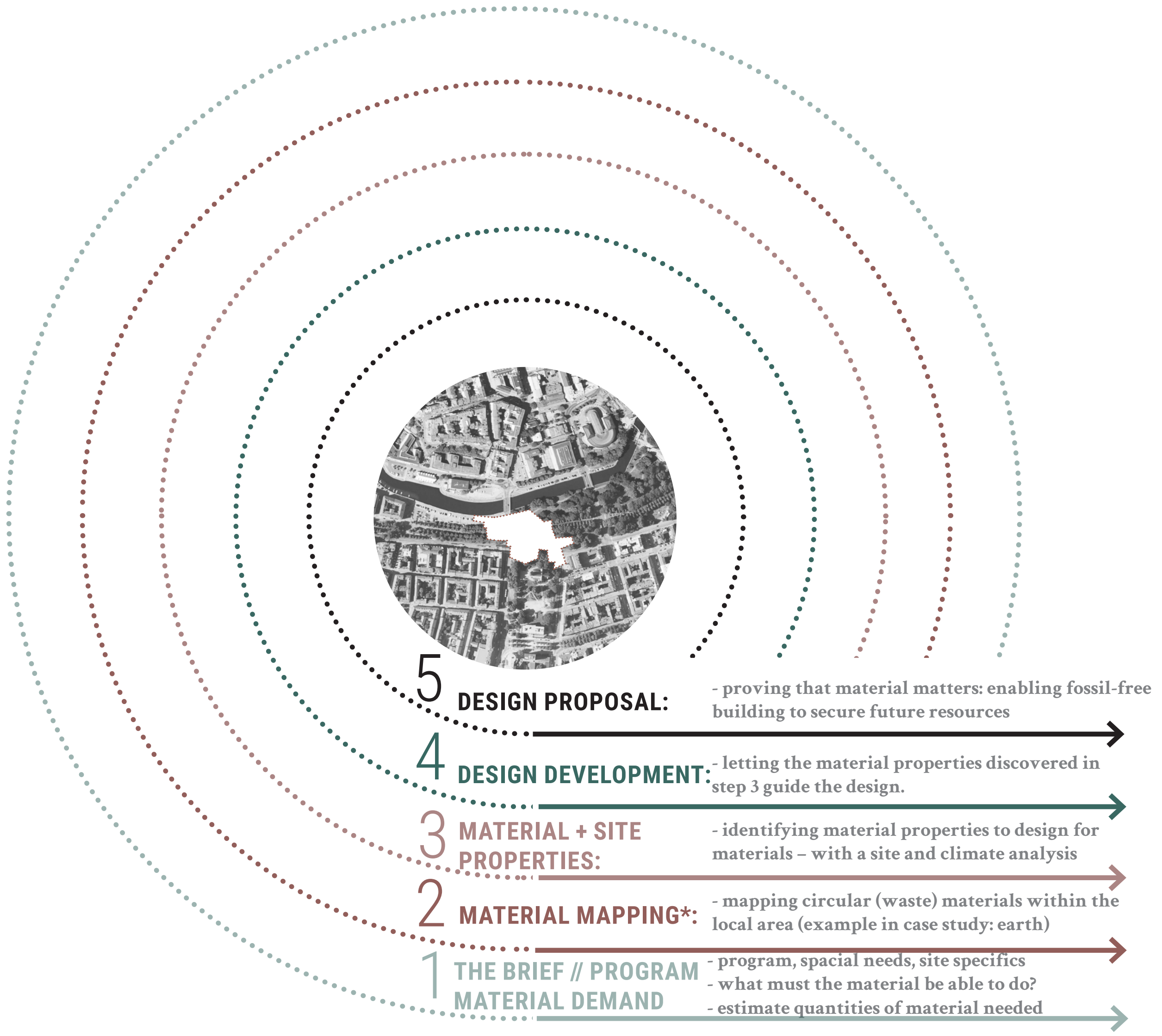
MATERIAL INTERDEPENDENCE - Material Selection

The concept is to identify a material that acts as a compliment to the Rammed Earth Structure, creating a sustainable hybrid. The design should support the material based on its properties; What is the most sustainable way to work with these materials? Identify how the design can protect the materials, enabling a low-maintenance and durable structure.

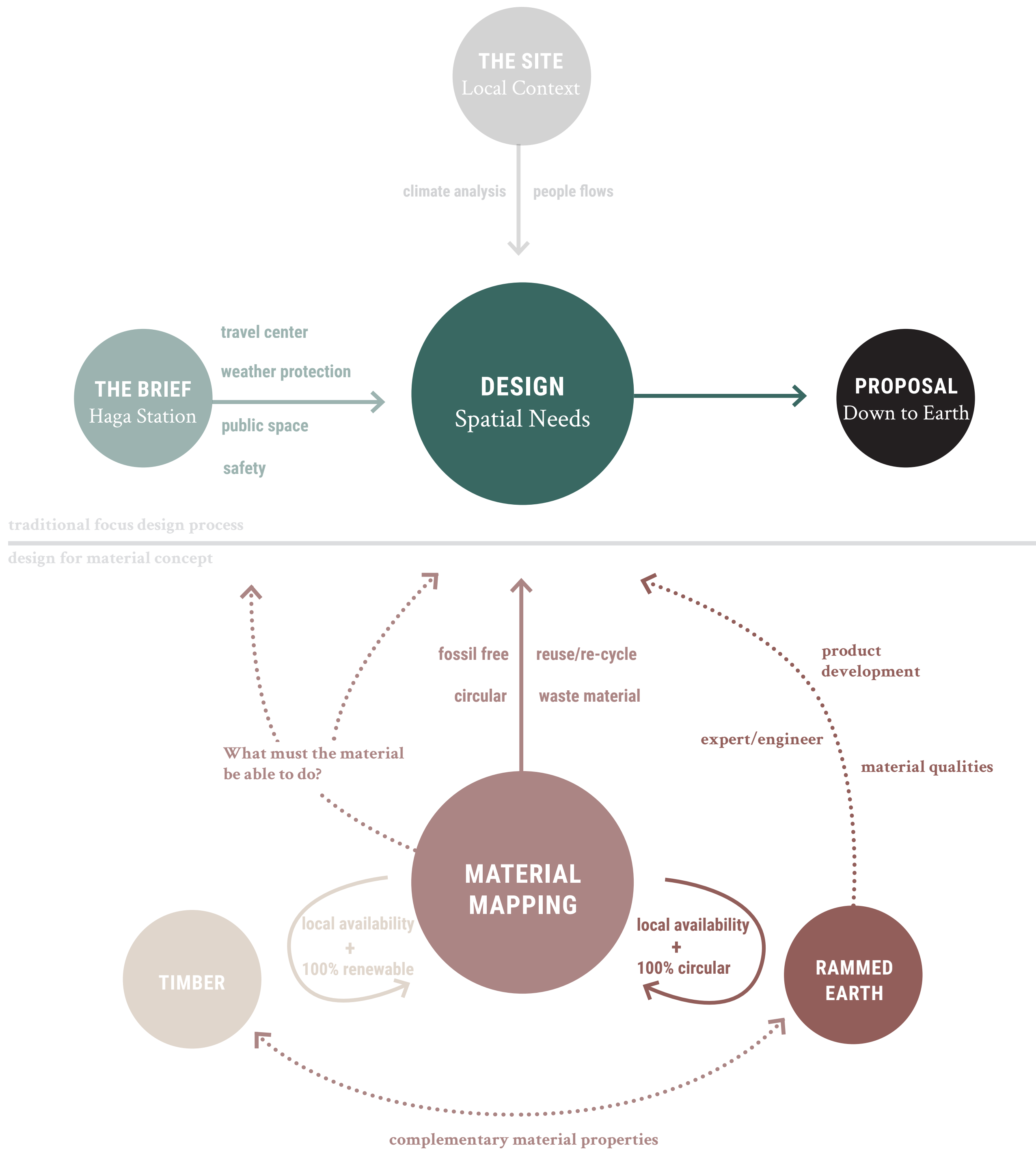
The additional compliment of structural material in the station, not to be found underground is timber. It is as a local renewable material with a low carbon footprint available in the Nordic context.

SUMMARY OF CONCEPT - towards a new design process

- always choose materials based on local context, availability & CO^2 footprint
- awareness of local site conditions and climate analysis is crucial when designing for material
- mapping strengths and weaknesses of available materials; how do they complement/support each other?
- design to enable the possibility for future reuse – buildings as material banks



The Circular Way – Envisioning a process Design for Material where material matters



Process Diagram - The Design for Material Strategy to be explored in the Case Study

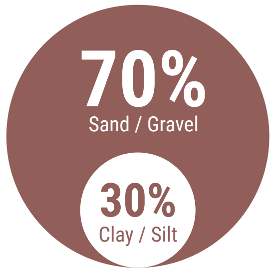
EARTH BASICS

"The Rammed Earth IS the vapour barrier, the Rammed Earth IS the air barrier - that's it."

Builder Sylvia Cook, of Aerecura, shares her technical insights on building the first high performance passive houses in rammed earth, in Ontario Canada.

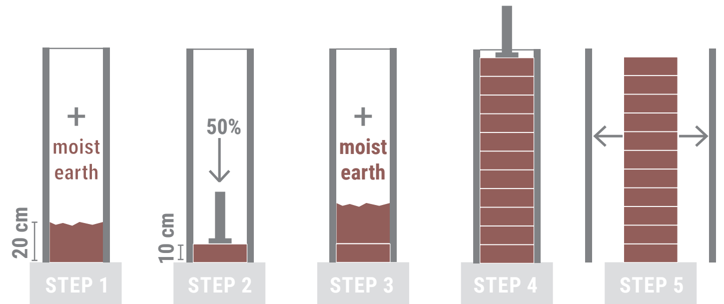
THE RAW MATERIAL
- mixture & soil composition

Rammed earth is a composition of 70% sand/gravel, 30% clay/silt (Easton, 2007). Depending on the project, the earth is always site specific. Normally you have to add one or the other to the mix. The lack of standardization within the earth building field is a disadvantage when comparing it to concrete (Martínez Escobar, 2014). This results in a need for specialized lab-testing in every new project. In order to improve the scalability of RE, ensuring quality standards for large quantities of excavated earth in urban areas will become key.



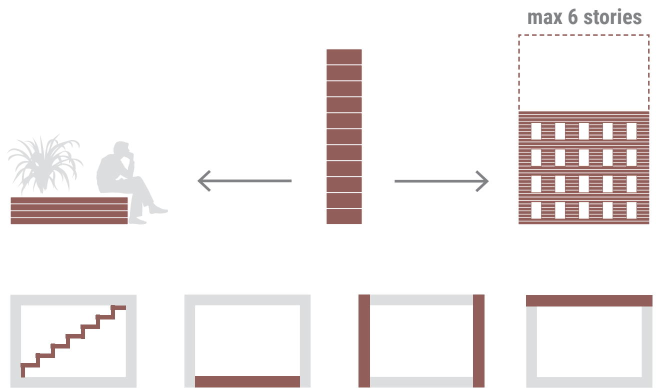
THE CONSTRUCTION
- pre-fabricated, re-inforced, insulated

Rammed earth construction is a massive and monolithic form of building with earth (Röhlen, Ziegert 2011). The mixture is poured into a formwork, similar to concrete, and compacted (rammed). The finished elements simply need to dry, and do not require baking. Insulation and/or reinforcement can be added within the formwork during the ramming process (see case study on page 30). Due to the heavy weight of the RE elements, on-site construction or prefabrication is to be preferred, minimizing transportation and CO^2 emissions.



DESIGN APPLICATION
- correct use of material & scalability

Rammed earth elements can be used in multiple scales and typologies. Design applications range from (load-bearing) vertical walls to horizontal (non load-bearing) floors, slabs, and roofs. Rammed earth can also be applied in furniture, including staircases (Rauch 2014). The use of clay panels or non load-bearing RE elements has great potential in terms of scalability. They can easily be pre-fabricated, are naturally fire-resistant, and can be designed to improve acoustics. Clay, the most crucial component in RE, acts as a binder and gives the material outstanding hygroscopic properties. In the Nordic context, where people spend most time indoors, the application of RE elements could significantly improve the indoor climate.



ARCHITECTURAL QUALITIES
- main arguments for building with earth

1.) earth is a globally accessible, bio-based, and completely reusable material resource

2.) earth is a flexible material enabling multiple forms of design of buildings

3.) clay creates healthy indoor climates, regulating humidity like no other material, it is non-flameable and can store heat

MATERIAL PROPERTIES // UNSTABILISED RAMMED EARTH
+ exposing the challenges and opportunities

PROPERTIES	RAMMED EARTH	CONCRETE
Density	**2,000 kg/m^3**	**2,350 kg/m^3**
Compressive Strength	2-4 N/mm^2	17-30 N/mm^2 [1]
Tensile Strength	0,4 N/mm^2	2-4 N/mm^2
Shrinkage Ratio	0,5%-2%	0,04%-0.08%
Drying Period[2]	20-30 days	5-7 days
Thermal Conductivity	**1.10 W/mK**	**2.30 W/mK**
Heat Capacity	**1.0-1.5 kJ/kgK**	**1.0 kJ/kgK**
Time Input	10-20 h/m^3	10 h/m^3 [3]
Embodied CO^2	**10 kg CO_2/ton**	**137 kg CO_2/ton**
Cost [4]	**300-900 €/m^2**	**130-150 €/ m^2**

1.) for standard purposes, but this value can go up to 50 or 60 N/mm^2 for some applications

2.) 23°C, relative humidity 50%

3.) based on personal experience, without considering time for formwork

4.) exposed 30 cm RE-wall. Numbers retrieved from Röhlen, Ziegert 2011 p. 274

Figure 6. (Martínez Escobar, 2014) Summary Concrete & Rammed Earth pp.70-71
Sources from: Bennet 2010; Minke 2009; Röhlen, Ziegert 2011

+ POSSIBILITIES // STRENGTHS

RECYCLABILITY
- Earth is completely circular, can be transformed to its original form/raw material indefinitely (If the material is unbaked and without added cement.)

STRUCTURE
- Rammed earth has good compressive strength and does not need, depending on structure/building height, re-inforcement
- Earth is fire resistant, it does not burn

THERMAL ABILITIES
- Rammed earth has high thermal mass, which contributes to thermal storage, and balancing temperature fluctuations keeping it cool in summer and warm in winter. Heat moves between the RE-surface and the interior at a slow rate matching the daily heating and cooling cycle.
-Insulation can be integrated in the ramming process of elements (see case study p.32) and meet regulations.

WEATHERING/DURABILITY
- The erosion of exposed earth surfaces can be calculated and controlled through different design strategies without additives(see examples on p30-37).

FORM
- Rammed earth can be curved, angled and pre-fabricated elements can be cut. The joints can be sealed using the same material mixture.

INDOOR CLIMATE
- The clay content in the RE-elements creates a healthy indoor climate by regulating the humidity absorbing and releasing moisture into the space.
- As a biobased material clay does not release any hazardous chemicals, on the contrary it has been proven to absorb odors and smells.

CONSTRUCTION
- Pre-fab or on site construction RE is a simple technique, with low risks and no harmful chemical additives and with minimal CO^2 emissions.

— CHALLENGES // LIMITS

RECYCLABILITY
- Earth material is non-renewable but circular and there is an abundance of the material. If cement is added it cannot be recycled to its original mixture.

STRUCTURE
- Load bearing building rammed earth-elements have large dimensions and thick walls, which would limit high rise load bearing structures in RE.
- Elements don't have a high tensile strength and won't span without support

THERMAL ABILITIES
- A 50 cm thick re-wall without added insulation has a U-value of 2.0 W/m2 K and does not meet european standards for a u-value of 0.30 W/m2 K (Martínez Escobar, 2014).

WEATHERING/DURABILITY
- As for all materials exposed in cold and wet climates, water is a threat.
- RE elements must be protected with a waterproof foundation and with a roof overhang, or horizontal elements controlling erosion.

FORM
- Load bearing elements dictate dimensions and can be subject to shrinkage during the drying process.
- Openings above windows and doors need additional structure and can be a design challenge

CONSTRUCTION
- The rammed earth building process can be labor intensive
- It should preferably be carried out on site to minimize transportation of heavy building elements.
- The drying period after ramming also requires more time than normal concrete casting techniques.
- For all structural earth projects, lab-tests on the earth-mix from the site are necessary to minimize shrinkage and maximize material performance.

Summary of knowledge retrieved from: Kapfinger, Sauer (2017), Röhlen, Ziegert (2011), Minke (2009), Dobson, (2015)

CASE STUDIES

RAMMED EARTH REFERENCES

+ conclusions & relevant findings

HOUSE RAUCH (2005-2008)
- example of calculated erosion & scalability

LOCATION / CONTEXT:
Schlins, Austria

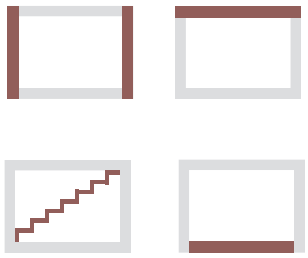
CONSTRUCTION:
On-site construction with local earth from the site

PROGRAM / FUNCTION:
Residential house on a steeply sloping hill

HIGHLIGHTS:
- Learning from what is known as the calculated erosion technique, with horizontal fired tiles every 40-60 cm to control the process of erosion. These horizontal bands create a pattern on the façade, defining the appearance and casting shadows.

- This project is also an example of scalability in terms of application. Rammed earth is used in the floors, interior walls and in a staircase proving the possibilities of earth as a building material.

- The complementing structure in the project is wood. The earth protects the timber structure with its hydroscopic abilities to absorb moisture. Rauch is highlighting the potential to work with earth in many different types of timber construction.



Rammed earth is used in walls, ceiling, staircases and flooring exposing many ways of using the material

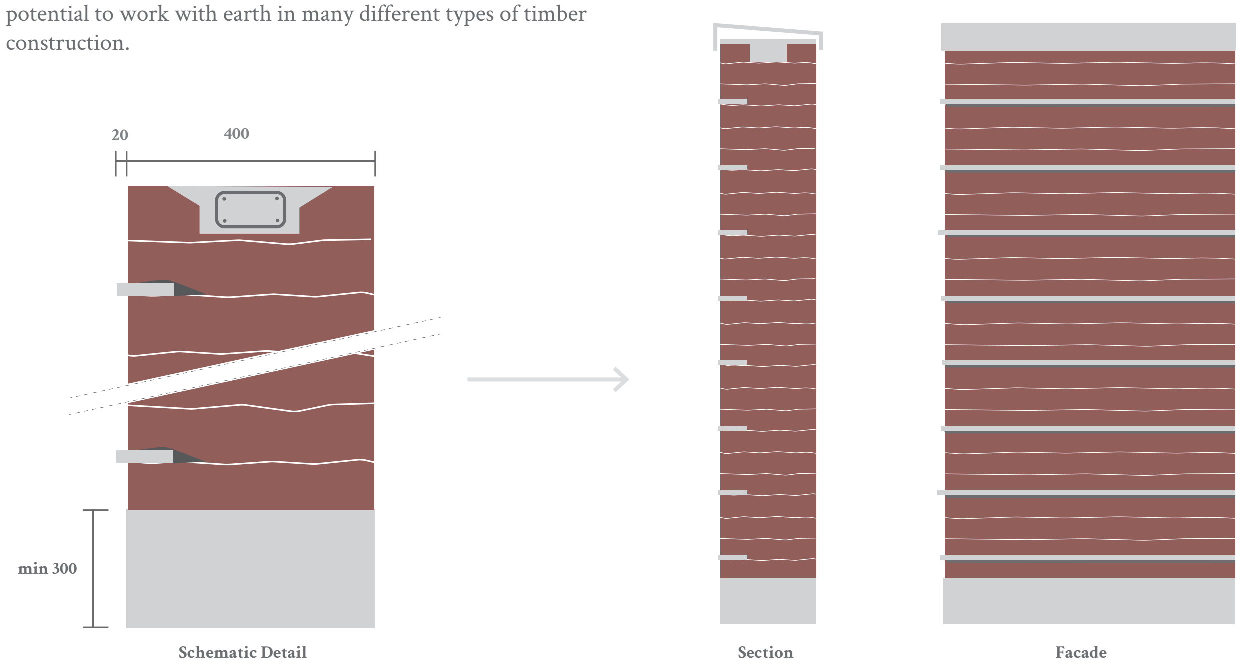


Diagram showing erosion check with protruding tiles – the horizontal bands creates a rhythm and casts shadows, defining the façade.

Figures 7-8. **House Rauch by Archictect Roger Boltshauser, Martin Rauch** (Bühler, Rauch, 2008).

ALNATURA HEADQUARTERS (2016-2017)
- high performance rammed earth structure

LOCATION / CONTEXT:
Darmstadt, Germany

CONSTRUCTION:
Pre-fabrication on-site

PROGRAM / FUNCTION:
- Headquarters and Office 10 000m^2

HIGHLIGHTS / FINDINGS:
- High environmental ambitions at a regular office-building budget. Platinum DGNB(German Sustainable Building Council) certified – confirms the performance and ecological concept.

- Large-scale commercial projects using unstabilized rammed earth in a cold climate.

- Insulation was integrated in the actual ramming process – where recycled foam glass gravel was "rammed" in the core. A geothermal wall heating system was placed directly in the RE - elements.

- Trass lime boarders were used in the project to controll erosion. This is to be preferred when upscaling the production of the pre-fabricated rammed earth.

- In order to tackle the time-consuming process of production, the RE-elements were produced as 30m long bands. The elements were later cut into 3,5m bands after removing formwork and stacked on site.

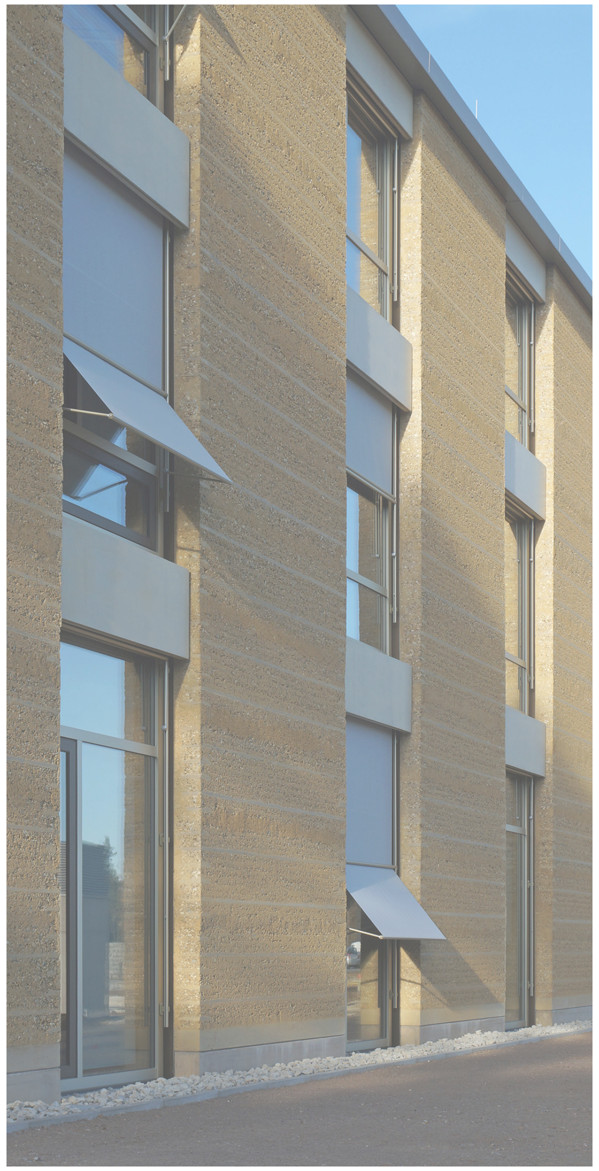
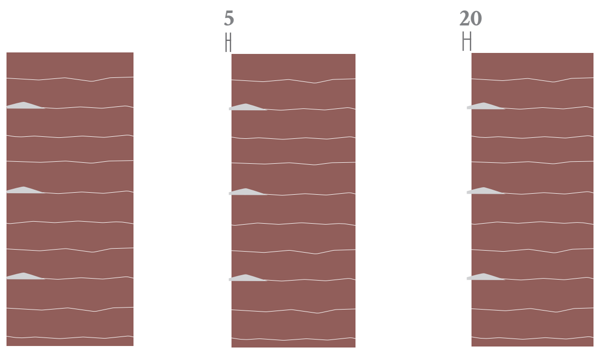


Figure 9. **Image of stacked elemens in the facade** (Halbe,



Trass-lime mortar used to control erosion
- these kind of erosion checks do protrude over time from erosion and have a more subtle appearance compared to the erosion checks in the Rauch House.

Figure 10. **Image of the recycled foam glass gravel insultation "rammed" in the core** (Halbe, 2019).

Figure 11. **Image of the pre-fabricated elements cut on site(Halbe, 2019).**

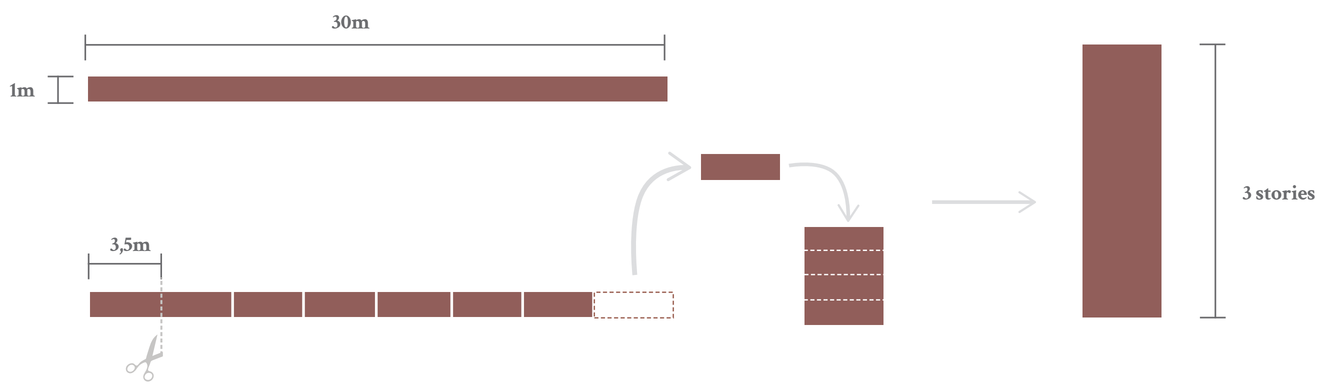


Diagram of prefabrication - enabling large scale construction of RE elements, where they can be cut and stacked, creating a large seamless structure

CHAPEL OF RECONCILIATION
- design for material

LOCATION / CONTEXT:
Berlin, Germany (Berlin Wall Memorial site)

CONSTRUCTION:
On-site construction

PROGRAM / FUNCTION:
Memorial Chapel of Reconciliation for the victims of the Berlin wall

HIGHLIGHTS:
- The Chapel is indeed a landmark for urban rammed earth construction, erected in the heart of Berlin. Showcasing the design possiblities of the material, creating 9 meter high curved walls.

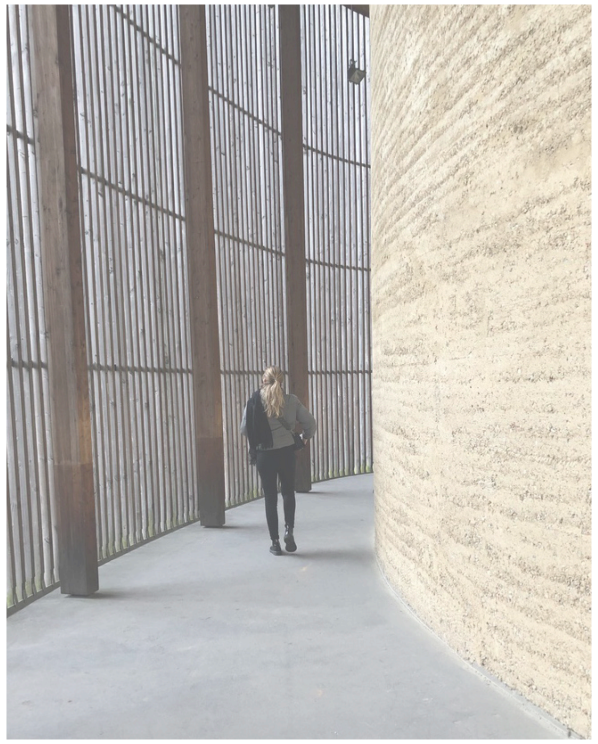
- The chapel literally bears more than the name. Remains from the neo-Gothic Church of Reconciliation that was destroyed in the war has been mixed into the rammed earth walls.

- The rammed earth-flooring has proven to be durable after thousands of visitors have walked on it. However reading about the construction this is a very labor intensive method.

- The chapel is a great example of design for material, where the double layered timber-shell facade protects the structure as well as creating a strong spatial experience.

Showcasing the strength & diversity of the material, using rammed earth as flooring in a public building

Reference Diagram: where the RE is enclosed in a wooden shell structure, protecting it from rain and creating a pathway around the building.



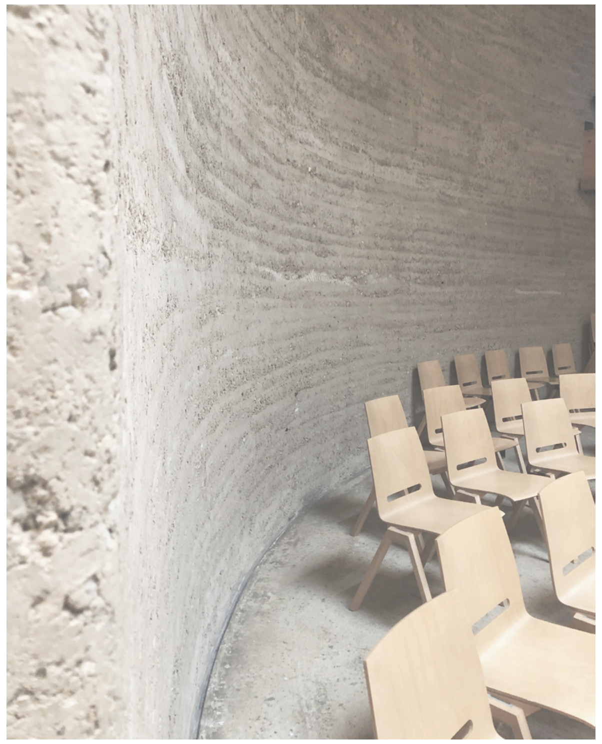
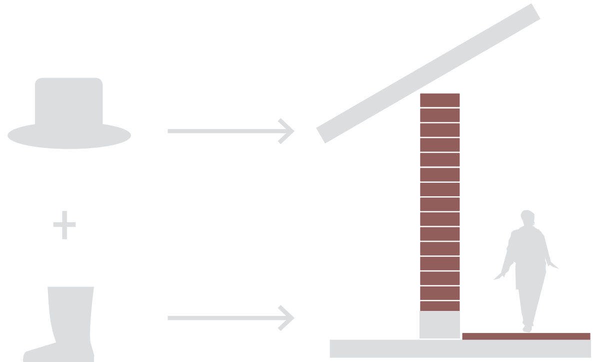


Figure 12-14. **Images from study trip to Berlin January 2020**

DESIGN STRATEGIES

RAMMED EARTH IN COLD CLIMATES

As highlighted in the Earth Basics section, rammed earth has the potential for a wide range of design applications. However, in the Nordic context some strategies need to be considered when building exposed earth structures. Unstabilized RE elements are sensitive to rainfall due to fact that earth is soluble in water. Below are some guidelines and design criteria for durable unstabilized rammed earth buildings in wet, cold and windy climates.



CALCULATED EROSION

- design with erosion checks

Whenever water runs off the façade rapidly, particles of the material are swept away. The erosion process is inevitable to a certain extent. However, the swelling process of the earth limits water penetration and stops the erosion (Rauch, 2014).

One solution for slowing this process is to insert horizontal bands – erosion checks – in the façade. These layers can consist of stones and fired clay (option 1) or courses of trass lime mortar that appear flush in the façade (option 2). Other design possibilities to control erosion can include using stones, customized brick, or fragments of material (Sauer, 2017).

THE HAT & BOOTS

- design for material shelter

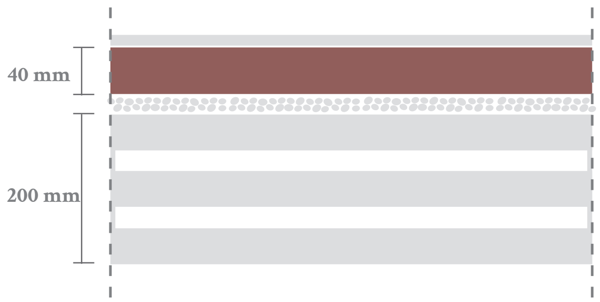
In the Nordic context the combination of wind and rain are serious threats for earth structures. Therefore additional weather protection is key. Waterproofing the foundation applies for all exposed rammed earth elements and should be minimum 300cm stone or concrete.

An alternative to the calculated erosion check is to work with roof overhang or a double facade (option 3). This strategy of designing for material shelter is more suitable in the context of Gothenburg where the climate has salt levels in the rain.

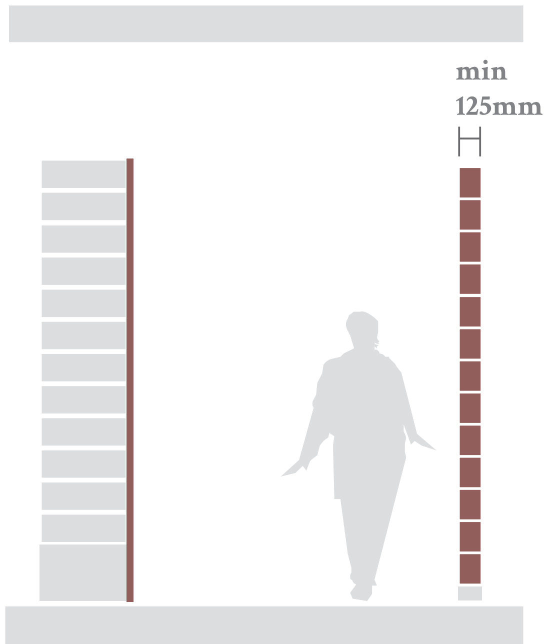
INTERIOR APPLICATION

- improving the indoor climate

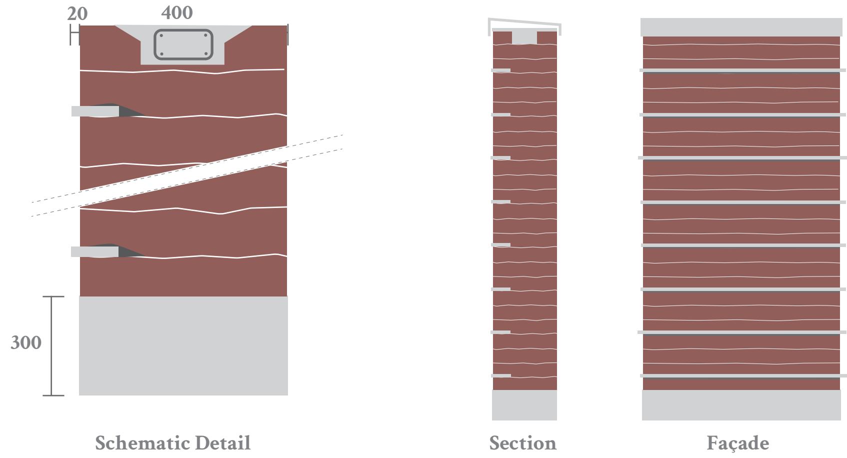
Clay-based elements have the most impact, in the Nordic context, on the indoor climate. As described in Earth Basics, clay possesses remarkable hygroscopic properties. It does not burn and could be developed as panels to improve acoustics and indoor humidity. There could be huge potential for replacing existing gypsum boards which have a high CO^2 footprint. Other applications could be using rammed earth as weight on a CLT slab structure to replace concrete, which today compromises the structure's possibilities of disassembly & recyclability. Clay protects timber construction by balancing the humidity and creates a good microclimate (Sauer, 2017).



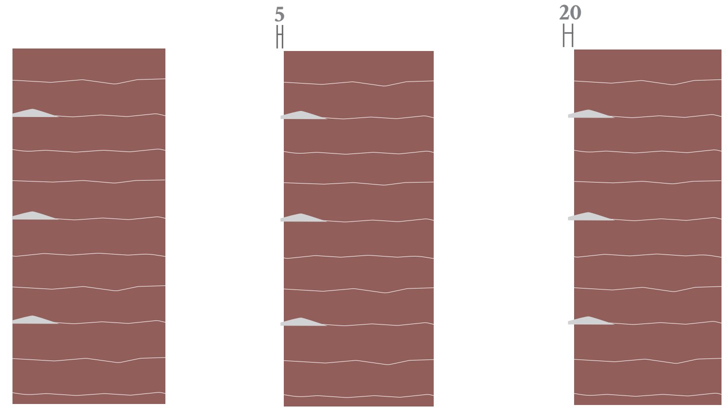
Section diagram showing rammed earth on CLT
- RE elements could replace the concrete which is commonly used when building taller timber buildings. The hygroscopic properties of the clay protect the wood from rot. Most importantly it can be disassembled in the future!



Section diagram showing interior wall- application
- RE elements of a minimum 200mm thickness can be used as wall separators improving the indoor climate. Clay plaster boards or RE-sheets can be added on the interior as a finish material, for instance when adding insulation to an old brick construction (Röhln, Ziegert, 2011).



1 **Diagram showing erosion check with protruding tiles**
- the horisontal bands creates a rythm and cast shadows defining the facade. This method was used in the case study reference of the Rauch House.



2 **Section diagram showing trass-lime mortar and the progress of erosion**
- the horisontal barriers control erosion by decreasing the flow of water. This method of erosion checks are most suitable in pre-fabrication because they are easier to produce and transport.

3 **Reference Diagram:** the Chapel of Reconciliation in Berlin
- where the RE is enclosed in a wooden shell structure (wooden lamellas, not glazed), protecting it from rain and creating a pathway around the building.

MATERIAL TESTING

LOCAL EARTH STUDIES // FINDINGS

+ exploration of local excavated material
from the Västlänken Project

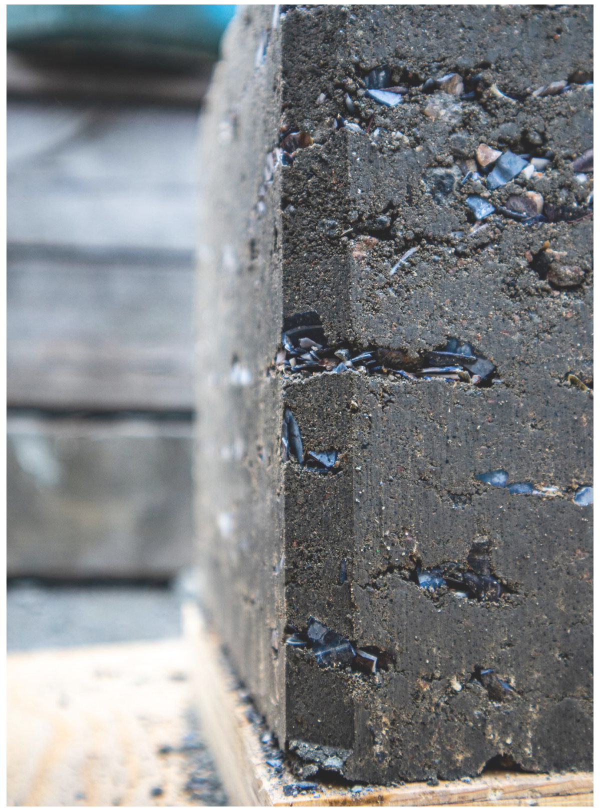
The material testing involved the process of drying, mixing and compacting local clay in a rammed earth prototype. One of the drawbacks of the rammed earth technique is the labour intensity, which became evident when conducting a small prototype. However the point of the testing was to understand the mixing process.

The clay from the Västlänken project sent Germany for lab-testing. The waste clay came back testing positive for further investigation suitable for earth construction

Exploring local earth material excavated from the metro - what can be added in the mixture? Crushed blue mussels was a part of exploring new mixtures in a rammed earth prototype. The idea wast to create a local material identity by adding a layer of mussels as an ornament, but it could perhaps also have effects on preventing erosion, which would need further testing.

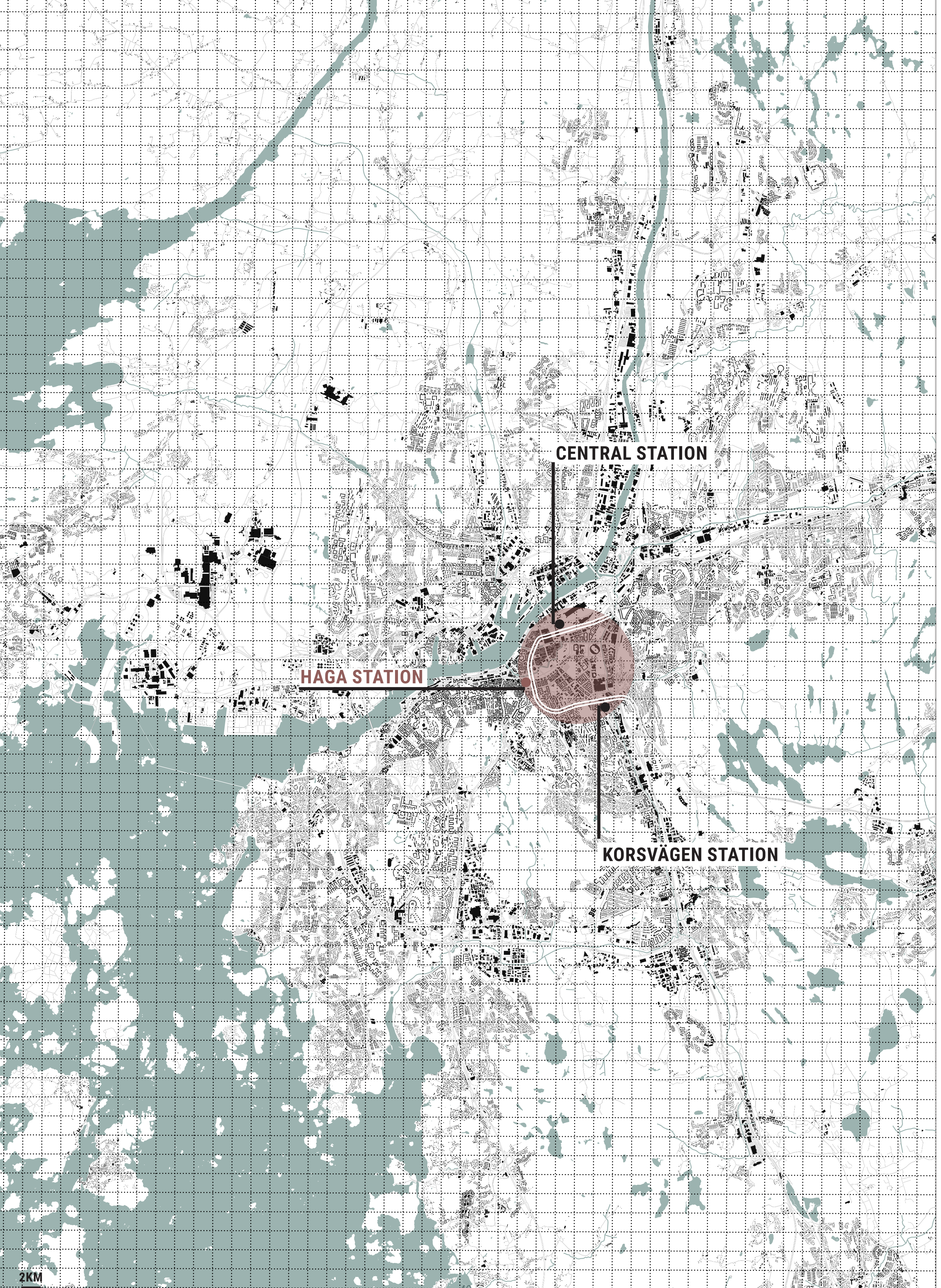
The Clay process - image showing the drying process of the wet waste-clay

Gothenburg Clay - testing the process of using the clay in a rammed earth prototype


Blue Mussels - The idea of adding blue mussels into the clay mix is explored, relating to the cities marine heritage and Fiskekörkan located by the station. A part from the aesthetics the mussels/shells could improve the insulation, structural aspects properties of the Rammed Earth elements. There is potential in the mixing and ramming process to introduce new layers of bio-based material.

Gothenburg Rammed - testing the local earth mixture adding crushed blue-mussels as layers in a rammed earth prototype. The idea wast to create a local material identity by adding layers of mussels as an ornament, but it could perhaps also have effects on preventing erosion. No pigment was addded in the mixture, the photo shows the rammed earth block after drying for a couple of days.



EARTH IN THE CITY - The Västlänken tunnels in the Gothenburg context, the movement of earth and rock masses impact the whole city

PART 3.

DOWN TO EARTH: THE HAGA STATION // URBAN EARTH STRUCTURES

- Design proposal: a travel center for the West Link Tunnel

THE HAGA STATION

PROJECT CONTEXT

+ Västlänken is an ongoing development of a railway tunnel in central Gothenburg between 2018-2026.

+ The Case-Study is a proposal for one of the travel centers

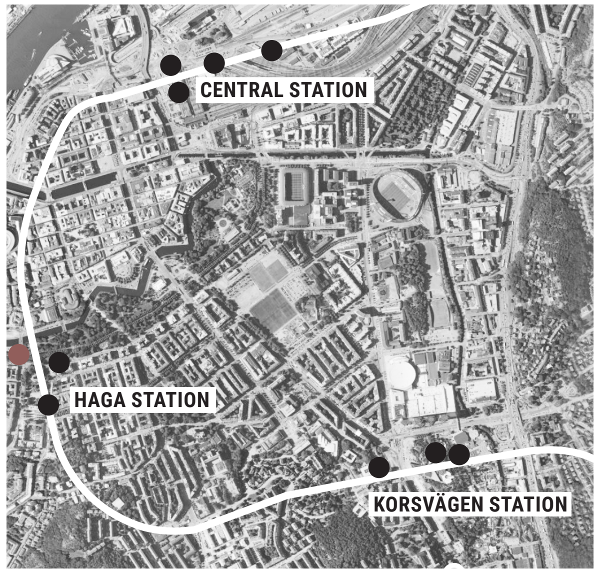
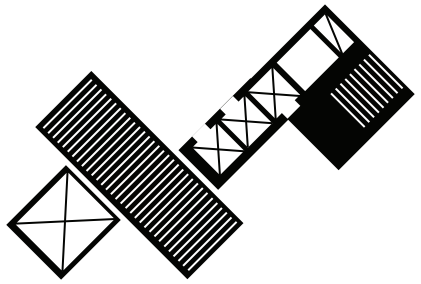


Figure 15. **Image showing the Västlänken tunnels route in Gothenburg (Göteborg Stad & Trafikkontoret, 2019)**



Vertical locked functions to the underground determined by the traffic department

FOCUS AREA OF THE SITE - Pusterviksplatsen

OTHER TRAVEL CENTERS

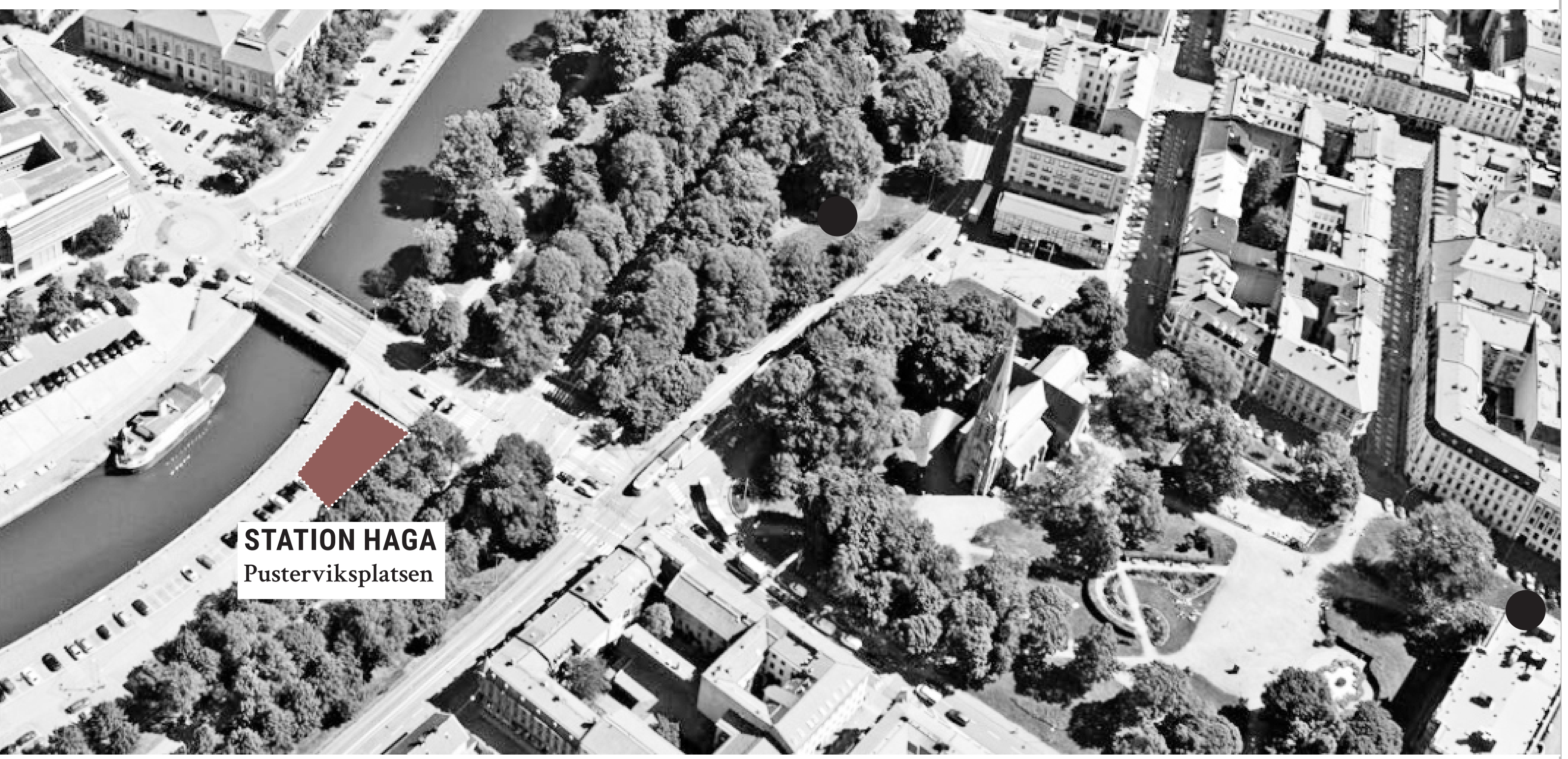


Figure 16. **Aerial images of the Haga Station site (Göteborg Stad & Trafikkontoret, 2019)**

CASE STUDY // PRECONDITIONS

THE SITE - direction & flows

Combined with the design for material concept - the station will be shaped after important flows around the site. The boundary of the site is a rectangular shape, framed by the roads and waterfront surrounding it. The locked functions determined by the trafic department are preconditions for the design, including parking and accessibility to the station.

The main direction is inside the building - set at an 45° angle to the site perimeter. Arriving from the underground, this is identified as the most important axis in the station. Sight-lines and orientation of the transparent and solid elements are a crucial part to explore. The design objective for the station building is to create shelter, absorb different flows and bring you down to earth.

Entrances Requested

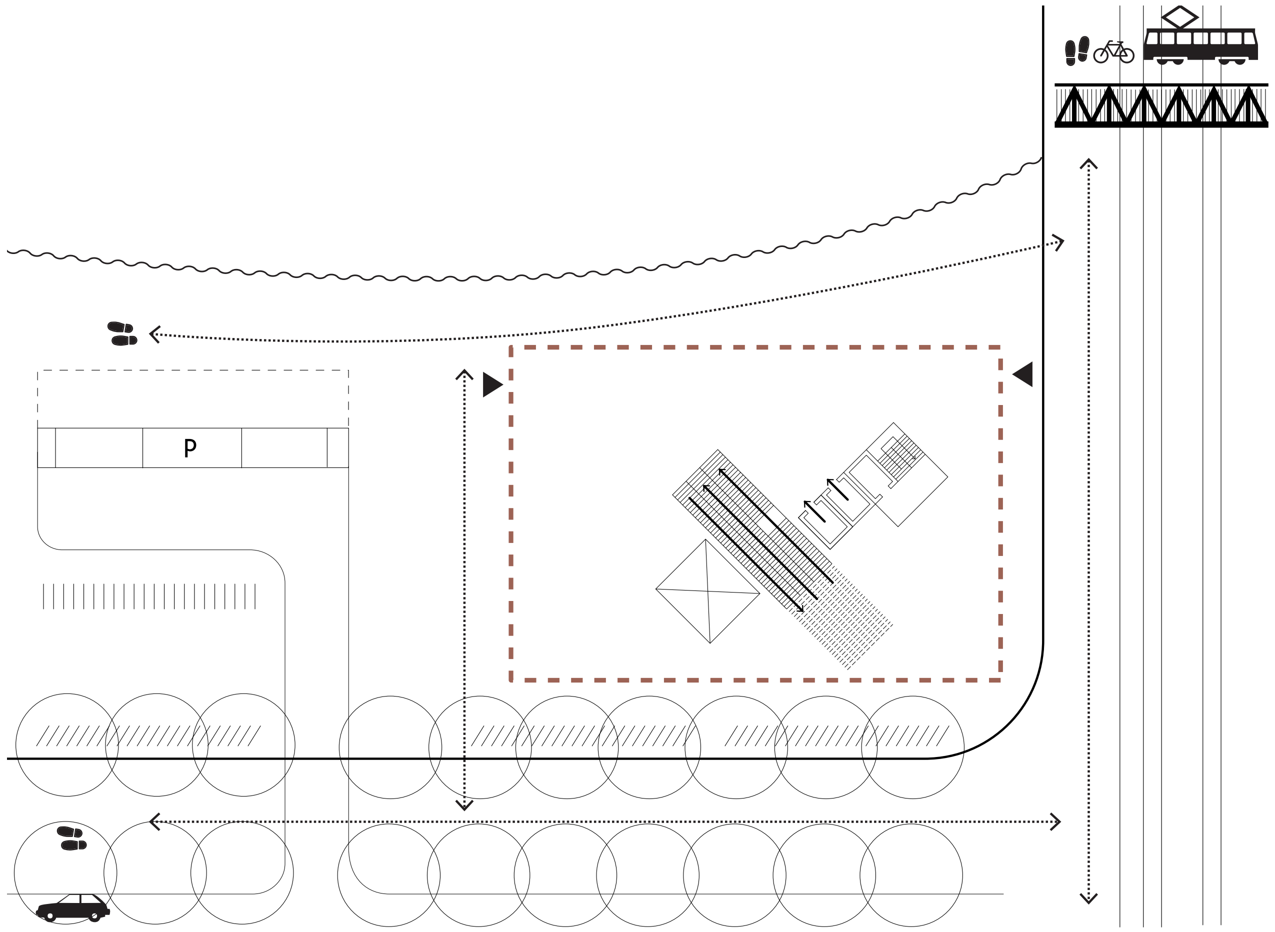
Station boundary from detail plan

Pedestrian flow

Bike parking

Styr & Ställ (rental-bikes)

Parking for räddningstjänst



Important flows and directions inside and around the station. Diagram shows the location of the locked functions on the site.

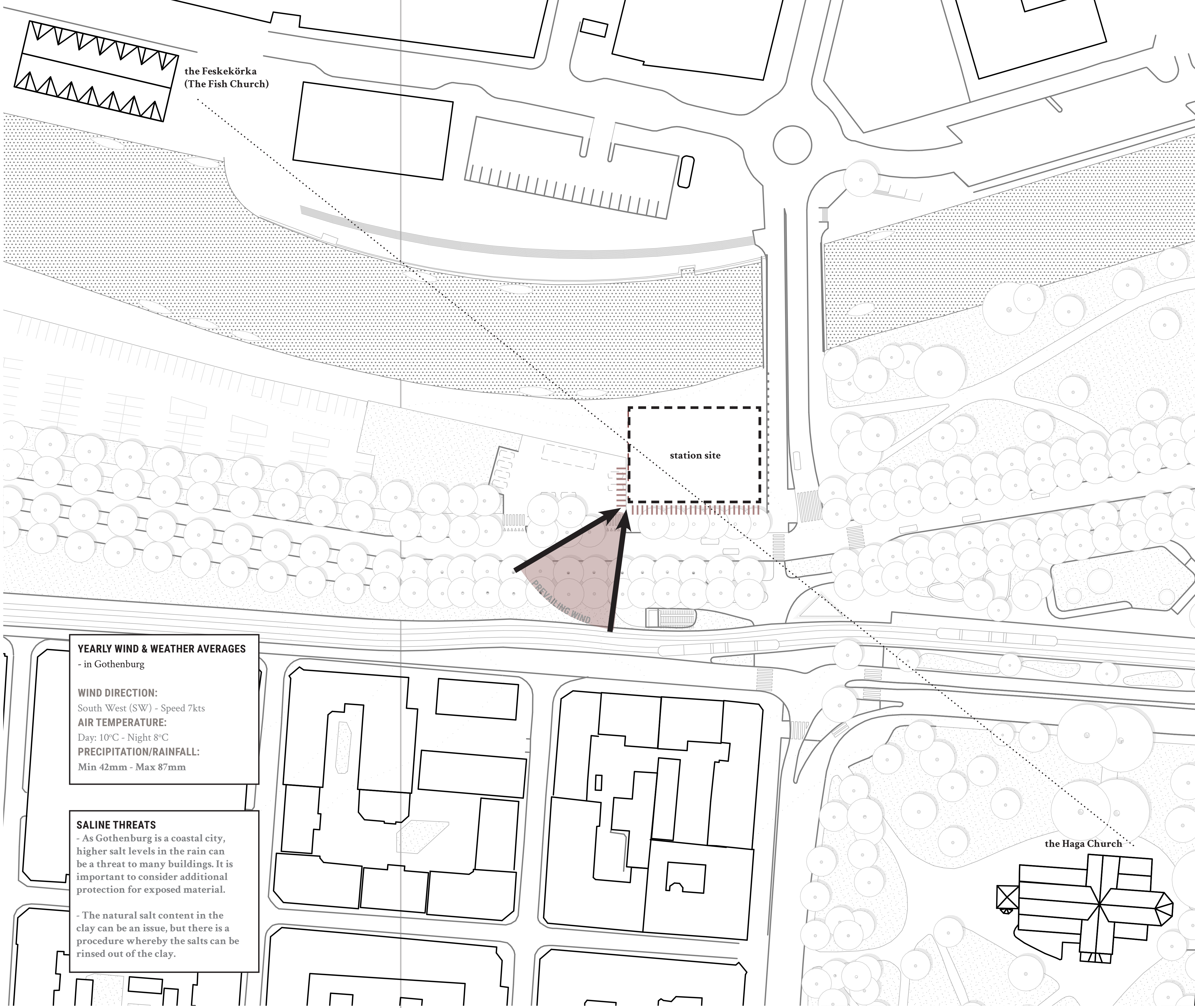
LOCAL CONTIDIONS // THE HAGA STATION

+ wind and rain factors
+ material exposure

In order to make a valid proposal for exposed earth structures a climate analysis of the site is crucial. In the local context of Gothenburg the weather can be destructive to any built structure. This analysis is one part of the Design for Material method, where the criteria of the site dictate the design and use of material. In the case-study of the Haga Station the conclusion is that due to the salt levels in the rain all facades should be limited to rain exposure of the rammed earth.

	SW DOMINANT WIND DIRECTION	MM PRECIPITATION/ RAINFALL
DEC	SSW	76
NOV	S	80
OCT	SSW	87
SEP	SW	81
AUG	SW	79
JUL	WSW	72
JUNE	SW	55
MAY	SW	47
APR	WSW	45
MAR	SSW	42
FEB	S	42
JAN	SSW	68

Data retrieved from Climate-Data.org and Windfinder

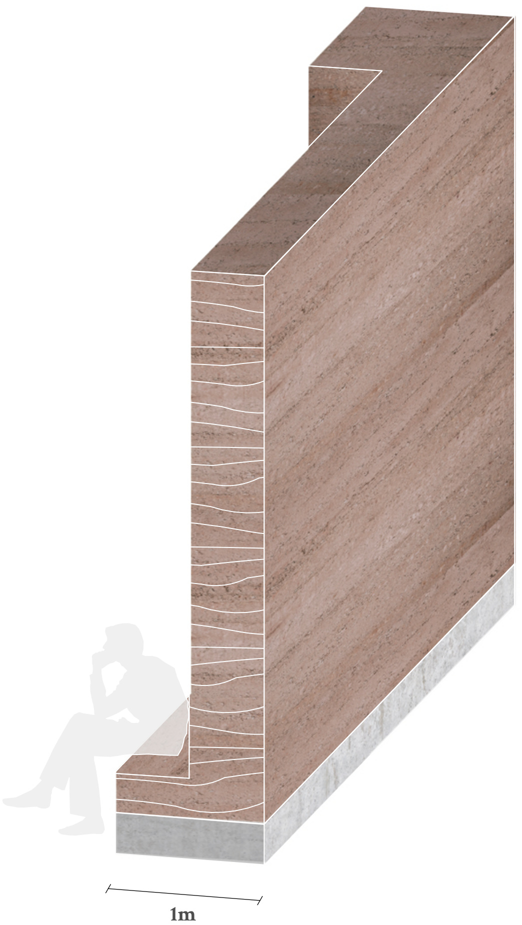


Facades sensitive to accelerating erosion from rain and wind

Siteplan 1:1000

10m

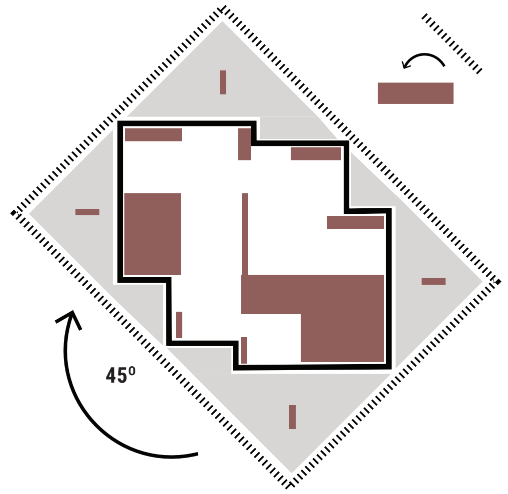
visual axis through site with important landmarks



THE MONOLITH

The rammed earth monolith showcases the thickness and purity of the material. The configuration of the monoliths are placed to create a contrast between transparency and the heavy earth walls enabling; material shelter, flows & views.

The Monolith Section-Axo 1:50 - The quality of eliminating layers; the rammed earth is your vapor and air barrier



vertical rammed earth structures

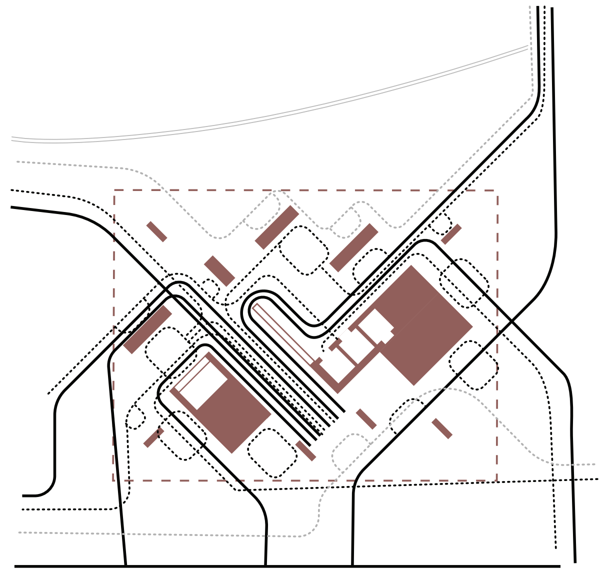
conditions subject to accelerated erosion, due to weathering and material exposure

sheltered façades, set back from the exposed perimeter

sheltered spaces creating clear entrances & waiting areas

SHELTER

Shelter is essential for any station building, especially in the Gothenburg climate. The 45 degree angles enable protection from wind and rainfall, sheltering both people and the unstabilized rammed earth structure.



vertical rammed earth structures

roof structure perimeter

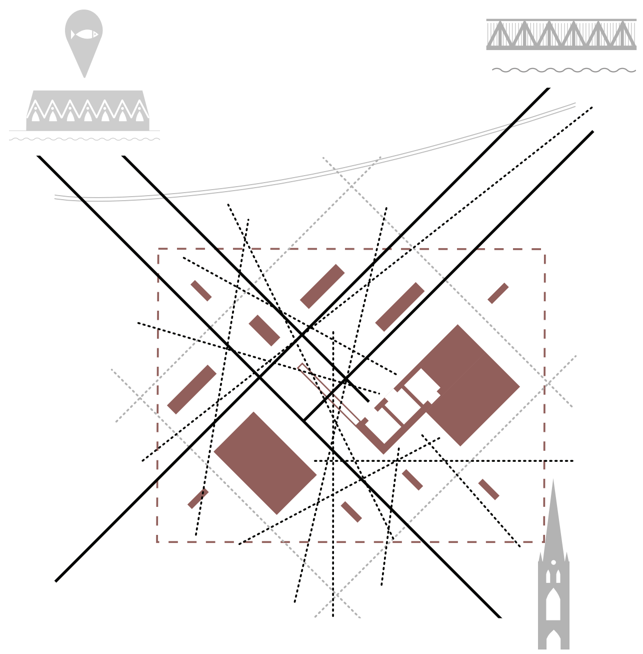
fast flow – local commuters // time-optimists

medium flow – tourists // ticket buyers

low flow – tourists // city strollers

FLOWS

The 45 degree angles embrace the existing flows on the site; see diagram on previous page. The design should accommodate the commuter as well as tourists making their way underground.



vertical rammed earth structures

roof structure perimeter

main views – critical for orientation upon arrival

transparent views – within and through the station

open corners – views from the 45 degree concept

VIEWS

Transparency and views are important aspects to help with way-finding and to ensure safety inside and around the station. The free rammed earth elements create open corners to direct and frame these views, dictated by the connection to the metro.

Diagrams of the design proposal embracing 45° angles created by the direction from the metro

MATERIAL CELEBRATION

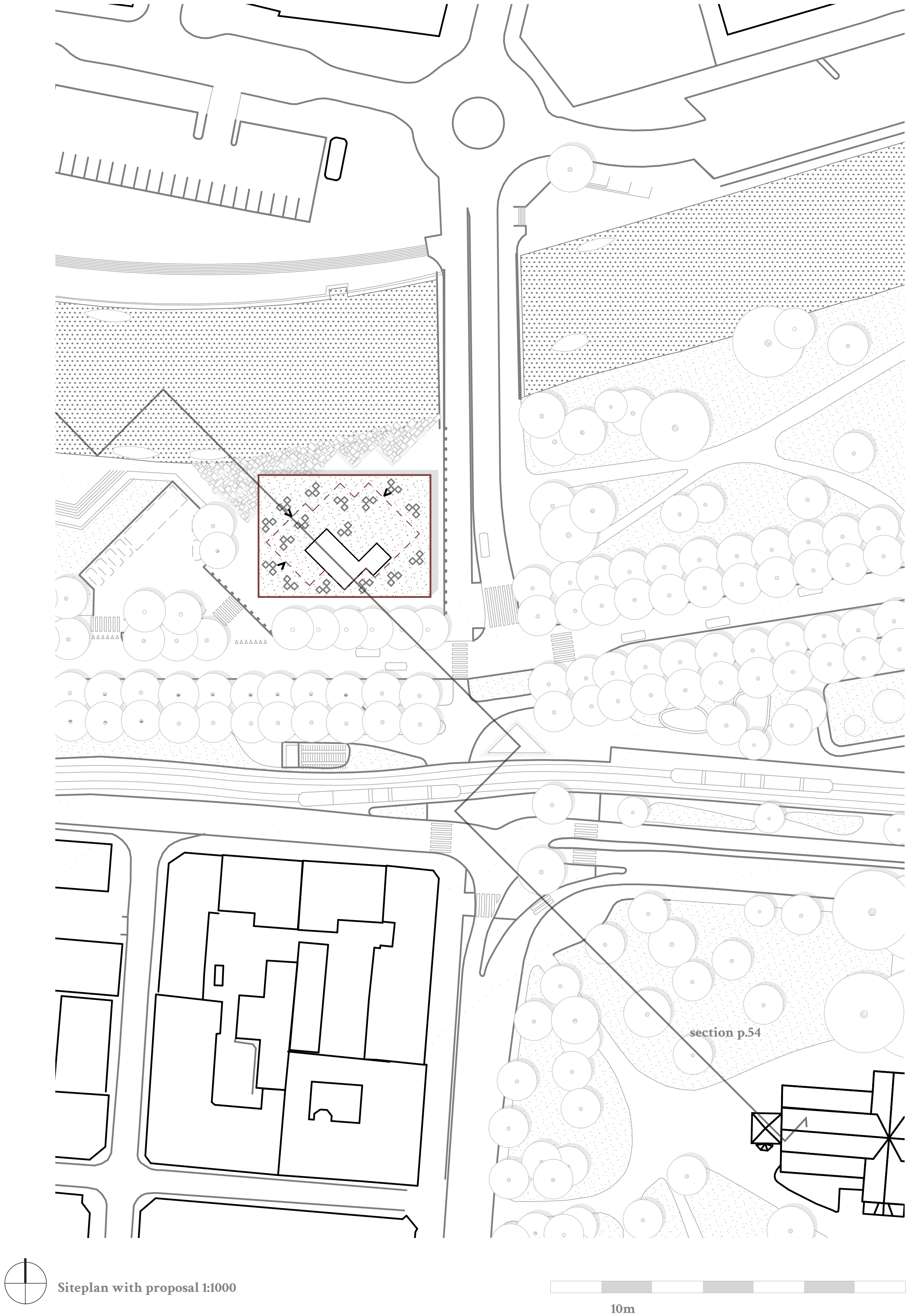
+ the earth monoliths unfolding from the underground
+ designing with excavated (waste) material

DESIGN CONCEPT - highlighting earth

The study of circular material flows shows that patchwork is common when designing for re-use or upcycling of material, creating a totality based on a diversity of objects. In the station, a new interpretation of the patchwork concept is created. The excavated rocks are used in different layers and shapes, and as aggregate in the earth walls. A patchwork of skylights in the roof sheds light on the RE walls, highlighting the qualities of the smooth monolithic earth structure.

The earth monoliths contrast with the patchwork concept, as the plasticity of rammed earth enables indefinite design options, forms and solid textures. These robust walls emerge from underground and can be transformed into the original mixture over and over again. This is what the celebration of material is all about.

The Haga Station - The building sends a message, showcasing the potential to build with an earth material in an unexpected context.



Siteplan with proposal 1:1000

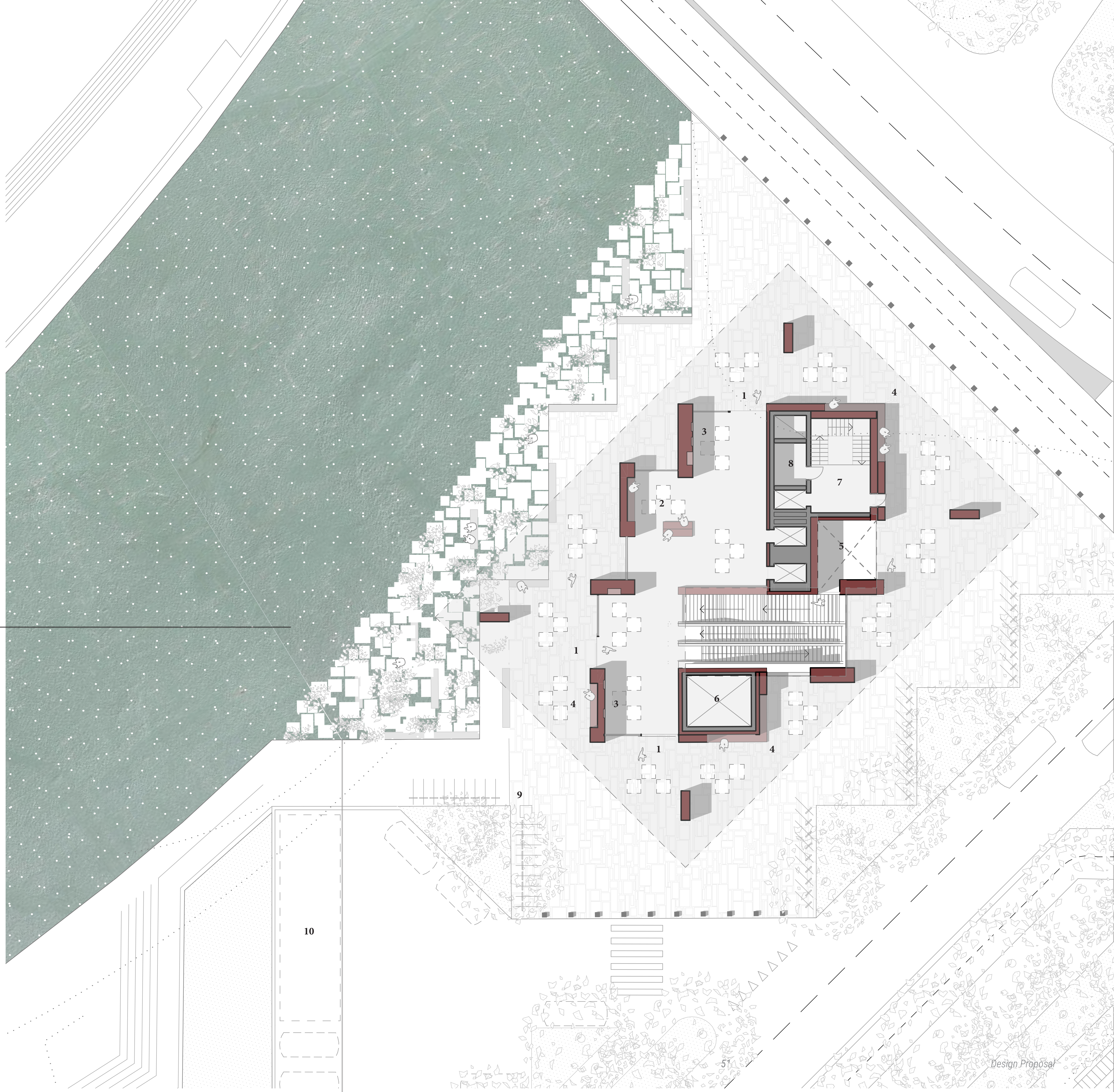
MATERIAL EXPOSURE – highlighting earth

The concept of the station is to allow the strengths of the material to guide the design. Exposing all sides of the material by placing the monoliths free-standing reinforces the qualities and layers in the material process. The rammed earth walls are 1 meter thick to strengthen the earth monolith and to tell a story about material richness, availability and the luxury of working with a circular material.

The roof is a key element in the design, protecting the earth, making it possible to expose the earth in the facade. The rectangular counter-shape, perpendicular to the site perimeter, strengthens the concept of the 45 degree angles that enable protection from wind and rainfall. This design shelters both people and the unstabilized rammed earth structure in the so often harsh Gothenburg climate. Skylights shed light on the earth, passively heating the elements and guiding the way to the metro.

The rocky waterfront is an important part of grounding the project, using rock from the excavation of the tunnels. It is also the foundation of the earth elements, minimizing the use of concrete and strengthening the concept of material emerging as a totality.

section next page



1. entrance/exit
2. waiting area
3. tickets & info
4. outdoor seating
5. light shaft to the metro
6. pressure release shaft*
7. service/egress*
8. technical*
9. styr & ställ (bike rental)
10. emergency vehicles*

* functions set by traffic department

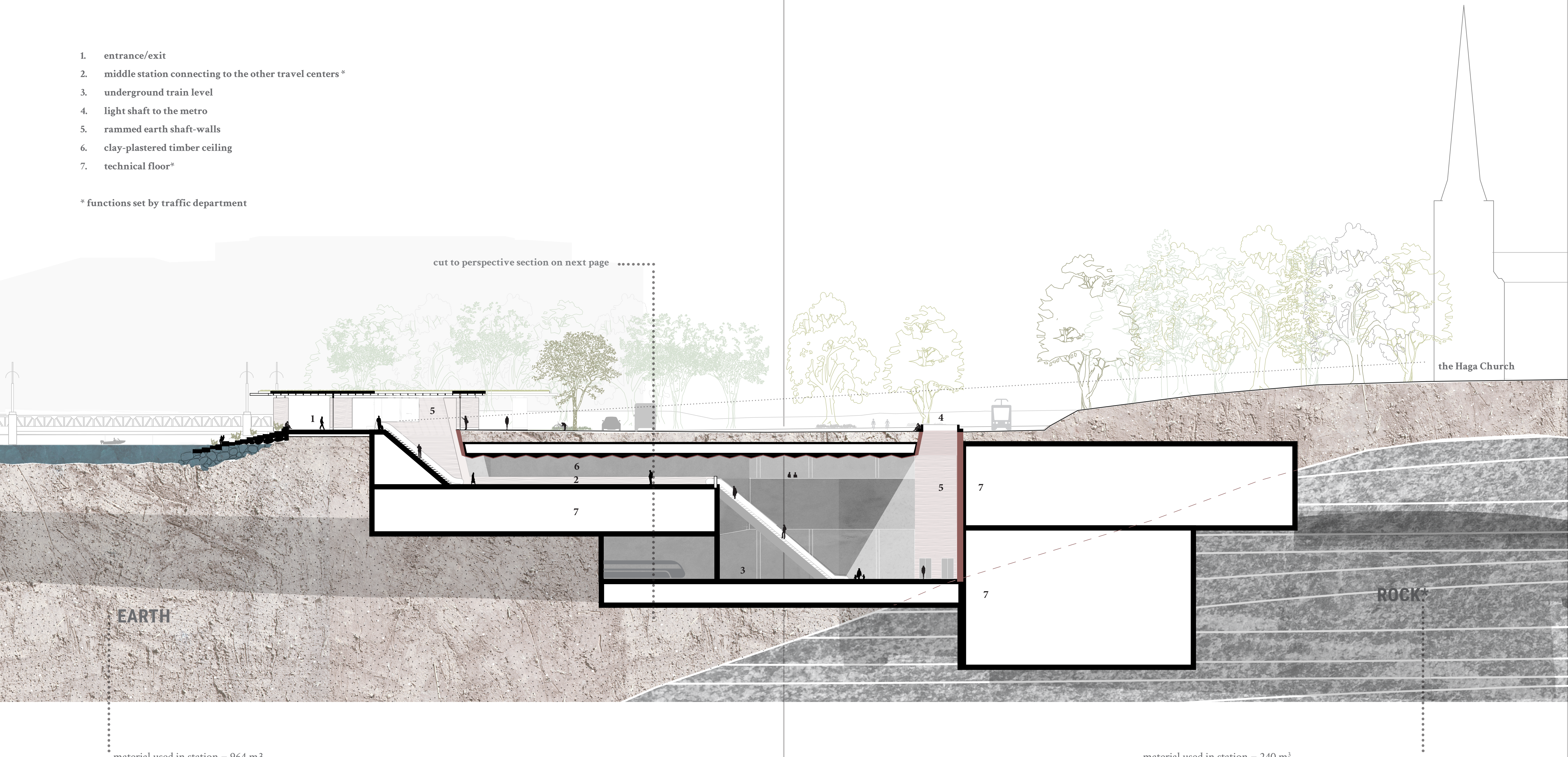
station plan scale 1:250

THE UNDERGROUND

+ section of geological layers
+ connections to the metro

1. **entrance/exit**
2. **middle station connecting to the other travel centers ***
3. **underground train level**
4. **light shaft to the metro**
5. **rammed earth shaft-walls**
6. **clay-plastered timber ceiling**
7. **technical floor***

*** functions set by traffic department**



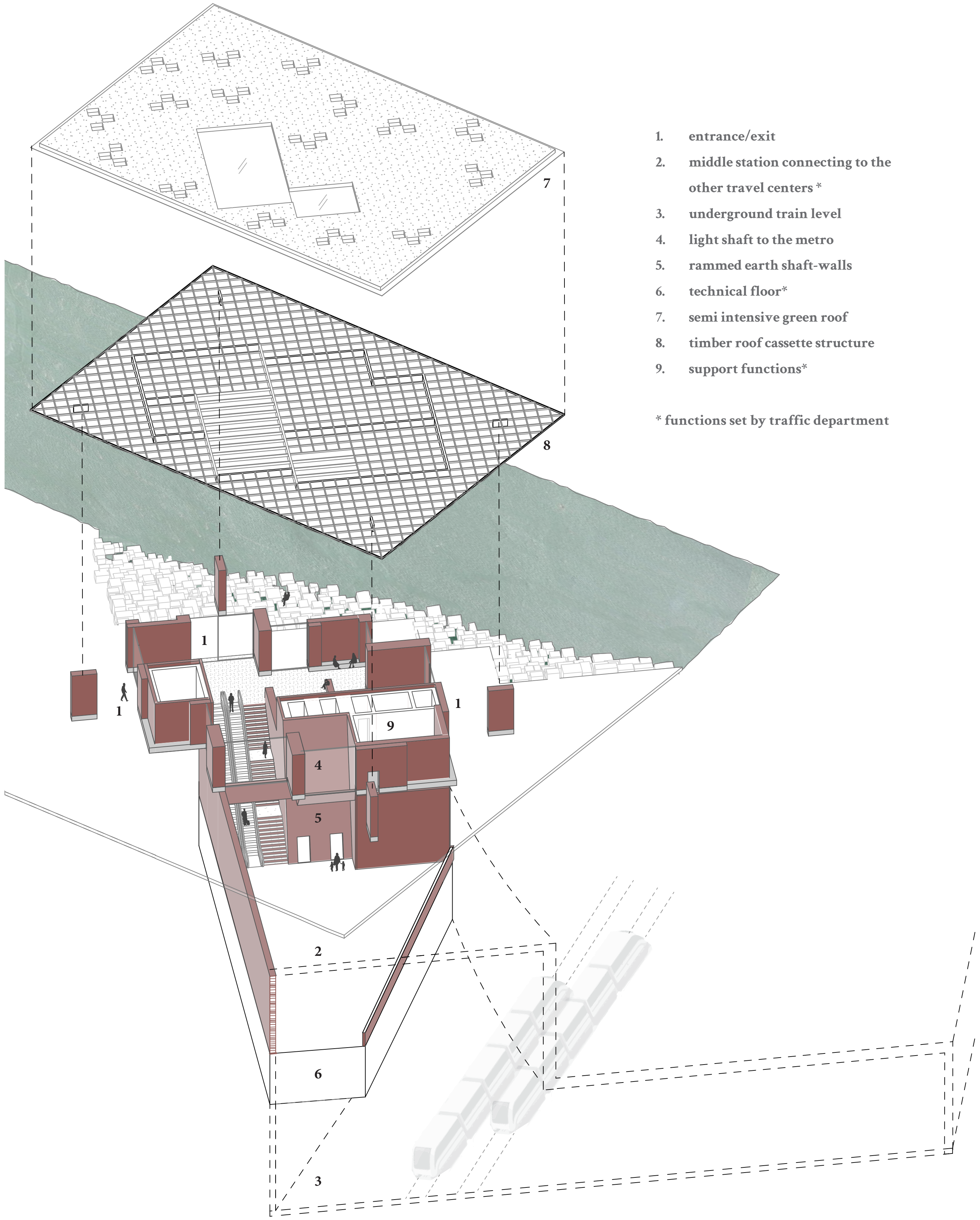
material used in station = 964 m3
total in excavated from tunnels for the West Link project = 1 500 000 m3

material used in station = 240 m^3
total in excavation from Västlänken tunnels = 1 700 000 BFM^3 **

*** According to the analysis of the drill cores along the stretch of the West Link, the rock consists largely of high quality tonalitic and granitic gneiss (Al-Najjar., et al., 2016).**

**** BFM^3 = bank cubic meter**

Section Scale 1:500 10 m



1. entrance/exit
2. middle station connecting to the other travel centers *
3. underground train level
4. light shaft to the metro
5. rammed earth shaft-walls
6. technical floor*
7. semi intensive green roof
8. timber roof cassette structure
9. support functions*

* functions set by traffic department

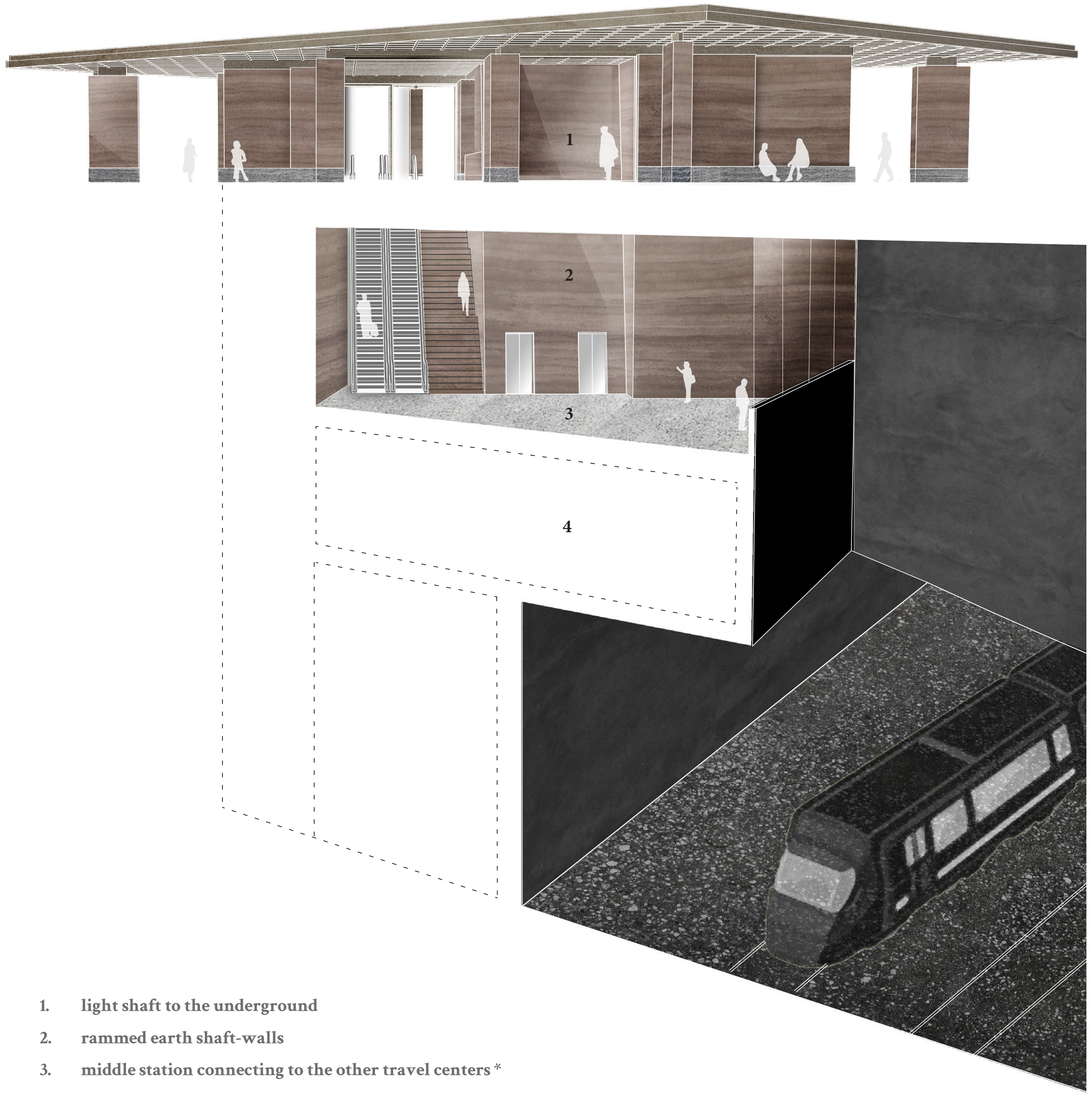
Axonometri scale 1:500

view to perspective section on next page

EARTH EMERGING

+ visual and physical connections to the metro
+ verticallity of the earth stucture

Earth is emerging; the dark biochar-clay plastered walls improve the air quality and contrast the warmer shades of the rammed earth walls. The stairs leading up from the middle station is rammed earth with stone treads, where you can walk and feel the texture of the earth layers.



1. light shaft to the underground
2. rammed earth shaft-walls
3. middle station connecting to the other travel centers *
4. technical floor*

* functions set by traffic department

Perspective section showing the south elevation of the station above and the connection to the middle station underground

EARTH TECTONICS

RAMMED ELEMENTS

+ defining RE-strengths towards scalability in the Nordic context

+ applying the design for material concept

MODULAR CONSTRUCTION – pre-fabrication

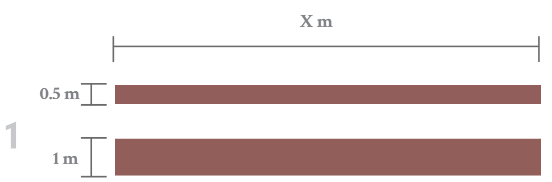
One of the strengths of rammed earth elements are the purity of the tectonics, eliminating layers and the monolithic thickness of the material. However, as mentioned in Earth Basics (Chapter 2), these elements are heavy and can be complicated to transport and move on site. In the construction of other contemporary rammed earth structures, pre-fabricated elements are often preferred. In the Al-Natura building (p.32) in Darmstadt, Germany, this construction method is used to simplify the construction and assembly on-site. CO^2 emissions are also minimized from transportation of the elements. This production could take place in the parking area of the station site and the elements could then be moved into place.

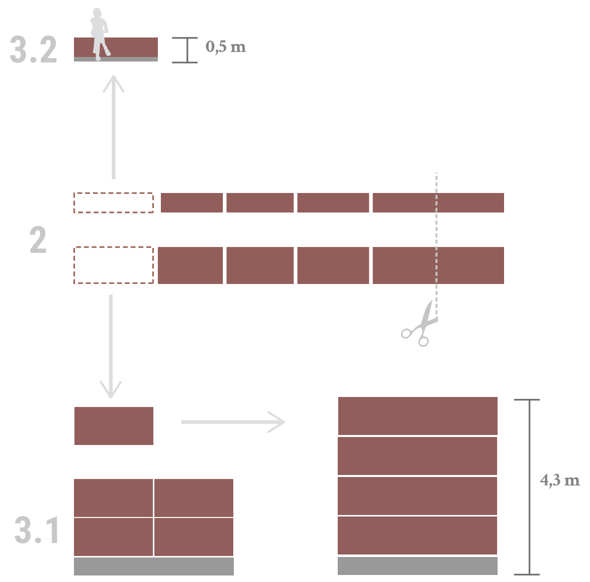
Circling back to the aesthetic aspects of earth, the seamless appearance of one element can still be achieved when prefabricating rammed earth walls. The joints can be sealed using the same mixture, which blends in over a few weeks; something that would not be possible in the case of prefabricated concrete elements.

THE NORDIC GUIDELINES – reflection on proposal

It is important to consider the diversity of the Nordic context; whether it is on the coast, at high altitude, with strong winds or heavy precipitation. And then there is the unknown factor of climate change, the effects of which can create even more extreme conditions. In Gothenburg, which suffers from both wind and heavy rain with high salt levels, the calculated erosion method has not been considered as a guideline. Due to the scale and proportions of the station building, the roof and the foundation are slightly over-dimensioned.

In terms of insulation, the biochar is rammed into the core of the structure. The thickness of the earth monoliths enable thermal comfort to be achieved through passive solar heating. The skylights in the roof heat up the elements and release the heat when the temperature drops in the evening.

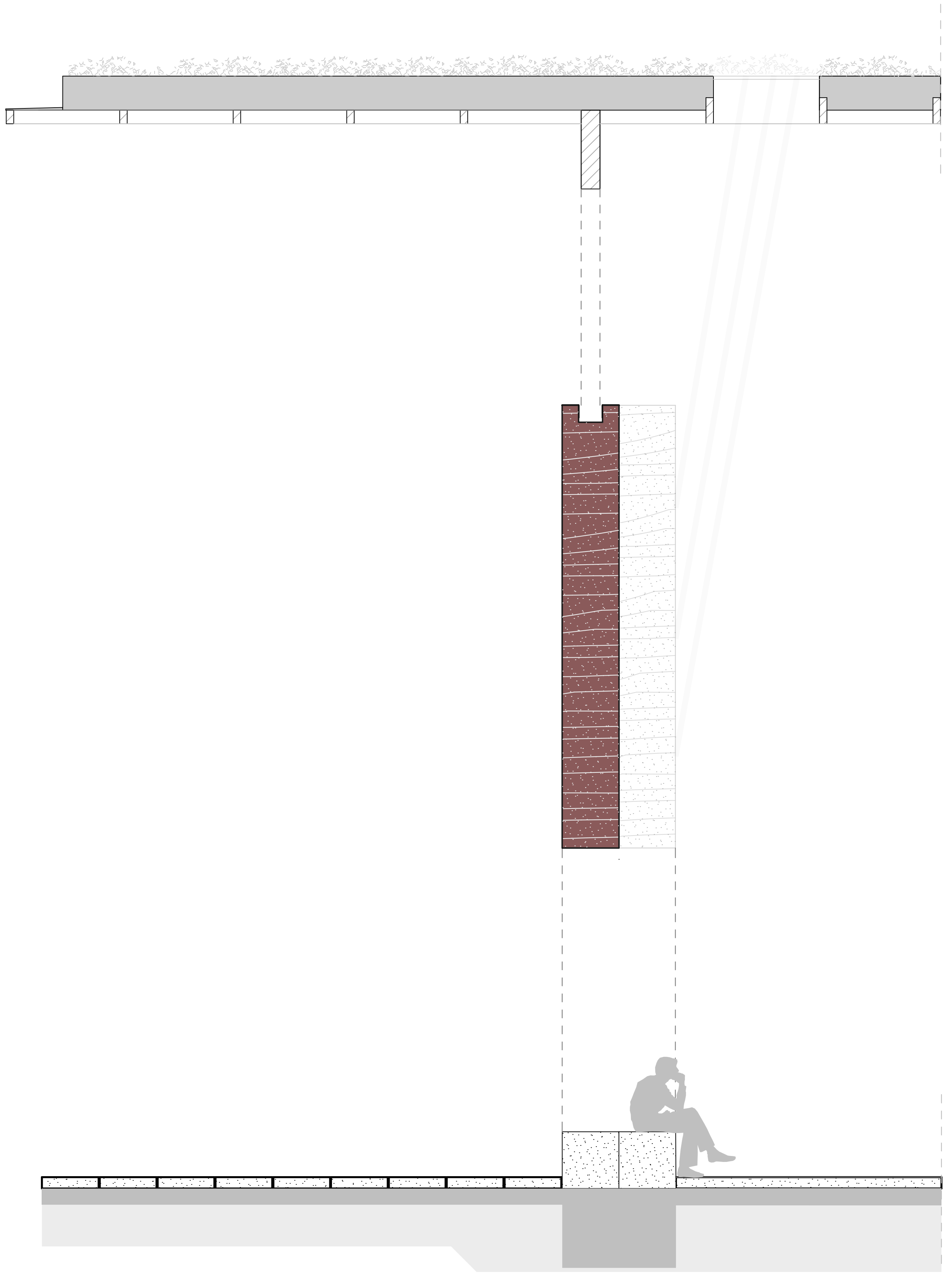




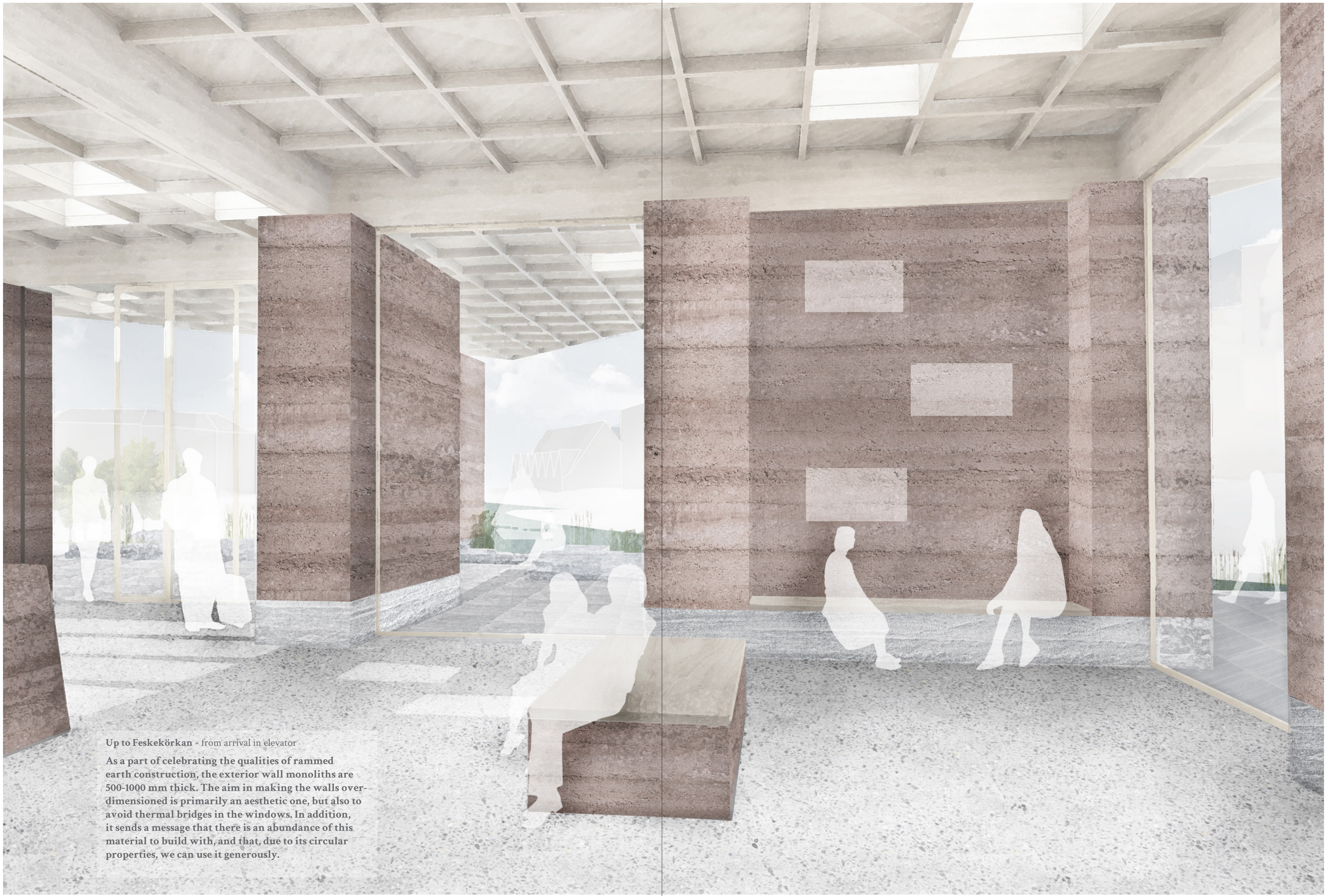
1. the earth mixture is poured in layers into a formwork with a width of 500 mm and length of X m (reference 30 m). The elements are mechanically rammed to a height of 500 or 1000 mm, to be stacked later.

2. the formwork can be released immediately after the ramming process is done (no drying time is needed). The long RE element is then cut into varying lengths depending on module (wall/ furniture) requirements.

3.1
3.2 the modules can more easily be transported to the site and stacked on top of a 300 mm concrete base. For interior furniture (3.2) the base can be minimized.



Concept Section 1:50 - radical tectonics; upscaling material. When designing for material in the case of the station, the roof and the foundation are over-dimensioned – sheltering both the material and people. The foundation unfolds into furniture, with the user leaning back on the earth walls.

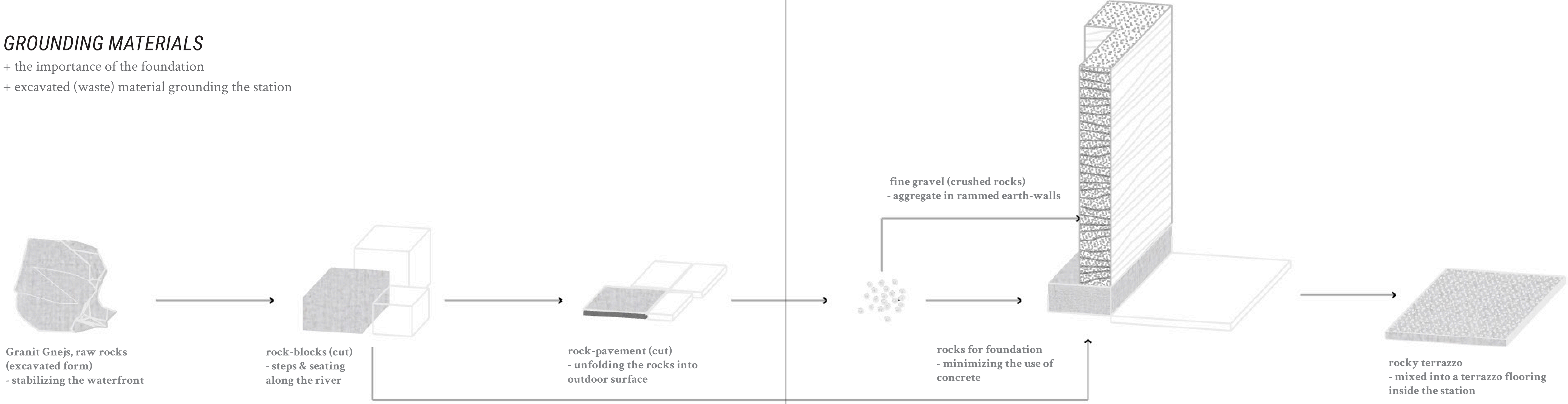


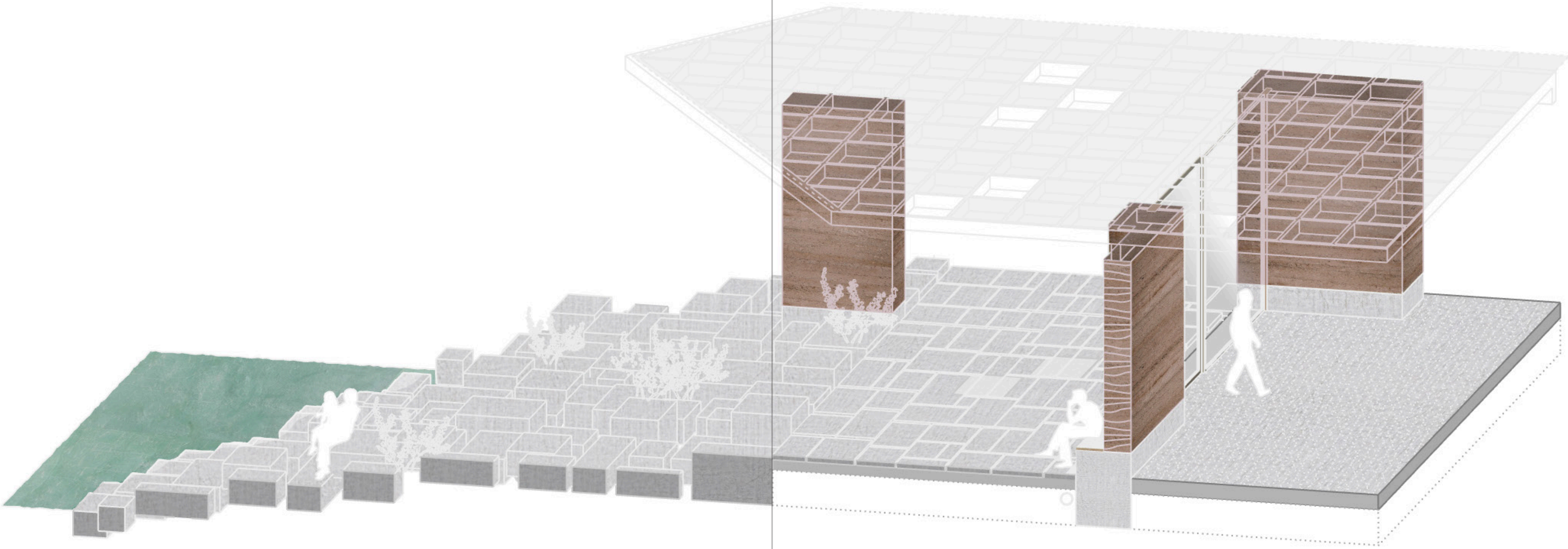
Up to Feskekörkan - from arrival in elevator

As a part of celebrating the qualities of rammed earth construction, the exterior wall monoliths are 500-1000 mm thick. The aim in making the walls over-dimensioned is primarily an aesthetic one, but also to avoid thermal bridges in the windows. In addition, it sends a message that there is an abundance of this material to build with, and that, due to its circular properties, we can use it generously.

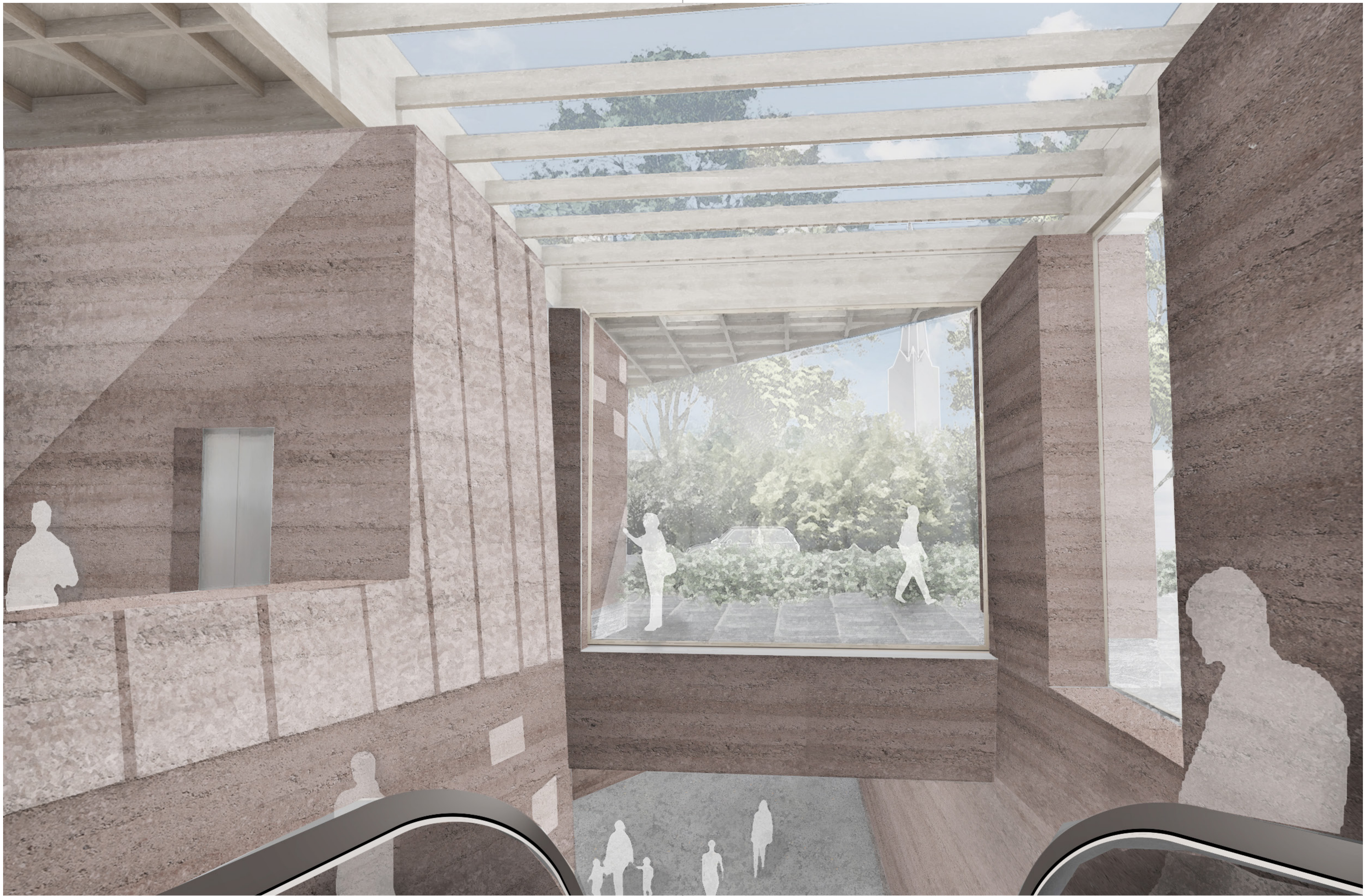
GROUNDING MATERIALS

+ the importance of the foundation
+ excavated (waste) material grounding the station



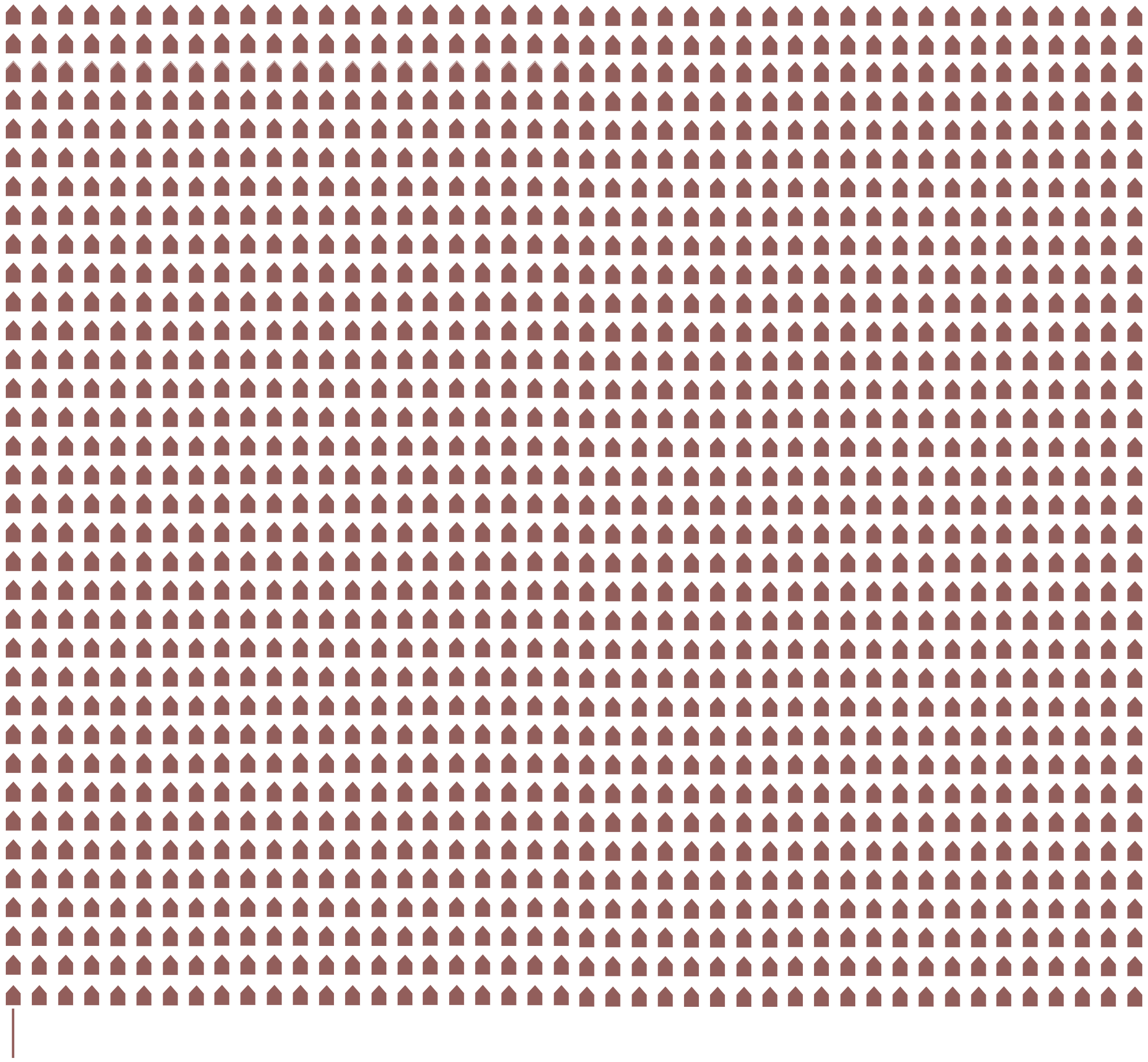


Excavated Layers of rock Masses - material process, unfolding as gradients of rock material



Down to Hagakyrkan - view from escalators down to the station underground

- What is the potential for using excavated earth* as a circular material resource, generating rammed earth structures in a Nordic urban context?



1x Haga Station = a total volume of 482m³ rammed earth walls (compressed + 50%x2 = 964m³)

1 500 000 M³ OF EARTH = 1 550 HAGA STATION BUILDINGS

...or possibly interior elements in 12 000 housing units; reducing CO_2 emissions and improving the Nordic indoor climate

PART 4.

SUMMARY // REFLECTIONS

- What is the potential for excavated earth in a Nordic context?

SCALABILITY

POTENTIAL ROADMAP
// MATERIAL PROCESS

+ schematic timeline of earth material flows
+ revealing leverage points in the process

This is a graphical summary of the research and knowledge development based on research findings. Following on from the Lendager Group's "Circular Opportunity Tool", it is crucial to understand blind spots as well as unique selling points (Lendager & Lysgaard Vind, 2018). The timeline is mapping the process to better understand the potential and challenges represented by excavated earth material in urban areas. In the circular economy, clay has a great potential to be developed into many different products, beyond the rammed earth technique. In the Nordic context, interior applications are highlighted as they have greater market potential in terms of scalability and application in many different buildings.

Ensuring quality standards for large quantities of earth/clay from excavation in urban areas will become key to unlocking the potential of earth as a future building material. This would provide new business and work opportunities involved in testing, drying, and storing the excavated earth. This process should ideally be decentralized, minimizing transportation.

Reflecting on the potential road-map of the material process, developing the on-site production integrating testing and mixing could be crucial when upscaling the RE-building method. The logistics in the building process is important in order to achieve the objective of a zero-emission building. The transportation of material should be minimised, and as the processing and production is safe and does not generate emissions some of the steps in the roap-map scheme could happen on-site, including pre-fabrication. This points out the importance of understanding the specific logistics, relating to construction of a circular material, at an early stage in the design process.

THE PROCESS

DEAL BREAKER

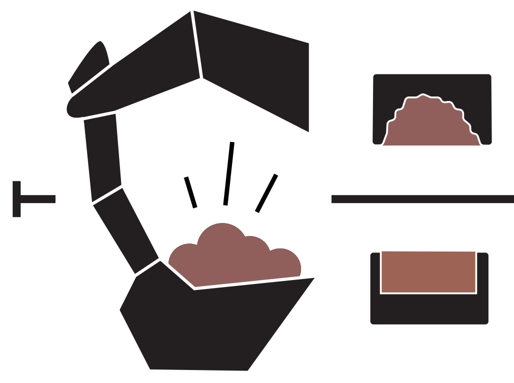
BARRIER / RISK

POTENTIAL / SOLUTION

CHALLENGES / OBSTACLES

overlaps & potential solutions in the process

MATERIAL SOURCING*



* focusing on earth masses from construction demolition waste

LOW HANGING FRUIT
- the material is a by-product from construction demolition waste and accessible in the urban environment

POTENTIAL DECOUPLING
- the earth material is a finite resource but has the potential to be a part of eliminating the waste system in the circular economy

OFF-SITE
- waste excavation from sources such as tunnel projects, parking garages etc.

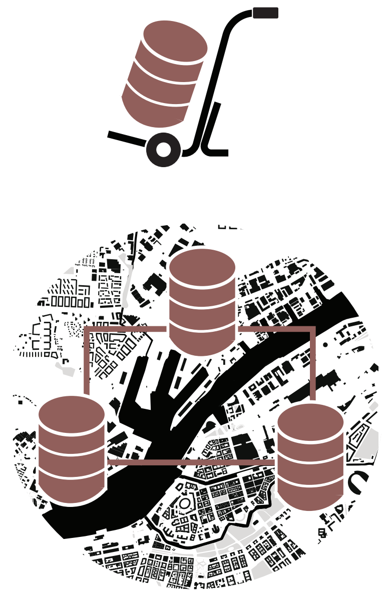
ON-SITE
- small scale excavation from basements

CO^2 EMISSION
- from the excavation process
– how can they be minimized or avoided?

FINITE RESOURCE
- it is important to remember that it is a non-renewable resource and should be handled so that its future recyclability is secured.

knowledge development on design for material will be crucial

STORAGE & TRANSPORTATION



developing the on-site process

ON-SITE PROCESSING
- the material could be processed on-site and integrated in the building site process where the product also could be stored

TEMPORARY STORAGE
- possibilities for temporary storage, using left over space in the city

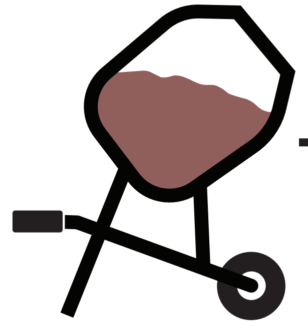
INFRASTRUCTURE
- to facilitate storage of earth and clay material

DECENTRALIZED
- if not to be used directly on-site, preferably decentralized to minimize transportation

COSTLY STORAGE
- space in urban areas to facilitate storage of the material can be expensive

EMISSIONS FROM TRANSPORTATION
- depending on mode of transportation, moving the material can lead to increased CO^2 emissions

MIX, DRY & TEST



ON-SITE TESTING KITS
- in order to determine the qualitiy and possible product development based on clay, the basic properties could be tested on-site

CDW IN THE MIX
- potential to use material from other CDW*, or bio-based waste material. Important not to compromise future recyclability

RESEARCH POTENTIAL
- potential for future research! Creating new mixes in a local context such as blue mussels, biochar or waste material from forestry & agriculture

LAB TESTING
- all material excavated needs to be tested in a lab for quality reasons

DRYING PROCESS
- depending on the end product, the clay needs to dry before mixing

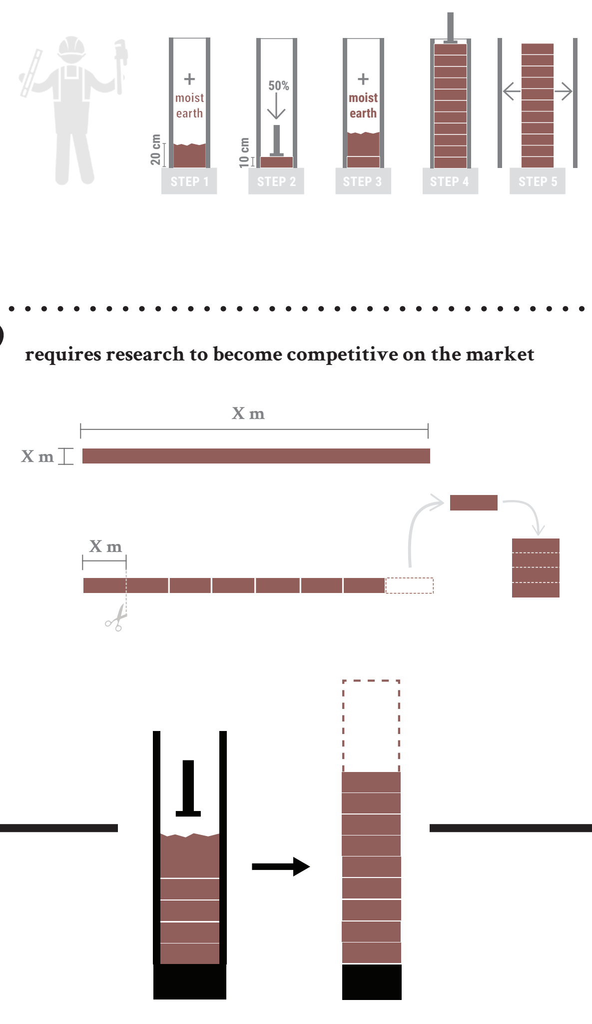
ADDING AGGREGATES
- gravel and sand material to the mix, or other aggregates could be tested to improve tensile strength

INSUFFICIENT CLAY
- not ALL clay mixtures are suitable for earth construction.

CONTAMINATED CLAY
- lab tests of the clay from Gothenburg showed some areas of the tunnels were contaminated, had excessively high salt levels, or contained organic fractions. However the clay from Haga Station was suitable for use.

requires research to become competitive on the market

PRODUCTION



DIVERSE PRODUCTION
- potential for diverse production, towards earth building becoming common practice!

MATERIAL EDUCATION
- small-scale production is still a way to build with rammed earth, an integrative collaborative process, as part of education about the material

PRE-FABRICATION
- possibilities for standardization of prefabricated RE elements could enable a product stock – due to the fact that elements can be stacked and joints can be sealed

INTEGRATING INSULATION
- during the ramming process insulation can be integrated, achieving building code requirements in the Nordic context

OFF-SITE PRODUCTION
- large scale pre-fabrication of wall elements using mechanical equipment off-site

ON-SITE PRODUCTION
- production of elements on-site, preferably small scale interior applications using manual tools or mechanical equipment

LONG LEAD TIME
- drying time requires a longer lead time for product development

LABOR INTENSIVE
- pre-fabricated or not, earth construction is considered to be a labor intensive production which makes is less competitive in developed countries

HANDLE WITH CARE
- RE elements, especially in cold climates, are heavy and need to be handled with care

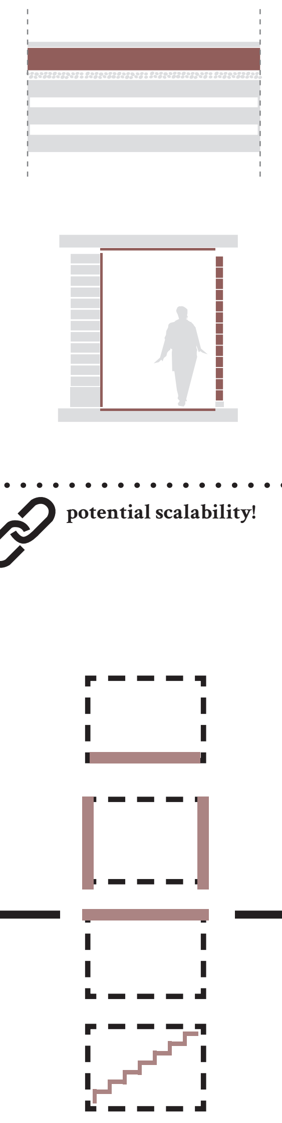
WEATHER PROTECTION
- similar to timber; if working with on-site production, earth elements need to be weather protected

LOCAL POWER STRUCTURES
- in the Nordic context the cement industry is dominating the market. Unless taxes on CO^2 from productions is introduced it is hard to make clay-based products competitive at benchmark-price

LACK OF KNOWLEDGE
The know-how is limited and education in the building industry and practical experience are crucial when working with earth construction. One part of this lack of knowledge is the addition of cement that is still common practice

potential scalability!

FINAL PRODUCT IN USE



NON-FIRED BRICKS
- compressed earth blocks could have great potential as interior elements, improving indoor climate and has good acoustic properties

RAMMED HYBRIDS
- rammed sheets for interior non load-bearing application as walls or as rammed elements on CLT slabs replacing on-cast concrete

REDUCING CO^2
- these products could reduce the CO^2 footprint of buildings if implemented at a large scale

REPLACING CEMENT PRODUCTS
- these could have significant market potential, clay panels could replace gypsum boards

INTERIOR APPLICATION
- Interior elements require low maintenance; walls, sheeting, or as rammed elements in a hybrid structure

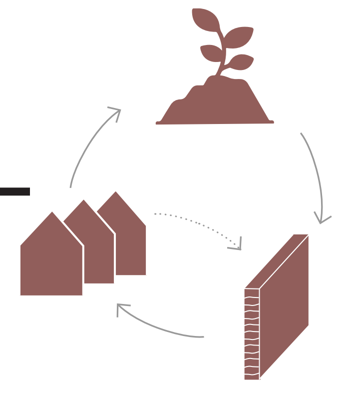
EXTERIOR MAINTENANCE
- elements used exterior elements, can need some maintenance depend-ing on exposure

WEATHER THREATS
- exposed rammed earth in the Nordic context could develop cracks and damage from poor weather protection

DEMANDS MORE RESEARCH
- more research is needed on exposed rammed earth and cracks from freezing. Could organic material be added in the mix?

a future proof product integrated in the built environment

THERE IS NO END OF LIFE



CIRCULAR FOREVER!
- earth is a future proof circular material, where the raw material is almost inexhaustible. This means that when kept in its raw form, without adding any cement or burning it, earth can be recycled to its original composition indefinitely

REUSE IN A NEW MIX
- depending on the clay-based product, it can be crushed and re-used in a new mix without additives

RECOVERING MATERIAL
- a massive rammed earth wall could be demolished and its material reused to build a new wall, or depending on the context, returned to earth in a bio-logical cycle

DESIGN FOR DISSASEMBLY (D4D)
- a clay plasterboard can be disassembled and re-used in a new project

COMPROMISED RECYCLABILITY
- the one action that could compromise the circularity of the material is adding cement to the earth mixture. This is still common practice around the world. It is important to educate future earth builders about the natural binding agent; clay

REFLECTIONS

DISCUSSION // SUMMARY

WHAT (ON EARTH) IS NEXT?

– connecting the thesis question to a larger discourse

In the search for the seriously sustainable, there is no silver bullet, no one material or technique that provides all the answers. Reflecting on this notion within the field of architecture and the built environment, many solutions are already out there. And diversity is a good thing; working with different strategies to achieve the same goal and securing a healthy planet for future generations. Materials that would ensure resource salvation and be a part of circular flows demand more attention.

This thesis has focused on earth as a left over resource from the Västlänken tunnel project and the potential to use it as a building material in an urban Nordic context. Gothenburg is only one example of a city dealing with these type of waste streams from infrastructure projects. Stockholm and Copenhagen are planning to expand their underground transportation. A new railway between Malmö and Lund will generate almost exactly the same amount (1 400 000 m^3) of earth as from Västlänken. The natural soil mixture from this part of Sweden is perfect for rammed earth construction. Furthermore, a recently published article entitled "The mission to get rid of 1.5 million tons of earth", described the earth as a huge logistical concern and appealed for innovative new ways to use the material in the local region (Nyrén, Svahn & Frennesson, 2020).

Reflecting further on the potential of rammed earth and clay-based materials in a Nordic context, there are many ways of developing these products. One is mechanical pre-fabrication, requiring more knowledge, equipment, and testing to enable larger production of elements. However it is still relevant to highlight the potential of small-scale production, as an integrative and collaborative process, and a part of education about the material. There is a global stigma towards earth-buildings, and it is not seen as a material relevant in industrial countries as a part of modern construction. In order for earth buildings to develop in the Nordic context there is a need for new regulations and education in the building sector. As lifted in this thesis, there are examples of projects testing the potential of upscaling the technique in Europe and around the world. Sweden has some of the largest construction companies in the world – and it is crucial to get them on board. This should not be a huge step, since the same companies own and are dealing with transportation and storage of these earth masses today.

Circling back to Gothenburg, the River City program is the largest urban development program in Scandinavia. There are plans for the municipal real estate companies to build 12 000 housing units in the coming decade (Business Region Gothenburg, 2019). In the same area, millions of tonnes of earth and rock are being extracted and could be a part of this future built environment. The Re-Circulate project, mentioned in Background (p.16), intends to explore the possibility of recovering and re-using material from demolished buildings and waste clay from Västlänken. both by researching innovative sustainable clay products and by developing a system for re-use of demolished and disassembled building products. These products will be tested and could be seen as a start of a new paradigm moving towards local climate neutral building materials.

To imagine earth buildings as a part of the Nordic urban environment is not a radical idea. Sweden has long had a history of building with clay-based methods. Today this know-how is limited and not common in building practice or in the academic world. But just as for timber constructions, the time has come to revisit earth building techniques and to create new building regulations. A revival of clay-based building techniques is taking place around the world. This thesis highlights examples that support the notion that the knowledge is already out there.

The main challenges for rammed earth building in the Nordic context are labor intensity, lack of standardization, and the material's low insulation value. The opportunity is the abundance of the material from demolition waste. In order for earth materials to become competitive and applicable in a Nordic urban context in terms of scalability, the largest potential might lie in pre-fabrication of indoor elements. Clay panels and rammed earth as infill in slabs have the potential to be a part of all building typologies. They could replace cement based products, improve the indoor climate, and together with timber become the new Nordic superstructure.

REFLECTING ON DESIGN FOR MATERIAL

- a summary of research output

The topic of earth-based architecture lies in the sweet spot between hardcore sustainability and embodied poetry. The rammed earth construction literally has layers, of both outstanding physical construction and aesthetic values. It has this duality of being soft and hard at the same time. Earth can have many different shades of colors and textures. We then have the notion that the material actually has no layers – the earth monolith acts as the vapor and air barriers. This material can improve the dry Nordic indoor climate, regulating humidity, temperature, and odors, and be a part of CO^2 reduction and resource salvation. It is an example of a low-tech material with great potential to meet the demands of a high-performance indoor climate. Although when looking at structural exterior elements, there are some drawbacks. The thickness of material is not (or is almost never) to be preferred due to area efficiency. And the technique does require pre-fabrication and a development of this industrialized process in order to become competitive on the market.

When researching the global use of the rammed earth technique it is important to understand the difference between unstabilized and stabilized structures. Where the addition of cement in the stabilised rammed earth(SRE) compromises future recyclability. In some countries the SRE is the only regulated way of building with earth, which could be seen as problematic. The whole point of clay-based structures is that it clay is the binder and that it has the unique ability to be fully recycled, while the cement-based process is irreversible. Reflecting on the potential of using the RE as a part of an hybrid structure this is a crucial fact in order to enable design for disassembly. And according to Martin Rauch, clay is proven to prolong the life of timber structures as it regulates the humidity in the wood.

This connects back to the design for material and the aspect of using the right material in the right place. Design for Material is the methodology that has been exercised in the discourse of this thesis, in understanding the potential of excavated earth. There is no 'one' design solution when following the "design for material" concept. However the more you unravel the materials' strengths, weaknesses, and availability, the more you can push the design towards more radical tectonics. It is important to know the material's limits in order to find other complementary material to support it.

There have been times when the relevance and scalability of the rammed earth technique as a viable material in the Nordic climate has been questioned. Again, it is about the right material in the right place – and perhaps the right building typology. Public buildings, schools or low-rise structures that are subject to change have the greatest potential. For instance, a school building could need to expand or be re-configured to meet new demands. The rammed earth elements could be demolished and reconstructed on the same site over the summer.

Finally, reflecting on the aim and purpose of the thesis and the chosen design object to respond to the research question; ***What is the potential for using excavated earth* as a circular material resource, generating rammed earth structures in a Nordic urban context?***

The initial idea was to detail a building and to take on a more technical approach responding to the research question. Later in the design process realising that the station is perhaps not a building typology that utilizes all of the qualities of an earth building, or reveals the full potential of building with excavated earth. It does not, like a school, office, or housing building, benefit from the optimal indoor climate, regulated humidity, or thermal comfort. Nor will the station building be demolished in 15-30 years. However the concept of ***design for material*** explored in the thesis is perhaps what is stronger and more relevant to discuss. This thesis is mapping the possible use of waste-clay in rammed earth as a local material that could contribute to further research. The idea of design for material should be developed further and could be used as a guide when developing other circular building materials.

The ambition of this thesis was to build on the existing knowledge of earth construction and that it can be a viable material in the Nordic context, if used in the proper way. Learnings are that it is crucial to understand the process of earth building and its challenges and opportunities - beyond the building-physical properties of the material. The demands and logistics of circular material in construction needs to enter the discussion earlier in the design process. This is where architects have the power to drive the knowledge development further and to get all parties and stakeholders in the building process on board. As architects we are the key players in terms of storytelling and have the power to direct the narrative in a more critical way.

The storyline of the station proposal is to expose the potential of the material being excavated from the metro. The building sends a message, showcasing the potential to build with earth material in an unexpected context. The aim is to make earth structures accessible and visible in the urban environment. The station is perhaps the best example of a public building where large amounts of people pass through, being able to experience the material's atmosphere and texture. This is a part of challenging the stigma and to start imagine the potential of introducing rammed earth in the modern built environment.

In the station building, the earth walls are exaggerated in their thickness, not for structural but for aesthetic reasons. The message: there is an abundance of this circular material, which is currently considered as waste – *let's use it!*

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APPENDIX.

COMPOSITIONS DRAWINGS

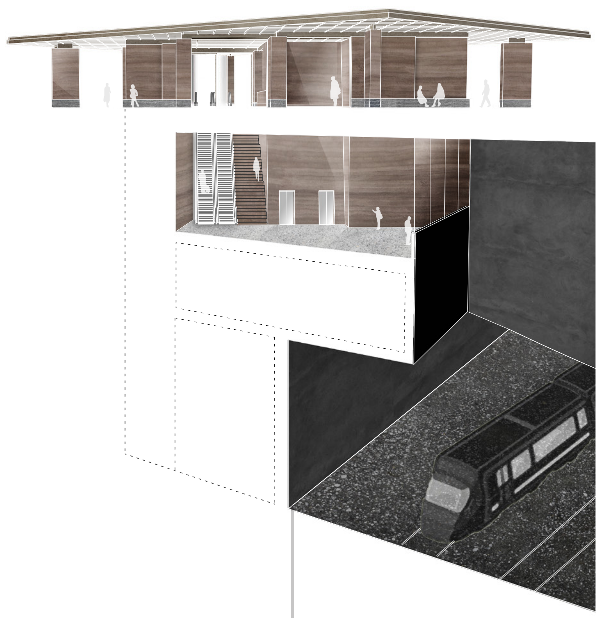
- A graphical summary of research and design output

Earth Emerging
Material Celebration

MATERIAL CELEBRATION

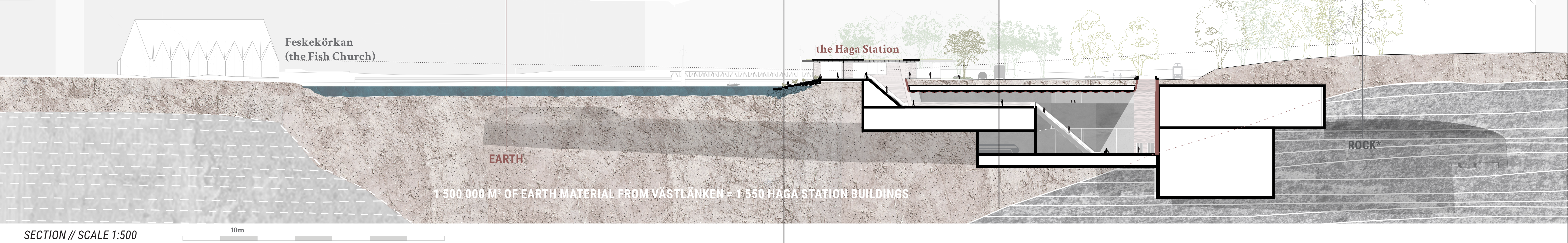
+ geological layers
+ excavated facts
+ scalability - exploring the potential of the excavated clay

Earth is emerging; Perspective section showing the south elevation of the station above and the connection to the middle station underground. The dark biochar-clay plastered walls improve the air quality and contrast the warmer shades of the rammed earth walls. The stairs leading up from the middle station is rammed earth with stone threads, where you can walk and feel the texture of the earth layers.



material used in station = 964 m3
total in excavated from tunnels for the West Link project = 1 500 000 m3

material used in station = 240 m3
total in excavation from Västlänken tunnels = 1 700 000 BFM3 **



SECTION // SCALE 1:500

POTENTIAL ROADMAP // MATERIAL PROCESS

- THE PROCESS
- DEAL BREAKER
- BARRIER / RISK
- POTENTIAL / SOLUTION
- CHALLENGES / OBSTACLES
- overlaps & potential solutions in the process

MATERIAL SOURCING*

LOW HANGING FRUIT
- the material is a by-product from construction demolition waste and accessible in the urban environment

POTENTIAL DECOUPLING
- the earth material is a finite resource but has the potential to be a part of eliminating the waste system in the circular economy

OFF-SITE
- waste excavation from sources such as tunnel projects, parking garages etc.

ON-SITE
- small scale excavation from basements

CO² EMISSION
- from the excavation process
– how can they be minimized or avoided?

FINITE RESOURCE
- it is important to remember that it is a non-renewable resource and should be handled so that its future recyclability is secured.

STORAGE & TRANSPORTATION

developing the on-site process

ON-SITE PROCESSING
- the material could be processed on-site and integrated in the building site process where the product also could be stored

TEMPORARY STORAGE
- possibilities for temporary storage, using left over space in the city

INFRASTRUCTURE
- to facilitate storage of earth and clay material

DECENTRALIZED
- if not to be used directly on-site, preferably decentralized to minimize transportation

COSTLY STORAGE
- space in urban areas to facilitate storage of the material can be expensive

EMISSIONS FROM TRANSPORTATION
- depending on mode of transportation, moving the material can lead to increased CO² emissions

MIX, DRY & TEST

ON-SITE TESTING KITS
- in order to determine the qualitiy and possible product development based on clay, the basic properties could be tested on-site

CDW IN THE MIX
- potential to use material from other CDW*, or bio-based waste material. Important not to compromise future recyclability

RESEARCH POTENTIAL
- potential for future research! Creating new mixes in a local context such as blue mussels, biochar or waste material from forestry & agriculture

LAB TESTING
- all material excavated needs to be tested in a lab for quality reasons

DRYING PROCESS
- depending on the end product, the clay needs to dry before mixing

ADDING AGGREGATES
- gravel and sand material to the mix, or other aggregates could be tested to improve tensile strength

INSUFFICIENT CLAY
- not ALL clay mixtures are suitable for earth construction.

CONTAMINATED CLAY
- lab tests of the clay from Gothenburg showed some areas of the tunnels were contaminated, had excessively high salt levels, or contained organic fractions. However the clay from Haga Station was suitable for use.

knowledge development on design for material will be crucial

* focusing on earth masses from construction demolition waste

PRODUCTION

requires research to become competitive on the market

DIVERSE PRODUCTION
- potential for diverse production, towards earth building becoming common practice!

MATERIAL EDUCATION
- small-scale production is still a way to build with rammed earth, an integrative collaborative process, as part of education about the material

PRE-FABRICATION
- possibilities for standardization of prefabricated RE elements could enable a product stock – due to the fact that elements can be stacked and joints can be sealed

INTEGRATING INSULATION
- during the ramming process insulation can be integrated, achieving building code requirements in the Nordic context

OFF-SITE PRODUCTION
- large scale pre-fabrication of wall elements using mechanical equipment off-site

ON-SITE PRODUCTION
- production of elements on-site, preferably small scale interior applications using manual tools or mechanical equipment

LONG LEAD TIME
- drying time requires a longer lead time for product development

LABOR INTENSIVE
- pre-fabricated or not, earth construction is considered to be a labor intensive production which makes is less competitive in developed countries

HANDLE WITH CARE
- RE elements, especially in cold climates, are heavy and need to be handled with care

WEATHER PROTECTION
- similar to timber; if working with on-site production, earth elements need to be weather protected

LOCAL POWER STRUCTURES
- in the Nordic context the cement industry is dominating the market. Unless taxes on CO² from productions is introduced it is hard to make clay-based products competitive at benchmark-price

LACK OF KNOWLEDGE
The know-how is limited and education in the building industry and practical experience are crucial when working with earth construction. One part of this lack of knowledge is the addition of cement that is still common practice

FINAL PRODUCT IN USE

potential scalability!

NON-FIRED BRICKS
- compressed earth blocks could have great potential as interior elements, improving indoor climate and has good acoustic properties

RAMMED HYBRIDS
- rammed sheets for interior non load-bearing application as walls or as rammed elements on CLT slabs replacing on-cast concrete

REDUCING CO²
- these products could reduce the CO² footprint of buildings if implemented at a large scale

REPLACING CEMENT PRODUCTS
- these could have significant market potential, clay panels could replace gypsum boards

INTERIOR APPLICATION
- Interior elements require low maintenance; walls, sheeting, or as rammed elements in a hybrid structure

EXTERIOR MAINTENANCE
- elements used exterior elements, can need some maintenance depending on exposure

WEATHER THREATS
- exposed rammed earth in the Nordic context could develop cracks and damage from poor weather protection

DEMANDS MORE RESEARCH
- more research is needed on exposed rammed earth and cracks from freezing. Could organic material be added in the mix?

THERE IS NO END OF LIFE

a future proof product integrated in the built environment

CIRCULAR FOREVER!
- earth is a future proof circular material, where the raw material is almost inexhaustible. This means that when kept in its raw form, without adding any cement or burning it, earth can be recycled to its original composition indefinitely

REUSE IN A NEW MIX
- depending on the clay-based product, it can be crushed and re-used in a new mix without additives

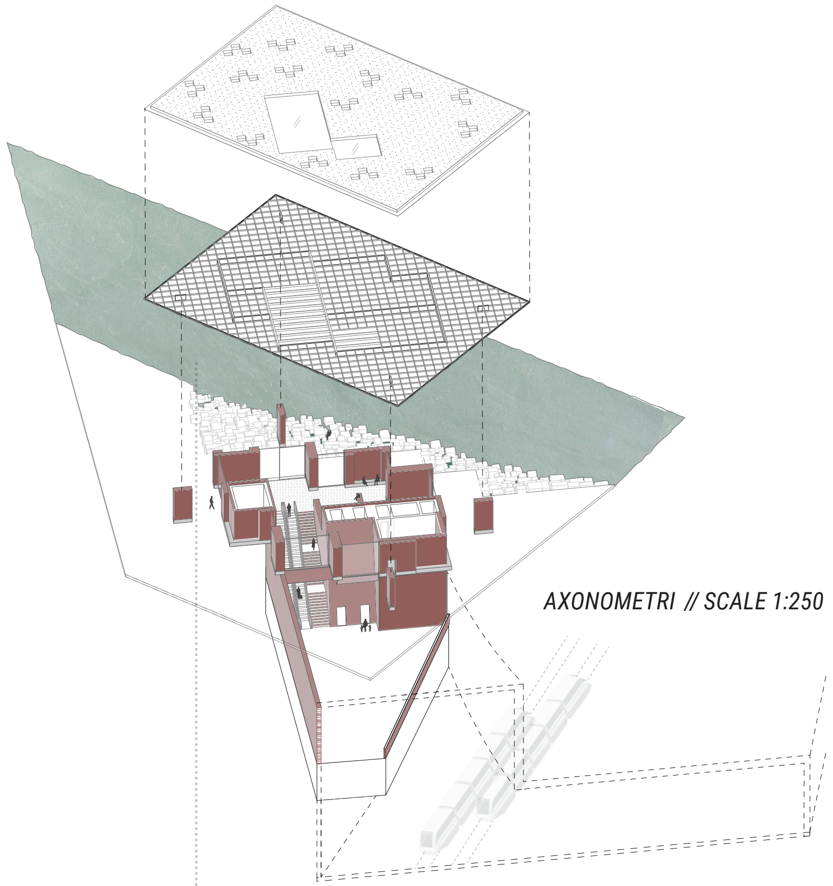
RECOVERING MATERIAL
- a massive rammed earth wall could be demolished and its material reused to build a new wall, or depending on the context, returned to earth in a biological cycle

DESIGN FOR DISSASEMBLY (D4D)
- a clay plasterboard can be disassembled and re-used in a new project

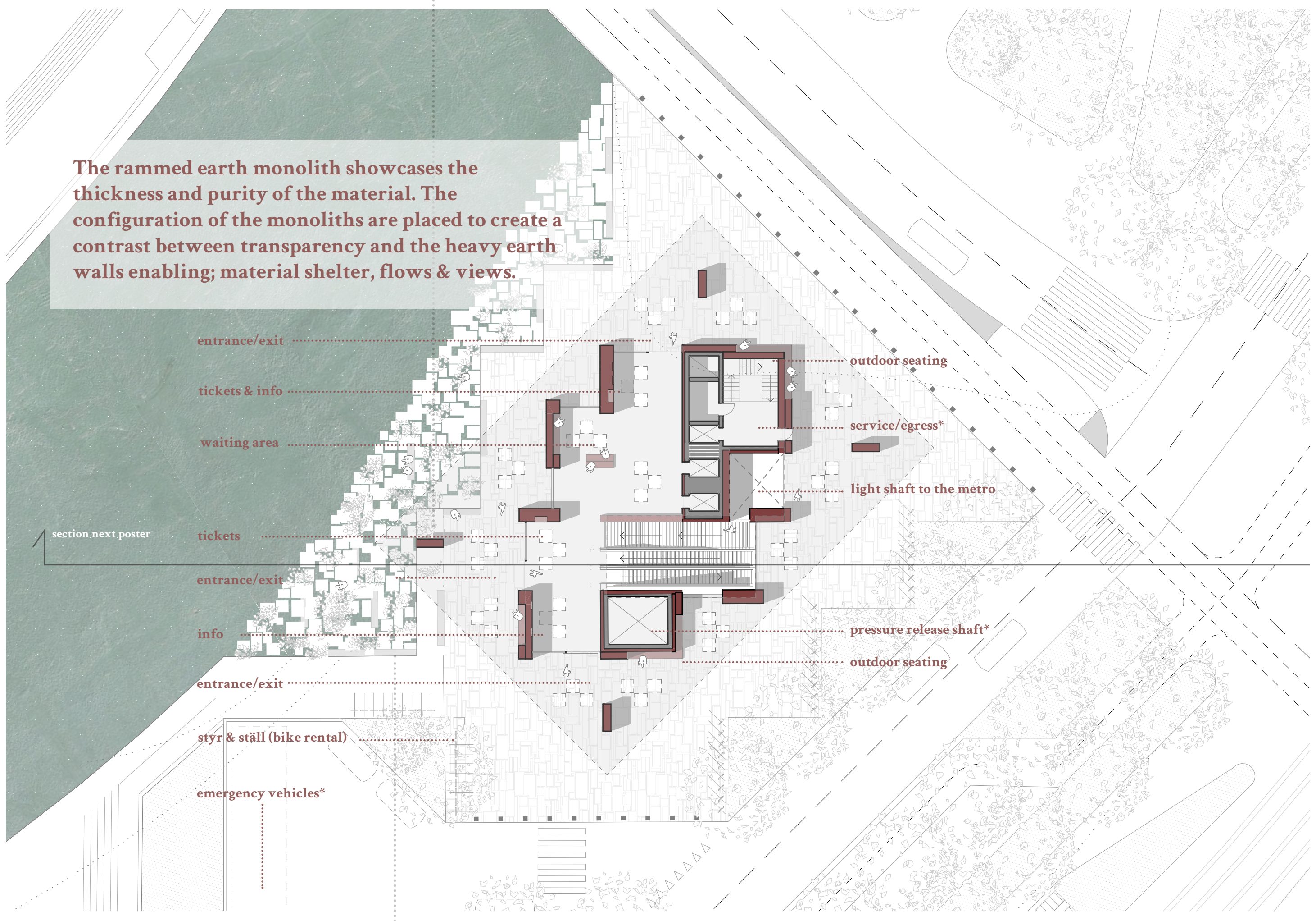
COMPROMISED RECYCLABILITY
- the one action that could compromise the circularity of the material is adding cement to the earth mixture. This is still common practice around the world. It is important to educate future earth builders about the natural binding agent; clay

* According to the analysis of the drill cores along the stretch of the West Link, the rock consists largely of high quality tonalitic and granitic gneiss (Al-Najjar., et al., 2016).

** BFM³ = bank cubic meter



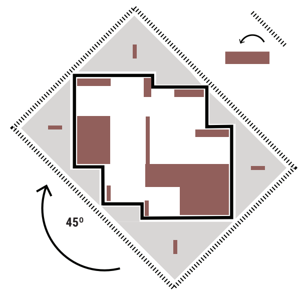
AXONOMETRI // SCALE 1:250



The rammed earth monolith showcases the thickness and purity of the material. The configuration of the monoliths are placed to create a contrast between transparency and the heavy earth walls enabling; material shelter, flows & views.

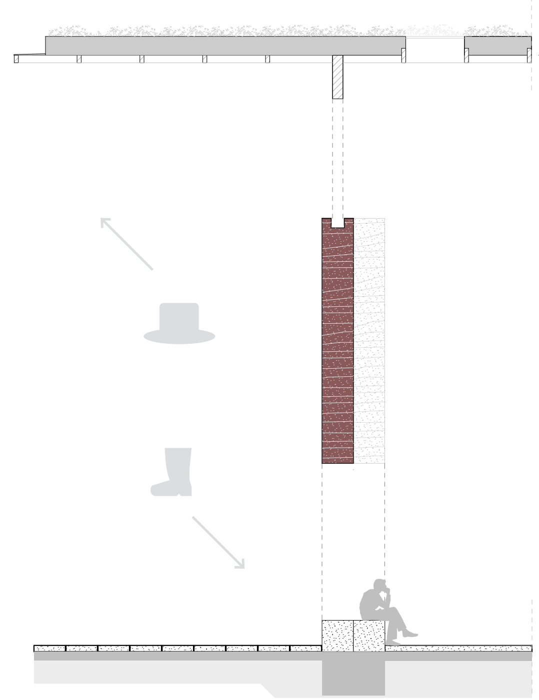
STATION PLAN // SCALE 1:250

* functions set by the traffic department

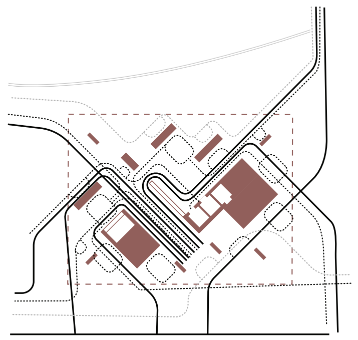


SHELTER

- vertical rammed earth structures
- conditions subject to accelerated erosion, due to weathering and material exposure
- sheltered façades, set back from the exposed perimeter
- sheltered spaces creating clear entrances & waiting areas



Design for material based on local analysis and research



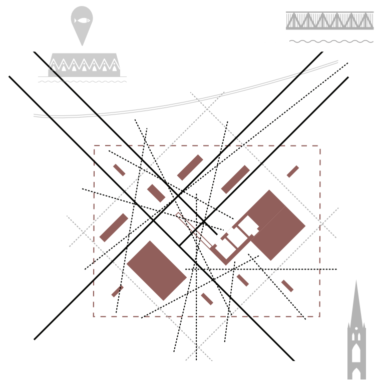
FLOWS

- vertical rammed earth structures
- roof structure perimeter
- fast flow – local commuters // time-optimists
- medium flow – tourists // ticket buyers
- low flow – tourists // city strollers

EARTH EMERGING

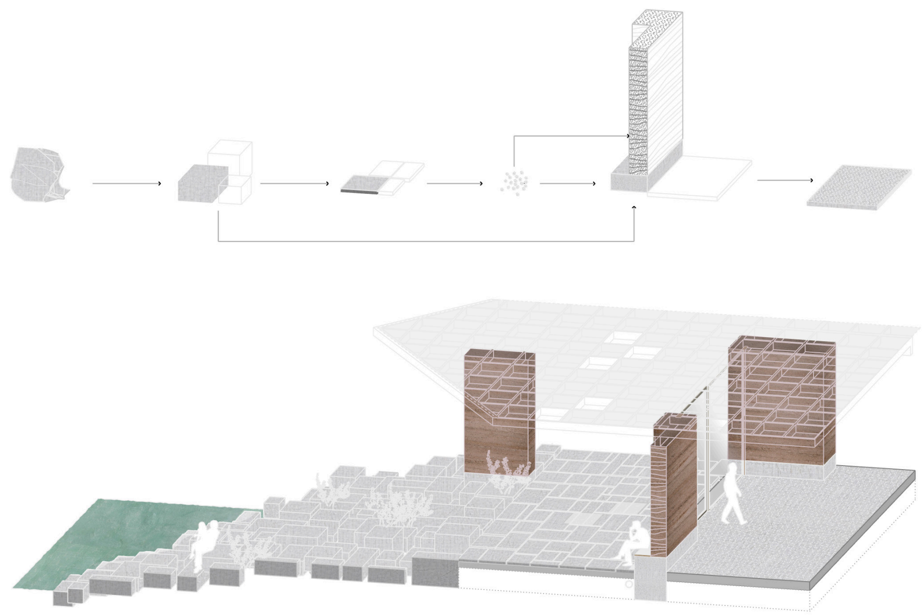
+ unfolding the underground - designing with excavated (waste) material
+ defining design strategies for the Nordic context

The concept of the station is to allow the strengths of the material to guide the design. Exposing all sides of the material by placing the monoliths free-standing reinforces the qualities and layers in the material process. The rammed earth walls are 1 meter thick to strengthen the earth monolith and to tell a story about material richness, availability and the luxury of working with a circular material.



VIEWS

- vertical rammed earth structures
- roof structure perimeter
- main views – critical for orientation upon arrival
- transparent views – within and through the station



EXCAVATED LAYERS // SCALE 1:100 - material process, unfolding as gradients of rock material

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