CT3300-09

Use of Underground Space

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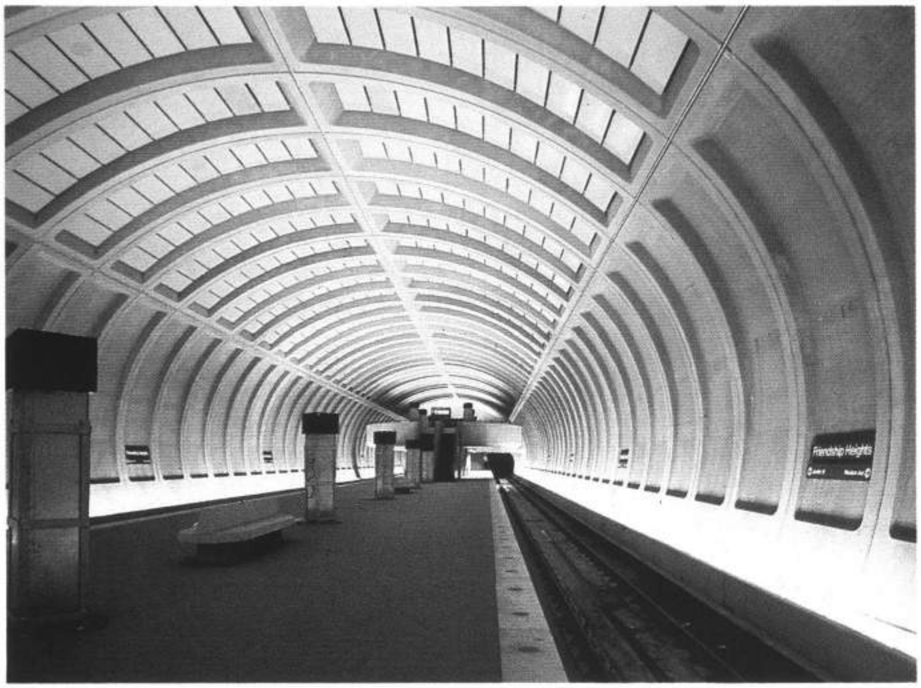

TU Delft **Faculty of Civil Engineering and Geosciences**
Department Geo-Engineering
Chair of Underground Space Technology

Preface

The multidisciplinary course "Use of Underground Space" is a course for students of Civil Engineering, Mechanical Engineering, Applied Earth Sciences, Architecture or Technology, Policy and Management. The lectures will give a broad view in the field of Underground Space Technology. Students obtain basic knowledge of the multidisciplinary aspects of the use of underground space. Based on knowledge about the characteristics of several construction technologies they are able to asses their applicability in different situations. This may be different geological or physical conditions. They are able to analyze and structure the complex decision making process that is related to the use of underground space and define an integral approach. A more detailed schedule of the lectures is available at the secretariat (room 00.160) and on the website (http://geo.citg.tudelft.nl/ogb/).

During the course students are expected to write a paper with a team of about 3-5 persons. It is recommended to compose a multidisciplinary group. The paper is written on a subject concerning Use of Underground Space and has the size of about 25 pages. The paper needs to have a broad view, though needs to be enough detailed on the crucial points of the subject. A multidisciplinary approach is preferable. In completion of the course (4 ECTS) an oral exam has to be done concerning this paper and the course. The level of knowledge is tested on the understanding and the ability to apply the relevant information from the lectures, literature and syllabi.

The course and the paper are based on the following points:

- The course of Use of Underground Space is additional to and integrates all courses relevant to Underground Space Technology given on the Faculties of Civil Engineering, Mechanical Engineering, Applied Earth Sciences, Architecture and Policy and Management.
- Students will use all relevant literature (including our library), syllabi and handouts.
- Knowledge about Underground Space Design can be restricted to the basic lines.
- The level of knowledge is tested on the understanding and the ability to apply the relevant information from the lectures, literature and syllabi.

These lecture notes focuses on a wide view of the relevant matter. More detailed information can be gained during the lectures, in the appendices in the Dutch lecture notes and in the library of the chair. Specific details will be discussed during the oral exam about the paper.

For questions and access to the library contact the student assistants in room 00.410 or call 015-2785286.

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1. Backgrounds and specific aspects

1.1 Introduction

The increasing interest in underground construction has resulted from a rise in more complex infrastructure and the increasing problems with space arrangement. The appreciation of the environment is also rising. The interest is greater than just putting large projects (infrastructure) underground. It also focuses on the question of what underground space construction can add to the organisation of a country. A *strategic vision* on the use on underground space may help to overcome the problem of increased demand of the rare space and the environment in a structural way. At the same time it could improve the functionality of infrastructure and space organisation.
A strategic vision is necessary for two reasons. Firstly, it means focussing on the (very) long term as the process, from planning to realisation, of a project takes roughly 30 years. Therefore it is important that underground constructions, with their long durability, also have a positive long-term effect. For this reason one should have a strong vision for future decades. Secondly “Strategic” means “multidisciplinary”, because underground space technology is linked with various disciplines like space organisation, environment, traffic and transport, safety, economy and architecture.
The challenge, at university level, is to (among other things) contribute to the underground construction industry's understanding of difficult soil conditions. Therefore it is important that one appreciates the extent of connections in the industry and that a multidisciplinary approach is necessary for success. It is also necessary to automate, robotize and innovate applications in the area of geotechnology, concrete technology, logistics and building-management.

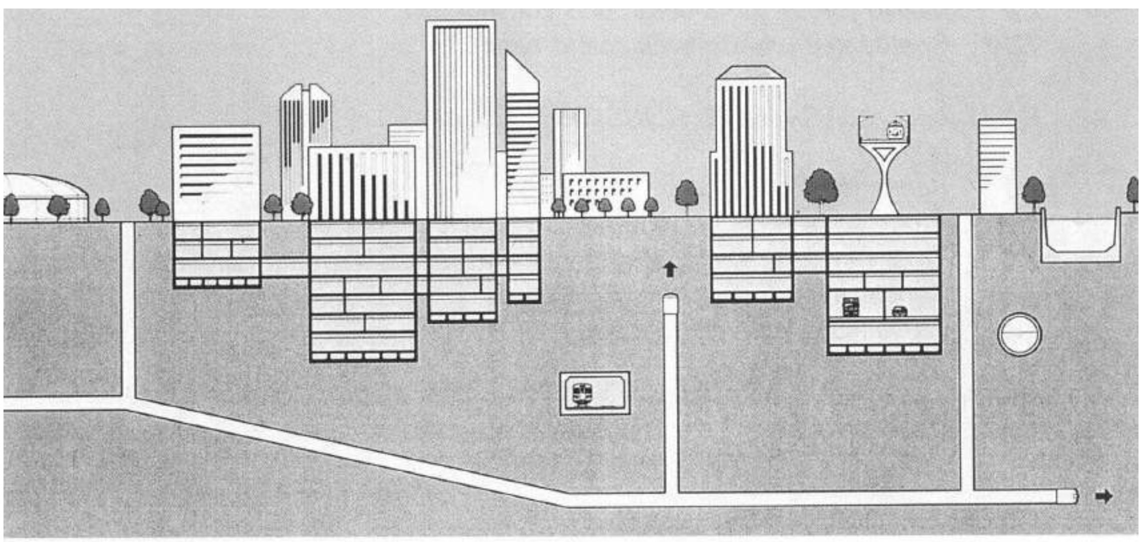


Figure 1.1: An example of intensive use of the underground.

Large projects which are already built may give us the idea that almost everything is possible. However we must realise that our expectations for building underground are often too high.

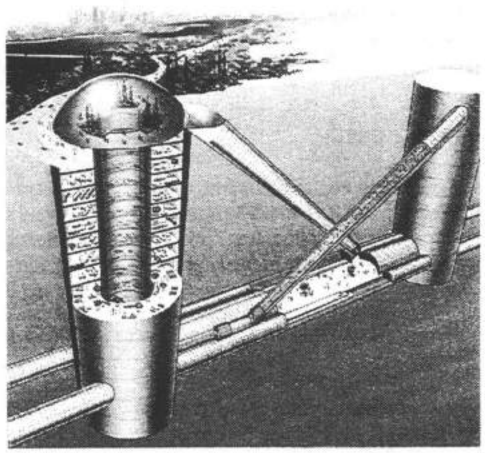


Figure 1.2: The expectations are sometimes far too high

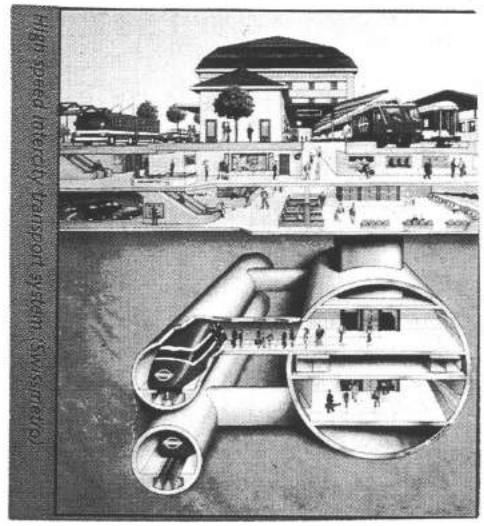


Figure 1.3: …..or only possible in the future.

Figure 1.4: There are already some complex systems in use.

This chapter will focus on the main aspects involved in the use of the underground space. The history, technology, motives, functions and difficulties of underground constructions will be covered. The last section will shed some light on underground construction within The Netherlands.

1.2 History of underground construction

1.2.1 Introduction

The use of the underground is not a new issue. Throughout the history of mankind, people have been using underground construction for different reasons. There is evidence that even ten thousand years ago people lived in caves. Around that time came new purposes for the underground. Water tunnels dating from before Christ have been found. Shelter and storage facilities as well as tunnels for shipping traffic also have a long history.
Although we are familiar with the use of the underground it has had quite a negative image for a long time. Some of the reasons that have contributed to the negative image are listed below:

- The hard labour in the mines.
- The poor conditions of the first tunnels.
- Underground shelter and defence are connected with the threat of war.
- Cellar housing in the beginning of the last century for poor people were seen as social inferior.
- The concept of heaven and hell (in some cultures).

Nowadays some people still find staying or working underground for a long time unpleasant. Tunnels used by traffic or trains can also raise negative feelings.
We have to learn from these historical examples to come to a more subtle view of the advantages and disadvantages of underground construction.

1.2.2 Common use of the underground

Some uses of the underground are almost common, because they have been applied regularly. These uses will remain necessary in the future. A few of these uses are listed below:

- Use of the underground for foundations, storage of groundwater and ecological aspects. These functions have a great importance and may even have the highest priority in the future.
- The use of the upper layers (3-5 metres) for storing different kinds of cables, (industrial) pipes, sewage etc.
- Small constructions of cellars and tunnels. They can offer good specific advantages for a low price.
- Incidental uses of the underground such as extraction of natural goods (salt, oil, sand etc.) and military use.

Figure 1.5 gives an idea of how underground constructions can influence the underground ecology.

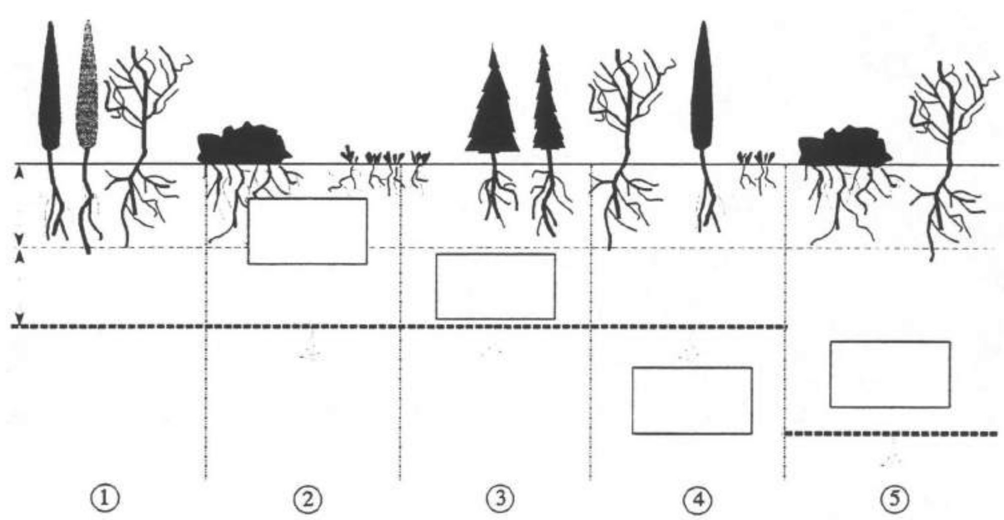


Figure 1.5: Influence of underground constructions on the ecology.

1. *Normal situation without any construction.*
2. *Shallow underground construction: direct disturbance of the biologically active zone and groundwater.*
3. *Half-deep construction: disturbance of groundwater and in that way indirect effecting the biologically active zone.*
4. *Deep construction under groundwater level: no or less disturbance.*
5. *Deep construction under groundwater level: fewer disturbances when it does not lie in the biologically active zone.*

Notes:
- Groundwater and the biologically active zone depend on physical and chemical soil properties. The groundwater level can also vary considerably.
- Disturbances in the underground biologically active zone have a direct effect on the ecology above ground level.

1.3 Underground Technology

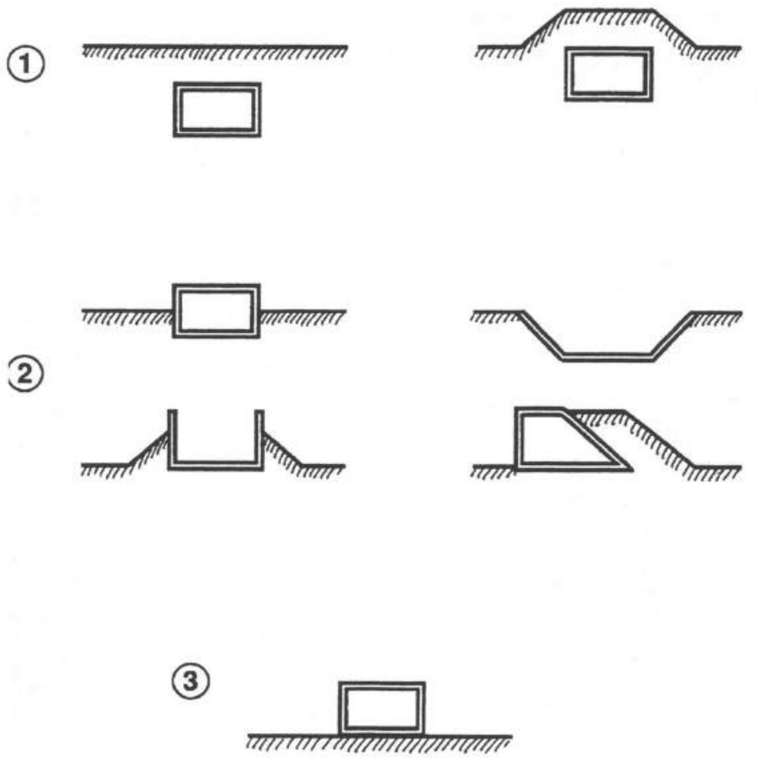
1.3.1 In general

The field of underground technology includes the following activities:

- Use of underground space.
- Realisation of underground works.
- Use of underground facilities.

Based upon the function of the facilities, underground construction is divided in the following sub-divisions:
- Tunnels for traffic, transport and facility services. The tunnels can be further divided by building method or depth.
- Underground building and public services. They can vary from well known cellar-constructions like parking, sewage purification facilities, terminals, stations, shopping centres and turnover facilities to the more unknown such as archive spaces, libraries, recreation facilities, discotheques etc.
- Small infrastructure systems for cables and pipes (including post, distribution of goods, household and industrial waste collection and storage, and the transport of oil, water and gas). These pipes and cables can be laid with different techniques (e.g. cut and cover and trenchless) within the demands of the facility.
- Underground storage of oil, gas, used goods and industrial and radioactive waste in unlined underground spaces as well as in buried and soil-covered constructions (see also Chapter 7).

Another way of dividing underground constructions into categories is by their depth.



1. *Underground: The complete construction lies under ground level or is covered with soil,except necessary surface connections for supply and discharge of people, traffic and goods.*
2. *In the ground: Most of the construction is under ground level (more than the necessary base-construction)*
3. *Ground level: The bottom of the construction is about equal to ground level.*

Figure 1.6: A diagram of the different depths of underground constructions

1.3.2 Design & Architecture

The designs for underground constructions differ from above ground building designs. The latter buildings can easily distinguish themselves by their exterior shape, form and colour, while underground constructions only have their entrance, internal shape and appearance available as a way of distinguishing themselves.
The design of an underground construction is highly influenced by demands of functionality, technical safety, health and social safety. Underground public buildings for example are given quite a different arrangement than their above ground counterparts.

When considering building underground, attention must be given to aspects such as accessibility, sound, vibrations, temperature, fire, earthquakes and perception. These aspects will be further discussed in the next section.

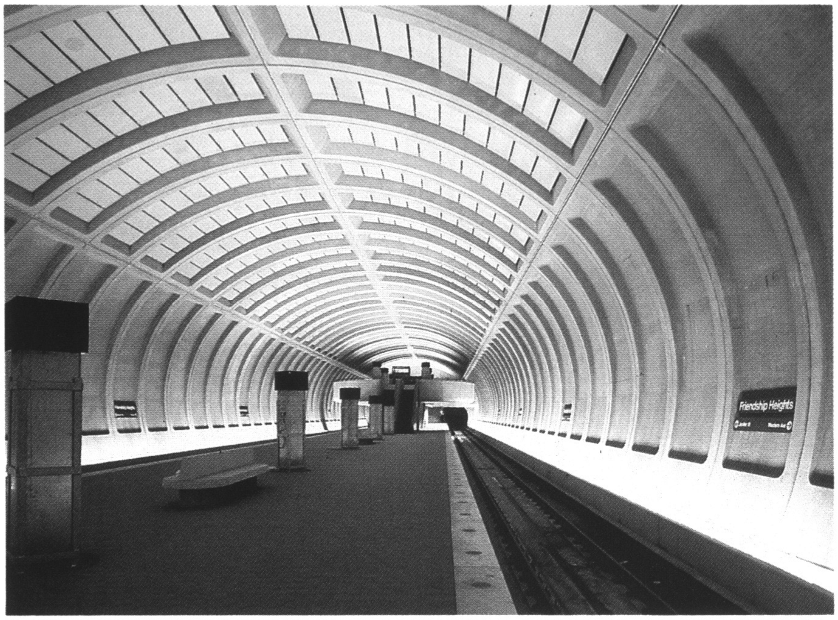


Figure 1.7: An example of good design of an underground space

1.3.3 Building aspects

Accessibility

An important design consideration for underground spaces is accessibility. It is not only essential to have an entrance for (disabled) people and goods, but also for light. Buildings above ground have many openings in their outside walls. In case of an emergency it is possible to exit the building through these openings. When the construction is located (partly) underground, the only possible exit points are entrances leading to ground level or to adjacent underground structures. Therefore it is important that there are sufficient escape routes available.

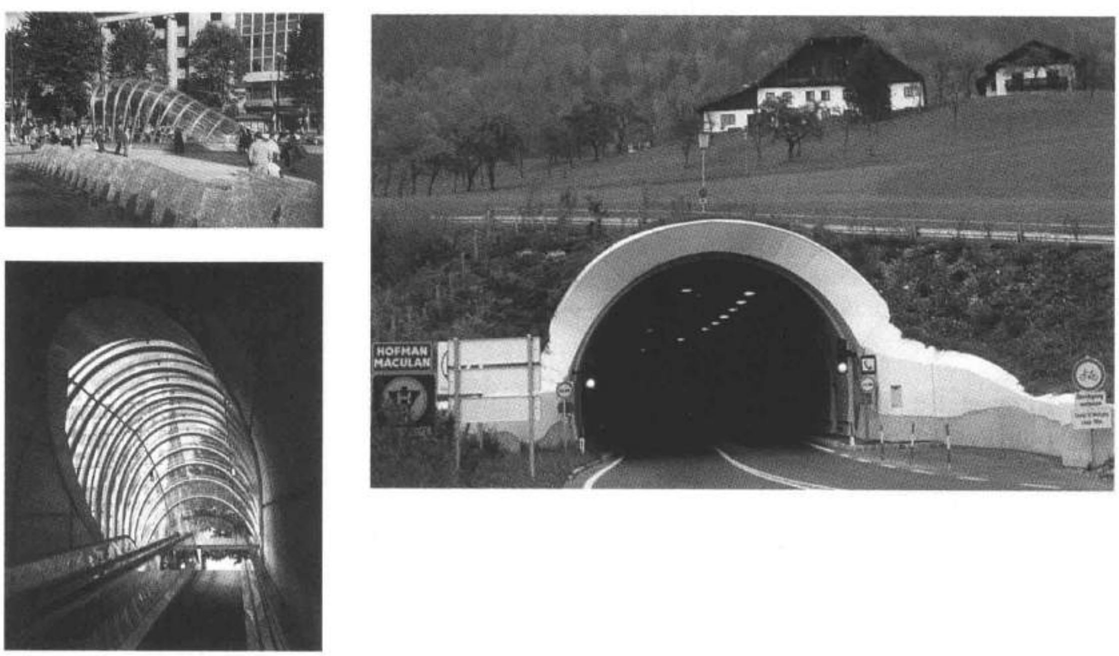


Figure 1.8: Examples of well designed (left) and badly designed (right) entrances

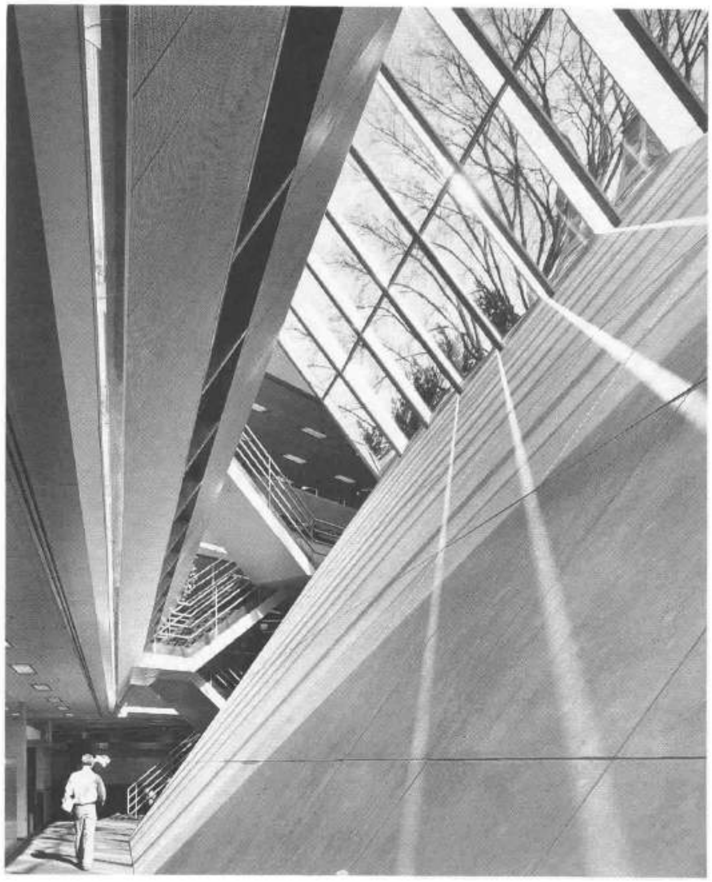


Figure 1.9: In the underground library at the University of Michigan, natural light penetrates three levels deep

Air & moisture

The supply of sufficient clean air is also of great importance for underground spaces. The required amount of fresh air depends on the size and function of the underground structure. The ventilation pipes that are necessary for transportation of clean and foul air will have to emerge somewhere at surface level. This can have a large influence on the appearance of the building at surface level.

Due to the difference between the constant temperature of the soil surrounding underground buildings and the temperature on the inside, water can condense on the walls. A good physical design can overcome such problems.

Sound & vibration

Underground structures have better sound and vibration insulation than their above ground counterparts. Sounds from the outside are absorbed by the surrounding soil while sounds from the inside can not travel far (thus causing nuisance to the surroundings). Ventilation holes and gas-pipes that are connected to the surface can be considered as sound leaks.

Insulation against vibrations is more difficult. When building at great depths, the insulation is often very good. However, when building at shallow depth the insulation is more problematic. Especially low frequencies can penetrate far into the soil. When building rail tunnels at shallow depths this is something that should not be forgotten.

Echoes

Echoes can be annoying in underground constructions. Therefore it is necessary to take appropriate precautions during the design phase. There are no design specifications for echoes in underground constructions, but the design considerations can be compared with those encountered when designing sport facilities or music theatres.

Temperature
The temperature of the soil and groundwater do not change very much throughout the year. Furthermore the exchange of warmth between the underground structure and its surrounding is very low. Underground buildings therefore have a constant climate and are free from frost. Radiation is also very low compared to houses above ground even when there are large temperature differences. Therefore it is possible to store both cold and warm goods. This means that warmth produced in these buildings needs to be pumped out with ventilators or air-conditioning. Warmth is generated by people, lighting and (electric) machinery. Friction warmth produced by High Speed Trains can be a problem in rail tunnels.

1.3.4 Safety aspects

Underground constructions require a different approach to safety than above ground structures. The most important safety aspects to consider are given below.

Fire
Most underground constructions are made of concrete and are surrounded by soil. This gives them good protection from fire; therefore fires do not spread easily in underground constructions. This protective advantage makes underground storage of flammable materials an interesting alternative to above ground storage. External fires can only enter the underground construction via the entrances; therefore the entrances should be designed to keep fire out.
When a fire starts in the underground construction it is difficult to reach by emergency services since the only way to enter the building is via the entrances. Escape routes and fire fighting systems are therefore an important part of the design process.

Possible causes of fire:
- *Vehicles carrying hazardous goods*
- *Road accidents*
- *Short-circuits in the electrical systems*

The effects of fire:
- *Temperatures in excess of 1300 ℃.*
- *Collapse of concrete structures after spattering of the concrete layer that protects the steel reinforcement.*
- *Strength reduction of steel structures caused by high temperatures, possibly resulting in collapse.*
- *Smoke formation obstructs possibilities for escape and fire extinguishing.*
- *Failure of sealing elements (especially in the case of underwater tunnels), leading to the failure of the power supply and therefore loss of lighting, communication and alarm facilities.*
- *Formation of toxic gases through combustion of plastic materials (e.g. insulated cables).*
- *Corrosion of reinforcement caused by hydrochloric gas that is formed during combustion of plastic insulated cables.*
- *Failure of the ventilation or smoke-extracting system.*

Consequences of damage:
- *Injury to persons*
- *Loss of life*
- *Damage to property*
- *Costs of renovation, demolition and reconstruction*
- *Reduction of infrastructure capacity during reconstruction activities*

Perception
Underground constructions are built all over the world. Some of them are hardly used, even during daytime. It appears that people do not feel safe in these underground spaces. Many subterraneous passages and metro stations are a good example of this phenomenon. The unpleasant experience does not always mean that the integral design is bad, but can sometimes be caused by a single negative component (e.g. a dark entrance).
Designers always should ask themselves during the design stages whether the station or shop invites people to stay there. A good atmosphere created by soft colours and the use of natural materials can

stimulate this. Creating open, well lit spaces can increase social safety since people are able to see each other. Dark corners and passages should be avoided at all times.
Lack of sunlight is another cause of the negative perception of underground spaces, since it makes orientation difficult. This effect can be countered by good colour indications and placement of striking objects. In the Tokyo metro, for example, photographs of buildings above ground are shown in the stations.

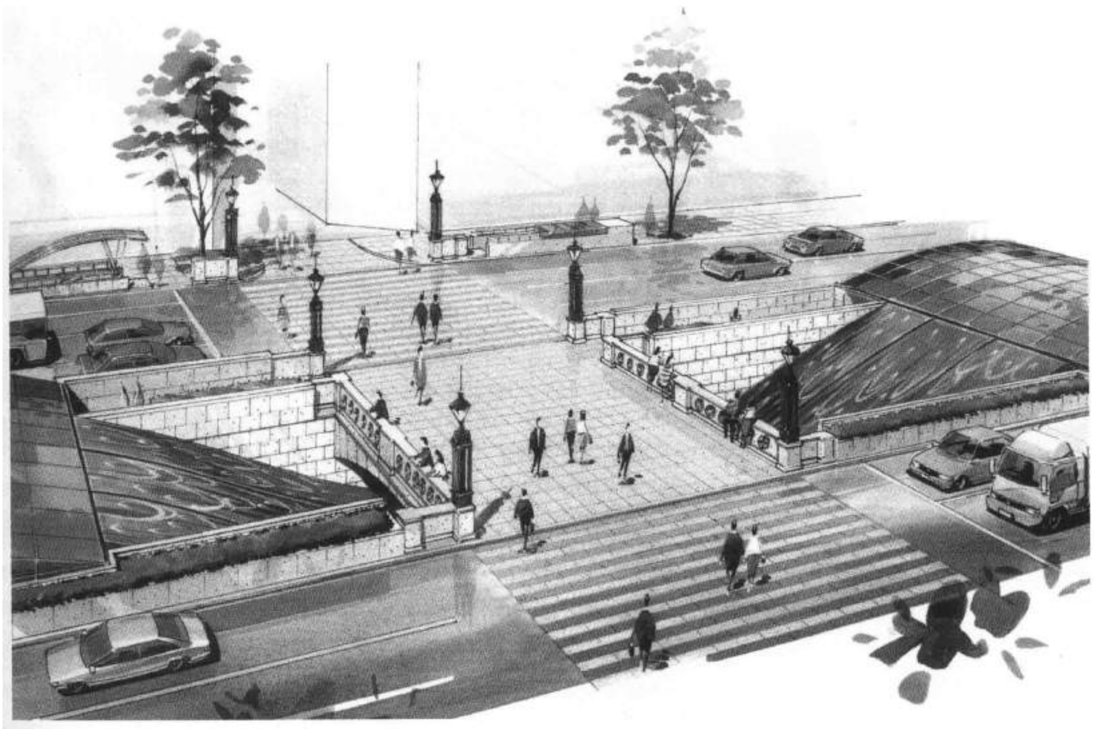


Figure 1.10: Running water over the glass roof of the mall refers to the former canal (Osaka).

Earthquakes
Recent earthquakes in Japan showed that underground constructions receive little damage from heavy earthquakes.

Vandalism
As a result of the character of an underground construction, it has only few entrances. This decreases the possibilities of vandalism. In the same way burglary is reduced.

1.3.5 Safety prescriptions

There is little experience in the arranging of underground constructions throughout the world. Research is merely aimed at creating solutions for constructions, rather than improving functionality and safety. This is illustrated by the fact that there are only a few laws and regulations for the design of underground constructions. Functionality and safety can be greatly improved when various parties are involved in the design process (e.g. municipality, fire brigade).

1.4 Motives for underground constructions

1.4.1 In general

Although it is not natural for human beings to reside in the underground there are a number of reasons why the underground can be a good alternative to above ground solutions:

1. Taking away/reducing hinder and thereby improving liveability.
2. Reducing/eliminating safety risks and damage to the environment.
3. Solving problems regarding infrastructure and spatial organisation, especially in areas where space is (becoming) rare.

Using a strategic point of view, these three reasons will increasingly lead to new underground solutions.

Normally constructions are built at ground level. The advantages of above ground construction are technical, financial and managerial. So there need to be specific reasons for going underground.
The stakeholders involved in a building project can be divided in: users, investors and operators, neighbours and the community or society taken as a whole. Figure 1.11 lists possible motives of different stakeholders in the use of the underground.

Motives	Specially relevant for
1. Underground space technology as the only possible alternative	Users, investors/developers, community
2. Big functionality	Users, investors/developers
3. Closing of from “the outside”	Users, investors/developers
4. Saving energy	Investors/developers, community
5. Durability and maintenance	Investors/developers, community
6. Higher building density	Investors/developers, neighbours, community
7. Higher accessibility / less barriers	Users, neighbours
8. Plural / efficient ground use	Investors/developers, neighbours, community
9. Combinations with other facilities	Users, investors/developers
10. Unattractive activities underground	Investors/developers, neighbours
11. Restricting nuisance	Investors/developers, neighbours
12. Restricting damage to the environment	Community
13. Preservation of precious functions	Neighbours, community
14. Growth of external safety	Neighbours, community
15. Economy and export	Investors/developers, community

Figure 1.11: Motives for underground constructing for different stakeholders

Many of the motives for underground construction are related to the quality of the environment. The quality aspect receives more attention when a society develops towards a higher standard of living. During the last decade there has been an increasing interest in areas such as quality of nature, preservation of landscapes and liveability. Furthermore there is more interest for spatial qualities such as efficiency of space, urban development and architecture.
Underground construction can play an important role in the previously mentioned developments.

1.4.2 Space and urban aspects

In the past few years the government has paid a lot of attention to the concept of a compact city. Plural use of space through building underground can play an important role in this idea. Creating a compact city is possible in two ways:

1) The use of undeveloped urban areas: Space in the central area of the city that has not yet been used is developed.

2) Compaction and change of function of existing urban areas: Certain functions can be placed underground; thereby making the old buildings obsolete (e.g. railway stations). These locations can then be given a new function, thus compacting the city or increasing the quality of life (e.g. replacing a station by a public park).

Some activities within the city can cause environmental hinder or decrease safety, e.g. motorways. So-called hinder-zones therefore often surround them, imposing strict rules on developments in these areas. It is relatively easy to put some hindering activities underground. With little adjustment great advantages are sometimes possible. Some examples are: infrastructure, industrial areas, fuel stations, water purification plants et cetera. The hinder-zones above ground can thus be reduced in size, leaving space for new use. A good example is the approach given in figure 1.12 .

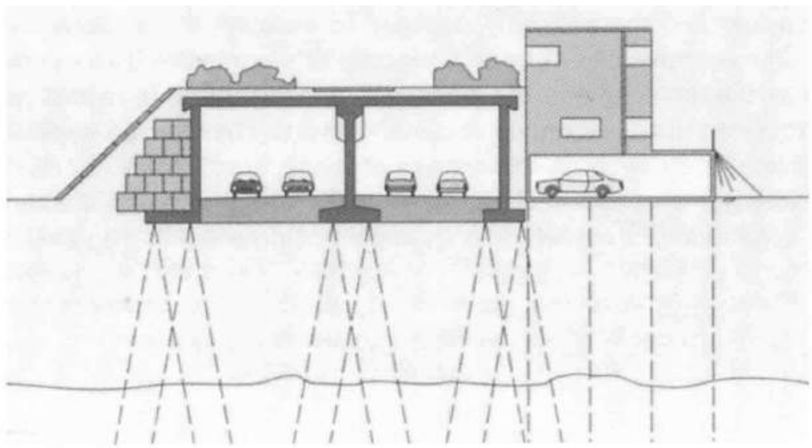


Figure 1.12: The hinder zone cause by the highway is reduced by covering it with soil. Now it is possible to build residential buildings close to the road. A2 nearby Leidsche Rijn (Holland).

Another important consideration is which constructions are to be placed underground. One possibility is placing a part of all constructions underground. Another option is placing certain buildings totally underground, while leaving others above ground.
Not every function is suitable to be placed underground. Of the buildings that are often found in the centre of a city, one could possibly place functions like parking, storage, installations, retail trade and entertainment underground. Houses and offices should stay above ground level. Cellars and parking that are part of residential buildings could possible be placed underground.

Figure 1.13: Example of plural ground use in the centre of a city.

1.5 Obstructions

In comparison to construction activities at ground level, underground construction has more difficulties that need to be taken into account. Most of these were already discussed in the previous sections. A summary of potential impediments and possible solutions is given in figure 1.14.

Potential Impediments			
Impediments		**Nuances/ possible solutions**	
I	**Costs**		
-	Underground construction is relatively expensive.	-	An objectieve cost comparison of above-ground and underground options requires not only the 'standard' construction costs to be included but also those costs and benefits that are less easy to express in terms of money (multiple land use, forms of nuisance, physical lifetime) mus be assessed in relation to the financial investments.
		-	In underground construction procedures, specific cost optimization is possible (e.g. with regard to tunnel diameters and multidisciplinary and integrated design)
II	**Perception aspects**		
-	Negative associations with underground spaces in general.	-	Measures relating to lay-out, design, safety and ventilation can exert a positive effect on the perception.
-	Realistic senses of unsafety and disorientation.	-	The *functionality* of the underground location of a facility must be clear to the user.
III	**Uncertainties with regard to application of technology, safety and use aspects**		
-	Unfamiliarity with certain construction methods (e.g. tunnel boring) may lead to over-estimation of risks and costs, or precisely the under-estimation of risks.	-	Hands-on experience can improve familiarity with new techniques.
-	There is uncertainty as to safety standards to be imposed for underground spaces.	-	Development of a clear-cut safeguarding vision has been initiated with regard to safety standards.
-	An underground space is inflexible; enlargement involves engineering problems.	-	A long-term vision can increase the economic and societal value of an underground facility.
IV	**Nuisance and damage during and after construction**		
-	Noise and vibrations are potential sources of nuisance during construction.	-	Technical measures (insulation, damping, etc.) can reduce vibration.
-	The realization of underground constructions can easily cause settlement and subsidence.	-	Engineering measures can be taken where subsidence of the ground level is unacceptable.
-	Construction work can create a traffic nuisance and reduce the accessibility of buildings and areas.	-	Application of trenchless techniques and tunnel boring methods enables substantial reduction of nuisance effects at ground level.
-	Maintenance and management of underground facilities is more difficult.	-	Specific inspection techniques are available for underground facilities.
		-	Damage to underground facilities caused by other excavation or construction operations can be partly prevented by means of appropriate records in the land register.
V	**Geo-conditions**		
-	The soil survey does not generally give a totally reliable picture of the physical geo-conditions.	-	The soil survey should be performed in an optimized way.
		-	Good preparation enables rapid and effective action to be taken if unexpected soil conditions and objects are encountered.

Figure 1.14 : Survey of potential impediments to underground constructing.

1.5.1 Financial problems

The financial aspect has not been discussed so far. The direct costs for underground buildings are usually much higher than for similar surface structures. The main problem is that investors are usually not the ones that benefit from the advantages that underground construction offer when compared to above ground constructing.
A good example of this problem is the case “Delft”. This case handles the question whether a planned railroad upgrade in the centre of Delft should be constructed above or below ground.

	Viaduct 2 rails	Tunnel (open trench) 4 rails	Tunnel (TBM method) 1 tube with 2 rails
Construction costs	308	494	536
Land/demolition/damage	122	146	37
Sub-item 1: Direct costs	430	640	573
	(100%)	*(148%)*	*(133%)*
Maintenance and operation	31	64	47
Sub-item 2: life-cycle costs	461	704	620
	(100%)	*(152%)*	*(134%)*
Nuisance (in money terms)	133	168	5
Sub-item 3: Total costs incl. nuisance	594	872	625
	(100%)	*(147%)*	*(105%)*

Figure 1.15: Survey of the case “Delft”.

The costs of a fly-over and a bored-tunnel are almost equal when the costs of inconvenience are also taken into account. This is good news, but it is not clear where the compensation money for nuisance should come. A pilot project could possibly get funds from the national government, but this is not a structural solution obviously.

Another important argument in the discussion of above ground versus underground construction is the possibility of multiple use of space when constructing underground. In the Delft case the multiple use of space was the main argument for spending more money on the bored tunnel alternative. It is expected that the open space that is created in the bored tunnel alternative will have very interesting development possibilities. The difference in costs between tunnel and fly-over can easily be compensated by profits made during development of the new open space.

It is of great importance that one realises that there are many factors that can influence the costs of a project. Optimisation of these cost factors can result in substantial differences in overall costs.
Important factors that influence costs of underground constructions are:

- *Type of construction*
- *Method of constructing*
- *Tunnel diameter*
- *Soil circumstances*
- *Safety measures*

Diameter of tunnel cross-section	Percentage cost
12.0 m	114%
10.0 m	**100%**
7.5 m	63%
6.0 m	50%
4.5 m	38%

Figure 1.16: Influence of the diameter on the costs of a tunnel.

It is important that costs optimization with regard to safety measures is looked into during the design phase. This aspect is often considered too late while designing. Designers should try to reduce the possible sources of danger. This could prevent the necessity for special safety-measures, which results in cost reduction.

1.5.2 Problems on societal level

Besides the previously mentioned difficulties, there is also a problem in the way decisions about underground constructions are made. The law does not yet solve all problems with regard to multiple use of space. Furthermore spatial planning is seldom done in 3 dimensions, which is an absolute necessity for underground construction. Conditions for underground construction can only be optimised when a 3-dimensional spatial planning is made. One possible solution could be the use of vertical zones. An example of a division of the underground space in vertical zones is given below.

Depth beneath ground level (m)	**Use**
0 – 3 to 5	Cables, pipes, sewers etc.
3 to 5 – 15 to 25	Cellar construction without construction on top and tunnels with a diameter < 3 to 4 m
Under 15 to 25	Tunnels with a diameter > 3 to 4 m
All depths	Weight priority for foundations, groundwater and ecological functions
> 3 to 5	Cellar-constructions (with constructions on top) only with a special permission, because they can harm the construction of tunnels, transport pipes etc. on a strategic level.

Figure 1.17: Idealised guideline for the underground destination plan.

Another issue is the lack of a integral method to determine effects of underground projects from a societal point of view. The last problem is that decision-makers are often not very familiar with the possibilities of the use of underground space. Figure 1.18 gives an overview of the difficulties encountered on a societal level and possible solutions.

Impediments relating to enabling factors			
Impediments		**Nuances/ possible solutions**	
I	**Legal aspects**		
-	Unclear legislation and regulation concerning decision-taking on (major) projects.	-	Harmonization and synchronization of legal procedures concerning decision-taking on (major) projects is under study.
-	Unclear public and private law provisions concerning underground construction.	-	Legislation and regulation concerning underground construction should be transparently presented and if necessary allowed to be amended.
II	**Spatial planning aspects and zoning plan**	-	Develop an integrated spatial planning vision on the use of both above-ground and underground space.
-	Spatial planning schemes and planning policy are entirely focused on above-ground activities.	-	Possible solution by amending the Spatial Planning Act.
III	**Lack of a (dynamic) integrated assessment framework**	-	Development of a (dynamic) integrated assessment framework, to ensure that all the relevant aspects and options are considered at each stage of the assessment process.
-	Underground options are often not - or not seriously - incorporated in the decision-taking procedure.		
-	Lack of a good method for comparison of differing underground and above-ground options.		
IV	**Lack of integrated decision-taking procedures**	-	Well-designed integrated decision-taking procedures can improve the manageability of the assessment process between various option, and can optimize the outcome.
-	Major projects feature an unclear and unmanageable decision-taking process, yielding a frequently suboptimal outcome with regard to utilization of underground space.		
V	**Unfamiliarity with the possibilities of underground construction**	-	To ensure optimized utilization of the possibilities of underground construction, certain actors must possess certain know-how; information strategies can be formulated with that objective.
-	Utilization of underground space is a relatively new concept in the Netherlands, and many possibilities are still unknown.		

Figure 1.18: Impediments relating to enabling factors.

1.5.3 Legal aspects

There are three important considerations when looking into legal aspects related to the use of underground space:

- Underground constructions should fit within existing spatial planning and the surrounding environment. There are many laws concerning use of the underground that should be taken into account: spatial planning laws, mining laws, environmental laws etc.
- There are two possibilities for acquiring the land needed for underground purposes. One can try to come to an agreement by means of buying the land, renting the land, or agreements on settlement. When no agreement can be reached, the land can be acquired by expropriation.
- Contracts must be signed for the realisation and use of underground facilities and the use of the underground.

1.5.4 Acceptation of underground use

Another aspect of underground constructing is the social acceptance of underground spaces. This requires a good design with special attention being paid to liveability and social safety. Underground structures that have public areas (e.g. stations) should give their occupants a safe feeling. This can be achieved by making sure the area is sufficiently lit and people can see each other (transparency). Stations that are almost deserted during certain times of the day can also give an unsafe feeling. Building small shops can be a good solution to increase the feeling of safety in these locations.

1.6 Underground Technology in the Netherlands

Building in the subsurface in The Netherlands means building under predominantly soft-soil conditions. In some places (mostly in the western part of the country) the situation is further complicated by a high groundwater table (up to -0,40 m below surface level). The high groundwater level is especially unfavourable for construction activities in the underground. In spite of these difficult conditions there are no large technical difficulties for building below ground level. There are technical solutions available for every possible circumstance. The main problem with underground constructions is the cost increase due to soil conditions, high groundwater tables and the presence of various objects in the underground (especially in urban areas). This increase in costs can be problematic since project feasibility is usually determined by affordability. The disadvantages of the Dutch soil conditions can be an advantage because the experience and specific techniques gained under these circumstances can raise the competitive position of Dutch construction companies around the world.

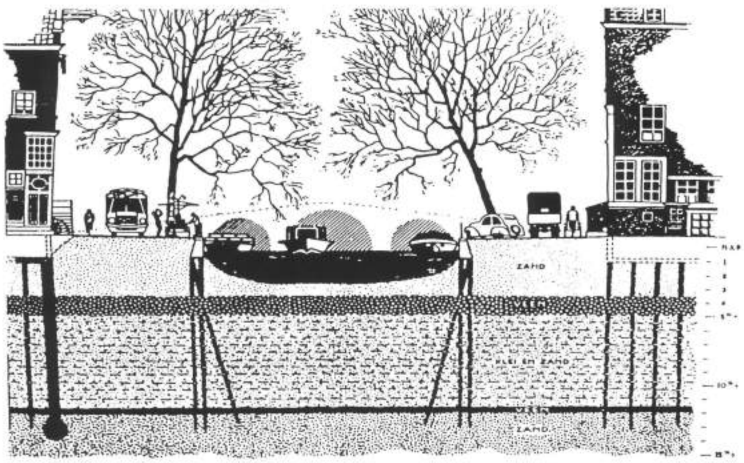


Figure 1.19: Presence of pile-foundations under houses in Amsterdam can be an additional difficulty for underground construction.

Special attention should be given to the heterogeneity of the Dutch soil and the sensitivity of sand formations to softening. It is also essential that one realises that for nearby constructions and pile-foundations not the scour is normative but the potential relaxation of the in-situ ground stresses.
Figure 1.20 shows a good example of an uncontrolled excavation for installation of a pulse-pile. The result was relaxation of the soil stresses, causing damage to nearby constructions. Uncontrolled excavation is the most important aspect with regard to tunnelling and construction in the Netherlands.

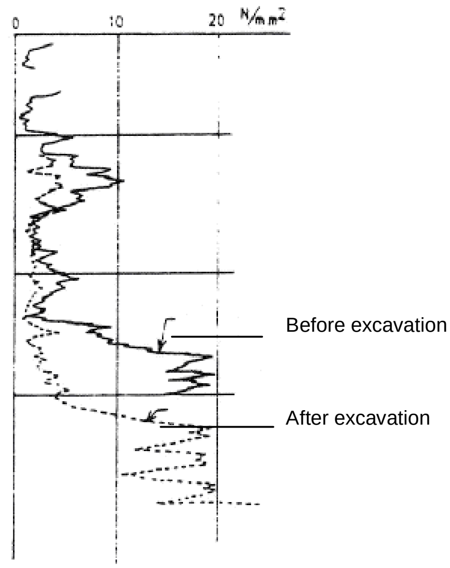


Figure 1.20 Uncontrolled excavation causing relaxation of the ground stresses and therefore settlement.

The Dutch government uses underground construction in order to find solutions for spatial planning problems such as the following:

- Establishing an attractive place for businesses in the “Randstad” (Amsterdam, Rotterdam, The Hague and Utrecht).
- Supporting the so-called ABC-policy of the Dutch government to influence the use of public transport by means of spatial planning.
- Integrating vast infrastructure projects within urban areas.
- Expanding building capacity in cities.

In order to gain information concerning underground construction the COB (Centrum Ondergronds Bouwen) was formed. The COB co-ordinates and initiates research, legislation and the passing on of knowledge gained about the underground. The main goal of the COB is to strengthen the economic position of the sectors involved with underground construction.

Some examples of completed large underground projects in The Netherlands are:

- The parking underneath Museumplein, Amsterdam
- Schiphol tunnel
- Groene Hart Tunnel
- Westerschelde Tunnel
- The souterrain/tram tunnel in the centre of The Hague.
- The High Speed Line. This line is partly under ground and sometimes covered.

Projects currently under construction are:

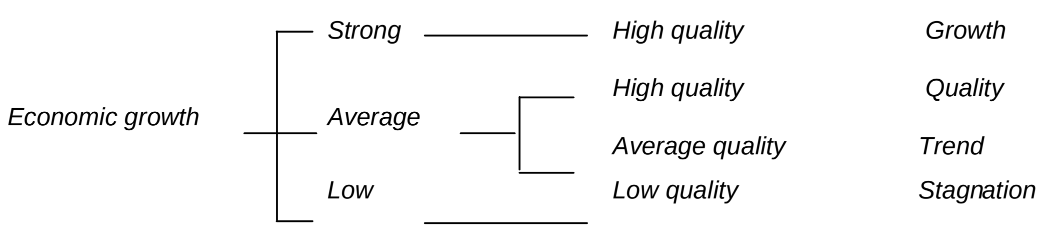
- The second metro line in Amsterdam
- Hubertus Tunnel
- Randstad Rail, a light rail line between Rotterdam, The Hague and Zoetermeer.
- Arnhem Central Station
- Rotterdam Station

2. A strategic view and broad assessment of underground construction

The choice between constructing at surface level or in the underground is a difficult one. An integral approach in the decision making process is essential for finding the most suitable solution.
This chapter will look at future scenarios and the role that underground space technology can play, followed by a broad assessment of underground construction. Finally some conclusions from a strategic study concerning the Dutch situation will be given.

2.1 Different ideas about the future

In order to formulate a strategic view for the future a number of scenarios were identified. The horizon of all these scenarios has been set at the year 2020. Note that these ideas are not meant to predict the future, but merely to investigate the different scenarios. They should be seen as plausible descriptions of the future to make us think about possible developments. Four scenarios are made, all based on different developments.
The main division was based on the difference in economic growth. Then a second division was made, based on quality. This was done because underground construction can contribute in an important way to (spatial) quality (See section 1.4). The diagram below illustrates how the scenarios were divided starting from the key factors *economic development* and *quality*.



Other relevant factors were:

- Economic developments (defining)
- Quality consciousness
- Distribution of labour in various sectors
- Mobility
- Pace and direction of technological progress
- Role of the government
- Compaction
- International developments

The development of these factors was varied from scenario to scenario, in such a way as to ensure that each scenario was sufficiently differentiated from the others whilst maintaining internal consistency. The "Trend" scenario is the only one made through extrapolation of the past. It is therefore possible to compare each scenario with the "Trend" scenario.

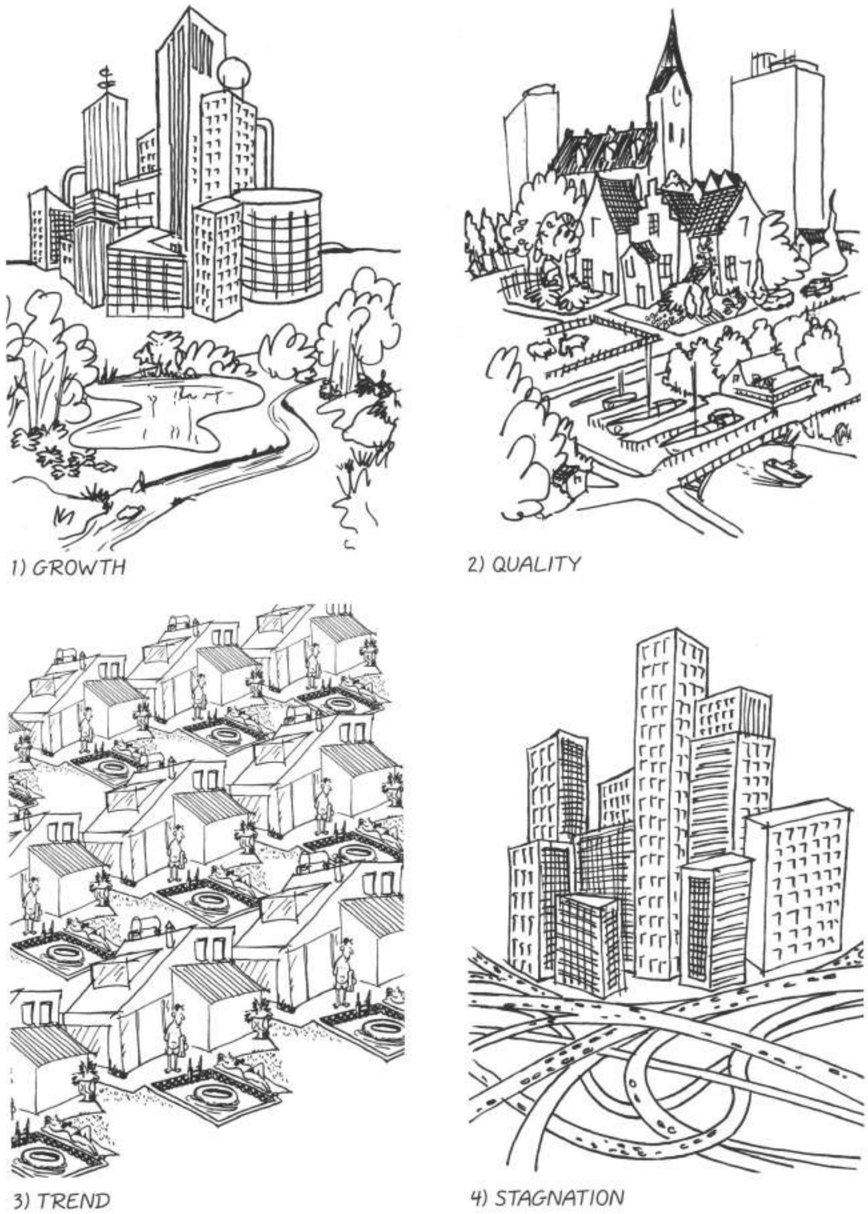


Figure 2.1 The four different future scenarios Growth, Quality, Trend and Stagnation.

The possibilities and preference for underground alternatives have been assessed for the relevant function types with reference to (integrated) criteria for underground construction. These criteria are costs, external safety, liveability for neighbourhood, residents, internal safety, user aspects (perception, functionality etc.) spatial utilisation and environmental impact. Because the possibilities for underground constructions do not only depend on the function but also on the location, a number of relevant location types have been formulated, each with their own characteristic features in relation to *inter alia* population, traffic and urban development.
These location types are:

- Large scale urban areas.
- Historical city centres.
- Residential areas (mixed and mono-functional).
- Business-fields (offices and small industry).

- Large scale industrial complexes
- Main infrastructure and turnover facilities
- Valuable landscape elements and natural areas
- Areas of intensive agricultural and horticulture

2.2 Developments that increase the demand of plural use of the underground.

In the four scenarios, different development has been assumed for a number of factors considered relevant. A strategic analysis shows that the (expected) demand for the use of the underground is different per location-type as well as per function type. A general conclusion from the analysis, with regard to the scenarios, is that the demand for the use of the underground (strongly) depends on the following developments:

- **An increasing quality consciousness**, especially considering higher demands with regard to external safety, liveability and the environment in general.
- **An increasing pressure on the space available**, resulting in a more efficient use of space and the need of condensation. The present growing pressure on urban space makes underground construction more and more necessary.
- **Rising mobility**, causing a growing consumption of space by infrastructure followed by more inconvenience and pollution.

The following developments can stimulate the use of the underground:

- **Strong economic growth**, not only because more money is available but also because economic growth will increase mobility and the need for quality.
- **Technological progress**, resulting in more technical possibilities and increased knowledge along with innovations which may reduce the costs of underground construction (when considered on an integrated basis).
- **An active government**. A strict spatial-, environmental-, and safety-policy along with a spearhead-policy on technique, special investments on infrastructure and more and more experience will lead to more use of underground technology.

2.3 Conclusions of a strategic view

Considering the four scenarios there are some conclusions that can be made. First the general conclusions will be given, followed by specific ones for “Growth” and “Quality”.

General conclusions
Criteria that generally disfavour underground constructions are costs, internal safety and user aspects. Criteria that generally favour underground constructions of a function type are external safety, living conditions for neighbourhood residents and space utilisation.
It is expected that over the coming decades the following facilities shall more often be built underground:

- Transport of goods: transport without vehicles and the storage in busy urban areas because it has a positive influence on the problems of mobility and environment. It also includes the construction of parking-garages if not already done.
- Main infrastructure and turnover facilities.
- Underground storage of oil, gas, waste and dangerous goods. The main reason being safety and also because of the huge advantages for the plural use of ground.

Conclusions concerning “Growth” and “Quality”
The following conclusions can be made:

- In large-scale urban areas, historical city centres and mixed residential areas, transport of goods and people both have important advantages when placed underground.

- In busy urban and residential areas, facilities causing nuisance through noise, smell and possibly safety risks, can be put underground in which case a building at ground level is not necessary. (e.g. shopping centres, laboratories, concert halls, cinema's etc.) Another reason can be the relatively easy way to control the temperature and moisture. (storage, archive)
- When building new crossings for main infrastructure and turnover facilities (transport of goods as well as people), underground solutions are preferable.
- In environmental important areas it is expected that (in the long term) infrastructure facilities will be (partly) placed underground.

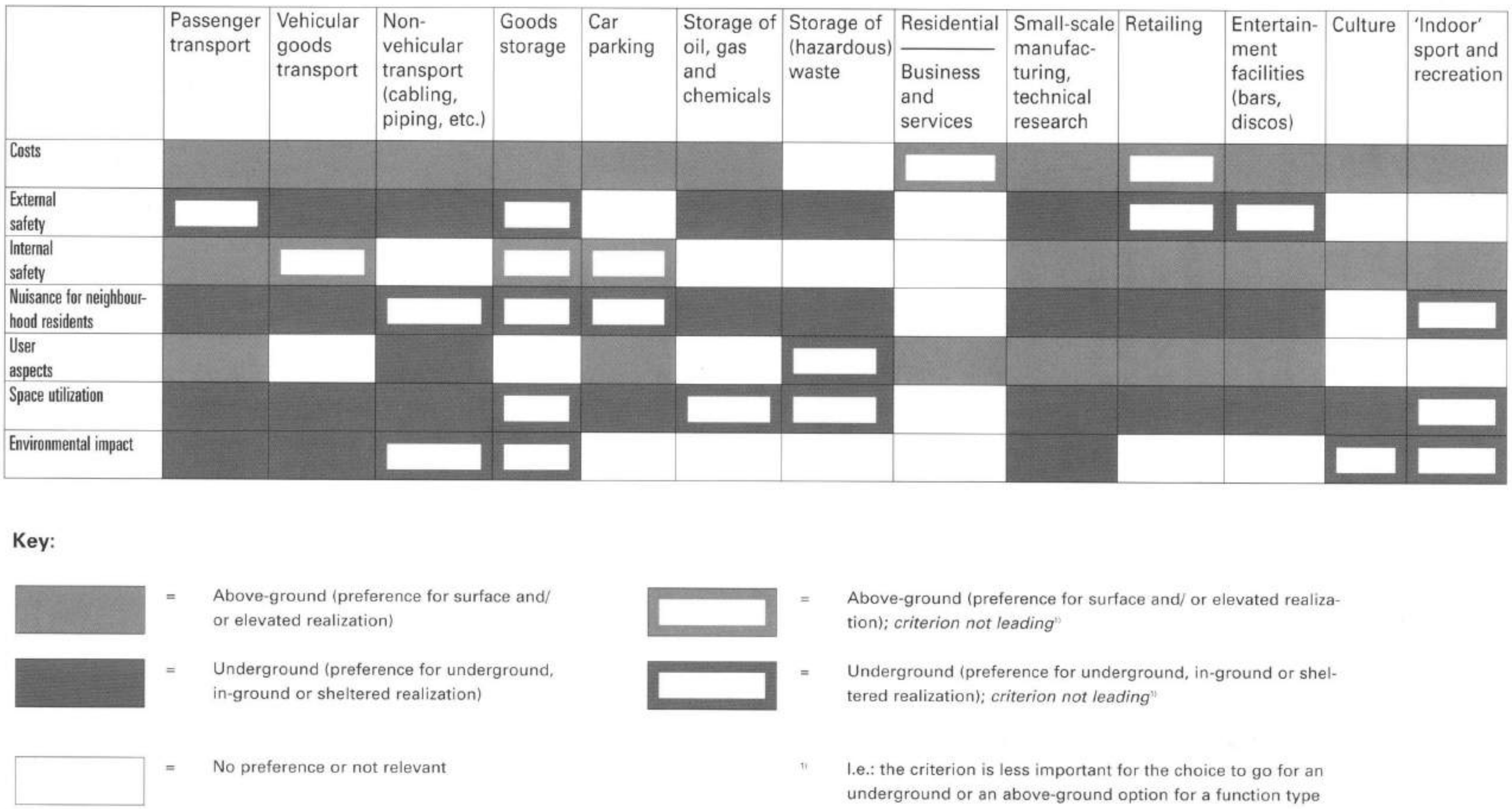


Figure 2.2: Matrix diagram showing expected preferences for the construction mode of function types for each location type on the basis of assessment criteria.

2.4 Feasibility

Whether constructing underground is feasible on a strategic level depends on the social and economic efficiency in the long term compared to the alternative at ground level. Economic feasibility mainly depends on the following criteria: costs, user aspects, space utilisation and the scope for a larger-scale application. The social efficiency is based on the aspects of external and internal safety, liveability, lack of space, the influence on the environment, and the way in which these negative aspects can be reduced or even removed. The difference in weigh between economic and social criteria varies depending on the function type, location type and future scenario.

The economically weak scenarios ("Trend" and "Stagnation") are very much influenced by economic aspects rather than social ones. Now it is especially necessary to make priorities because of the relatively high costs of underground constructions. Alternatives that are considerable even in these weak scenarios are:

- Underground transport in large scale industrious and city areas
- Underground storage (see chapter 7)
- Realisation of a variety of functions on strategic locations to come to a compact city

In comparison to the investments that have to be made, the following options are often quite profitable in a social view:

I: Looking at Underground transport we can think of UTP (Unit Transport per Pipe), OLS (Underground Logistic Systems) and PAT (Pneumatic Waste Transport). These underground systems all move goods unmanned through a system of pipes and assembly points. Depending on their location and certain circumstances they can be an economically viable alternative in comparison to realisation above ground. This is because of the positive side effects such as better quality control and a higher efficiency. A structural approach is needed which can lead to a broad appliance. Furthermore, standardisation is needed which can lead to broad application. These developments can be stimulated by a good policy banning obstructing traffic in certain areas, for instance, and through some profitable financing methods.

II: Underground Storage can be complied with goods (sometimes in combination with transport), waste, dangerous goods, chemicals, water, oil and gas. The realisation of this storage underground can also become an affordable solution in the long term, not only because of the spatial advantages but with regard to quality aspects. Again these developments can be guided by a good policy such as banning deposit of dangerous goods at ground level in certain areas.

III: The condensing of a city in strategic locations through the use of underground construction appears in different ways:
- High quality public transport stations in combination with shops, parking, and storage etc.
- Underground shopping centres in combination with parking, storage, distribution centres etc.
- Underground main infrastructure at the border of and through city areas.
- Underground realisation of parts of functions that can cause hinder and safety-risks for their environment such as small industry and small retail trade, in a way that we can come to a compact city.

A professional approach to condensing cities can make most underground alternatives a good option in an economic and social view. The yield of ground per square meter is an important aspect in this consideration.

If we want to use underground technology on a national scale within an optimal time-scale, we must also think of private finance. The private parties can play a role in the realisation and exploitation of underground facilities. One can expect that in the economic strong scenarios ("Growth" and "Quality") private finance can have an important role. In order to come to a structural approach it is essential that zoning schemes are developed in a broad way. This means that they are made with a long term vision (several decades) and in three dimensions so that all opportunities can be taken into consideration.

To encourage private finance in the economic weak scenario (“Stagnation”) pre-financing by the government in association with a controlled policy in favour of underground technology has to be an option. In order to stimulate private finance a good spear-point policy aimed especially at the economic weak scenarios is needed.

2.5 Weigh in full of underground construction

Despite the advantages with regard to social, environmental, and space organisation aspects, it can still be difficult to find an economic solution for underground alternatives.

Only when space at ground level is very rare can underground constructions be an economic good alternative, though normally the direct costs of underground constructions will be much higher. A broad assessment is therefore an absolute necessity for giving underground alternatives a fair chance. One should not use the traditional calculation models with prefixes, but more a model of thought. Only relevant specialists with high quality knowledge should use calculation methods in order to compute small parts of the thought model.
The analysis should, as much as possible, be a monetary analysis. These analyses should be clear and easy to understand for managers, decision-makers and the public. Another important factor is that the consideration of underground construction has to be objective and neutral. An unrealistic, incompetent or incomplete argument in advantage of underground constructing does not help; it only works against it.
In order to get more information about underground constructing and to come to better solutions more experience and knowledge is needed. Therefore it is necessary to define some pilot projects to gain this information.
The most important factor to remember is that the demands on a broad assessment at a strategic level are different (easier) from the ones made at an organisation level. At realisation level (projects that are already being build) there can be a lot more complications.

2.6 The Dutch situation

Below some of the conclusions of a strategic analysis concerning the Dutch situation are summarised.

International transport corridors
These corridors often require many civil constructions in order to cross all local and regional roads. It is preferable to choose in-ground constructions to reduce hindrance and the extensive use of space. In some cases it is even better to construct parts of the corridor completely underground. The space along the corridor marked as hindrance zone disappears when we put the corridor underground. In that way these areas can be used for other functions such as offices, residences et cetera.

“The Green Hart”
Underground construction can help to reduce the damage to the so called ‘Green Hart’ that is caused by growing spatial demands.

New land
With newly acquired land there can be optimal spatial planning and tuning of both above ground and underground public transport facilities. This can reduce costs and is therefore in all future scenarios a good alternative.

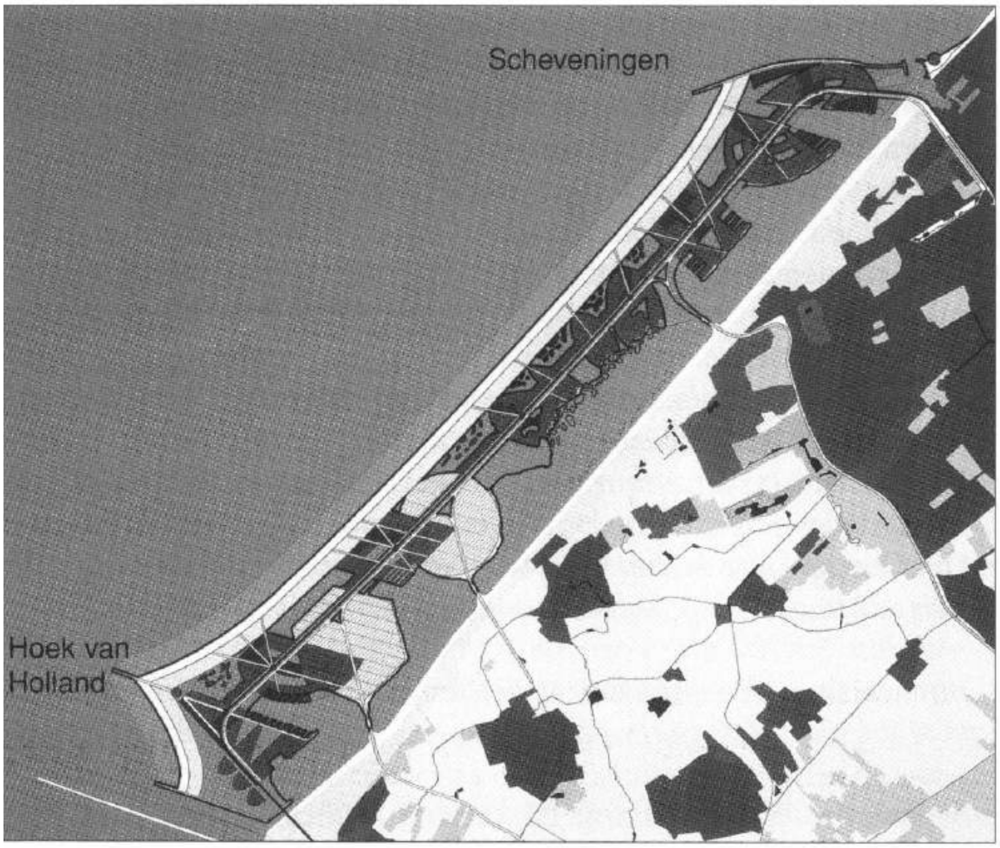


Figure 2.3: Plan for new land at the coast between Hoek van Holland and Scheveningen

Mainports Rotterdam and Schiphol

Efficient use of space in both cases is very important because of spatial constraints. There is also a relatively high amount of budget available because of the high economical potential of these areas. This is the reason why underground alternatives for construction of transport and storage facilities will increasingly take preference over above ground solutions.

Areas with salt-layers in deep soil

Maybe these deep layers can be used for long-term storage of waste and dangerous goods with the option of retrieving them at a later stage.

3. Influences of Geotechniques

3.1 Introduction

The geological soil types and the history of loading influence the characteristics of soil and are therefore very important to the design and construction of subsurface constructions.
Remember that geotechnical influences should always be taken into account when considering sub-soil constructions. The changes that take place due to activities in the subsoil can cause great damages to surrounding buildings.
In this chapter we will look at several geotechnical aspects such as homogeneity, deformations, settlements, safety factors et cetera.

3.2 Homogeneity – Heterogeneity of soil

There is a large chance that there will be great varieties in structure, composition and features of the soil in both vertical and horizontal directions. The conditions can change considerably over a short distance. An extensive soil investigation will increase the level of knowledge and help to reduce risks. Despite of this there is always the possibility that unforeseen situations do occur. Risks related to soil variations can only be reduced by a thorough analysis, but never completely removed.

3.3 Deformations and Settlements

Underground construction always needs excavation. In the hole that is created the construction can be built. The remaining free space causes relaxation of the surrounding ground and needs to be filled up. Furthermore the soil on either side of the hole has the tendency to subside. This can lead to settlement. During the building phase, but also after completion, the construction can be lighter than the displaced groundwater. This can cause floating of the construction, which should be prevented at all times. Groundwater pressures can occur or change due to the excavation process. These pressures can have a great influence on the balance of forces and deformation.

Bored tunnels
It seems that during the boring process excavation and construction take place at the same time and therefore no space between the tunnel and the surrounding ground is created. That is however not the case.
During the excavation process relaxation will occur at the front of the shield, which will cause the ground to subside.
The diameter of the shield is slightly bigger than the tunnel pipe simply because the construction has to be built up within the shield. During excavation, the remaining space between tunnel and soil is filled up with injection mortar. The level of control of this process influences the “tail opening effect” (=staartspleeteffect); which includes the deformation of the surrounding ground, the settlement of the surface, and the influence of these effects on foundation piles.

3.4 Safety Factors

When safety factors are chosen lower than usual, but still high enough to prevent instability/failure, large deformations can occur. Safety factors smaller than 1,4 can be marked as critical. This doesn’t include the uncertainty factors for loads (e.g. 1,3) that are integrated in the overall safety factor.
Example: A safety factor for the ultimate bearing capacity / stability of 1,5 and a uncertainty factor of the expected load of 1,2 gives a overall safety factor of 1,5 x 1,2 = 1,8.

Alternating stresses in the subsurface can be a result of boring, ramming and excavation activities. These activities should be carried out in a controlled way in order to prevent unwanted relaxation and soil deformations. See figures 3.1 and 3.2 for more information.

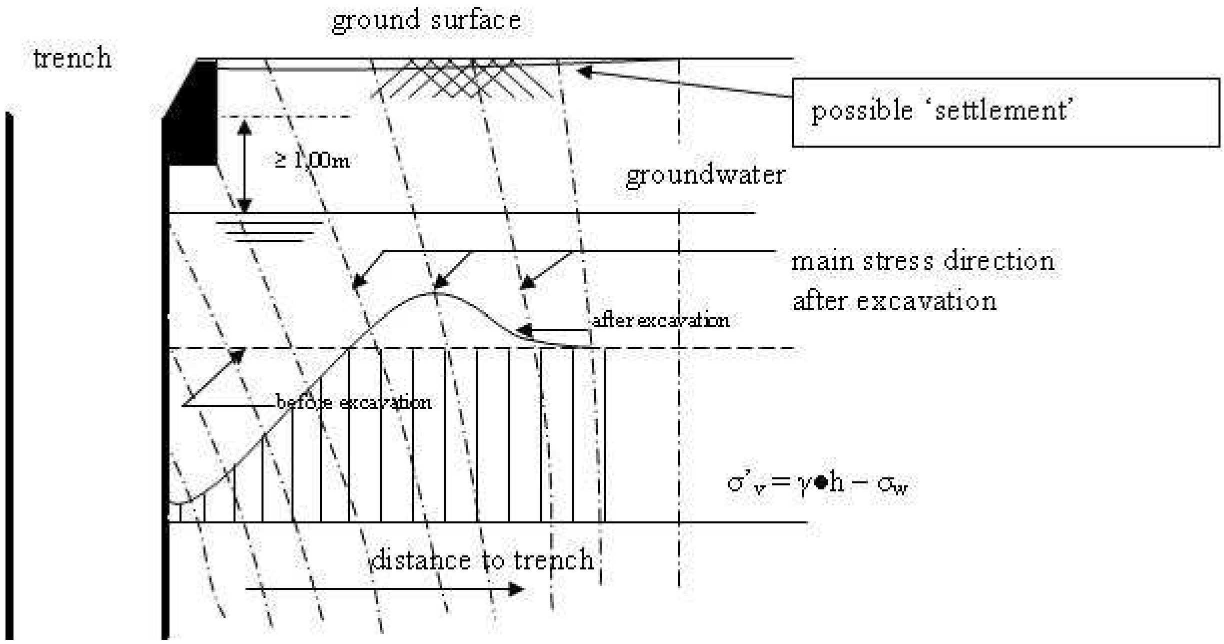


Figure 3.1: influence on alternation of grain stresses caused by a trench

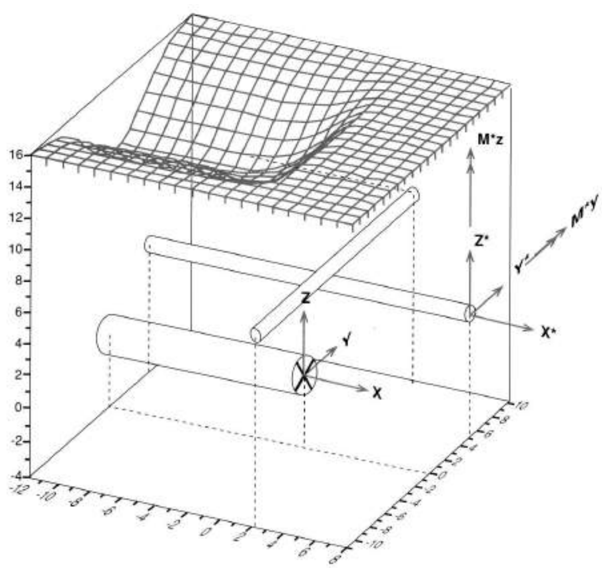


Figure 3.2: Influence on the surface while boring underneath.

3.5 Soil types

Soil types can vary in permeability, strength and structure. For a good understanding of soil behaviour it is recommended to do extensive soil research. This can lead to generalisations that can be used to base decisions on.
Constant processes on earth change the composition of the soil (e.g. erosion and rock destruction, and the formation and deposition of sediment). The erosion and geological processes have a great influence on the characteristics of the soil. A great variety of soil types have been formed in the millions of years of the earth's history. Ground types also vary because of pure local features such as inclined surfaces, cavities and artificial disturbances. The typologies of soils are based essentially on grain size. Three types of deposits can be distinguished, based on the mechanism by which they were created:

Glacial deposits
Deposits of rock material were eroded and deposited by glaciers during the Pleistocene. The debris that is carried by a glacier is deposited when the glacier starts to melt. Boulder clay originates from the melting process of a stationary glacier. Such a glacier contains a wide variety of particles, from rock to clay particles. In front of the glacier there are meltwater deposits. These are more uniform in size and shape. The size of the particles that are deposited at a certain location depend on the rate of flow of the melting river.

Wind deposits
The deposits can be divided in dune deposits, cover sands and loess (löss). The dune deposits and cover sands consist of soil particles with similar size and shape. These Eolic soils are therefore sensitive to erosion by running water and wind. Slope erosion in loess soils can be prevented by applying vertical drainage. Ten percent of the earth's surface is covered with loess.

Alluvial deposits
Alluvial deposits are created by rivers and consist of a variety of soil particles such as silt, clay, sand and gravel. These soil types show a great variety of characteristics.

3.5.1 Rock soil

Rock is mostly formed from silicates (compounds of oxygen, silicon and other elements). Rock can show extreme variations in characteristics. The characteristics depend on the following factors:
- The mineral of which the soil consists and its characteristics.
- The structure (special attention should be paid to weaknesses and the interlocking of particles).
- Layer structure and the interaction of various layers.

Strong Rocks	Weak Rocks
UCS > 100 MPa	UCS < 10 MPa
Little fracturing	Fractured and bedded
Minimal weathering	Deep weathering
Stable foundations	Settlement problems
Stand in steep faces	Fail on low slopes
Aggregate resource	Require engineering care

UCS:
Unconfined (or unaxial) Compressive Strength: load to cause failure to a cube of the material crushed between two flat plates with no lateral restraint.

In rock soil there are two main methods of tunnelling; explosives and machine-boring.

Explosives
Explosion is a chemical reaction whose propagation speed exceeds the speed of sound. The power that is developed is considerable. The effect of explosives is twofold:
- A shock wave is created by the sudden release of energy. This shock creates a crushed zone, in a radius equivalent to that of the hole, and a fractured zone with cracks extending up to 20 or 30 times the diameter of the hole. The shock produces a compression wave in the rock, which is then reflected back from the free surfaces of the mass, thus subjecting the rock to fraction forces.

- Pressures develop as a result of the gaseous discharge. A considerable quantity of gas (1000 vol. gas = 1 vol. dynamite) is released in a small open space. The pressure on the rock is therefore increased.

There are a number of risks associated with this method that have to be considered. Depending on the rock conditions blasting can have more or less effect than expected. Research and monitoring should always be done.
Blasting causes uneven rock fall, which means that the created profile does not match the theoretical shape. Depending on the difference between actual and desired shape there is more concrete needed for the lining than necessary. These quantities can be considerable, resulting in additional costs. Blasting also creates cracks, which spread through the rock mass around the work, and can thus affect stability and water resistance.
Finally the blasting method creates ground vibrations, which can affect or even cause damage to nearby buildings.
A few solutions for these problems are:

- The layout of the blasting pattern has a large influence on most effects and should therefore be well considered.
- ‘Pre-splitting’, simultaneously detonating rather small charges in parallel bore holes located close to each other. This creates cracking only in the same plane as the bore holes. Thus a cylinder is created along the axis of the tunnel.
- Mechanical pre-cutting consists of using a cutting machine to make the plugs where the explosives are to be placed. It has been found that the biggest vibrations occurred blasting the plugs. This method therefore reduces vibrations, cracks and the amount of explosives needed.

Tunnel Boring Machines
Boring machines are an attractive alternative to explosives as they offer more rapid excavation. They can be used in zones where explosives are dangerous or even prohibited. Problems resulting from rock-drill noise, compressor usage and vibrations are prevented. The advantages are accurate cutting of the ground and thus fewer over-excavations, increased stability and no disturbance of the ground. There are two basic types:

- *Partial face machines*: These machines cut out the section in several stages. The advantages are: high efficiency, easy use and mobility, relatively small size, low costs.
- *Full face machines or Tunnellers*: These machines cut out the whole section in a single operation. In hard ground tunnelling machines usually include a circular plate or head that is equipped with cutting tools. These vary from simple spikes (soft ground), tungsten carbide, or cutting rollers. These machines require high investments and are quite large.

3.5.2 Soft Soil

The main problem when tunnelling in soft ground (clay, gravel, sand, mud) is that the ground above weakens and tends to sink, thus filling the excavation in progress. This causes settlement in the upper layers and the weakening of the tunnel walls. The presence of water aggravates the situation. See also paragraph 3.9: The Dutch situation.

3.5.3 Intermediary soil

Apart from the two extremes rock and soft soil there are several combinations of the two, called intermediary soils. This ground can cause problems during tunnelling as a result of changing parameters and large local differences in the underground (e.g. boring in soft soil that holds large boulders).

3.6 Soil Investigation

3.6.1 General Information

Soil investigation is an important component of underground construction projects. In smaller projects especially (e.g. trenchless technology projects) soil investigation does not always get the attention it needs. The soil investigation should be planned and carried out with the focus on the project and its specific problems.

If more characteristics of the soil and groundwater are measured the soil investigation becomes more reliable and efficient. Using not only ground-mechanical and geohydrological characteristics but also geophysical aspects will increase the reliability of the results.

Knowledge of the history of events in the project area can save considerable amounts of time and money. The following example illustrates this fact. A bored tunnel project is carried out underneath an open field. The tunnel boring machine gets stuck at a certain point for unclear reasons. After investigation it is discovered that the TBM has encountered an old construction in the underground (e.g. a bridge foundation). When an historical investigation would have been carried out this would have been known and measures could have been taken.

The amount of soil investigation should be sufficient and be determined by an analysis of the risks and the associated costs. This requires logical thinking and sound investigation. More specific information can be found in literature on soil investigation in general.

3.6.2 Standard Penetration Test (SPT)

The Standard Penetration Test is a well-known test in the world, especially in the United States. A steel tube is hit into the ground. The number of hits needed to get the tube 1-foot in the ground is a value for the soil condition. (the so-called N-value). The advantage of this technique is that along with the N-value also a sample of the soil becomes available. A disadvantage is that the SPT is less accurate than the CPT. There are tables that compare SPT values with CPT values; these are however not very reliable.

3.6.3 Dutch Cone Penetration Test

The Dutch Cone Penetration Test is a test developed in The Netherlands for its soft soil conditions.
While a cone is pushed into the soil resistance of the soil is recorded by measuring the required pushing force. The cone-resistance at the tip of the cone as well as the friction of the soil on the shaft of the cone is measured. The cone is hydraulically pushed into the soil from an anchored or weighted vehicle. With a piezocone the water pressure during the penetration can also be measured. By doing so small clay-layers can be detected, since they often hold over pressured groundwater.
The CPT measurement gives general information about the stratification of the ground and an indication of the failure and deformation features of the soil.

Difficulties associated with CPT:
- The cone should regularly be calibrated and maintained.
- The penetration test should be done accurately.
- The cone can have aberrance so the penetration is not pure vertically.
- If the ground has a great stratification the interpretation becomes very difficult. Doing a bore-test right next to the penetration is than recommended. A relationship between the two tests can then be drawn.
- The relation between the friction number and the soil type is only usable in case of natural homogeneous deposited layers above the groundwater level.

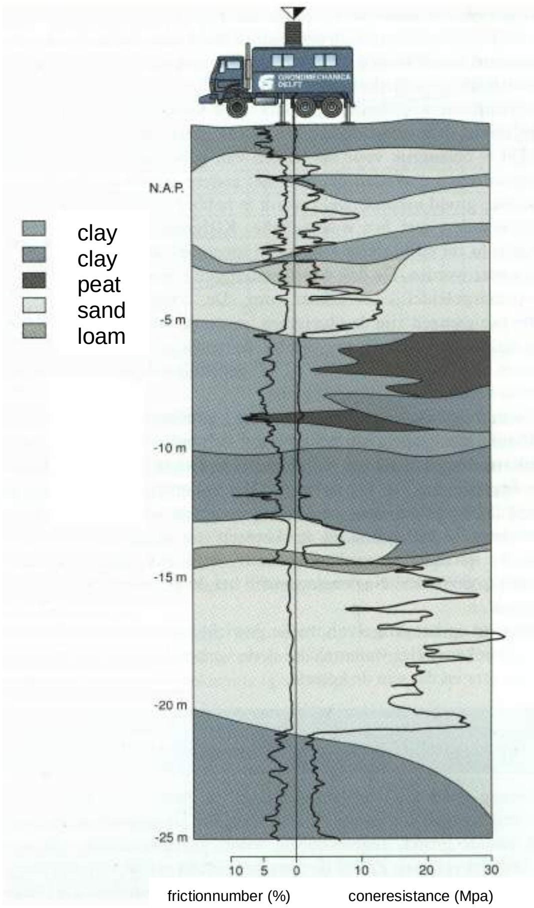


Figure 3.3: Example of a Cone Penetration Test

3.7 Groundwater

Groundwater has a great influence on the subsurface. In construction projects it is important to know the highest water table that can be expected. This can be determined by looking at the history of measurement data. The most important hydraulic factors that influence groundwater levels are:

- daily precipitation (rain, snow)
- seasonal evaporation
- tidal movements

When designing and constructing subsurface constructions the following considerations associated with groundwater should be taken into account:

Water pressure

The groundwater level, the water pressure in the pores and the composition of groundwater can vary greatly. These parameters can differ from place to place and through time (sometimes over very short periods). These changes are sometimes caused by a third party.

Groundwater flow

When a construction is built in the underground the flow pattern of the groundwater should be examined. This flow pattern depends on the structure of the different soil layers. The characteristics of these layers can differ greatly, resulting in unexpected flows of groundwater.

Differences in capillary rise

In The Netherlands there are several discharging layers confined by low permeable layers, even at small depths (<25m). A tunnel construction can disturb these layers. This can create a shortcut in the flow of groundwater. This can have undesired consequences such as additional seepage in a polder or the formation of brackish water.

Construction as barrier

It is possible that the construction forms a barrier for the groundwater. Due to this the water pressure can build up next to the construction or the flow pattern can change. These effects can cause damage to surrounding buildings and the structure itself. For example piping under or over a subsurface construction can occur, resulting in large soil deformations. A drainage system can solve these problems.

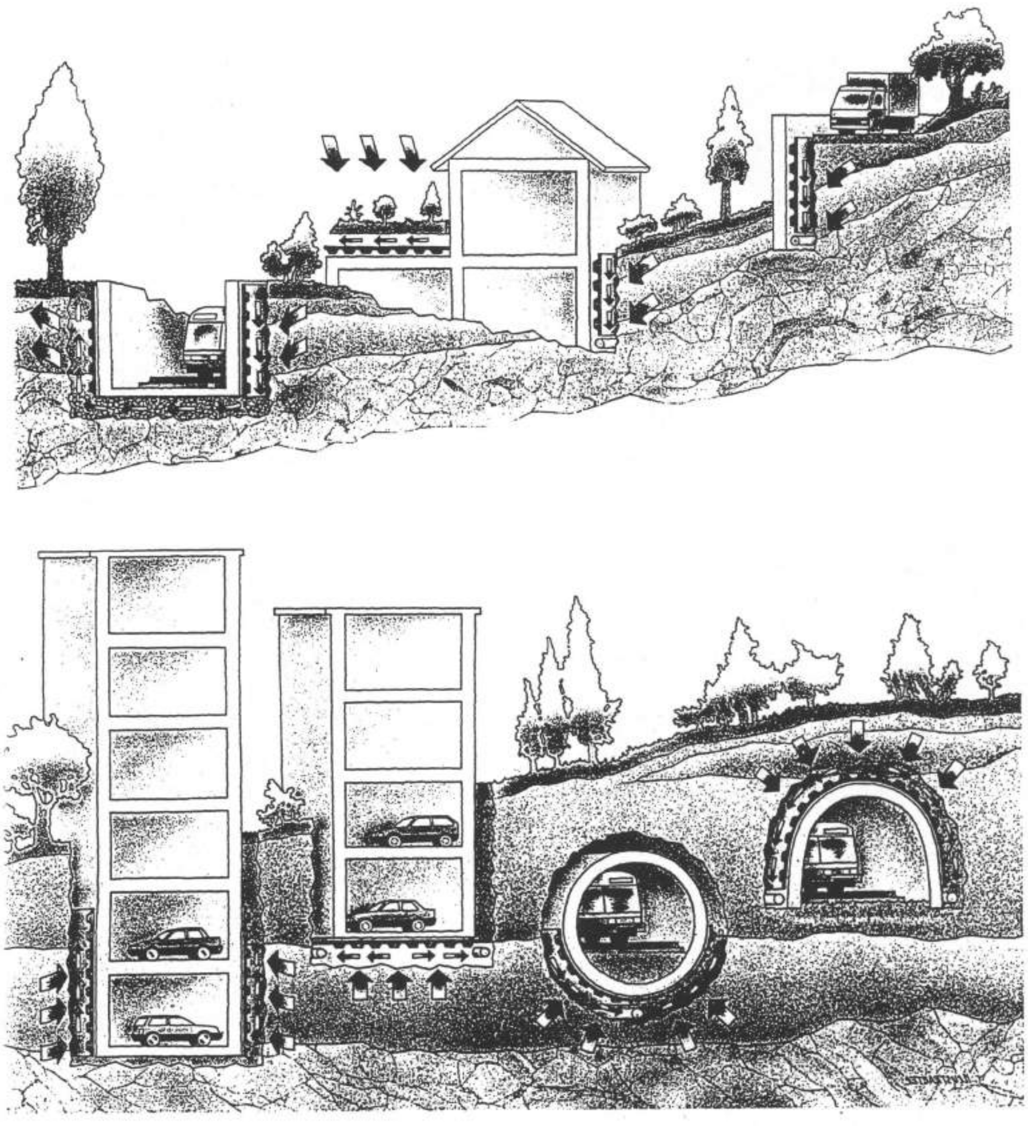


Figure 3.4: Protection against groundwater often forms a barrier for water flows.

Buoyancy of a construction

In The Netherlands the groundwater table is often located close to the surface level. This results in high upward groundwater pressure, which can cause a tunnel or pipe to float upwards when it is not heavy enough. Sufficient soil cover above the structure can provide enough weight to solve this problem (see figure 3.5).

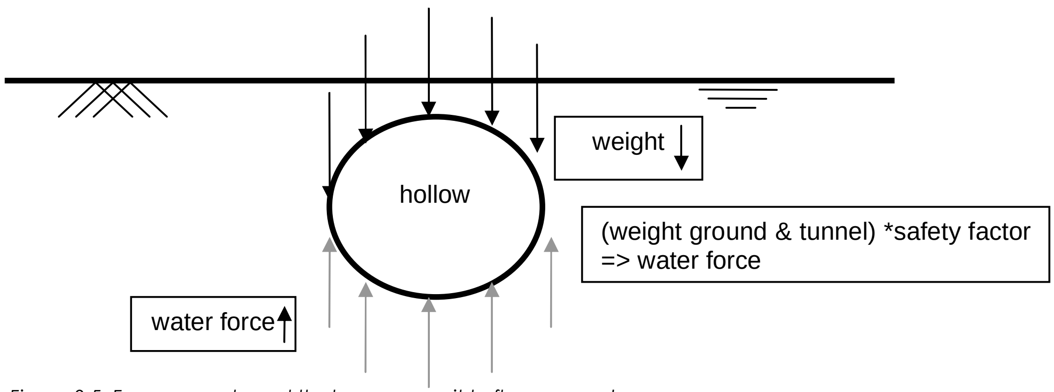


Figure 3.5: Forces on a tunnel that can cause it to flow upwards.

Saturation and liquefaction
Loosely packed grains in sand formations (pockets) are sensitive to saturation and liquefaction. Vibrations, ground removal and ground deformations can result in an increase in pore volume, which can result in saturation or liquefaction.

3.8 Soil Improvement

When soil conditions, for some reason, are considered unfavourable the soil can be improved. This allows for alteration of soil properties, which become better suitable for the desired construction. This improvement can be done in several ways. The listing of injection methods below is not complete, only the most important techniques are discussed.

Injection of the underground
Structure and permeability of the ground, and its variations, determine the possibilities for application of injection methods or other ground improvement techniques and the reliability or quality of the work. Depending on the injection liquid, the granules are cemented together especially for stabilising the soil (improving stability and strength) or the pores are filled to form a seal (improving watertightness). To do this injection pipes are put in the ground in a defined pattern.
Another way an injection in the ground can improve soil conditions is by freezing the ground. This technique is useful if the permeability of the ground type is low or strongly varying. Note that freezing is only a temporary solution, which can be useful when the soil conditions are only required during the construction phase.

Figure 3.6: Example of soil injection for soil improvement.

Permeation grouting

This technique is based on the fact that the pores are filled with an injection liquid. This process is better suited for coarse soils (rock/gravel).

The injections (grouting) should first be made with the most course-grained injection liquid, which lessens the permeability. The finest liquid is afterwards used to make the seal 'complete'.

Jet grouting

Jet grouting can be used in all kinds of soil with the exception of peat. Peat has unfavourable elastic characteristics that can cause the grout pillar to constrict after completion of the grouting process.

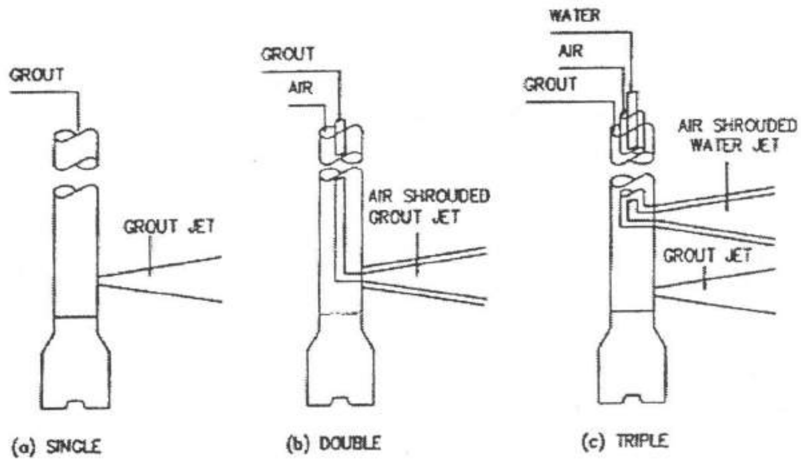


Figure 3.7: Different ways of grouting

All grouting methods are based on the principle of putting a jet pipe in the ground by using a bore-machine. This jet pipe cuts the soil and inserts a cement mix. The process can be executed with 1, 2 or 3 pipes:

1-phase: In this system the cutting jet is combined with the filling jet

2-phase: Two separate bore-pipes. The ground is first cut with a forceful water jet and than mixed or filled with a less forceful cement jet. The advantage of this system is the improvement in the effectiveness of the grout jet

3-phase: Three different bore-pipes for grout, water and air. The advantage of this system is the better mixture of the grout and soil.

Fracturing

Fracturing is also called hydrofracture grouting. A fracture area is created in the soil by putting in large amounts of grout under high pressure. This technique is used to jack up settlements. It is necessary to monitor the process carefully. If the settlements are not equally compensated there could be disastrous consequences for the structure above.

Compaction grouting

Soil is compacted by displacement around the injection point by grout. The soil is compacted and clamped. This technique is used to undo settlements developed due to consolidation, relaxation due to excavation or loss of form due to the boring of a tunnel.

Mechanical Mix in Place (MMiP)

A twist drill is put in and out of the soil. During this operation an injection-liquid is put in under high pressure through the hollow core of the twist drill. A soil-ground mixture is formed in this way. By making pillars next to each other walls can be formed.

Application	Permeation Grouting	Jet Grouting	Compaction Grouting	Fracturing	Soil Mixing
Waterproof horizontal layers, recovering and creating	++	+	--	--	-/+
Impermeable walls to prevent soil-pollution	++	++	--	--	-/+
Constructive wall	-/+	++	--	--	-
Building pit walls/ temporary earth retaining construction	-	++	--	--	-/+
Underground building pit stamping	++	++	-	--	--
Deepen cellars	++	++	--	--	-
Bearing power improvement of the foundation	+	-	++	-	--
Pile foundation (afterwards)	+	++	--	--	--
Little soil improvement	++	++	--	--	++
Settlement compensation TBM	--	--	++	+	--
Settlement compensation building pit	--	--	++	-/+	--

Figure 3.8: Possible applications for different injection methods

3.9 Dutch Situation

3.9.1 Introduction

Layers of eroded material were deposited in the past in the delta of large rivers. These layers are often very soft. This has influenced the possibilities for building in these areas. The soft soil conditions require specific attention to subsurface aspects such as foundations. In The Netherlands a high water table complements the soft soil. This combination provides difficult conditions when constructing in the underground. The stability of the soil is very low and there are great soil variations in horizontal and vertical direction.

3.9.2 Geological structure

Rock occurs in The Netherlands at a very deep level. The top of the rock deposit is at 200 to 300m depth; this forms the bottom of the Dutch basin. On top of these layers of rock there are sediments from the Pleistocene and Holocene.

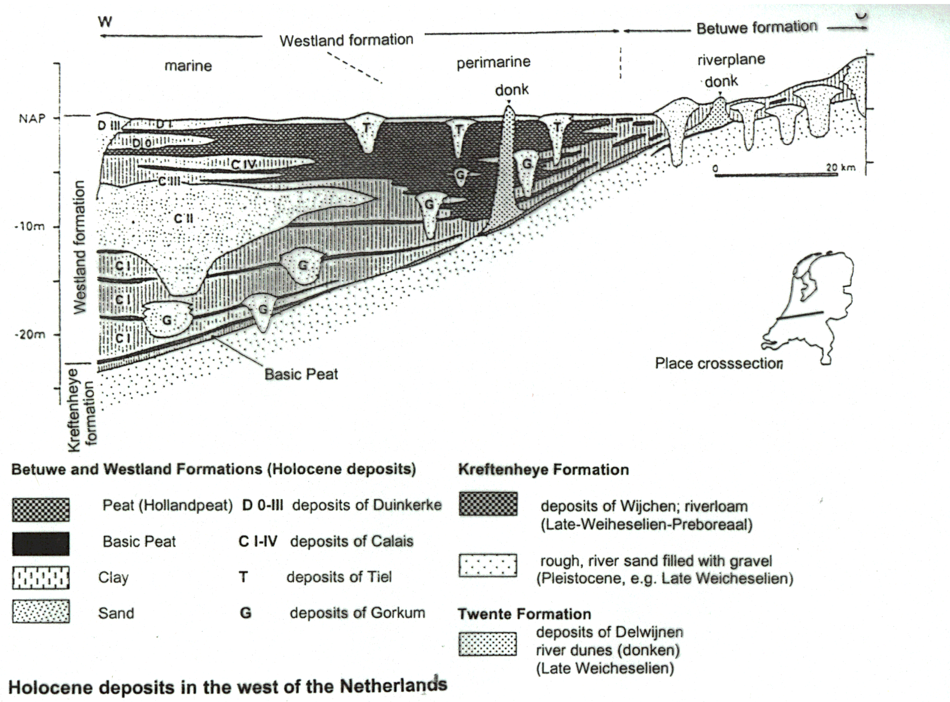


Figure 3.9: Schematic cross section of Holocene sand layers in The Netherlands

Pleistocene

Pleistocene layers are formed due to the supply of soil material by the big rivers, the sea, and land ice. The biggest influence on this was the climate during the settlement process. The climate has undergone great changes when looking at the geological time scale.

The coarsest deposits were formed during the coldest periods before and after Ice ages. The clay layers were formed due to settlement of the finest sediment of the sea or the riverbeds. The level of the sea was not constant. Final settlement of both fine and coarse material occurred due to the changes of the coastline. The sediment deposited on the edge of the Pleistocene consisted mainly of sand and therefore this forms a good layer to place a foundation on.

The occurrence of gravel layers, due to river deposits, in the Pleistocene sand can cause great problems for boring tunnels and making diaphragm walls. The Pleistocene deposit is highly permeable and this can cause a large water nuisance in case of pressure de-watering.

In the west of The Netherlands the top level of the Pleistocene layer is at 10 to 20 meters below the surface. Due to the weight of the land ice Pleistocene layers in the east and north of The Netherlands can be overconsolidated. This aspect caused changes to the characteristics of the ground, such as a higher cone-resistance and a higher (neutral) ground pressure.

contour lines of the top of the pleistocene layer in meters beneath NAP

Pleistocene around the surface

River area with local riverdunes

Top sandlayer

Figure 3.10: Altitude of the upper Pleistocene sand layer

Holocene

The top layers of the soil consist of layers that were deposited during the Holocene. During the Holocene the sea level rose due to higher temperatures. The groundwater table became higher and caused, together with available vegetation, the forming of peat. Layers on top of this later compressed the peat. Many different factors caused different deposits. These therefore vary in thickness, structure, and type. All these factors caused a complicated structure that can change easily in any direction. A thorough soil investigation is therefore recommended. This applies also to peat soils situated away from the coast or rivers. Local deposits near the surface can occur everywhere. A geomorphological map can indicate the soil type.

3.9.3 Geohydrology

The pores between the grains of soil can be filled up with water, depending on the availability of water and the depth. This is called groundwater. Also above the water table there can be water in the soil due to the capillary rise. This can have an important influence on subsoil structures. The water table in The Netherlands is, as already stated, generally very high.

When planning a subsoil structure one should make a clear overview of the geohydraulic situation. Studying map material, making a water balance, and conducting research to find out the geohydraulic features of the soil are ways of doing this.

In The Netherlands there are two main types of groundwater flow:

- Infiltration areas where the groundwater is supplied by precipitation (rain, snow etc)
- Seepage areas with over pressured water beneath an impermeable layer. The seepage depends on the difference in capillary rise of water in the layers and the resistance of the layer (permeability).

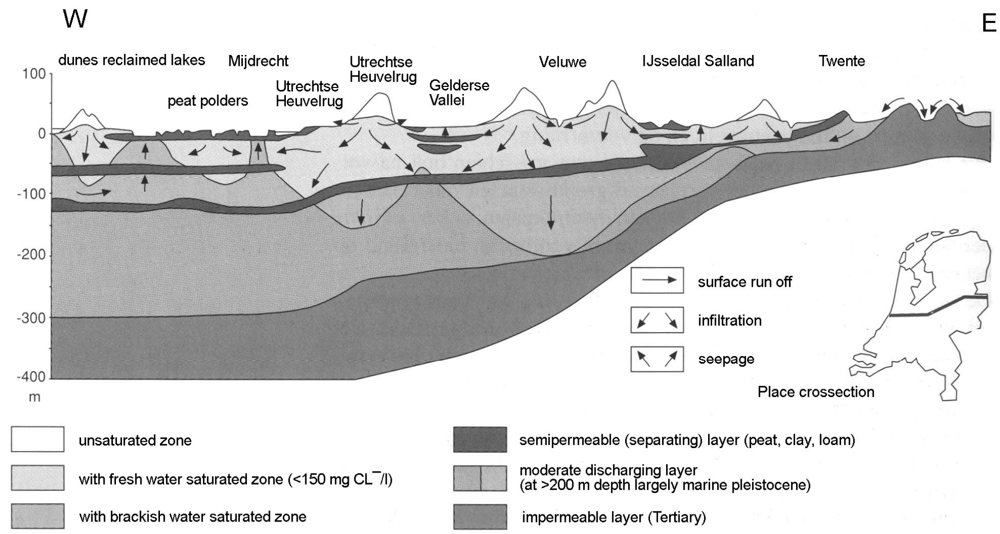


Figure 3.11: East-west cross section of the Netherlands

The groundwater flow takes place mainly in the highly permeable Pleistocene sand deposits. Water-resistant or low permeable layers (clay and loam) separate the discharging layers. In the lowest layers there is only vertical transport of water. Old sand beaches and sand fillings in trenches can form local groundwater flow layers in clay.

Some examples:
In the south of The Netherlands there is a water-resistant layer at several dozen meters below the surface from Kedichem to Tegelen. In the north there are separating layers of glacial clay, Eemien clay and Pot clay. In the west the permeable layers are covered with low permeable Holocene top layers (clay and peat). In the east groundwater flow layers occur on small depths; they are locally covered with fine sand deposits. In Brabant (in the south of the Netherlands) these layers are covered with loam and in the north with boulder clay.

Polder
The western part of The Netherlands mainly consists of polders that have been reclaimed from the sea. These man-made areas result in specific conditions. In polders the groundwater level is kept artificially low, which can result in seepage. The groundwater can be brackish when the polder is located close to the sea. The presence of salt water can cause damage to the polder environment; this situation should therefore be prevented.

Specific Soils
There are some soils that have characteristics that can cause difficulties when building a subsurface construction. Some potentially problematic soil types are listed below:

- “Boomse klei”
- Stiff clay
- Loose sand
- Loam
- Big stones
- Peaty soil
- Banks of shells
- Thick sandlayers

4. Risks

4.1 Introduction

Before risk analysis can take place it is necessary to understand the concept of risk. A common definition of risk is:

"Danger for damage or loss, the dangerous or wrong chance or chances, which will happen"

In the definition, a chance and a result (damage or loss) are mentioned. However, the accent lies on chances when performing a risk analysis. Quantifying and comparing the risks only based on chances is, however, not realistic. For example, a 50 % chance of a loss of 100 Euros is a risk of a different magnitude than the 50 % chance of a loss of 1000 Euros. Among risk analysts there is no unanimous definition of risk. More definitions of the term risk are common, which will make a quantitative analyse possible. Four of the definitions are:

- Risk is the chance of an undesirable event taking place by a process or object;
- Risk is a result of an undesirable event;
- Risk is probability times consequence;
- Risk is the function of chance and result.

The first two definitions are not useful for the general case. The risks, which differ from small chances with extremely large results to large chances with small results, will not find expression in the use of the first or second definition.
The third definition gives a better base for the comparison of risks. In fact, an expectation value of the result of a process will be determined. In some cases this is the same as the loss, which will become deterministic on the long term. The chance of an undesirable event and the result of this event are both important in this definition.
Chance is dimensionless; this means that the dimension of the risk will be the same as the dimension of the result. This is quite logical since the effects of an undesirable event are often more dimensional (e.g. material damage, injured persons, fatalities, human sorrow). Because of this the actual risk can not be expressed in one number.
The last definition of risk is the most general definition. In fact, the first three definitions are special forms of the fourth. With this definition, it is possible to lend weight to the result of an undesirable event, which is dependent on the seriousness of the result. This is especially important with small chances and large results, at which a definition of a deterministic loss in a long term will not obtain.
The result of an undesirable event can be either deterministic or stochastic. When a stochastic result is considered, a probability-density-function for the risk can be defined, of which the expected value can be determined.
A risk analysis can be used for many purposes, e.g. testing the safety of a norm or economic optimisation of certain processes and objects. The general purpose of risk analysis is to provide a base for rational decision making.
When new norms are developed it is important that these meet the results of a risk analysis. Safety aspects are laid down in a national safety policy, which contains norms related to safety. Processes and specifications of objects have to be re-adjusted when different norms become available.
By an economical optimisation the costs of the process, or the object in coherence with the risk, are important. However, the risk has to be expressed in a monetary unit. Minimising the sum of the cost of realisation, preserving the process or object, and the risk are usually important for such analyses. The limit for the risk is not laid down in advance in such analyses.

4.2 Circumstances that lead to damage

Risk is the function of chance and result, as written before. This usually results in a value for the damage done to the construction or its surroundings. The following circumstances can lead to such damage:

1. Incomplete or inaccurate soil investigation
2. Disruption of the natural composition of the soil
3. Large forces or vibrations created by machinery
4. Break down of machinery
5. Deviations in steering in case of bore-techniques
6. Curve corrections due to the above deviations
7. Personal injuries (personnel / third parties)
8. Bad communication between designer and contractor

Ad. 1
The soil investigation consists mainly out of soundings and probes. This is not sufficient. Historical data is also needed, such as:

- Geological data
- Glacial periods
- Former course of rivers
- Former buildings

Extensive soil research should be done, especially in cities. The costs of the investigation are small in comparison to the costs that could arise when certain events take place.

Ad. 2
In cities there is hardly any undisturbed soil (foundations, historical objects et cetera).
Ad. 4
To prevent machines from breaking down, maintenance is necessary and should also be taken into account. Reserving certain hours or days of the week for maintenance of machinery can prevent a lot of problems.

Ad. 5 & 6
Always look for the reasons of the deviation. It is important to understand the interaction between soil and machinery. The soil reacts to the drilling of the machine. It is possible that the soil characteristics could change so much that the machine should be changed to prevent undesirable events.
An example of conditions that can quickly change: some clay soils have the characteristics of being very stiff. However, as soon as water is added they become very soft, which can give enormous problems during construction.

Ad. 8
There are often problems that occur during the execution phase of a project. The designer does not always realise which problems can occur and which processes take place during execution. Optimising communication between designer and contractor can prevent problems and reduce costs.

Other circumstances that can lead to damage are:

- Not knowing what to do when the initial damage threatens to cause damage.
- Incorrectly determining the failure chance, consequences and correction measures. It is possible that the used theoretical models do not work in these specific conditions.

4.3 Responsibilities for damage

For underground construction projects the risks are always larger than for similar above ground projects.
An important question during the early project phases is: "Who should take the responsibility and thus the risks?"
Different answers are possible, such as:

1. The future owner / operator / client, the one who is paying for the project
2. The designer
3. The contractor (Implementation)
4. Insurance (CAR)

The client asks for a certain construction. He has set functional requirements such as the dimensions and the lifetime of the construction. This should be translated into a design by the designer. When calculations are made the designer must use certain assumptions, which can be difficult and become a risk.

The **right assumptions**!

Sheet-pile walls

If one places a sheet-pile wall, different lengths can be chosen.
a. long
b. less long
c. short

The cheapest design is the best design.

Considerations:

- The construction should not fail
- Deformations and deflections should be looked at.
- If there are no constructions in the vicinity that can be affected due to settlement of the ground (due to movement of the toe of the retaining wall) the retaining wall can be short

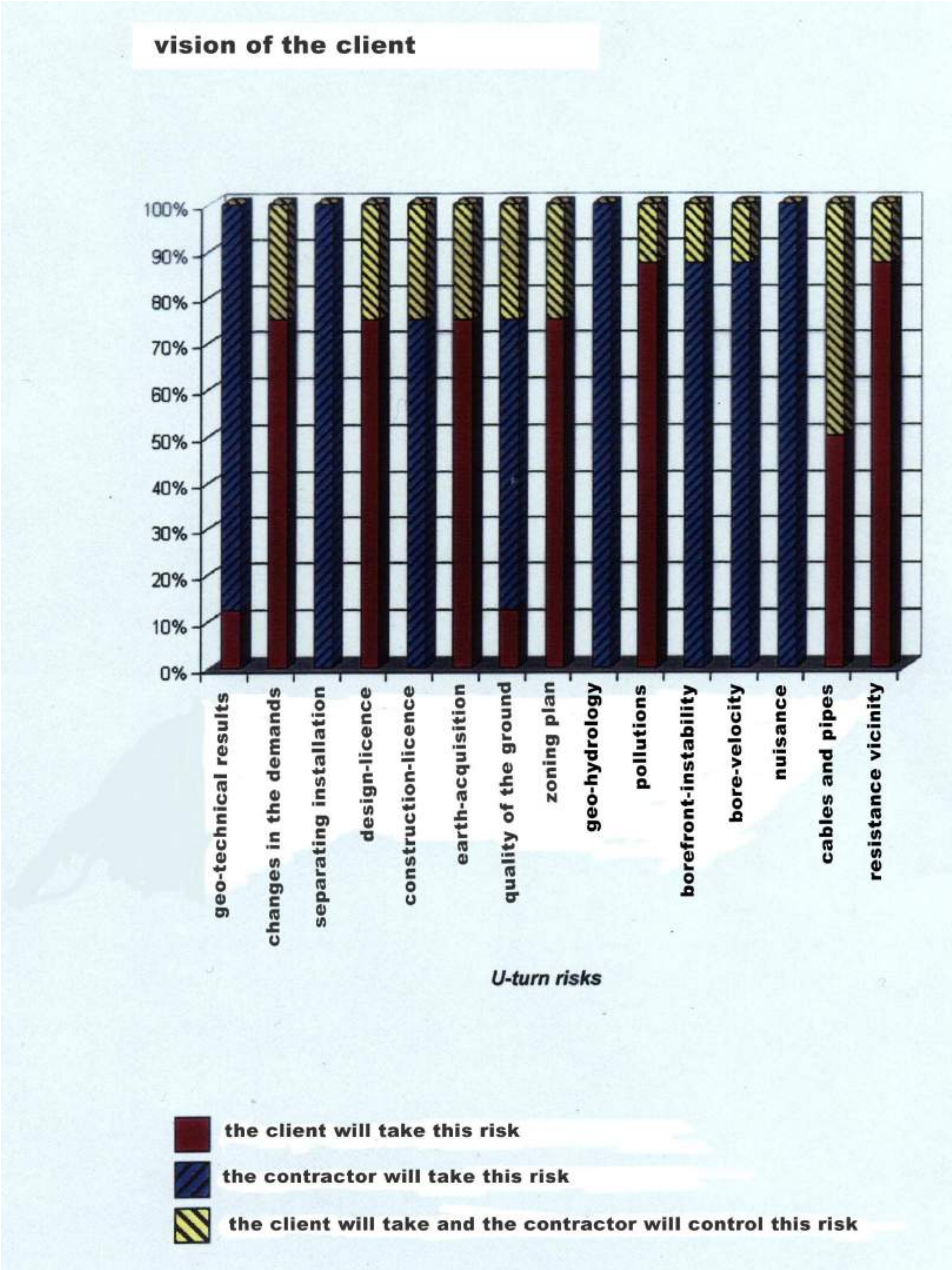
The Impact on φ:
Normally φ is about 30º - drilling 35º Density gets greater

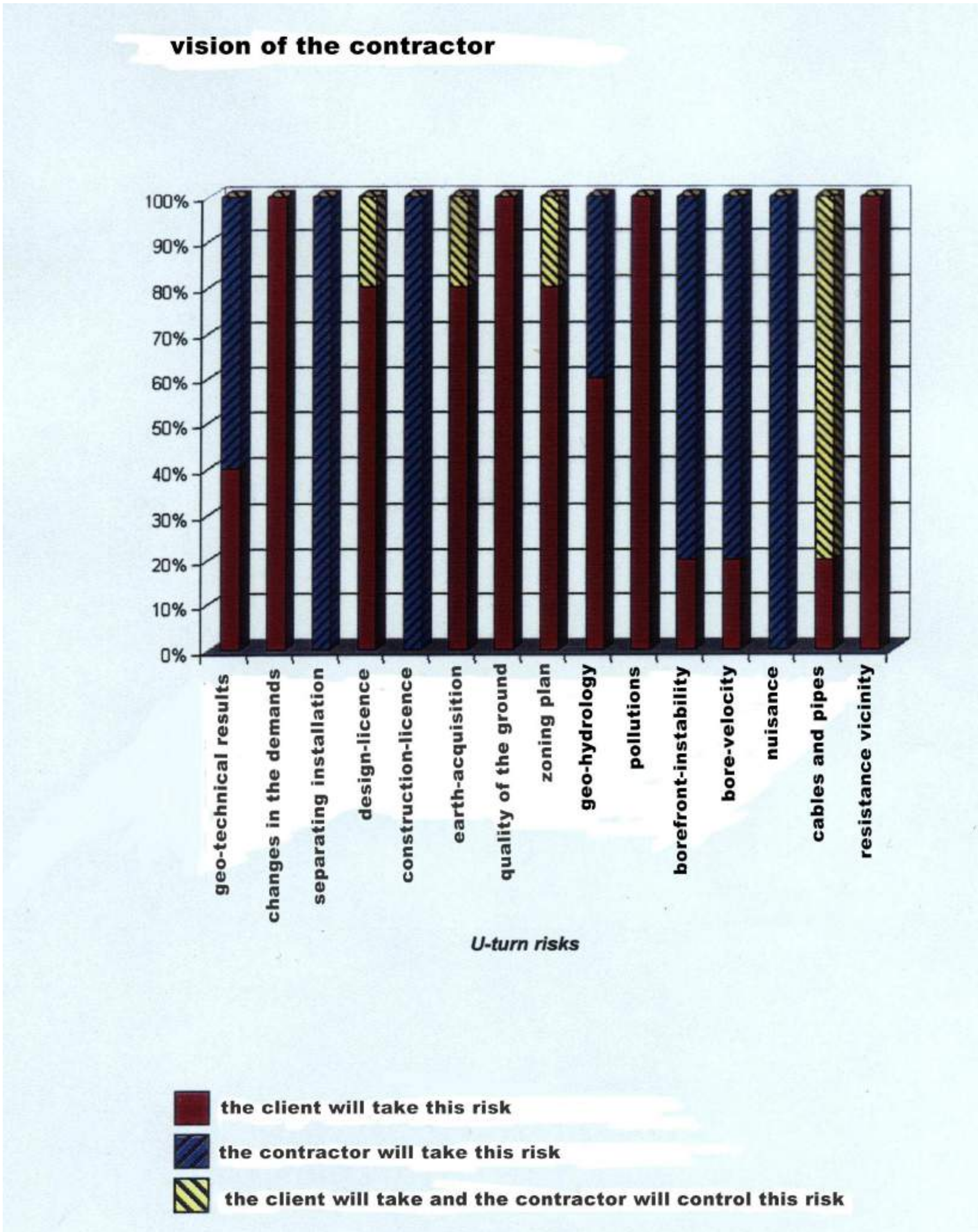
Also the δ has a great impact. Depends on experience what δ you take. If you have no experience take δ=0

If there is sufficient movement along the sheet-pile depends on the vicinity.

leakage :
If there is a leakage there is less strength

Who is responsible for making the right technical assumptions? Clearly not the client!
This is always a big point of discussion, and has lead to different visions of the contractor and the client. This is shown in figure 4.1 and 4.2. In figure 4.1, the vision of the client is shown. For example: the client wants the contractor to take all the risk of the geo-hydrology. The vision of the contractor is shown in figure 4.2. He wants the client to take the risk of the geo-hydrology. What should be done?


vision of the client
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
geo-technical results
changes in the demands
separating installation
design-licence
construction-licence
earth-acquisition
quality of the ground
zoning plan
geo-hydrology
pollutions
borefront-instability
bore-velocity
nuisance
cables and pipes
resistance vicinity
U-turn risks
the client will take this risk
the contractor will take this risk
the client will take and the contractor will control this risk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U-turn risks
the client will take this risk
the contractor will take this risk
the client will take and the contractor will control this risk

Build and Design Contract

This contract form is based on functional requirements. For example: There should not be too much leakage from a dug trench. There are two possible solutions: using a grouting technique or an injection technique. Instead of describing the method that should be used, a build and design contract merely states that the leakage in the trench should not exceed x litre per second per meter of trench. The requirement is thus based on functionality and the contractor is not obliged to use a specific technique. Since the contractor is now responsible for design as well as construction, it is possible to optimize these two processes. This can reduce risks and costs of the project. This contract form thus benefits both client and contractor.

Some examples of why certain risks should be carried by certain parties:

- The contractor should take the risk of soil differences occurring between borings. If the client takes the risks, he is unwise. He cannot determine the necessary scope of the borings. This depends on the sensitivity of the ground; the contractor has more experience with this.

- Driving a pile into the ground is like a penetration test. If a deviation occurs, the contractor can decide to do a second test. He is responsible for what happens when using a build and design contract and thus will do anything to prevent things going wrong.

- Another attention point is piles that are close to each other and work in groups; this has consequences for the load carrying capacity.

Conclusions:

- The client is not well enough informed to carry risks during the execution phase of a project.
- There must be a team working on both design and implementation. When there is interaction the entire project can be optimised, this is beneficial for both contractor and client.

5. General construction methods

5.1 Introduction

This chapter covers the general construction methods that are used in subsurface construction. In principle there are three types of underground structures:

1. Cellar constructions: with a limited physical range, which form a construction in itself or are part of a larger structure;
2. Tunnels: line-shaped underground structures for roads, railways and public transport;
3. Caverns and cavities

Constructing these various structures can be done by numerous building methods, which will be discussed in the following sections.
A survey of all relevant building methods is shown in figure 5.1. The numbers refer to the sections where the building methods are discussed.

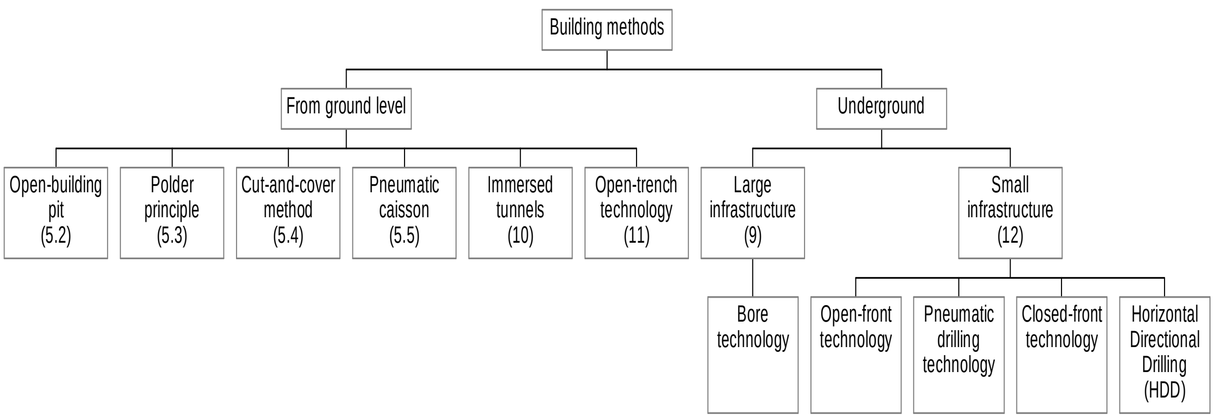


Figure 5.1: Survey of relevant building methods

There are many factors that influence the choice of building method and they are often beyond the range of civil engineering aspects. A general survey of these factors is given below:

- Functional requirements, including usability and safety aspects
- Available space
- Level of acceptation regarding construction hindrance
- Relation with other parts of the project and/or other projects
- Condition of the soil, restrictions regarding the influence on the groundwater level and/or pore water pressures
- Possibility to reuse or sell excavated soil
- Risks during construction
- Damage to the surroundings (due to soil deformation)
- Environmental regulations and considerations
- Durability, flexibility
- Available construction time
- Costs

5.2 Open building pit

An open building pit consists of a horizontal and a vertical boundary that keep groundwater and soil out of the pit. There are several potential alternatives and combinations for (horizontal and vertical) building pit boundaries.

5.2.1 Vertical building pit boundary

Constructing the vertical boundary can be done with various methods. The available methods are listed below:

1. Slopes
The building pit is constructed by excavating slopes, which means that no wall construction is needed.

Advantages
- Cheap solution
- Easy to create

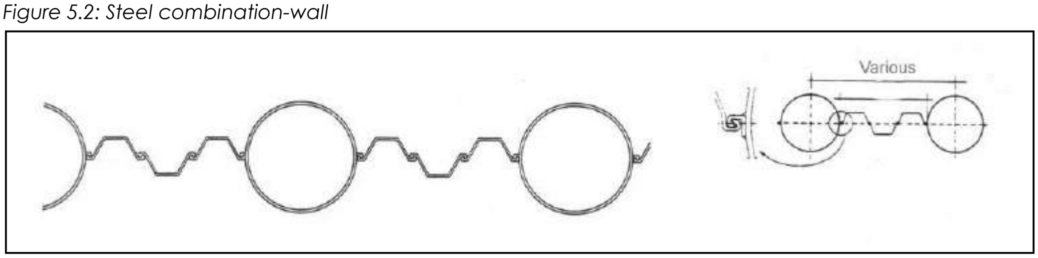
Disadvantages
- De-watering is often necessary. This will disrupts the existing soil hydrology.
- A large area is necessary. In an urban environment this is often impossible, especially when constructing deep building pits

2. Sheet pile wall / combination wall
Steel sheet piles are driven into the ground creating a non-permeable wall in order to retain soil and water.

Advantages
- Many different product combinations and strengths available
- Relatively short building time
- The wall elements can be reused

Disadvantages
- Limited length of the elements
- Hindrance to the urban environment because of vibrations and noise
- Wall is relatively weak which results in danger of settlements

Figure 5.2: Steel combination-wall



3. Bored pile wall (with slurry) / diaphragm walls
The bored pile wall (figure 5.3a) consists of bore piles, which are built overlapping each other. When the soil is excavated the hole is filled with slurry. Afterwards concrete is pumped into the hole, the slurry is pushed out and the concrete starts to become solid.
The diaphragm wall is built (see figure 5.3b) by excavating soil and pouring in slurry. This slurry is replaced by concrete after a reinforcement cage is placed. The horizontal stability of the wall can be strengthened with anchors and struts.

Advantages
- Stiff wall, resulting in less danger of settlements

- Useable at big depths and / or big retaining heights
- The method can be used in densely populated areas
- Wall becomes part of the permanent structure
- No vibrations

Disadvantages
- Long construction time and expensive

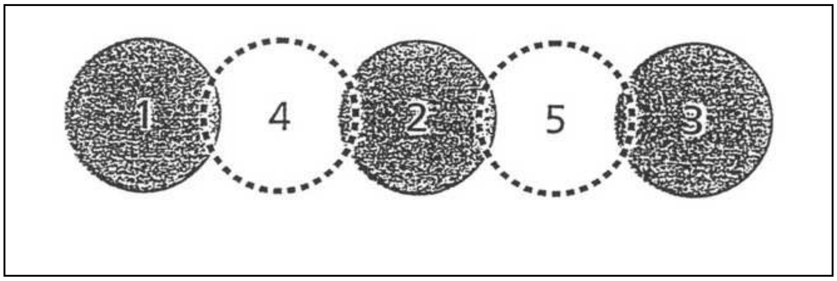


Figure 5.3a: Bored pile wall

Usually only half of the piles are reinforced. The primary piles are reinforced, the secondary piles, which are executed by partly drilling into the young concrete of the primary piles, only receive a minimal required amount of reinforcement.
Primary piles in figure 5.3a are numbers 1 to 3, while the secondary piles are shown by numbers 4 and 5.

4. Screw pile wall (no slurry)
The construction is similar to the bored piles wall, with the exception that no slurry (bentonite-clay) is used. An auger (twist drill) excavates soil and makes screw pile walls.

Advantages
- No vibration

Disadvantages
- No water retaining capability

5. Walls by chemical injection
Walls are created by mixing existing soil with chemicals that are injected into the soil.

Advantages
- The method is especially suitable for securing stability of marginal properties
- Creates the possibility of making retaining walls beneath marginal structures when there is a lack of space
- The wall also retains water

Disadvantages
- Only suitable for coarse soil types
- Not suitable for areas with groundwater flows

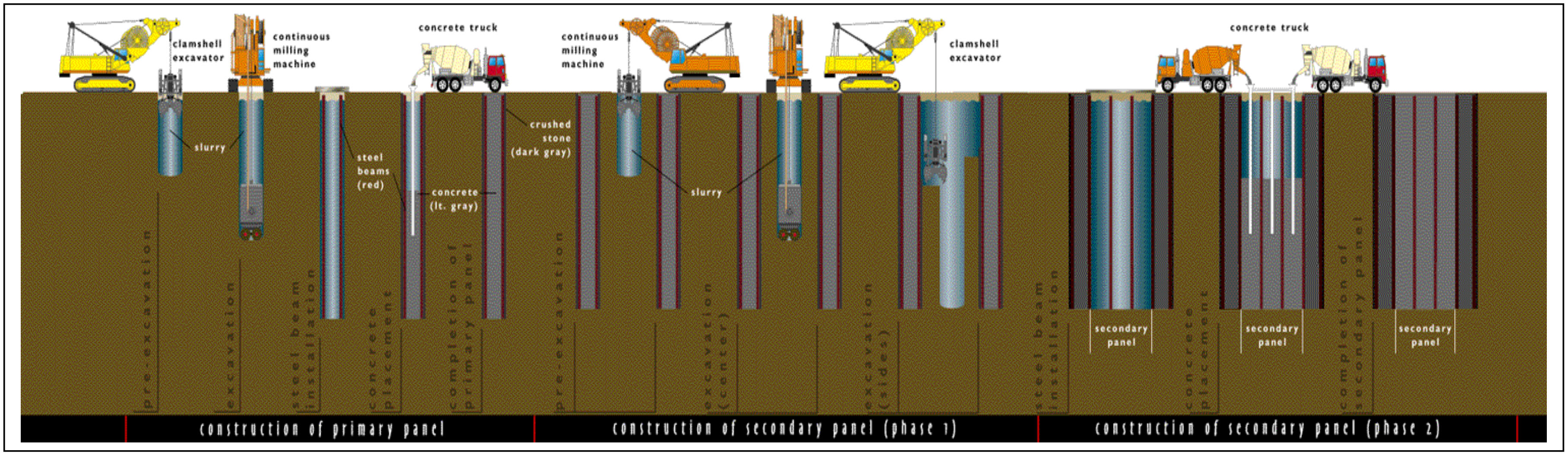


Figure 5.3b: Phases when building a diaphragm wall

6. Berliner wall
Vertical steel profiles are placed with wooden beams or shelves between them, forming a wall.

Advantages
- Cheap construction

Disadvantages
- No water retaining capability.
- Low retaining height.

7. Jetgrouting wall
The wall is made out of jet grout columns. Existing soil is mixed with grout under high pressure (very high pressure grouting - VHP) and eventually with extra air and water. Jetgrouting takes place with a rotating bore tube.

Advantages
- Suitable as a ground and water retaining structure and as reinforcement for marginal structures.
- Suitable for almost all soil conditions
- The wall can sometimes be used as part of the permanent construction

Disadvantage
- The columns have to be constructed properly besides each other (figure5.3a), otherwise groundwater will seep through

8. Freezing method
A temporary wall is constructed by freezing the moisture and water in the soil (figure 5.4), this can be especially useful under special circumstances.

Advantages
- Water and earth retaining structure
- Independent of soil type and condition

Disadvantages
- Deformations because of freezing and thawing (swell)
- Only temporary construction
- Not suitable in groundwater flows
- The efficiency is dependent on type of soil minerals

9. Mixed in place (MIP)
The walls are created by mixing cement and the soil with an auger. The soil is not removed but increased in strength and stiffness by the cement.
.
Advantages
- No removal of soil

Disadvantages
- Soil properties have strong influence on final wall properties
- Low retaining heigth

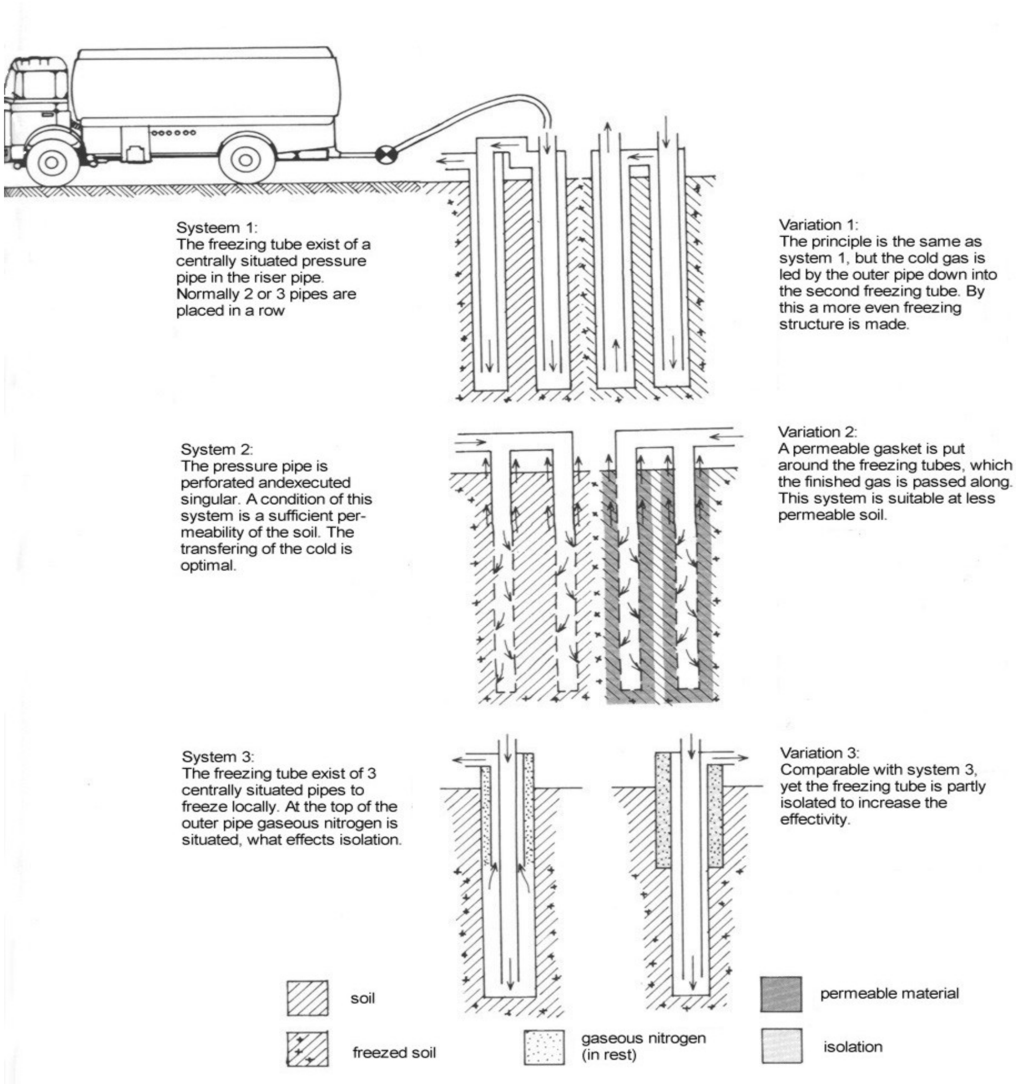


Figure 5.4: Freezing methods

5.2.2 Horizontal building pit boundary

To construct the horizontal boundary (the bottom sealing) of the building pit, the most ideal solution would be to use a natural, impermeable layer. When an impermeable layer is missing or when this layer is situated to deep in the subsurface, dewatering can be used to keep the building pit free from water or an artificial layer can be constructed.

A. Open building pit with dewatering
This method is especially useful when suitable natural horizontal layers are absent. Dewatering creates a dry area to work in; this disrupts the existing soil hydrology however. A possible solution to this can be to return the water to the subsurface at a certain distance from the building pit. The advantage of this method is that it is easy to execute.

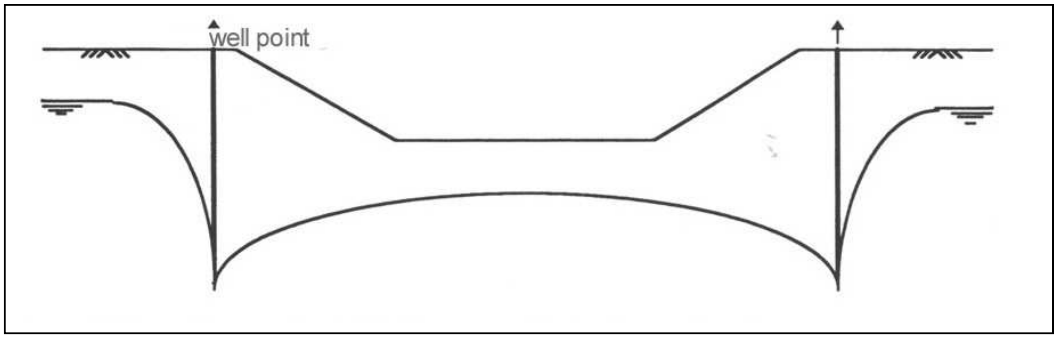


Figure 5.5: Building pit with slopes and dewatering

B. Natural impermeable layer
When a natural impermeable layer is present and this layer is situated at suitable depth, a horizontal boundary can be made by bringing the building pit walls into this layer. Special attention should be given to leak and seepage water. It is also important that the designer is aware of the danger of the bottom of the building pit bursting when the groundwater pressure exceeds the weight of the soil layer on top.

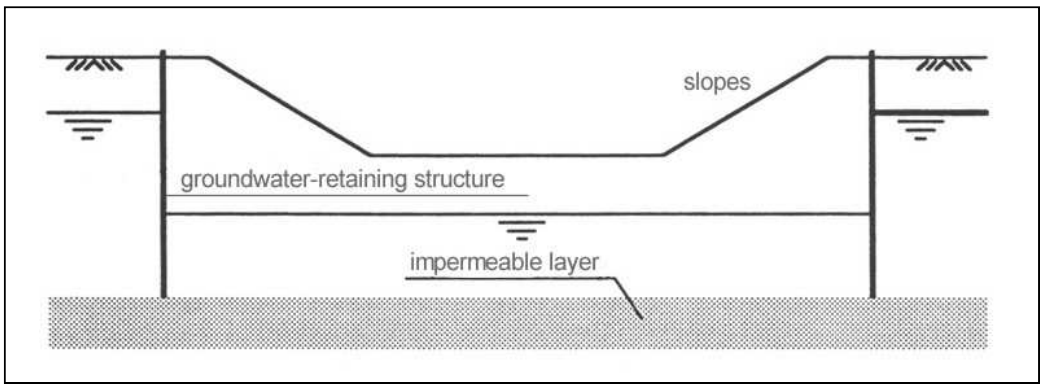
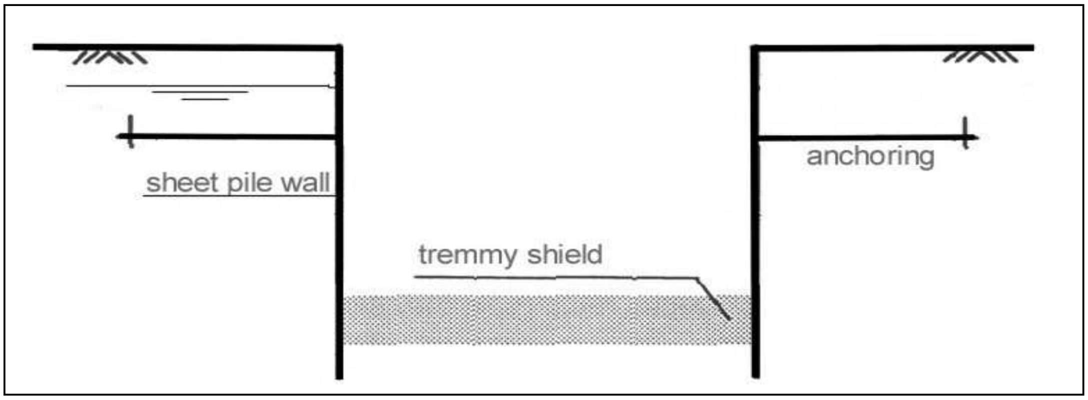


Figure 5.6: Building pit with slopes and natural impermeable layer

C. Artificial layer
When there is no natural impermeable layer, an artificial one can be created. This can be done in various ways. It is still important to prevent bursting of the bottom of the building pit. It is necessary, therefore, that the impermeable layer and the ground layer on top weigh more than the groundwater pressure. When groundwater pressure is very high this equilibrium can also be obtained by using tension piles underneath the artificial layer.

C1: Tremmy shield, possibly anchored
A concrete floor is constructed under water. After the hardening of the concrete, the water is pumped out of the building pit. The floor is used as a gravity construction or it is anchored with tension-elements (prefab-concrete piles, Vibro-combination piles, grout anchors etc.).
The floor can be used as part of the final structure, especially when the floor is reinforced. This construction can however have large risks associated with it, especially regarding the adsorption of the concrete with the walls or piles.

Figure 5.7: Tremmy shield



C2: Horizontal chemical injection
By mixing the existing soil with chemicals a horizontal impermeable layer can be created. This layer is situated at a certain depth below the bottom of the pit (depending on the balance between the top load on this layer and the water pressure at the bottom of the layer).
This method can be executed with light and compact equipment, but it can only be used to make temporary constructions.

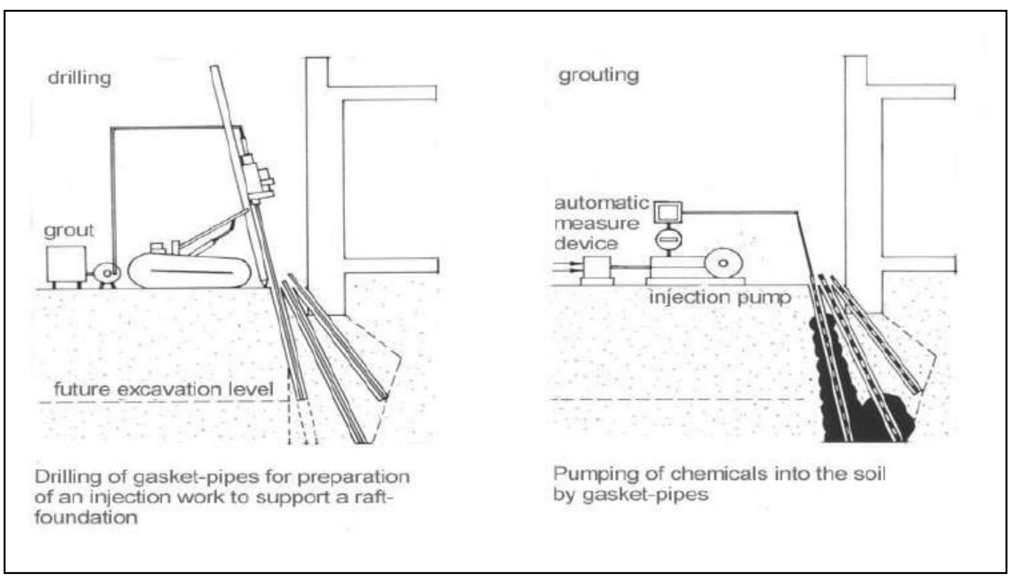


Figure 5.8 Chemical injection

C3: Jetgrouting (VHP)
With this technique horizontal, impermeable layers can be constructed. The greatest advantage is that with this technique relatively strong permanent constructions can be created.

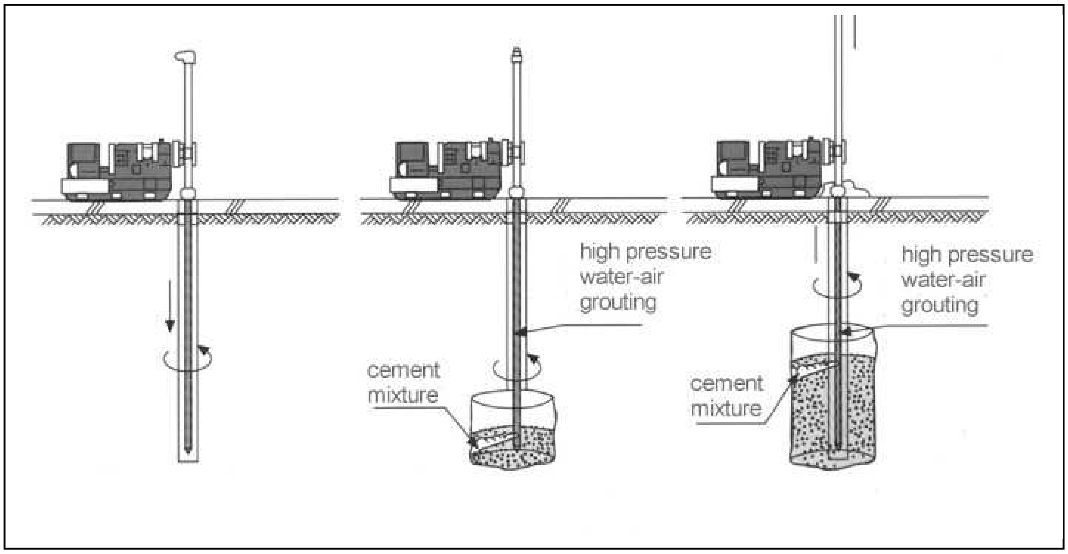


Figure 5.9: Jetgrouting

5.2.3 Combination of horizontal- and vertical boundaries

Table 5.1 shows several combinations of horizontal and vertical boundaries. On the vertical axis the vertical boundary possibilities are shown, on the horizontal axis the horizontal boundary possibilities are shown. All combinations of methods are theoretical possible, but some are more practical than others are. The greater the figure or letter, the more complicated the technique becomes. The combinations marked with a star are suitable for local and / or special circumstances. The combinations marked with an X are very uncommon.

	Combinations of pit boundaries	*Horizontal* A. Open building pit with dewatering	B. Natural impermeable layer	C1.Tremmy shield, eventual anchored	C2. Horizontal chemical injection	C3. Jetgrouting (VHP)
Vertical	1. Slopes	1A	X	X	X	X
	2. Sheet pile wall / combination wall	2A	2B	2C	2D	2E
	3. Diaphragm walls / bored pile wall (with slurry)	3A	3B	3C	3D	3E
	4. Screw pile wall (no slurry)	4A	4B	4C	4D	4E
	5. Walls by chemical injection*	5A	5B*	5C*	5D*	5E*
	6. Berliner wall	6A	X	X	6D*	6E*
	7. Jetgrouting wall	7A	7B	7C*	X	7E*
	8. Freezing method*					

* = Special or local applications X = Hardly used

Table 5.1: Combinations of building pit boundaries

5.3 Polder principle

This method uses a natural impermeable layer as horizontal boundary. The walls and the bottom layer do not only make it possible to construct the structure, but also remain in the final situation. This method is suitable for cellars, parking garages, tunnels and also for deep roads. There is only one restriction: the permeability of the soil has to be sufficiently low. Drainage is not only necessary during execution, but also in the final situation.

Figure 5.10 shows the principle of the construction. A drainage system is necessary because soil layers are never fully watertight and some water leakage, through the locks in the sheets pile wall, can be expected.

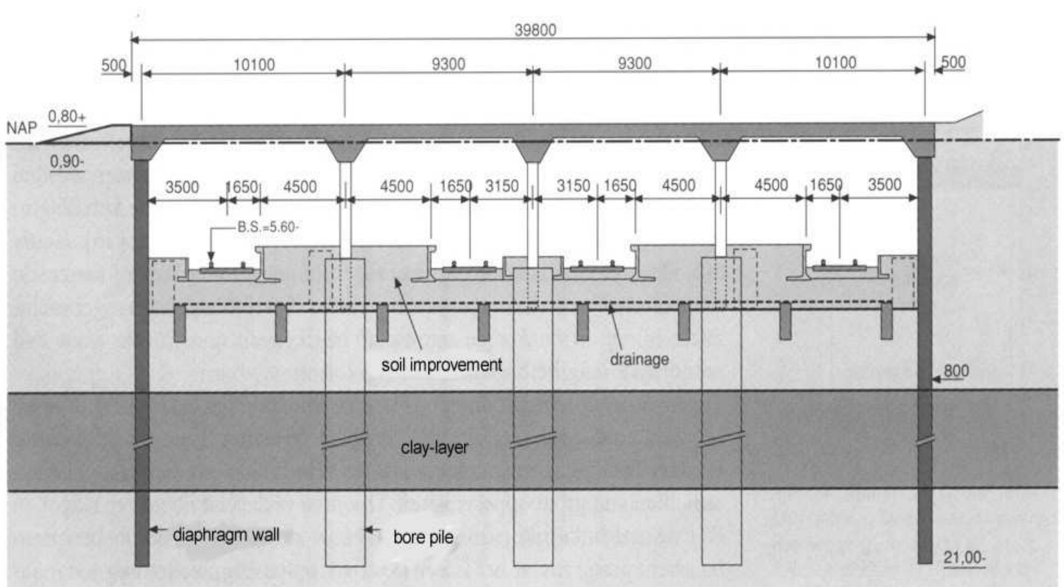


Figure 5.10: NS-station Rijswijk, polder principle

The principle is called “polder principle” because in polders an artificial water level which is lower than the rise of the groundwater under (semi-) impermeable layers is also maintained.

5.4 Cut-and-cover method

In cases where surface hindrance has to be limited, the construction can be build by the cut-and-cover method. This method consists of first building the walls (usually a concrete diaphragm wall), after which the roof of the construction is created. After this the original situation at surface level is restored again, the building pit is thus removed from sight. Then (as far as the strength or the deformations of the sidewalls allow) excavation takes place beneath the roof with small excavators. Then a floor or a strutting is added, after which excavation can continue to a deeper level. The main principle of the cut-and-cover method is shown in figure 5.11. In the roof are recesses that make it possible to transport materials and equipment in and out. To control the groundwater level during the excavation the methods explained in paragraph 5.2 can be used. Another method is to maintain an increased air pressure inside the building pit, thereby preventing inflow of groundwater (see also the next paragraph).

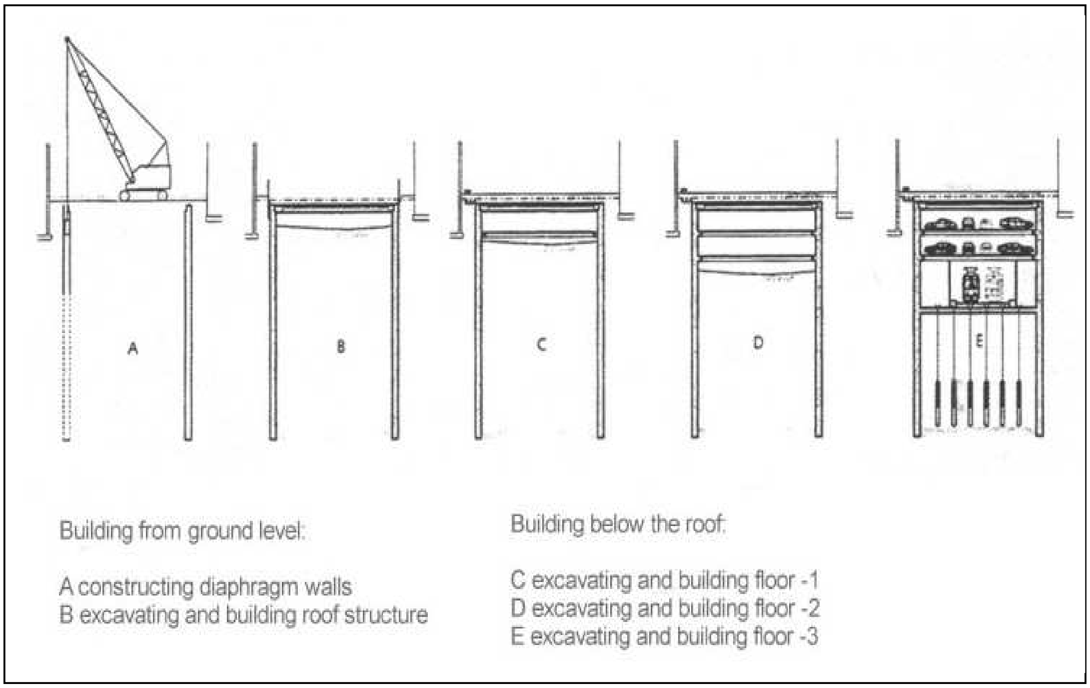


Figure 5.11: Phases of subway tunnel execution, cut-and-cover method

5.5 Pneumatic caisson

A pneumatic caisson can be considered in situations where there is little space and / or when extracting groundwater is not permitted.

To build a pneumatic caisson, the entire construction is built as a closed box (caisson) at surface level (figure 5.12). The bottom of the caisson is featured with cutting edges. Beneath the construction a space is created where an increased air pressure is maintained. In this room, personnel spray away the ground beneath the caisson with jet pipes after which the soil is pumped out (figure 5.13). This decreases the bearing capacity beneath the cutting edges, and the caisson settles because of the dead load. Sometimes bentonite is used to lubricate the side walls of the caisson, this decreases friction during settlement. The groundwater is controlled by increased air pressure in the excavation space. As the caisson has to be sunk deeper, the air pressure has to be increased. The so-called "caisson law" contains restrictions on the length of time spent in the excavation space and the minimal decompression time (figure 5.14). This law has to be taken seriously to avoid health problems that may affect the personnel (caisson sickness).

The main advantage of this method is that the construction can take place at surface level, which makes the construction process very controllable. Furthermore there is no need to decrease the groundwater level and it is possible to build large structures. The disadvantages are working under increased air pressure (caisson law) and the visual intrusion during the execution phase.

The pneumatic caisson method can be used for cellars, ventilation buildings (of tunnels), tunnels and subway stations.

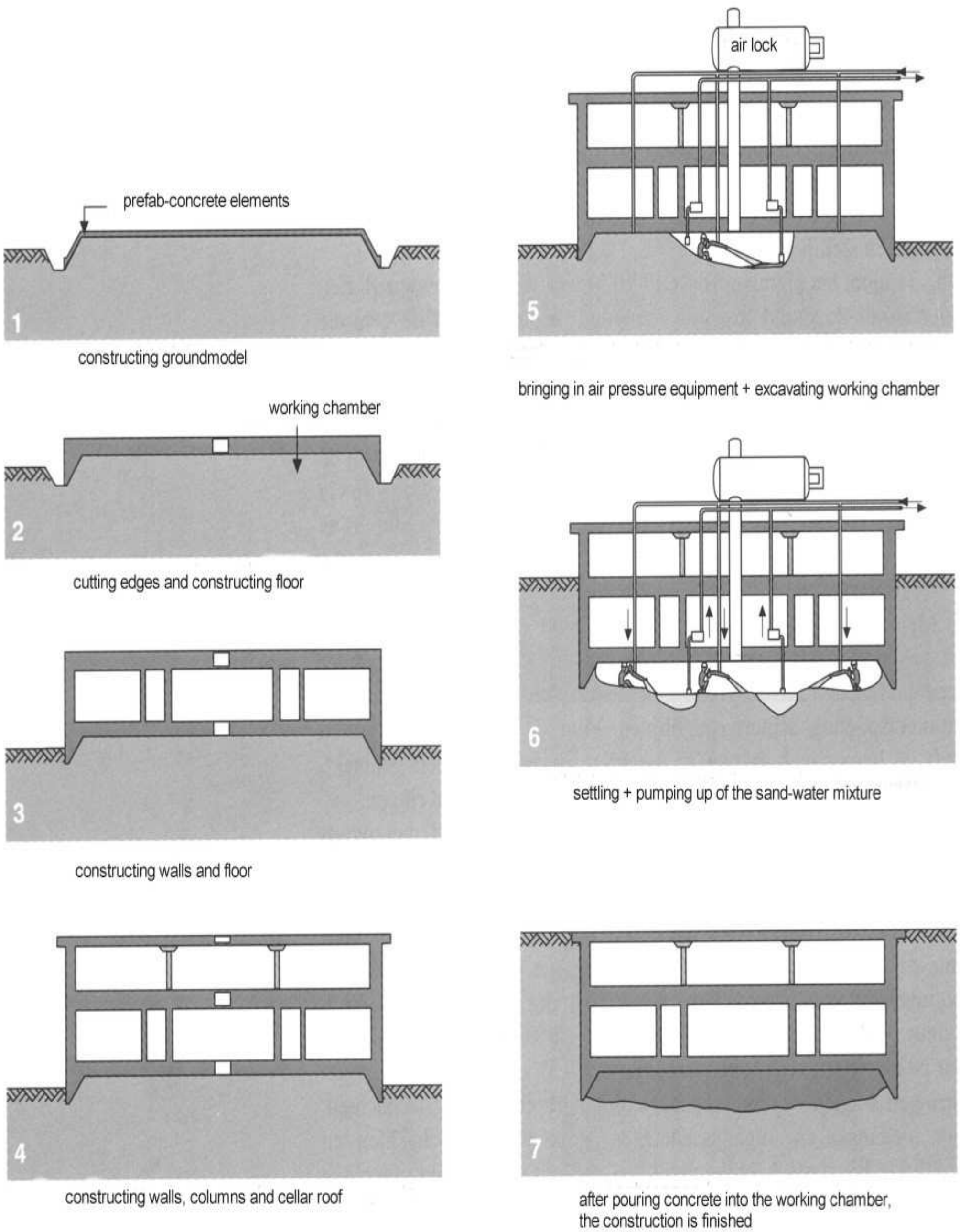


Figure 5.12: Phases during execution of a pneumatic caisson

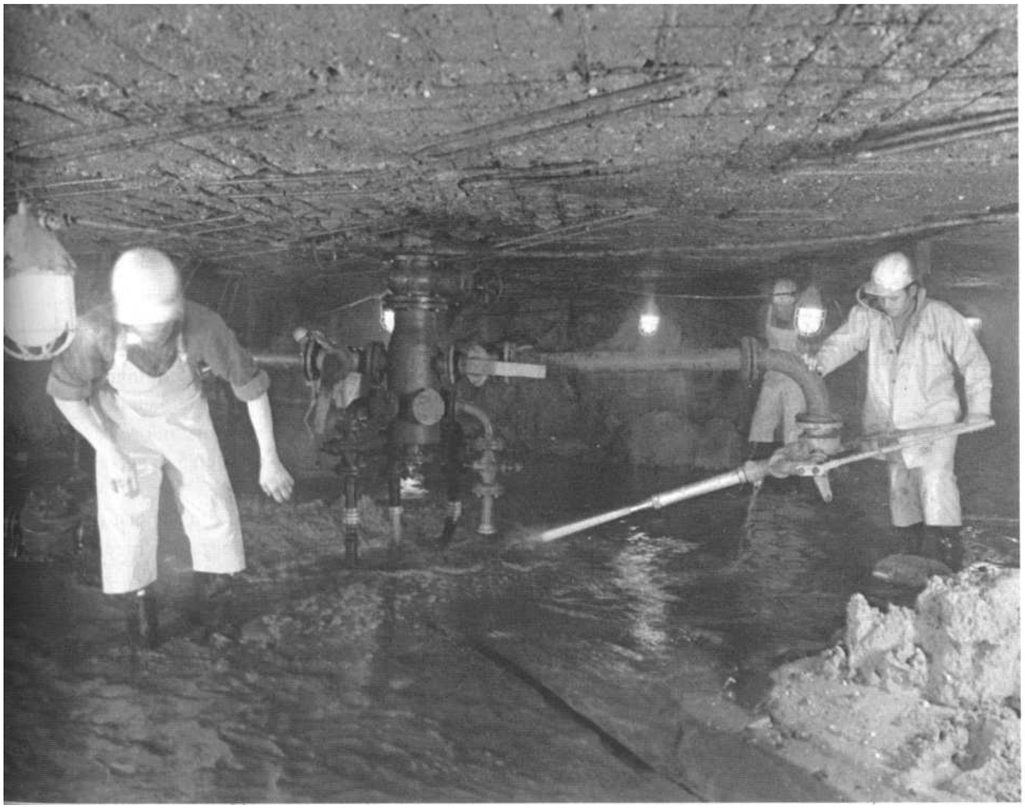


Figure 5.13: Personnel working in space beneath the caisson of the East-line in Amsterdam

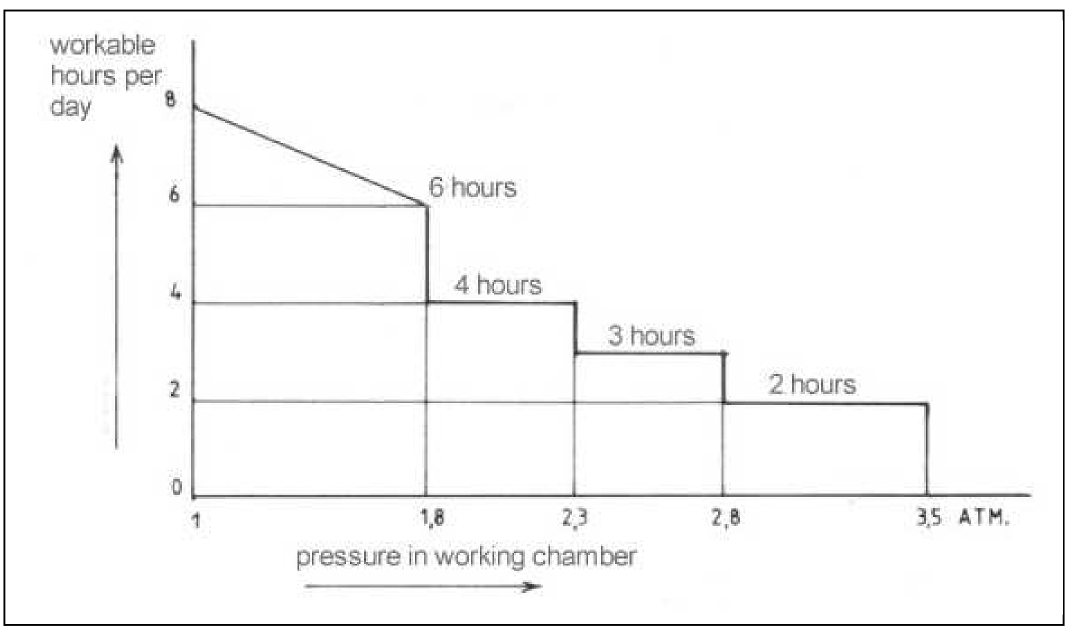


Figure 5.14: Workable hours when working under increased air pressure based on 8 workable hours

5.6 Tunnelling methods

Tunnels are line-shaped, underground structures. They can be built from the ground level with the open building pit method, the cut-and-cover method and the pneumatic caisson method. Special techniques in this context are the bored tunnel method and the immersed tunnel method, which will be discussed in chapters 9 and 10.

5.7 Open–trench technology

Open-trench technology includes the techniques for subsurface placement of road and rail infrastructure. In recent years new construction methods have been developed, such as membrane-solutions, the U-polder, the V-polder and the TOMAS method. These methods are more or less in the experimental stage. They are discussed to some depth in chapter 11.

5.8 Trenchless technology

To an increasing extent trenchless technology is used for construction of “small infrastructure” (cables, pipes, tubes and mini-tunnels). “Directional drilling” and “micro-tunneling in combination with pipe-jacking” are the two most representative examples of this development. Besides the realization of new pipelines, trenchless techniques are also used to renovate existing pipelines. This subject is discussed to some depth in chapter 12.

6. Cellar constructions

6.1 Introduction

A cellar construction is a structure with a limited physical range. Methods that can be used to create a (deep) cellar construction are discussed in the following sections. Some techniques used to create a cellar construction were already discussed in chapter 5 “*General construction metho*ds”.

6.2 Open building pit

The cellar construction is usually built separate from the pit wall. In some cases, such as underground parking garages, the earth-retaining structure (steel sheet pile wall or concrete diaphragm wall) is also the permanent wall of the cellar construction.

A solid wall made with chemical injections or jet grouting is used only in special cases. Usually it concerns a structure where a cellar or tunnel is situated adjacent to an existing building or situated at a critical depth in relation to the building. This is shown in figure 6.1. Under this building a solid wall is put in, which prevents inflow of groundwater. When the building is made on a raft foundation, the solid wall also has a supporting function.

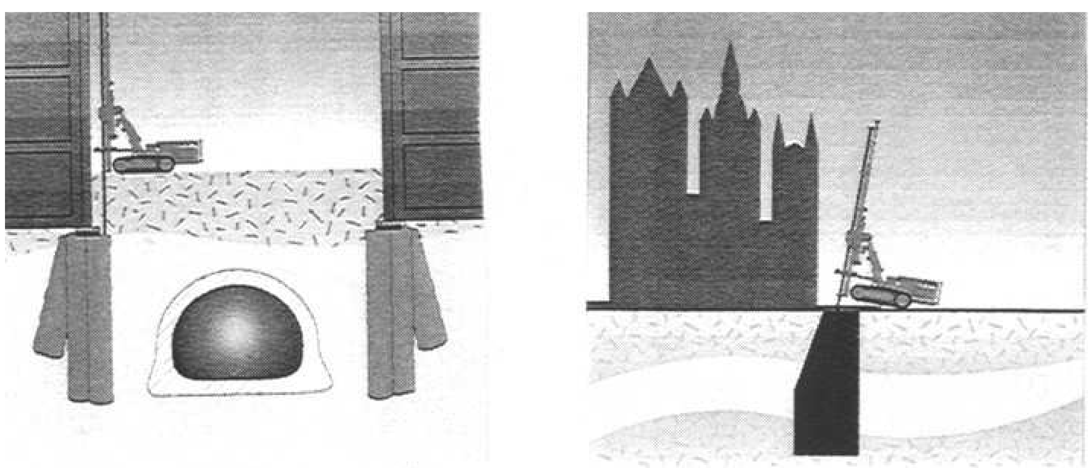


Figure 6.1: Injection against / under an existing building

6.3 Polder principle

In a cellar construction, built according to the polder principle, the bottom seal consists of a natural low-permeable layer. The vertical boundary is formed with a sheet pile wall.

The seepage water has to be pumped out permanently. Due to the direct contact with the groundwater, the air humidity level in the cellar will be very high. That is why the polder principle is often applied to underground parking garages, because for these there is no regulation regarding air humidity. The floor of the parking garages usually consists of clinker paving.

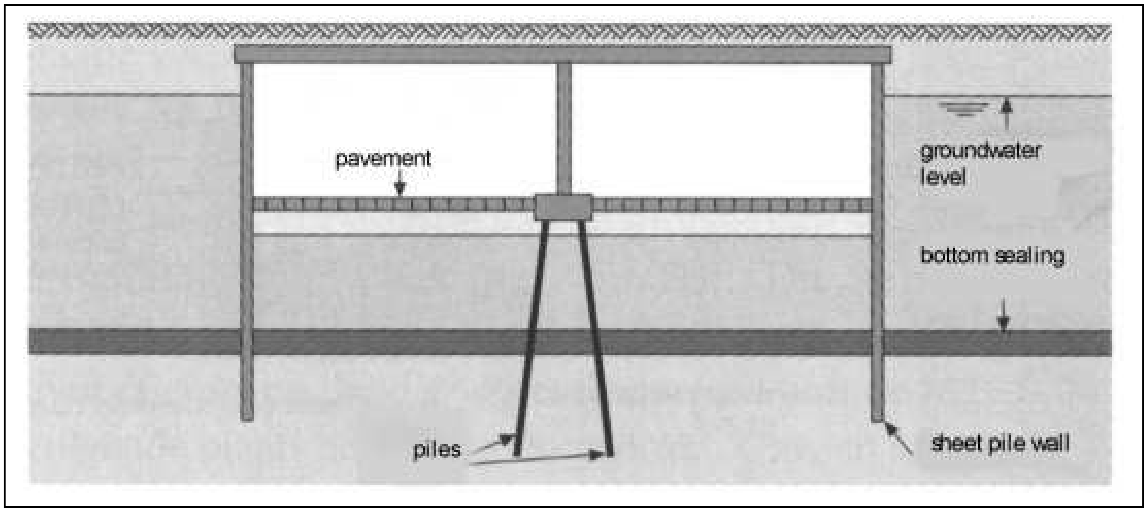


Figure 6.2: Parking garage, built according the polder principle

6.4 Cut-and-cover method

In cases where the above ground infrastructure has to be restored as soon as possible, the cut-and-cover method is a good option for cellar construction. After the required depth is reached, the cellar roof is constructed. Figure 6.3 shows a cut-and-cover method application located in a park.

A variant of the cut-and-cover method is the simultaneous construction of the super and sub structure. This variation starts with the construction of foundation piles and cellar walls. Subsequently the super structure is built on top, while the cellar is simultaneously constructed. This means the construction is going both upwards and downwards from the surface level. On one hand, the time necessary to construct the entire building is reduced; on the other hand, the disadvantage of this variation is a more complicated execution process.

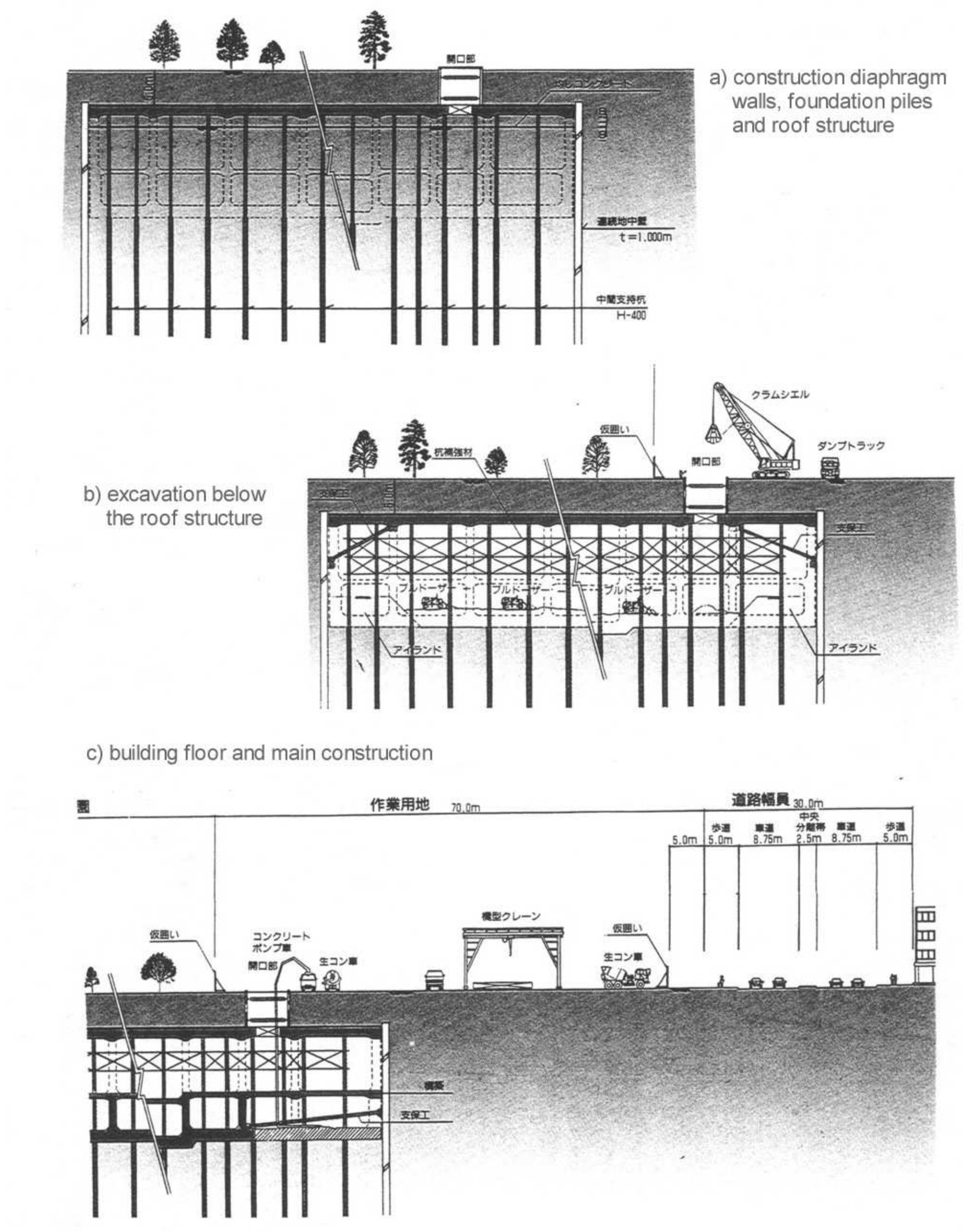


Figure 6.3: Kiba park site, cut-and-cover method

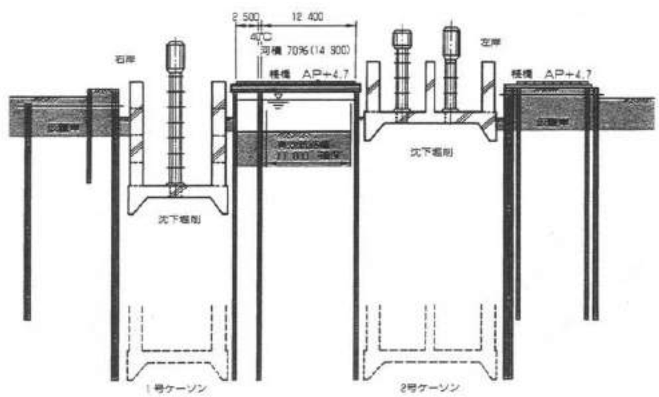
6.5 Pneumatic caisson

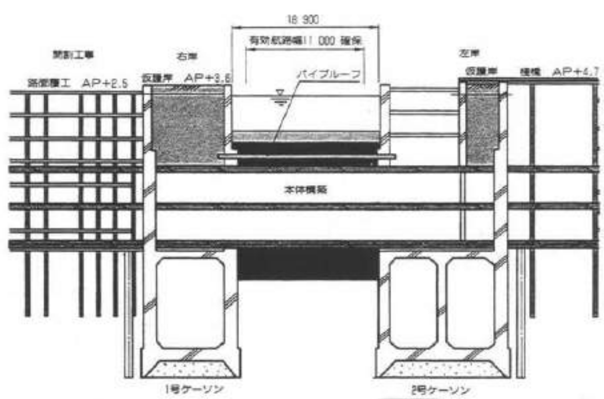
A cellar construction built using the pneumatic caisson method can be considered for situations when there is not much space and / or when it is not permitted to extract groundwater.

Figure 6.4 shows the execution phases for the construction of a tunnel beneath a river (the Sendaibori River Crossing Project). Pneumatic caissons were used as foundation for the tunnel. Furthermore the soil was frozen as a temporary measure during the construction of the tunnel.

Figure 6.4: Tunnel crossing the Sendaibori River, pneumatic caisson

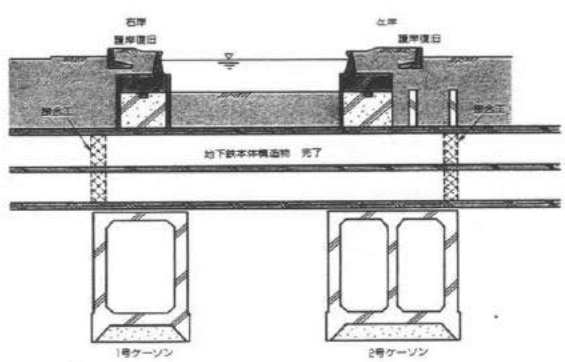
After completion of a temporary shore protection (and works supporting to the main construction) pneumatic caissons were implemented along both sides of the river.





As a next step the subsoil underneath the river has been frozen temporarily followed by excavation for the tunnel.

Final situation.



6.6 Special examples

Figure 6.5a shows the combination of a cellar construction and a bored tunnel that is situated at great depth. The phases of execution are shown in figure 6.5b and the longitudinal section is shown in figure 6.5c.

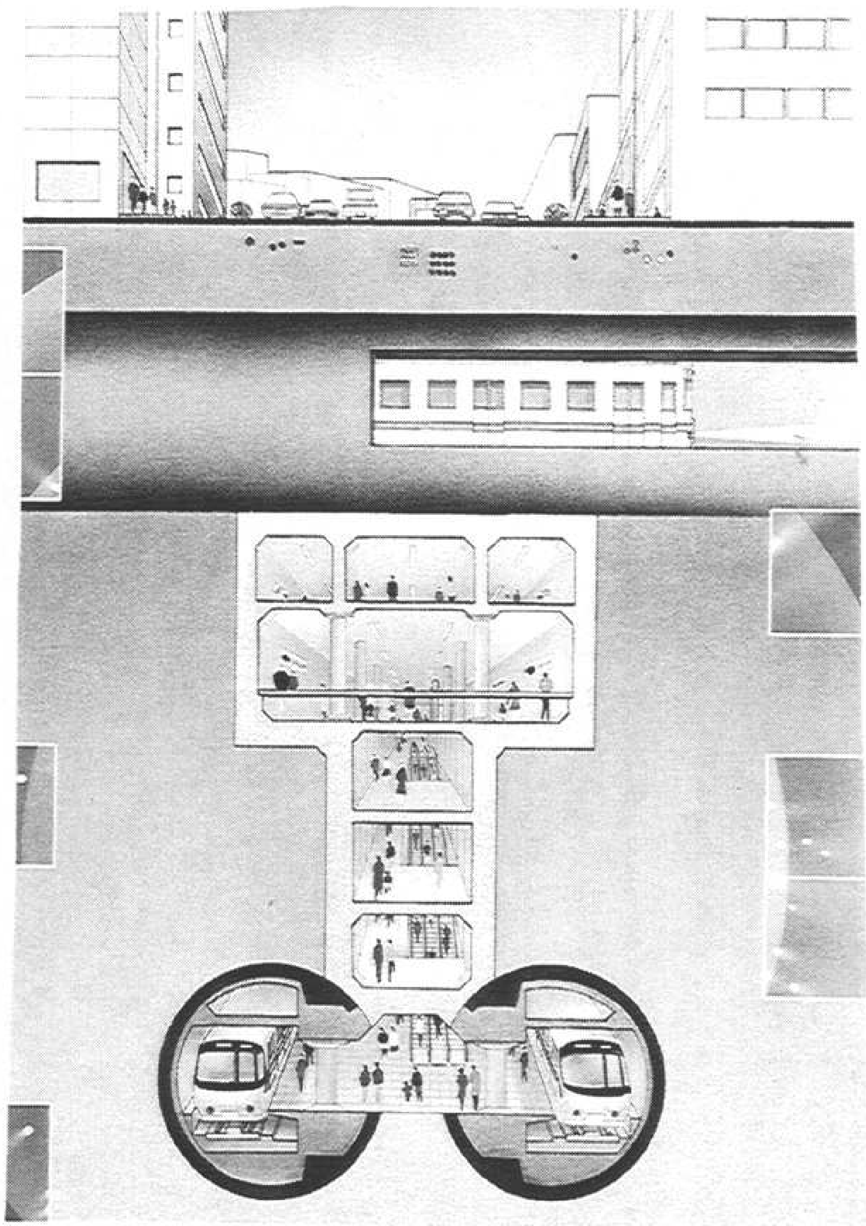
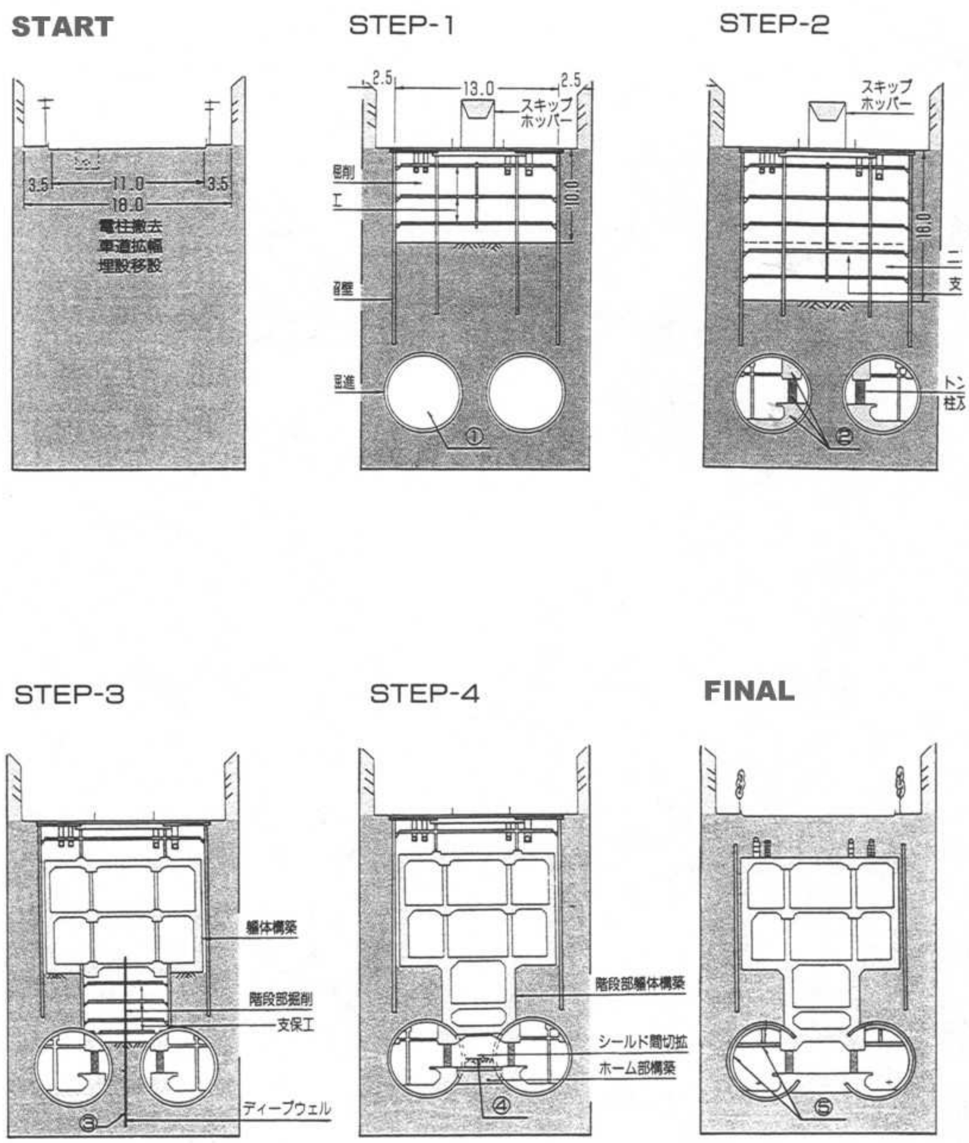


Figure 6.5a: Shinjuku station, connection of a cellar construction within a bored tunnel at great depth


START
STEP-1
STEP-2
STEP-3
STEP-4
FINAL
3.5
11.0
3.5
18.0
電柱撤去
車道拡幅
埋設移設
2.5
13.0
2.5
スキップ
ホッパー
10.0
16.0
躯体構築
階段部掘削
支保工
ディープウェル
階段部躯体構築
シールド間切拡
ホーム部構築

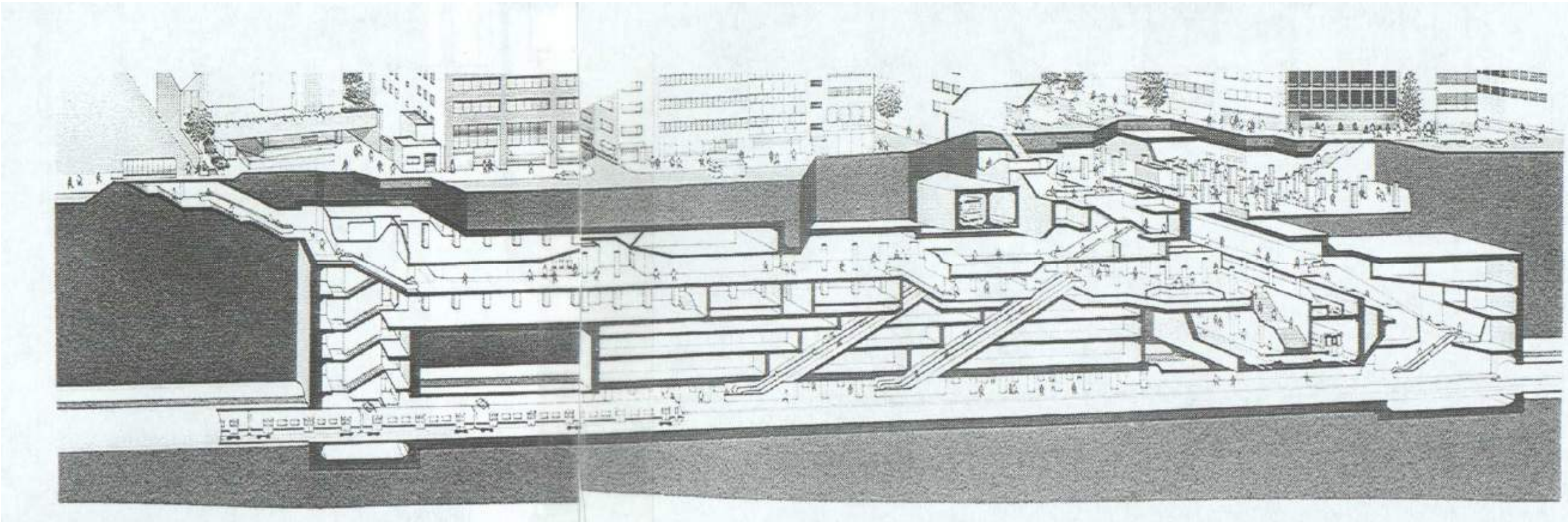


Figure 6.5c Longitudinal section

6.7 Execution problems

The main execution problems of cellar construction appear in the urban environment. The lack of available space and level of acceptance for hindrance during the building process mean that the execution is restricted by many requirements, especially requirements regarding the groundwater level. In the urban environment de-watering on a great scale is often not permitted, because it can causes settlement. To prevent this, a good design for the execution of the cellar construction is required, which usually implies a design that avoids de-watering.

When de-watering is not allowed and a natural impermeable layer is not present, one of the problems of the cut-and-cover method is the building of an underwater concrete floor, which is anchored by tension piles. The piles can be rammed from street level. A problem with this method is that they then might form an obstacle during excavation. To implement piles or anchors under an already built roof is also very difficult. A grout-bow as described in section 6.10 could be a solution to this problem.

Working under increased air pressure is also a solution to the above-described problem. Decompression times have to be taken seriously (see also chapter 5), which decreases the effective working time and thereby increases the building costs.

In certain circumstances the required execution time can be a very important criterion in the choice of a building method.

6.8 Building costs

The building costs and execution times for cellar construction are strongly determined by the chosen technique.

The building costs roughly consist of the following costs:

- Planning / engineering
- Foundation
- Building pit
- Groundwork
- Concrete work
- Installations
- Construction site costs
- General costs, profits and risks.

In the KIVI-report for cellar constructions [KIVI, 1994, *Kelderconstructies; Op naar de diepte!]* a cost comparison was made for a cellar construction under various geological circumstances and with various building methods.

6.9 Dutch situation

The presence of a high groundwater table has a large influence on the execution of cellar constructions in The Netherlands (especially in the western part of the country). Besides these geotechnical and geohydrological circumstances there are additional challenges to be found with regards to existing constructions and the urban environment. The building methods that are applicable are restricted to open building pit, polder principle, caisson method and the cut-and-cover method.

The cut-and-cover method was hardly used in The Netherlands, but during the last years there have been a number of projects where this method was applied. The subway station Wilhelminaplein in Rotterdam and the tramtunnel Grote Markstraat/Kalvermarkt in The Hague are examples of this. The subway station Wilhelminaplein is unique since it was built around the existing subway tunnel. The execution phases are shown in figure 6.6. The roof (thickness: 2,5 m) was poured over the steel combination wall at ground level (fig. 6.6a). Beneath the roof excavation took place until the top of the tunnel was reached. Then the roof of the tunnel was strutted against the roof to prevent floating of the tunnel in case of de-watering disturbances. The combination wall was also strutted with a horizontal strut, which guaranteed the horizontal stability of the tunnel during excavation (fig. 6.6b). Tension piles were put in place, after which the floor of the new station could be poured. Furthermore concrete walls were constructed against the inside of the combination walls (fig. 6.6c). Once the temporary strutting was replaced by the permanent V-shaped strutting, the side walls of the original tunnel were removed, after which the completion of the station could take place (fig. 6.6d).

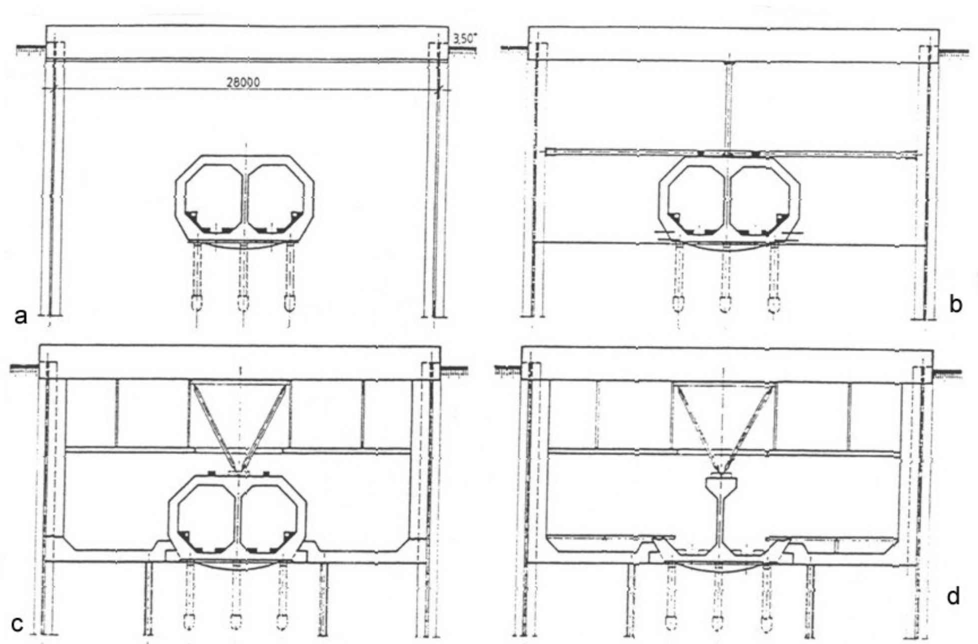
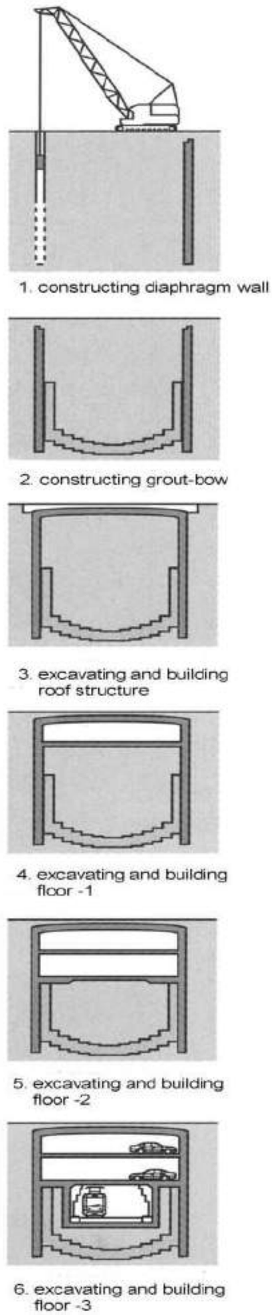


Figure 6.6: Cross section station Wilhelminaplein during various execution phases



The tramtunnel Grote Markstraat in The Hague used a grout layer as bottom sealing. This is shown in figure 6.7. The bow that can be seen at the bottom of the tunnel was made by jetgrouting from street level. The upward groundwater pressure is transferred to the diaphragm walls by the bow-shape.

This project has become notorious for water leakages that occurred. Horizontal grout layers should have been implemented to a greater depth; the diaphragm walls should have been constructed to a greater depth. This would have been a more expensive solution, but it could have prevented the problems that occurred. In the end the project was delayed for a number of years. When the project was finished, the concrete floor shown in figure 6.7-6 took over the water retaining function.

Figure 6.7: Basement Grote Markstraat, cut-and-cover method with grout-bow

7. Tunnels built from ground level

7.1 Introduction

Tunnels are line-shaped underground civil-technical structures for roads, railways and public transport. They can be built with the techniques discussed in chapter 5, such as the open building pit method, cut-and-cover method, and the pneumatic caisson method. Special techniques in this context are the bored tunnel method and the immersed tunnel method, which will be discussed in the chapters 9 and 10.

7.2 Building from the ground level

A tunnel can be built according to the open building pit method: a temporary building pit or trench is formed; this pit is kept dry with a temporary de-watering operation (figure 7.1). The tunnel is then constructed in the building pit, after which the remaining part of the trench is filled up with sand until the original surface level is restored.

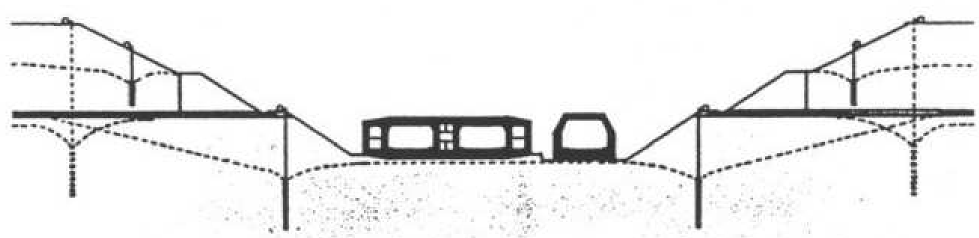


Figure 7.1a: Open-building pit method for tunnels:, slopes and de-watering

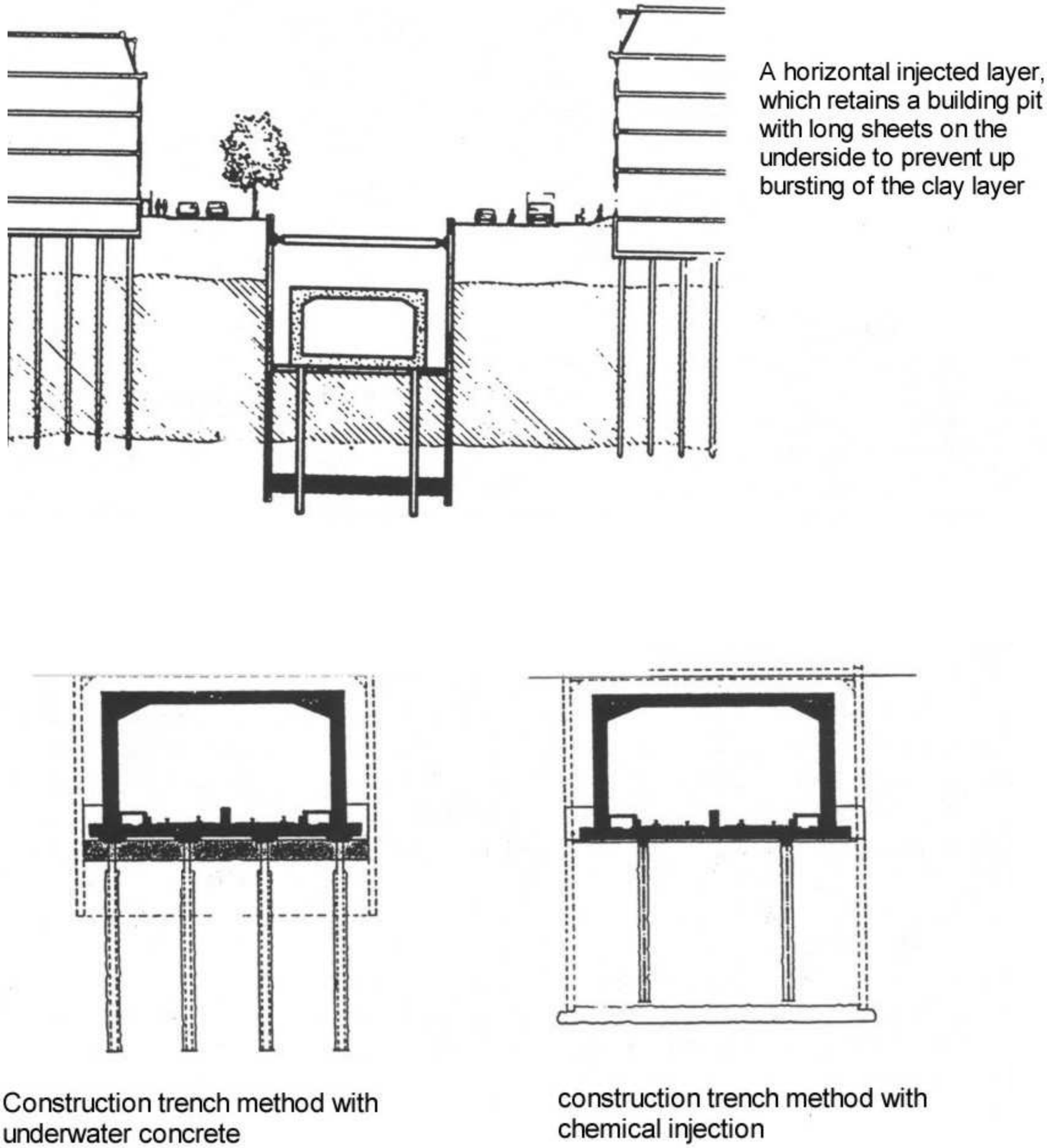


Figure 7.1b: Open building pit methods for tunnels

To speed up the construction time, prefabrication should be considered. Prefabrication was used in Rotterdam with the construction of the East-West metro line (between Eendrachtsplein and Marconiplein); a specialised construction was implemented, called the shell tunnel (figure 7.2).

On the ‘s-Gravenweg in Kralingen the metro had to pass under a narrow road over 1,000 m distance, along both sides of the road were valuable properties and cultivated ground. Because of these specific conditions a specialised construction, namely a shell tunnel, was chosen for this part of the route. The floor of the tunnel was constructed on previously driven concrete piles inside a construction dock of steel sheet piles. The walls and roof were prefabricated as one element. These sections, the shells, were positioned and fixed on this floor to form a monolithic cross section. The sections were shell-shaped, 3 m in length, 35 cm thick, and each weighed 37 tonnes. They were manufactured at the concrete works at Kats in Noord-Beveland (Zeeland) and transported to Rotterdam by ship. By choosing this method of construction, much of the concrete work, which would normally be carried out in situ, was replaced by a system of assembling prefabricated units. This method of construction can be described as an “assembly line system” in which – thanks to the efficiently organised work schedule – the various operations followed one another in a co-ordinated and coherent manner. Construction progressed rapidly (30 m a week) and the length of construction area at any one time was limited to 500 m. Before the Kralingse Zoom, the tunnel widens to become a four-track, funnel-shaped access to Kralingse Zoom station, the first station above ground level on the East-West line.

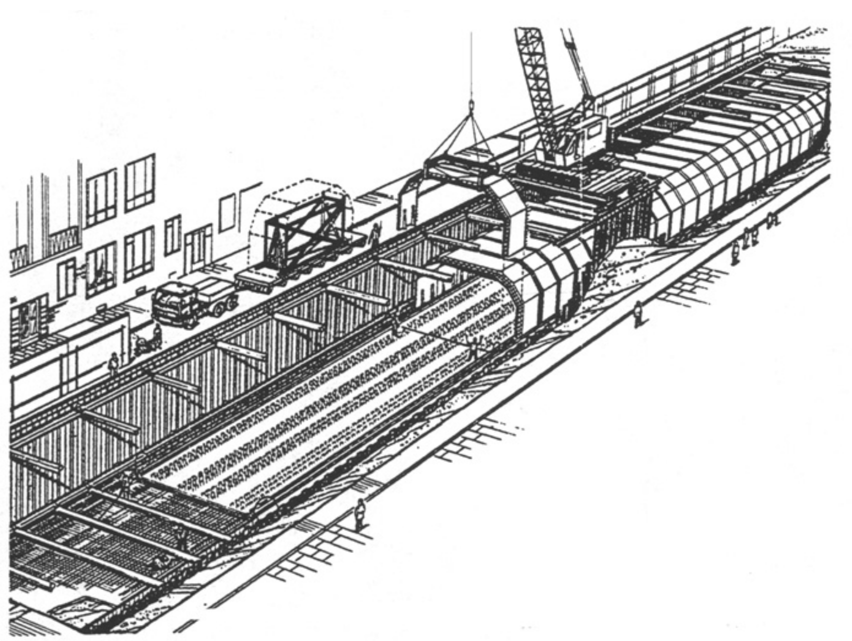
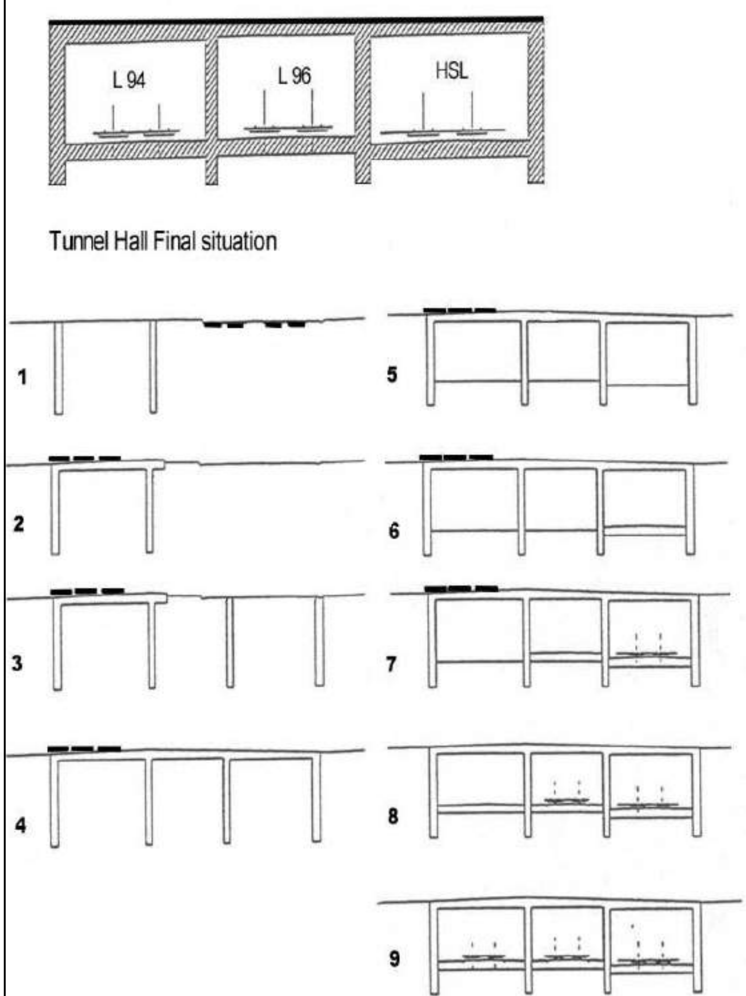


Figure 7.2: Implementation of prefabrication: the shell tunnel. A crane on a mobile platform lowers the shells into the trench

7.3 Cut-and-cover method

An interesting example of the implementation of the cut-and-cover method is the construction of a high speed rail line in Belgium (section Brussel-Halle) adjacent to an existing railway in combination with the transferring of the rail tracks (figure 7.3). In this project bored pile walls were used, which were chosen because of the nearby railway that had to remain operational and thus imposed strict deformation demands. In case of an execution with diaphragm walls or steel sheet pile walls the deformations would be much larger than when using bored pile walls.



Tunnel Halle

This tunnel contains four tracks for regular trains and two for high-speed trains. In the building scheme it is taken into account that at least three tracks can be used at any time

1. Four tracks adjacent to building pit;
2. Three tracks on top of the first part;
3. Building part for high-speed train;
4. Building section in between;
5. Excavation under roof;
6. Building tunnel for the high-speed train. The high-speed train needs a larger profile for the air-circulation;
7. First regular tunnel part is completed;
8. Last regular tunnel part is completed; tracks can be removed from top of the tunnel;
9. Tunnel is completed

Figure 7.3: HSL Brussel – Halle: Phases of execution of the used cut-and-cover method

7.4 Caisson method

Another building method is the caisson method, as described in chapter 5. This method was used for the East line of the subway in Amsterdam. There complete parts of the tunnel (length 40 m) and stations were built at ground level, followed by undermining causing a gradual settlement of the elements into the soil, until the elements reached the correct level. The caissons were linked, which created a continuous tunnel tube. In Amsterdam a tunnel tube with a total length of 3400 m was constructed with this method. Figure 7.4 shows the building of caissons in Amsterdam.

Figure 7.4: Caissons for the East-line of the Amsterdam subway under construction

Between the two tower cranes the air locks of the just immersed caisson are still visible. In the background one can see two caissons that are still under construction.

7.5 Tunnel dimensions

The tunnels dimensions depend on the required function; different requirements apply for various vehicle types. The required diameters for certain transport types are summarised below.

Nr.	Profile – Use	Inner-diameter [m]
1	Guided bus, 1 traffic lane	4.70
2	Tram, single track	5.90
3	Subway, single track	5.95
4	Train 200 km/h, single track	7.75
5	Train 250 km/h, single track	8.50
6	Tram, double track	8.75
7	Subway, double track	9.60
8	Train 300 km/h, single track	9.88
9	Motor road cat. B IV, 1 traffic lane, 2 directions (3.10 m)	10.50
10	Train 200 km/h, double track	10.65
11	City expressway cat. A II, 2 traffic lanes, 1 direction (3.25 m)	11.20
12	Train 250 km/h, double track	11.25
13	Expressway cat. A I, 2 traffic lanes, 1 direction (3.50 m)	11.70
14	Train 300 km/h, double track	12.50
15	Expressway cat. A I, 3 traffic lanes, 1 direction (3.50 m)	15.40

Table 7.1: Survey of the required inner-diameter per transport type

The requirements and user wishes (table 7.2) determine the final tunnel dimensions. The slopes that can be found at the entry and exit of a tunnel can not exceed certain gradient values; these maximum values are fixed in national regulations.

Implementation of these requirements and wishes in a circular shaped tunnel (figure 7.5) is uneconomical compared to the use of available cross section surface in a rectangular tunnel.

The reasons why circular shaped tunnels are often implemented are:

- Used building method – bored tunnels;
- Better mechanical behaviour of circular shaped constructions at greater depths compared to rectangular shaped constructions

Users demands and wishes	***Road***			***Railway***			***City-rail***		
	Cat. AI Expressway	Cat. AII City expressway	Cat. BIV Motor road	Passengers	Freight	High speed	Subway	Tram	Guided bus
Geometry									
Design speed [km/h]		90	80	160	80	300	110	70	80
Max. slope [%]		4.5	5	2.5	2.5	2.5	4	4	6
Advisable slope [%]				0.5	0.5	0.5	1	1	1
Min. horizontal curve [m]		350	260	1700	800	4500	240	240	135
Advisable horizontal curve [m]		800	700	>10000	>4000	>6000	>400	>75	540
Min. vertical curve (top) [m]		6000	2500	10000	2500	16000	2500	1000	1200
Advisable vertical curve (top) [m]		6500	9000	>16000	>4000	>25000	>3600	>2000	20000
Min. vertical curve (dale) [m]		700(800)	500	10000	2500	16000	2000	1000	350
Advisable vertical curve (dale) [m]		13000	14000	>16000	>4000	>25000	>3000	>2000	1500
Banking [m]							<0.15	<0.15	
Platform-length [m]				270-430	-	430	>125	>30	40-80
Min. Transversal slope [%]	2.0	2.0	2.0						
Advisable transversal slope [%]	2.5	2.5	2.5						
Max. transversal slope [%]	5.0	5.0	5.0						
Cross-section (profile)									
Profile of free space				UIC GC	UIC GC	UIC GC	Various	Various	
Required profile because of pressure surge [m^2]				30/55	-	70 / -			
Technical use of space									
Footpath									
Required height overhead wire/headroom				+5.50	+5.50	+7.00			
[m+BS]				-0.80	-0.80	-0.85			
Required height ballast bed/rail-attachment				3 m free	-	3 m free	8 m free		9 m free
[m+BS]				3 m free	-	3 m free	5 m free	3.50	5.50
Width island-platform [m]				+0.84	-	+0.84			
Width side-platform [m]				1.65	-	1.65			
Height platform									
[m+BS]									
Distance platform – centre distance track [m]									
Clearance height above surface [m]	4.50	4.50	4.50						
Traffic lanes per direction	2 – 4	2 – 4	1						
Width traffic lanes [m]	3.50	3.25	3.10						
With division stripe [m]	0.15	0.15	0.10						
With marginal stripe [m]	0.20	0.20	0.15						
With redress lane [m]	0.60	0.30	0.35						
With object distance-margin [m]	1.50	1.00	1.00						
Crash barrier [m]	0.225	0.225	0.225						
Min. inner-width double traffic lane / socket [m]	9.05 – 10.45	8.50-8.95	8.30 – 8.75						

Table 7.2: Survey user's requirements and wishes

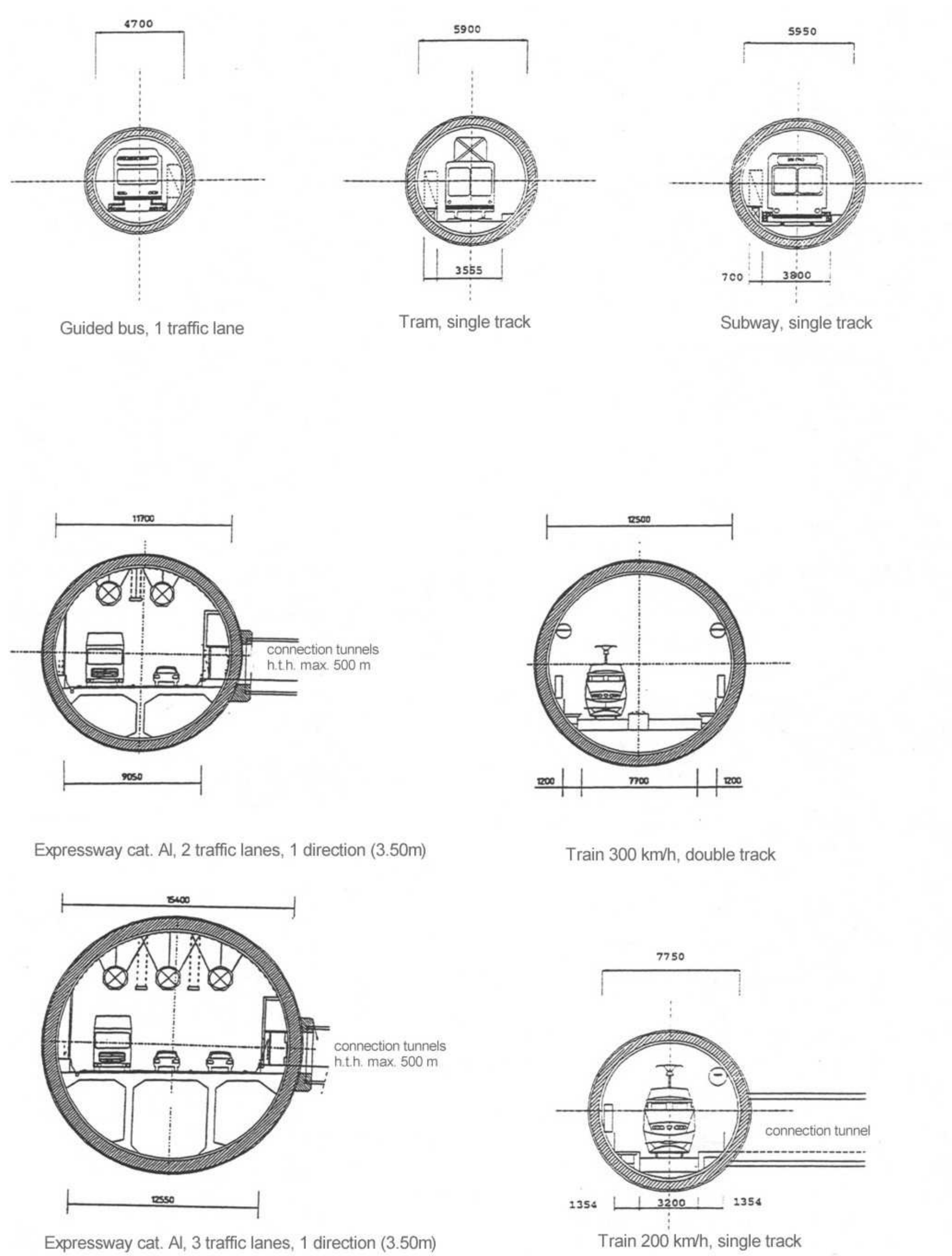


Figure 7.5: Cross-section of tunnels determined by functional requirements

7.6 Usability and safety aspects of tunnels

The structure of an elongated traced-out-tunnel is not suitable for daily use: without lighting the tunnel is just a dark hole, without ventilation there is the danger of poisoning symptoms and without de-watering the tunnel could be flooded.

Furthermore there are dangers like car accidents, fires, and accidents with dangerous materials. The consequences can be much higher than those of similar accidents on the open road. Besides damage to vehicles and human injuries, there can also be damage to the tunnel installations or elements. The tunnel has to be supplied with installations to make the tunnel safe. A checklist of the required installations for traffic tunnels is reproduced below.

All that is necessary for the proper utilisation of a road tunnel is provided by the tunnel installations, which are hidden from sight.
The electromechanical equipment of a tunnel includes:

- General installations for:
  - The tunnel lighting (day and night) and sun louvers;
  - (Drainage) pump installations;
  - Tunnel ventilation;
  - A monitoring system that can be programmed;
  - A remote-control monitoring system, or a remote control and monitoring system;
  - Lifts and/or escalators.
- The power supply connected to main grid, the main supply distribution system, an emergency supply with no-break, the peak and off-peak supply, a high voltage installation and possibly an alternative power supply;
- For communication:
  - An intercom system;
  - A loudspeaker public address system;
  - A radiotelephone installation;
  - A high frequency radio communication system;
  - Telephones.
- Safety provisions include:
  - A fire extinguishing installation;
  - Emergency posts and dry chemical fire extinguisher stations;
  - Emergency galleries;
  - CO and/or visibility measurement;
  - Protection of tunnel installations against collisions and/or vandalism;
  - Emergency routes in case of accidents.
- Traffic control and monitoring provisions such as:
  - Traffic control system;
  - A traffic detection system;
  - A television installation;
  - A height detection system;
  - A control room and/or central point for additional monitoring.

7.7 Execution problems

Tunnels need to be watertight. Even minimal leakage can be very destructive to the road surface or the construction. Localising and repairing of the leaks is difficult and expensive. Leaks are caused by cracks in the concrete or damage to the joints. Reasons for damage can be:

- Drying up of the concrete
- Changes in the climate
- Changes in temperature by hydration of the cement

When the execution processes are done correctly there should not be any problem regarding watertightness of the tunnel.

7.8 Dutch situation

Large tunnels in The Netherlands are often immersed tunnels. This tunnel building method will be discussed in chapter 10. An example of a Dutch tunnel executed by the open building pit method is given in figure 7.6: the Willemsspoortunnel in Rotterdam. In this building pit several horizontal strutting layers were implemented, which made the execution process very complex.

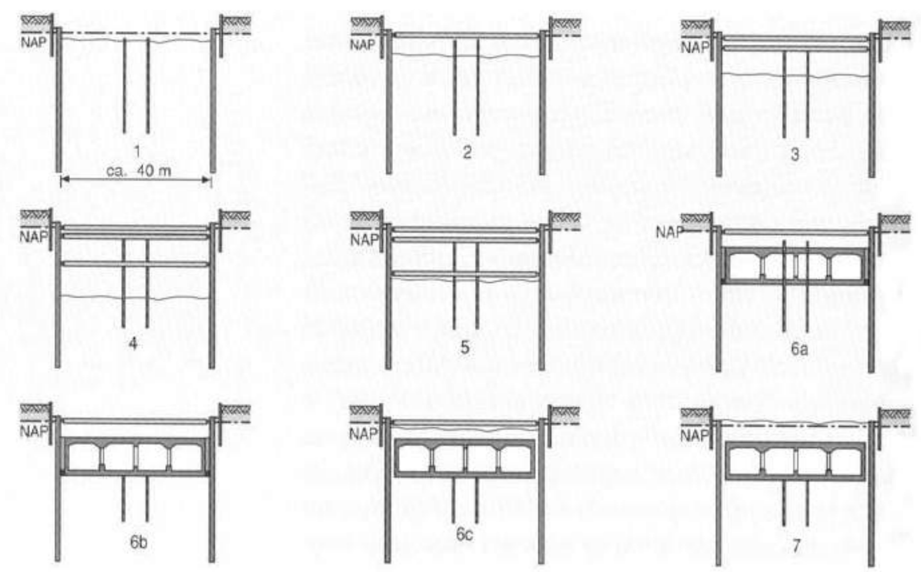


Figure 7.6: Building pit Willemsspoortunnel Rotterdam

8. Bored tunnels

Besides the construction methods from surface level and the immersed tunnel method, there is a third important technique for building tunnels, namely the shield method. This method is suitable for building in soft soil conditions, varying from limestone and clay to sand. The technique was invented by the French engineer Marc Isambard Brunel. It was first used to tunnel under the Thames in London, in the beginning of the nineteenth century.

The shield is actually a cylinder of steel, which bores through the ground. In the front the ground is excavated, then the ground is transported to the back along the already built tunnel part. The actual tunnel is built inside the shield. This usually consists of prefabricated reinforced concrete segments, joined together with bolts. When the tunnel part inside the shield is completed, the shield is pressed forward by screw pumps attached to the previously completed tunnel section.

The principle of bored tunnels has been known for a long time. Figure 8.1 shows the construction of a tunnel under the St. Clair River (Canada), which took place more than one hundred years ago. This tunnel is still in use, which shows how long a well designed tunnel can last.

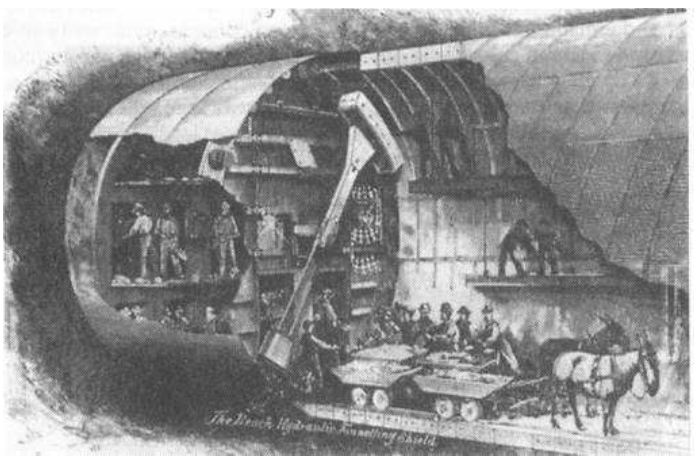


Figure 8.1: Tunnel construction under the St. Clair River more than 100 years ago

Tunnel techniques have radically changed since then and tunnel boring machines (TBM's) have been designed to meet the needs of specific geological, geotechnical and geohydrological circumstances. A survey of the modern TBM types is given in this chapter.

The successful use of TBM's in soft soil depends on a great number of factors. The most important aim is that the boring process should cause as little inconvenience as possible. Control of settlements at surface level and soil deformations that could affect foundation piles, buried pipelines, sewerage systems et cetera is an aspect that requires significant attention. A second important aspect is the prevention of uncontrolled groundwater flows into the TBM's (see figure 8.2).
When boring in soft soils conditions beneath the groundwater level the soil and groundwater pressure must be adequately supported in the front of the boring machine (so called boring front stability). This can be achieved by applying one of the following methods: the liquid shield (slurry shield, hydro shield) or the earth pressure balance shield (EPB-shield). The next section will discuss the difference between these methods.

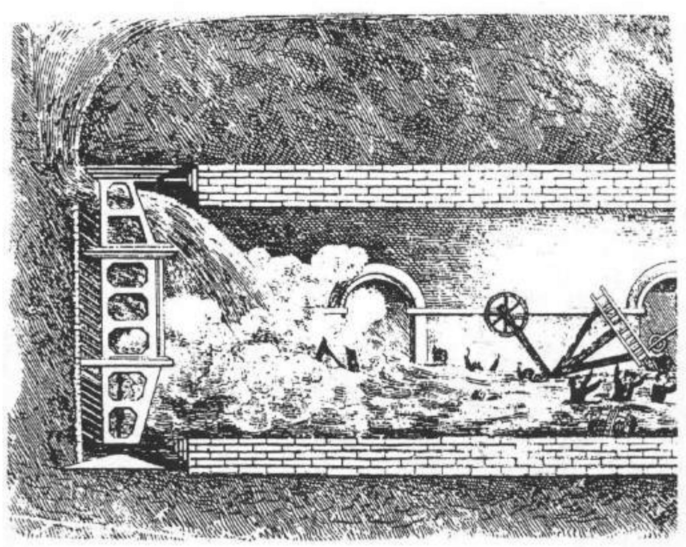


Figure 8.2: An important aspect is to prevent soil and groundwater streaming uncontrolled into the TBM

8.1 Shields

8.1.1 Liquid shield

Liquid shields (bentonite shield, hydro shield, slurry shield) use a bentonite suspension to support the earth body in front of the shield. By maintaining an overpressure in the mixing chamber, the bentonite penetrates (a few centimetres) into the ground pores, which creates a skin of plaster.
This skin of plaster becomes impermeable, so the entire front takes all the pressure from groundwater and soil. By doing this the bore front can be supported by air pressure, when inspections of the cutter wheel dredge or other temporary works are necessary.

The excavated soil becomes mixed with slurry, and is transported in suspension via pipes. Once above ground the excavated soil is separated from the slurry, after which the slurry is re-circulated.

The slurry shield is not suitable for all types of soil. In clay material, it becomes very difficult and expensive to separate the bentonite suspension from the soil. In addition, clay balls can be created, which stick in unfavourable places and cause blockages within the discharge pipes. Materials of a very rough grain size can also cause problems, because the slurry penetrates easily into the earth body and a skin of plaster does not form (or only very slowly).
The German slurry shield method (Hydro-shield) uses an air buffer (air cushion) to prevent sudden large pressure differences in the liquid during drilling. The air buffer works like a giant spring, which maintains the pressure at a constant level during the volume fluctuations. This method functions well as the cutter wheel dredge does not have to be concerned with support during drilling. The only parts of the TBM that make contact with the bore front are the cutting edges assembled on the open spoke wheel.
Only in cases of reparation, or the removal of an obstacle in front of the TBM, are people put under overpressure in the excavation space. The increased air pressure does not always need to be equal to the water pressure at the location of the tunnel. A part of the pore water is pushed away by the air pressure, but because of the capillary powers, water is still kept around the grains. This way the air penetrates a certain distance into the soil, until there is balance between the air pressure and the capillary tensions that holds the water in the ground.

In Japanese slurry shields, control of the support pressure is kept by regulating the valves and measuring equipment of the slurry system. However, with this method, the control of the pressure is more difficult than a self-regulating system, like the air-buffer.

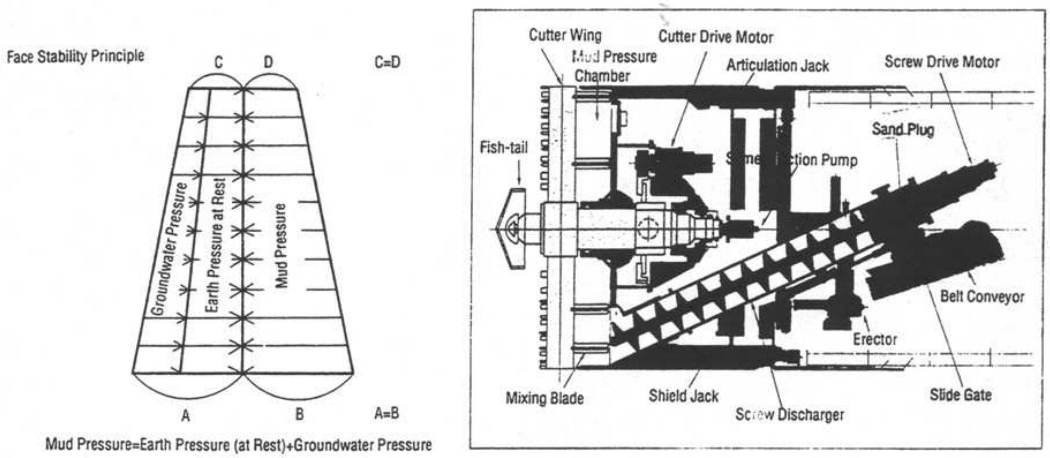
It is also striking then, that the slurry shield machines have relatively closed cutter wheel dredges, which give a higher degree of mechanical support to the bore front. This however causes greater friction of the dig shield with the soil, which in turn makes a higher clutch necessary.

A special system that uses a liquid support is the **Thix-shield**, which is developed in the seventies by Ph. Holzmann. The Thix-shield is based on a combination of a road-header (out of rock machines) and a liquid shield. As excavation instrument a cutter is used, which is fixed on a movable arm. The cutter strongly resembles cutters which are used for dredging. This type of shield has some advantages compared to a common cutter-wheel dredge. Because of the flexibility of the excavation arm each tunnel form can be excavated. One is not longer restricted to circular-shaped tunnels. Besides this it is also possible to excavate selectively with the arm, so that obstacles can be isolated. Furthermore it is possible to bring the arm inside the machine for reparation. The installing power of the cutter arm is considerable lower than by a cutter-wheel dredge, but the way to go is bigger. About the relation between production rate and bore front stability is not much known. The limited power can be a risk when large obstacles are encountered. The mixing chamber, which is totally filled with a bentonite liquid, is quite big and open. Instability of the bore front seems to be a risk when too much soil is cut and the material breaks. The mixing chamber can be entered quite easily and to increase safety the front can be closed with metal plates.

8.1.2 Earth pressure balance shield (EPB-shield)

When an earth pressure balance shield (EPB-shield) is used, the excavated soil is first taken into the work-chamber. The soil is then removed from the work chamber with a screw jack, accommodated within the pipe (figures 8.3, 8.4 and 8.5). The soil is released from the pipe by a slide gate. The screw jack force in combination with a narrow exit will compress the ground in the tube, which will make a relatively waterproof barrier. Sometimes the soil does not comply with (i) the demands of plasticity with regards to the “mixing chamber” or (ii) “blockages in the screw jack”. This problem can be solved by injecting mud, bentonite or foam.
The pressure of the soil mixture in the mixing chamber of an EPB machine has to be at least as large as the soil pressure at the bore front. By keeping the excavated volume in balance with the volume of transported soil, the pressure at the bore front will be kept under control. The soil will be kept under control by jacks, which will press the bore-shield forward.
By using two screw jacks in a row, each turning at different velocities, one can keep the soil ball under control, even under bad circumstances. When gravel or rocks can be expected a so called “ribbon screw” can be used (figure 8.6).

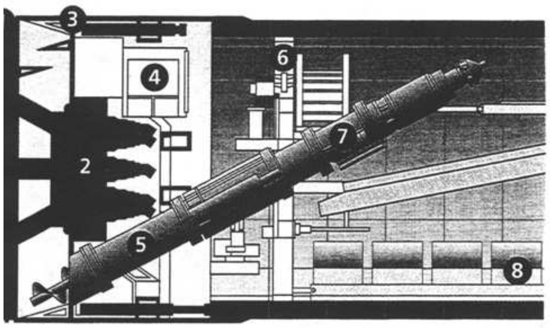
Earth pressure balance shields are very suitable for soils that hold clay. The excavated clay in the mixing chamber has to be flexible and homogeneous, so the supporting pressure will be evenly distributed along the surface of the bore shield. Beside that the permeability of the soil in the mixing chamber has to be such that the groundwater can be retained. Some additions (silt, bentonite, etc.) can be used to alter the characteristics of the soil.
One of the latest developments for the EPB-shield is the application of foam in order to condition the soil. The foam will give the soil some plasticity and because of the formed air bubbles, the soil will be somewhat compressible. This innovation can greatly increase the application of the EPB-shield. Finer sand mixtures and sand with a considerable gravel fraction can be excavated with this kind of EPB, as demonstrated by the metro boring in Milan. Usually the foam is biologically decomposable, so the muck can be transported and dumped off site without extra treatment.



Construction and Features

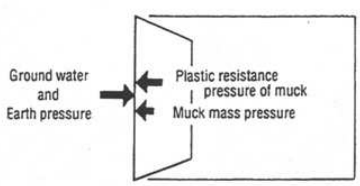
(1) The spoke-type cutter keeps the mud pressure well coping with the earth pressure and groundwater pressure.
(2) Injecting of slime to the face is efficiently performed from the fish tail.
(3) The machine is equipped with the efficient mixing blades that convert the excavated muck into the mud with impermeability and plastic flow properties.
(4) Safety of the working is promoted by correct control on the earth pressure in the face.
(5) Stabilized control on excavation is attainable by converting a variety of soil into the mud.

Figure 8.3: EPB-shield

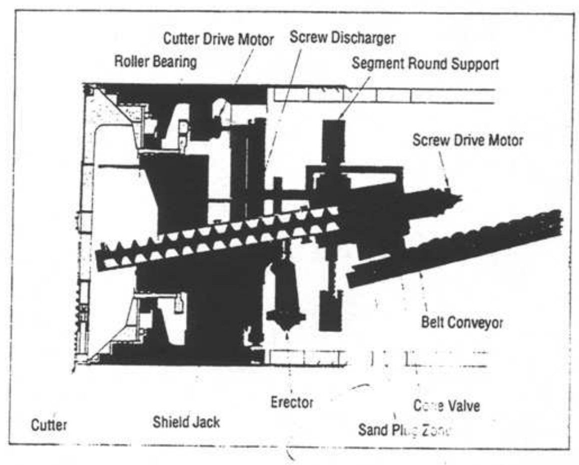


1. *Cutting wheel*
2. *Drive unit*
3. *Push cylinder*
4. *Air lock*
5. *Screw conveyor*
6. *Erector*
7. *Screw conveyor gate*
8. *Segment handler*
9. *Segment crane*
10. *Conveyor*

Cutting face pressure balance



The ground water and earth pressure is counter-balanced by the plastic resistance pressure of the muck and muck mass pressure in the cutter pressure chamber.

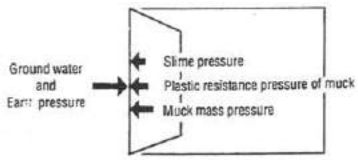


Construction and features

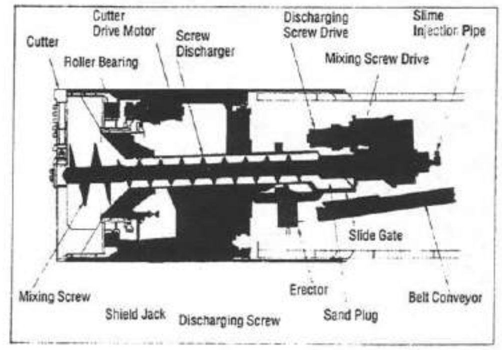
- The machine is equipped with a screw discharger for discharging the excavated muck. Near the discharge outlet, there is a sand plug formation zone, in which excavated muck is compacted into a low-permeability sand plug.
- The earth and ground water pressure is held by the sand plug.
- The sand plug formation zone is adjustable in length so as to suit the soil conditions.
- The machine is equipped with a cone valve to completely close the outlet valve, to adjust the degree of sand plug compaction and to adjust the discharge rate.

Figure 8.4: EPB-shield (continuation)

Cutting face pressure balance



The ground water and earth pressure is counter-balanced by the applied slime pressure, the plastic resistance pressure of the muck and the muck mass pressure in the cutter pressure chamber.



Construction and features

- The mixing screw and discharging screw are concentrically arranged so that they are independently driven, which permits the selection of the optimum operating speed for each screw.
- The discharge end is equipped with a sand plug formation zone, in which a low-permeability sand plug is continuously formed by compacting the plasticized excavated muck.
- The earth pressure and ground water pressure is held by the sand plug.
- The rate of slime-injection into the cutter pressure chamber can be controlled to the optimum for plasticizing the excavated muck in the particular soil conditions.

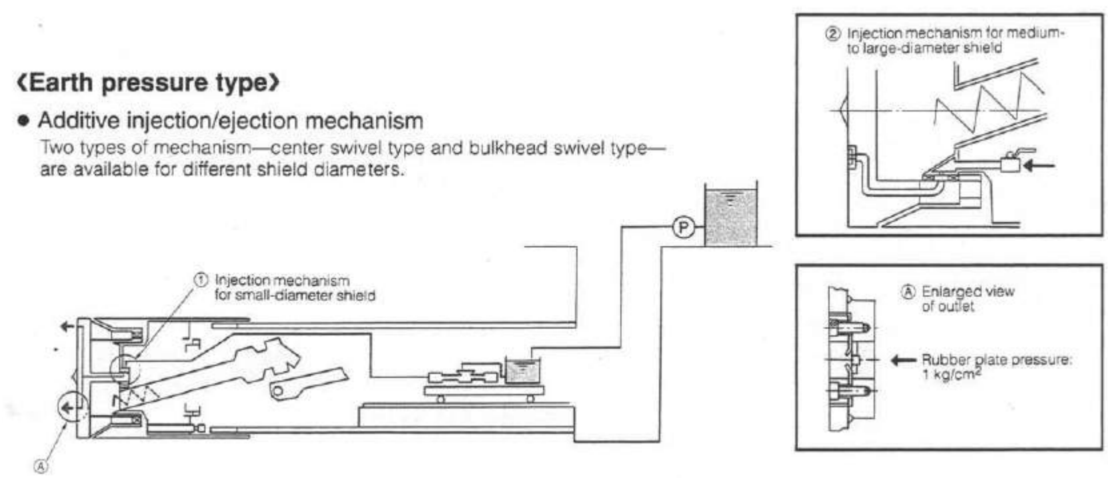
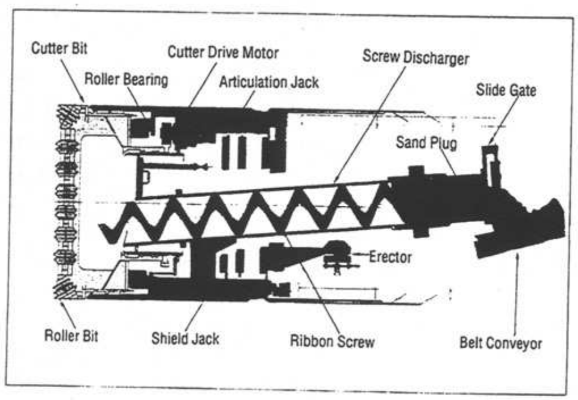
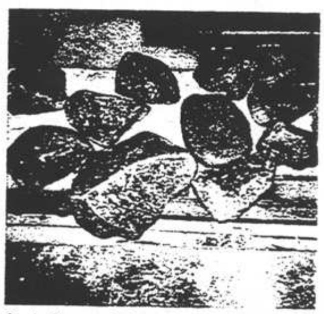


Figure 8.5: EPB-shield with possibilities for "slime injection"



Structure and Features

(1) A flat-type cutter disk is used. This shape is advantageous in the stabilization of easy-to-collapse ground.
(2) Hitachi Zosen has developed on original "tip inserting type" roller bit to attain a higher grade crushing function and wear resistance. The roller bit is capable of crushing rocks having a compressive strength (c) of over 1,000 kgf/cm2.
(3) Easy-to-replace method. When the bit worn out, it can be replaced from the inside of the shield. This enables to estimate the wearing amount of roller bit for each rock.
(4) The automatic excavation system is adopted for the shield machine. This increases the accuracy of tunneling work and safety.


Crushed large rock pieces


Crushed rock pieces being discharged

• Multi-control screw (M.C.S.)

The combination of the variable-length plug zone provided in the center and the speed of screw improves the water cut-off ability of conveyor.

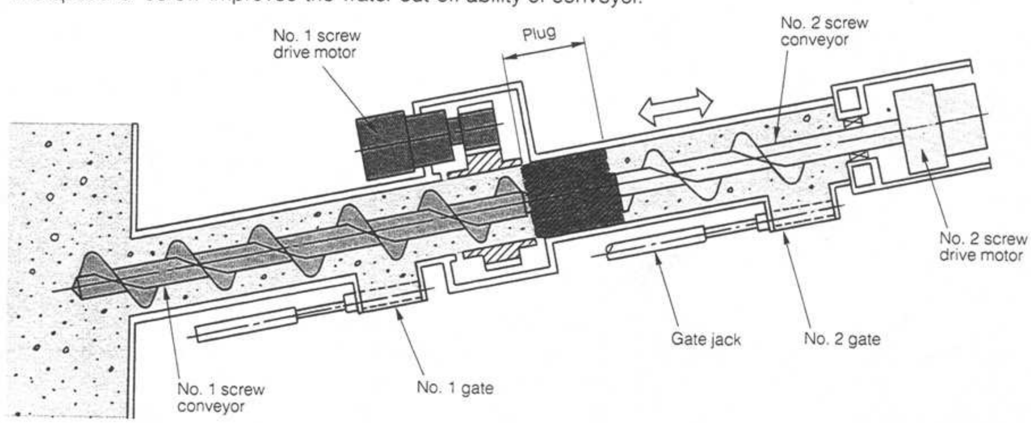
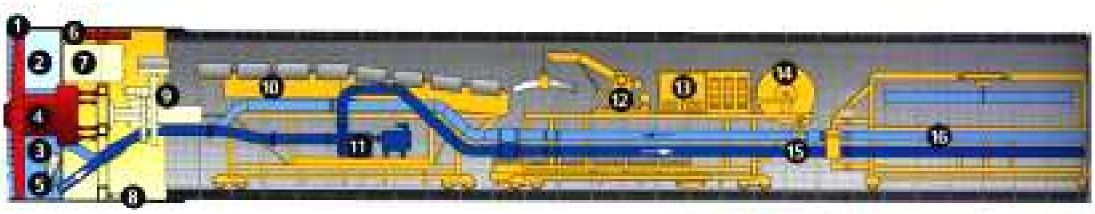
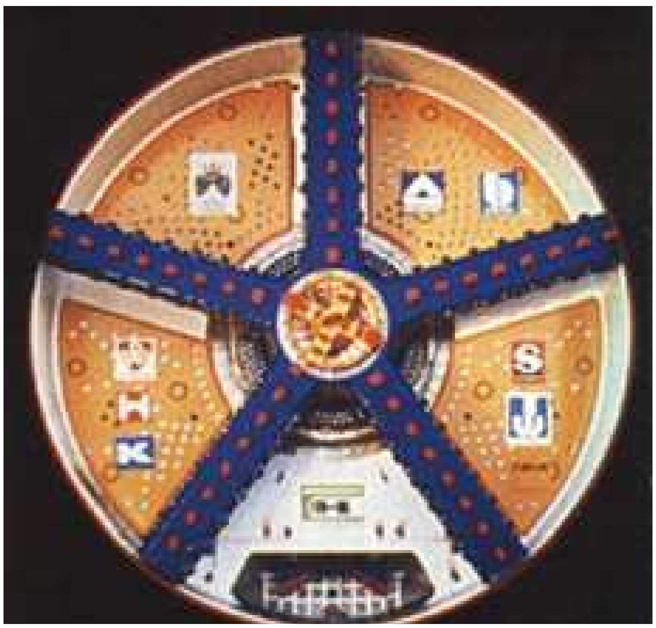


Figure 8.6: EPB-shield (i) for boring in rock (above) and (ii) with a double "slide gate" (below).

8.1.3 Mixshield

The logical consequence of gained experiences with the shield-method in Europe is the development of the mixshield. It was developed especially to cope with changing soil conditions, which were uneconomical to work in when using the same excavation machine. The different shield types can be changed very quickly when using a mixshield (Figure 8.7), adapting the excavation machine / bore method / transportation system to optimally meet the changing circumstances. Possible operation methods are: (i) as slurry-shield, (ii) with air-pressure as supporting pressure, and (iii) as EPB-shield.





1 Cutting wheel
2 Air bubble
3 Bentonite suspension
4 Drive unit
5 Stone crusher
6 Push cylinder
7 Air lock
8 Steering cylinder - Shield tail
9 Erector
10 Segment conveyor
11 Slurry pump
12 Segment crane
13 Main electric panel
14 Cable reeling drum
15 Discharge line
16 Feed line

8.2 Selection of a TBM for soft-soil-conditions

There are many processes that take place in and around a tunnel boring machine. In order to get better insight into a tunnel boring project it is wise to understand the various functions that a TBM has:

- Excavation of soil
- Transportation of excavated soil and tunnel elements
- Construction of tunnel lining

Using only a TBM for construction of a tunnel is insufficient. The TBM is part of an entire bore system, which consists of the following components:

- *TBM*: bore shield with cutter-wheel, jacks, segments-erector, tail-sealing mechanism and grout installation
- *Train*: trailers with transformers, extensions systems, segment transportation systems et cetera that are located behind the TBM
- *Operating system*: central unit that operates the machine and guarantees continuity
- *Logistical system*: supply or removal of soil, additives, materials, tunnel segments and staff to and from the ground level
- *Above ground installations:* separation plant, segment storage area, soil removal, bentonite mix installations etc.

When deciding what type of TBM would be best suitable for a specific project, there are a number of selection criteria to consider:

- Soil profile of the route that has to be bored
- Groundwater pressures and variations
- Diameter of the tunnel
- Depth and alignment of the tunnel
- Nuisance to the surrounding area (settlements, soil deformations)
- Logistics / available space
- Performance / progress
- Safety
-

8.3 Special developments

Machines from Japan, which can bore alternative shapes, are entering the market alongside the circular TBM's. The Double-O Tunnelling (DOT) shield (figure 8.8) and the Multi Face (MF) shield (figure 8.9) are examples of this. The excavation by a DOT shield (an EPB shield) is be done with two cutter-wheels, which are situated in the same vertical plane and which are turning in opposite direction out of phase.

The **advantages** of this type of excavation compared to a similar tunnel with a large diameter and two separated tunnels is as follows:

- Less soil to excavate (also less soil to remove)
- Less material required for lining
- The tunnel lies shallower by a horizontal configuration
- The tunnel can be bored with two road/rail levels above each other or besides each other (which can be handy when there are nearby underground structures)
- Because the cutter-wheels are rotating in opposite directions, the torsion moments, created by rotations of the wheel, will be reduced

The **disadvantages** are:

- The settlement is larger than when two separate tubes are built
- A vulnerable wall or row of columns is created in the middle, which can be a safety issue

The geometry of the lining is the same as that of a single tunnel. Only two differently shaped elements are necessary. These are necessary at the location where both circles cross. A row of columns, combined with beams, will support the roof in the middle of the tunnel. Using a wall (possibly partly open) in the middle is also a possibility.

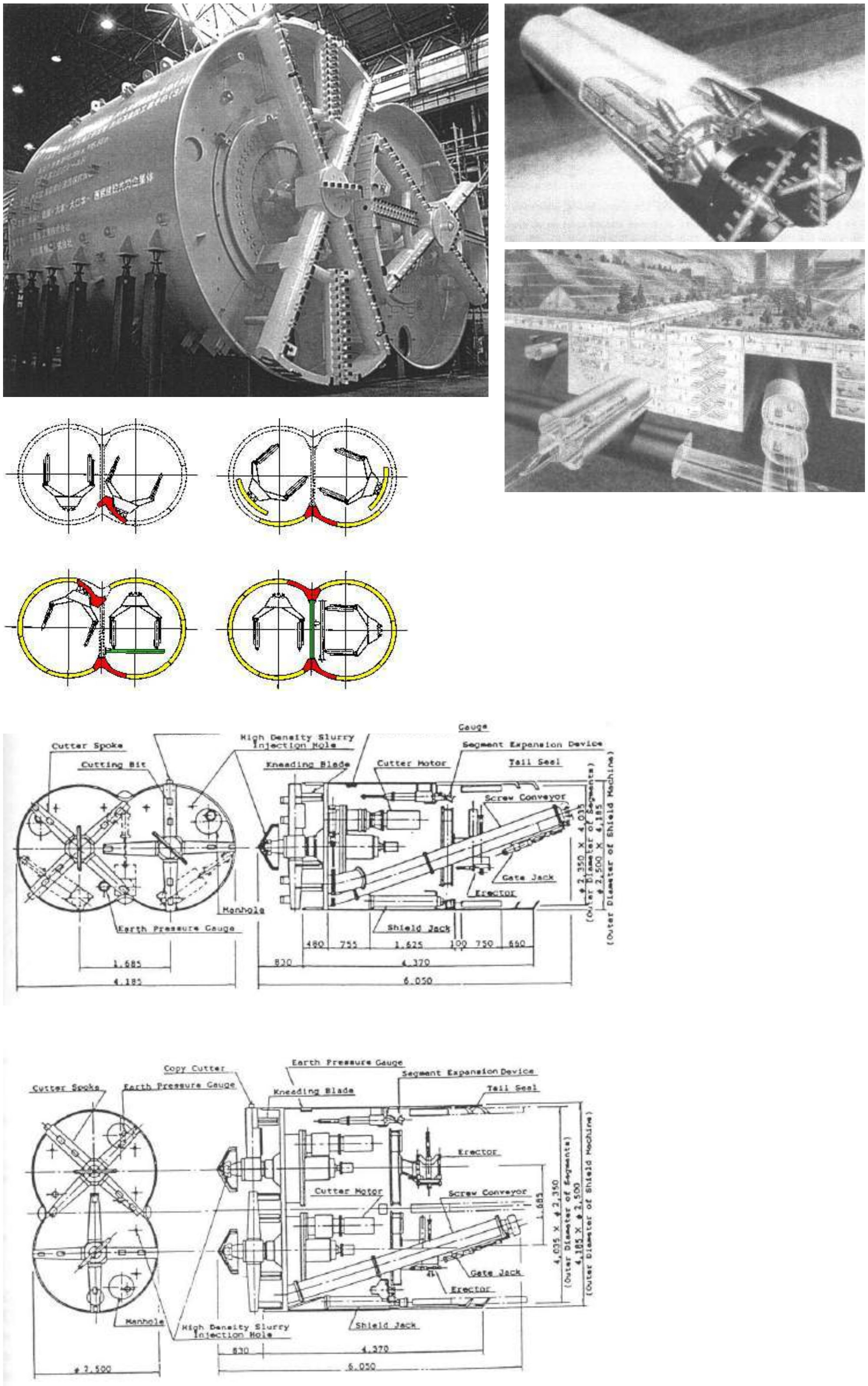


Figure 8.8: DOT shield method

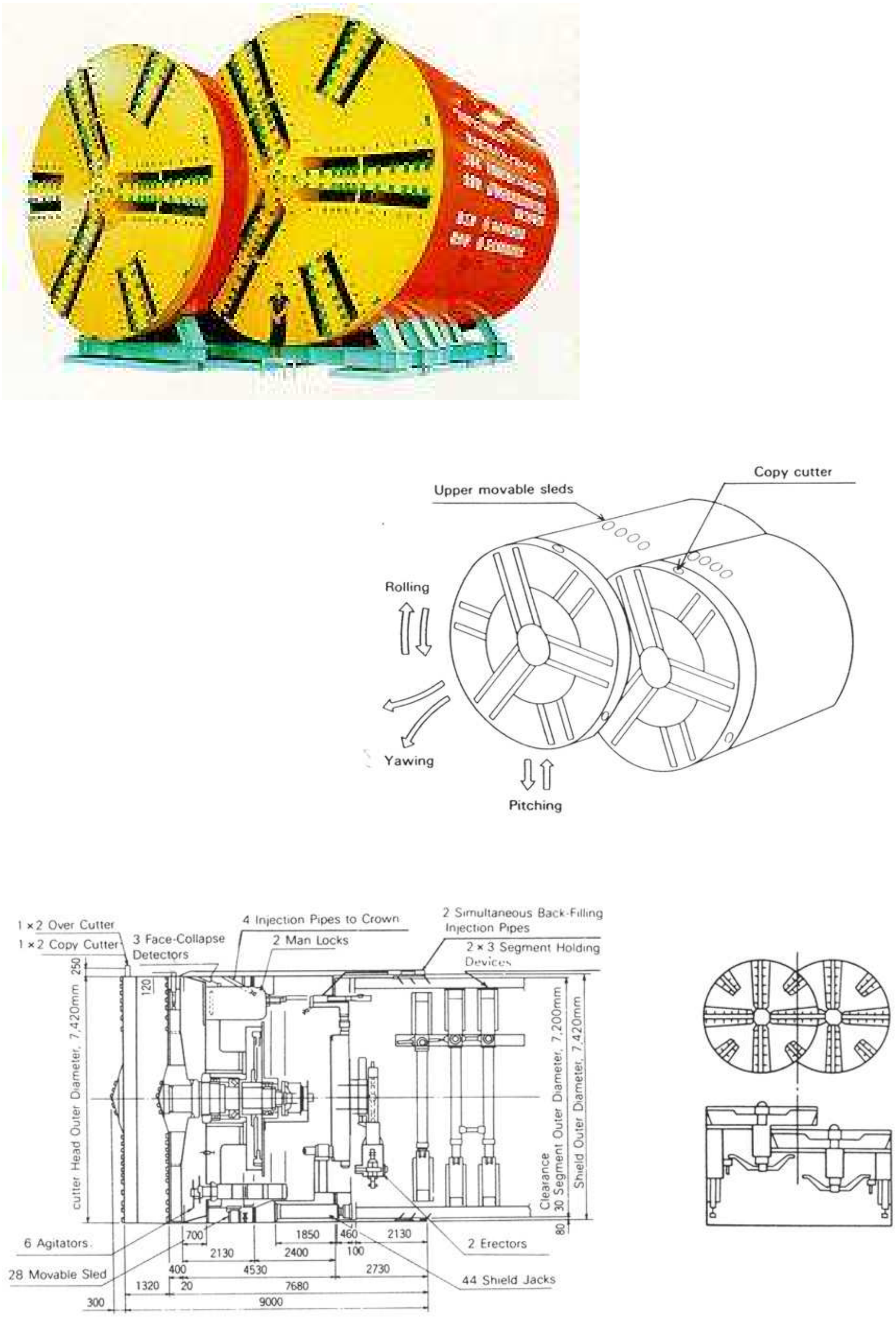


Figure 8.9: Multi-face shield

8.4 Tail sealing mechanisms

Sealing the crack between the inside of the shield of the TBM and the outside of the constructed tunnel lining is a very important part of the tunnel boring process.

Because the tunnel lining (segments) is sometimes constructed off centre inside the TBM-shield (e.g. when making corners), some differences in the thickness of the tail crack can appear. This variation in thickness can also be a result of accepted construction tolerances in dimensions and position of the segments.

The work carried out inside the modern TBM's is generally done under atmospheric pressure. The tail-sealing mechanism of the TBM has to take on the pressure difference between the outside (grout, groundwater pressure) and atmospheric pressure. Because the thickness of the tail crack can vary over the tunnel-line, the tail sealing mechanism has to react flexible to these changes. During the construction of the tunnel, the tail sealing mechanism should be easy to substitute. Two of the most common tail sealing mechanisms are explained below.

Rubber tail sealing mechanism
The so called S1 tail sealing mechanism of Wayss & Freytag AG is a massive neoprene profile with a thin nose.

The profile is constructed (hinged) on the inside of the shield of the TBM. The nose of the profile glides over the outside of the tunnel lining. The profile will be pressed to the tunnel side by a pre-stressing force, because of the tightening of the bolt and the difference in pressure between the inside and outside of the tunnel lining.

The grout injection pipes end directly behind the tail sealing mechanism. These pipes come out of the shield housing of the TBM. During the forward movement of the shield, grout will be pressed into the tail crack via the injection pipes under high pressure. The grout pressure is greater than the isotropic earth pressure.

The length of the neoprene profiles is 0.6 to 1 m. The tail sealing mechanism is made up of relatively narrow parts, lying next to each other. Initially the parts don't overlap each other. When the neoprene profiles are pressed against the tunnel lining by the earth-pressure, the profiles will overlap each other (figure 8.10).

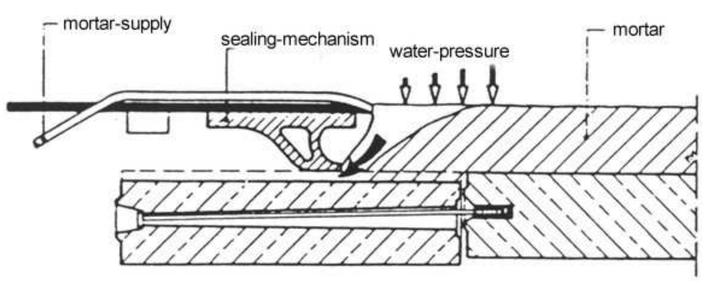


Figure 8.10: Rubber tail sealing mechanism

Tail sealing mechanism by means of wire brushes
The wire brush seals are used by several Japanese and European manufacturers of TBM's.

The wire brushes are assembled in at least two rows, one behind the other (in series), with a mutual distance of about 0.3 m (measured in the direction of the tunnel axis). With higher pressures, which have to be stemmed, several rows of wire brushes can be installed in series.

The ends of the wire brushes will glide over the outside of the tunnel lining and can react flexible to irregularities in the geometry of the tail crack. The space between the mutual rows of wire brushes will be filled up with special grease. This grease is kept under pressure.

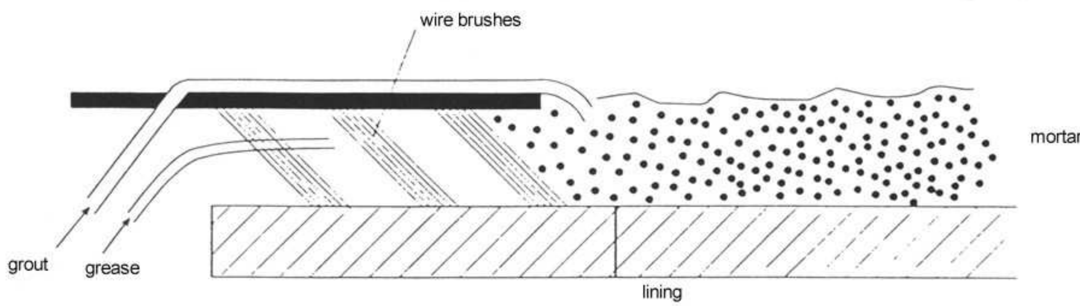


Figure 8.11 Tail sealing mechanism, using wire brushes

The grease pressure between the outer and the second outer row of wire brushes is about 2 bar higher than the prevailing isotropic earth-pressure and roughly 1 bar higher than the pressure of the injection grout. The application of higher grease pressure will always give a grease-keeping grout-mortar. The amount of grease, which has to be pumped to keep the grease pressured, can be enormous. The grease pressure in the rows of wire brushes will decrease when distance from the tail crack increases. (Figure 8.11)

There are many good examples of this type of tail sealing mechanism. The wire brush seals were used for the construction of the tunnel below the Støre Belt in Denmark (EPB-TBM): four rows of wire brushes, which have to stem at least 80 m water column.

Emergency tail sealing mechanism
Besides the regular tail sealing mechanism, an emergency tail sealing mechanism is also put in place. This emergency tail sealing mechanism can consist of a hose, which is filled with air. The hose normally lies in a folded state in a groove inside the shield. The groove is located slightly closer to the front of the TBM than the regular tail sealing mechanism. When the regular tail sealing mechanism fails, the emergency tail sealing mechanism will be blown up. The emergency tail sealing mechanism is also used during repair of the regular tail sealing mechanism.

8.5 The tunnel-lining

The lining is constructed directly behind the TBM. The basic function of the tunnel lining is to offer resistance to the earth and groundwater pressure. During construction of the tunnel, the lining has to offer resistance to the reaction forces (jack pressures) from the shield. The interaction with the surrounding soil is special interesting when looking at these tunnel constructions. The ratio between wall thickness and tunnel diameter is usually about 1:20, making stiffness an important attention point. The soil contributes to the strength and stiffness of the tunnel, but also acts as a load on the same tunnel. Additionally, these loads are dependent on the transformations of the lining. It is obvious that the forces involved with the tunnel construction process are quite complex and require much attention.
Although the segmented concrete lining seems to be an economically attractive solution, there are certain circumstances when another type of lining can be more suitable. Four types are discussed below:

Steel-segments lining (SSL)
The bore tunnel system with the longest history is SSL. This lining is constructed with crucible steel ring-shaped segments. The tunnel ring is made up of a large number of segments. They are connected in axial and radial direction with a bolted connection. A water sealing material is used in the joints that are below the groundwater level. With the permanent bolt connection the SSL is a stable construction even without support of the soil and can therefore be used under relative soft soil conditions.

Concrete-segments lining (CSL)
CSL is derived from the SSL system. The reinforced concrete segments replace the steel-segments, most of the time this system is chosen because of lower costs. The stability of a CSL depends largely on the surrounding soil. The transformations at the joints have to be limited with regard to transmission

of forces and reduction of concrete contact stress. The behaviour of the joint determines the transmission of forces throughout the ring. The shape of the longitudinal joint determines the moment capacity. The segmented rings interact within the ring joint, which creates the need for a clutch mechanism. The clutch consists of a toothing joint or a flat joint with a conditioned friction surface. The stiffness of this clutch also determines the transmission of forces in the segmented rings. Application under relatively soft-soil conditions demands great attention to the specifying of the joints. The CSL is the most used ring type for modern tunnels.

Extruded concrete lining (ECL)
In contrast to the SSL and BSL, the ECL consists of a homogeneous tunnel lining, without hinge points. (Figure 8.12)

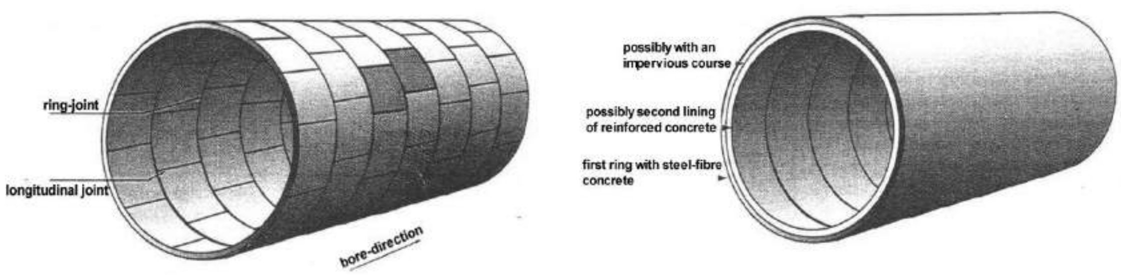


Figure 8.12 BSL and ECL

This method creates the lining by using a movable (in sections) formwork. Injection points at regular intervals supply plastic concrete, which will be pressed between the soil and the formwork at the tail of the TBM. By moving of the TBM the back part of the formwork will be disassembled and moved forward. Besides the concrete pressure, the inside formwork has to resist the jacking forces from the TBM. Steel fibres can be added to the extruded concrete when more strength is required. The tunnel is often strengthened by a second lining, guaranteeing the water tightness. Hereby the second lining can take over a part of the stresses. The ECL is constructed with one or two linings in Europe and Japan, with diameters from 3 to 10 meters, in ground layers varying from sandy to bricky. The control of the extruding process and the interaction of the (steel fibre) concrete with the soil is essential when using this system. The suitability of this type for Dutch soil conditions also depends on the (stiffness) qualities of the soil. Following the ECL-method, methods were developed that allow for a reinforced concrete construction to be constructed behind the TBM in a continuous process (Figure 8.13).

Multi-lining systems
For certain reasons it can be desirable or necessary to build a second tunnel lining inside one of the previously mentioned lining types. In Japan, the earthquake load is often the reason for applying a second reinforced concrete lining (e.g. to get enough weight against possible rising). With the ECL, a second lining has been proved increasingly necessary as it improves the level of waterproofing in the tunnel. It is conceivable that in extremely soft (settling-sensitive) soil a combination of concrete segment lining with a reinforced concrete lining is an economical solution. Multi-lining systems can be considered for the beginning and end parts of a tunnel, which, in the Netherlands, are often situated in the soft Holocene sedimentary. This solution can also be interesting for locations with varying soil layers that have great differences in stiffness.
Finally, the second lining can be desirable in order to reduce the risk of failure caused by extremely large loads such as explosions, crashes and train disasters. Risk analyses and the development of a safety philosophy for bored tunnels need to consider the application of multi-lining.

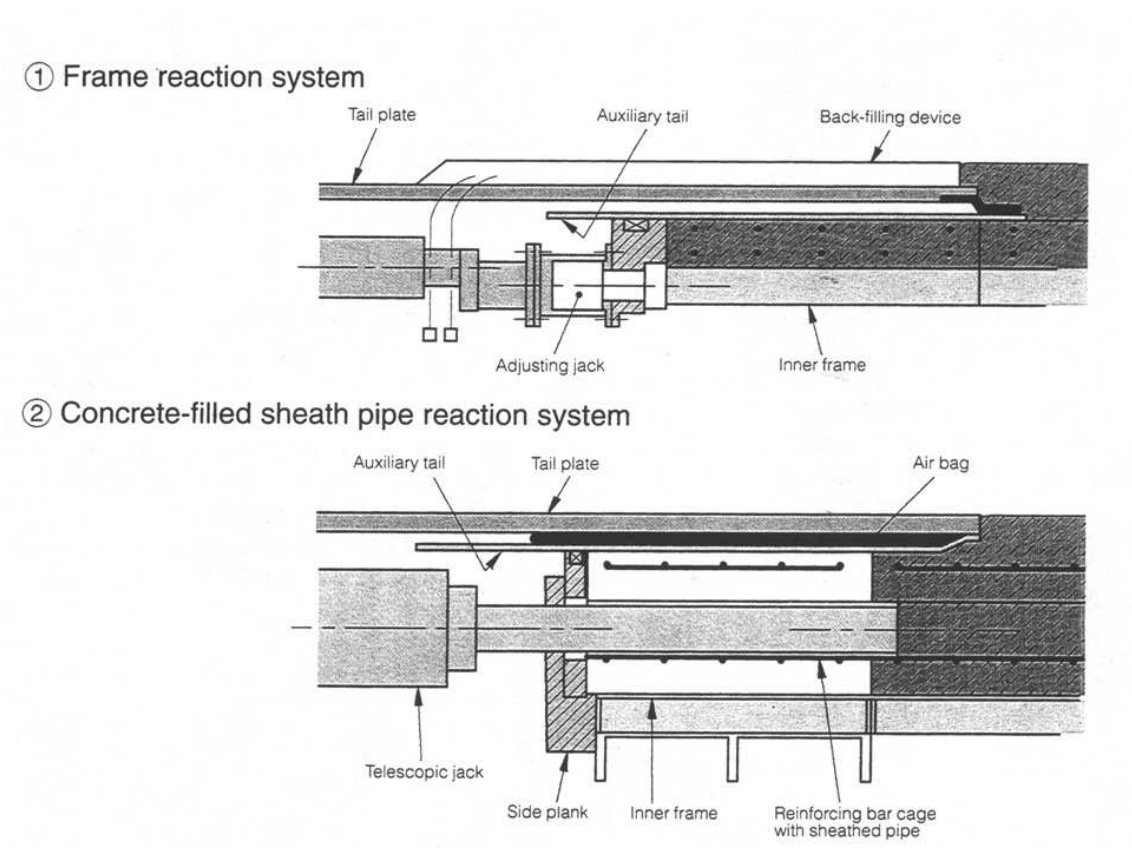


Figure 8.13: Kawasaki's Extruded Concrete Lining (ECL) method

Approach of the design of the tunnel lining

Besides the many different types of lining, design rules are an important consideration. Many design rules are drawn up in other countries, especially for the design of tunnel linings. The strong interaction between the tunnel lining and the surrounding soil is a specific characteristic of the bored tunnel. The influence of the sedimented and relative soft soil layers on the strength and stiffness of the lining provides a great extent of uncertainty with respect to the application design rules developed in other countries. This interactive behaviour demands an iterative design process. A relatively large amount of modelling of both the soil as well as the tunnel lining will be used. This is necessary since the stiffness of the construction has to be determined first so the calculation can begin.
The obtained results can lead to an adjustment of the stiffness level. Besides the loads in the operating phase, the loads during the construction phase should be included as they are often dominant. One will normally determine basic dimensions based on practical and economical considerations, which are based on experiences with other tunnels.

Loads

The loads that should be considered are initially soil and groundwater loads. Additionally the loads caused by transport and installation of segments are important. The loads of the jacks during directional corrections can be large for the segments. Furthermore loads during the operation phase, e.g. temperature and traffic, should be calculated. One also has to consider the special loads created by explosions, fires and accidents.

Construction of the segmented tunnel lining

When the TBM has bored 1.5 meters, the lining will be constructed with a ring of prefabricated concrete elements inside the shield. The TBM can push off against the constructed ring to bore the next part of the tunnel. Each ring is smaller on one side than on the other side. By placing the small side of the ring against the broad side of the previous ring, a straight pipe will be created. A curve can be made by placing the rings differently in relation to each other.

Segments
To give the tunnel the desired alignment it is necessary to use special rings. By placing different conical rings behind each other, horizontal and vertical curves can be constructed. A combination of both is possible, which would create three-dimensional curves. A combination of different systems can be used. The choice of the segment size is determined by the following factors:

1. The **width** of a segment will be as large as possible to optimise the average velocity of the TBM. Prescribing factors: (i) the maximum length of the jacks, (ii) the available space for transport and placing of the segments, and (iii) the maximum weight which can be handled by the erector. The usual widths range from 1.2 to 1.8 meters.
2. The **length** of the segments will be determined by the number of parts, in which a complete ring in segments will be divided. The following factors are important: (i) the available space and capacity of the erector, as above, (ii) the number of actions required during the production and construction, and (iii) the power transmission in the segments. The number of parts, in which a ring will be divided, varies but is usually between 6 to 8 plus a key stone.
3. In order to determine the **thickness** of the segments, the following factors are important: (i) the power transmission in the segments together with the chosen length and width, (ii) the size of the loads of the jacks on the segments, (iii) the details of the joints in combination with the sealing mechanism and the power transmission between the segments, and (iv) the way the segments will be connected. The thickness of the segments, a very important factor in the total costs, varies from 250 to 400 mm. As a first estimate, the thickness of the segments is D/20, in which D is the outside diameter of the tunnel.

Due to the forces on the segments, is it often necessary to use reinforced concrete. The total amount of reinforcement in the segments varies from 70 to 90 kg/m^3. The segments will be fast produced, therefore the reinforcement cages will need to be welded and this creates stiff, manageable cages. Concrete with steel fibres is a good alternative for reinforcement.

The segments have to be connected to each other, either permanent of temporary. The reasons are (i) stability during construction, (ii) transmission of forces in the final situation, and (iii) the initial transformation of the sealing-profiles. In the final situation the transverse and longitudinal forces caused by the earth and water pressure would make it possible to remove the connectors. Possible connectors are:

- Straight bolt
- Bent bolt
- Slanting bolt
- Dowel, only longitudinal
- Massing/groove-profile in the joint, only longitudinal

Water tightness
In order to prevent water from entering the tunnel the following components should be considered:

- Water tightness of the segments, which creates demands regarding thickness of the segments and the permeability of the concrete,
- Water tightness of the joints, for which neoprene profiles and hydrophilic rubber could be used. (Figure 8.14)

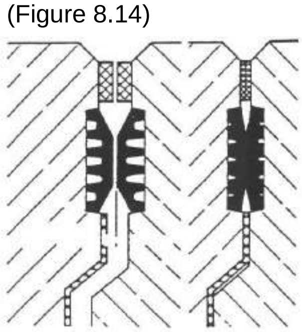


Figure 8.14: Waterproofness of the joints

Usually the segments are provided with an inside groove. Because of this it would be possible to make a seal on the inside of the tunnel in case of an emergency. Leak water will possibly be drained via longitudinal and transverse joints to the main drainage of the tunnel.

In a view of the relatively long operational phase of a tunnel (50 to 100 years) the **durability of the lining** is an essential aspect. Important factors for this are:

- **Concrete:** Noxious chemicals, which will affect the concrete, can be found in the groundwater.
- **Reinforcement:** The reinforcement in the segments can corrode when the concrete is carbonated and / or when chlorides are penetrated into the steel inside the concrete.
- **Water tightness:** The lining water tightness will be determined by the fine-tuning of sealing profiles to meet the specific circumstances, and use of a high quality concrete. In addition, a well chosen grout can contribute to the durable waterproofness of the lining.

Grout

As mentioned before, the outside diameter of the shield is greater than the outside diameter of the tunnel ring. Because of this, a crack behind the shield and around the tunnel ring will arise during movement of the shield. To prevent excessive transformations, these spaces will be filled with cement-grout during the forward movement of the shield. Furthermore grouting can be used to increase the resistance to penetration of noxious chemicals in the underground, and to improve the water tightness. The following grouting methods can be used: "sand / cement", "water glass additions (Japan)", and "sand / bentonite". The material can be injected at the tail of the TBM or through an opening at right angles to the segments. Today this usually happens at the tail of the TBM (Figure 8.15).

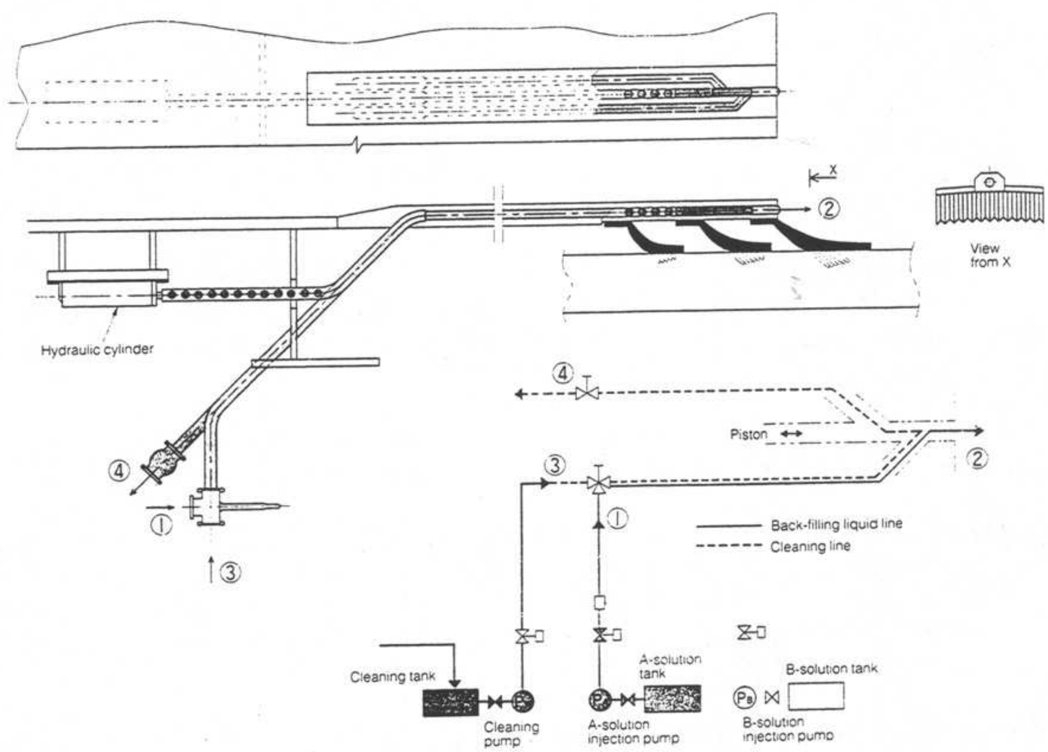


Figure 8.15: Kawasaki's simultaneous back-filling device

8.6 Starting zone of the construction of a bored tunnel

The soil surrounding the starting shaft of the tunnel has to undergo treatment, such as freezing or grout-injection, in order to prevent (i) instability on the tangent plane starting-shaft / bored tunnel by starting the boring of a tunnel, or (ii) water penetration of the vertical wall of the starting shaft of the TBM. Just after passing the shaft wall, the tail sealing mechanism and the continuous grouting outside the tunnel lining will complete the connection of the bored tunnel to the starting shaft. This all is shown in Figure 8.16 and 8.17.

So that the ground outside the diaphragm wall will not collapse when the diaphragm wall is broken out to launch the shield machine, this outside ground will be frozen where the shield machine will be launched to form a wall of frozen ground which is both strong and impermeable to water. Further, the ground ahead of this frozen zone has been improved by chemical grout injection under a separate contract.

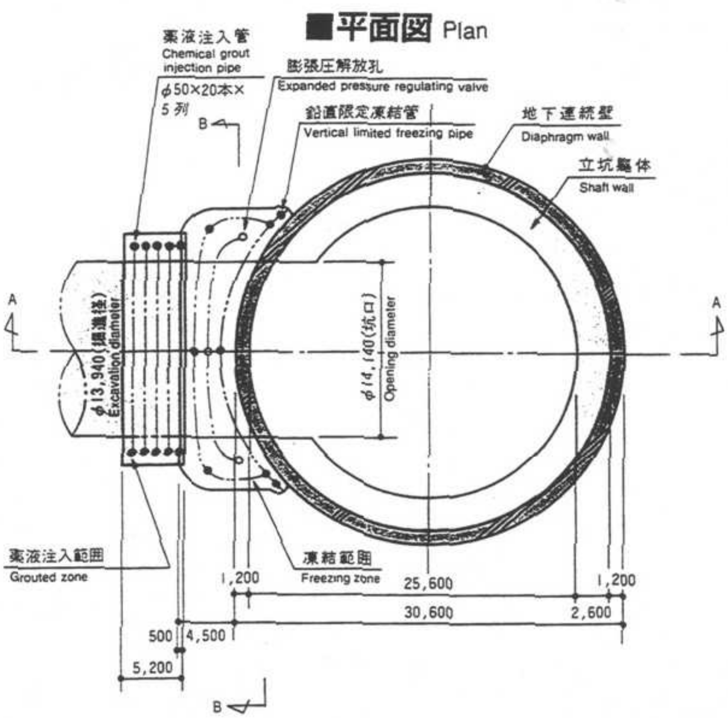


Figure 8.16: Starting zone of a bored tunnel

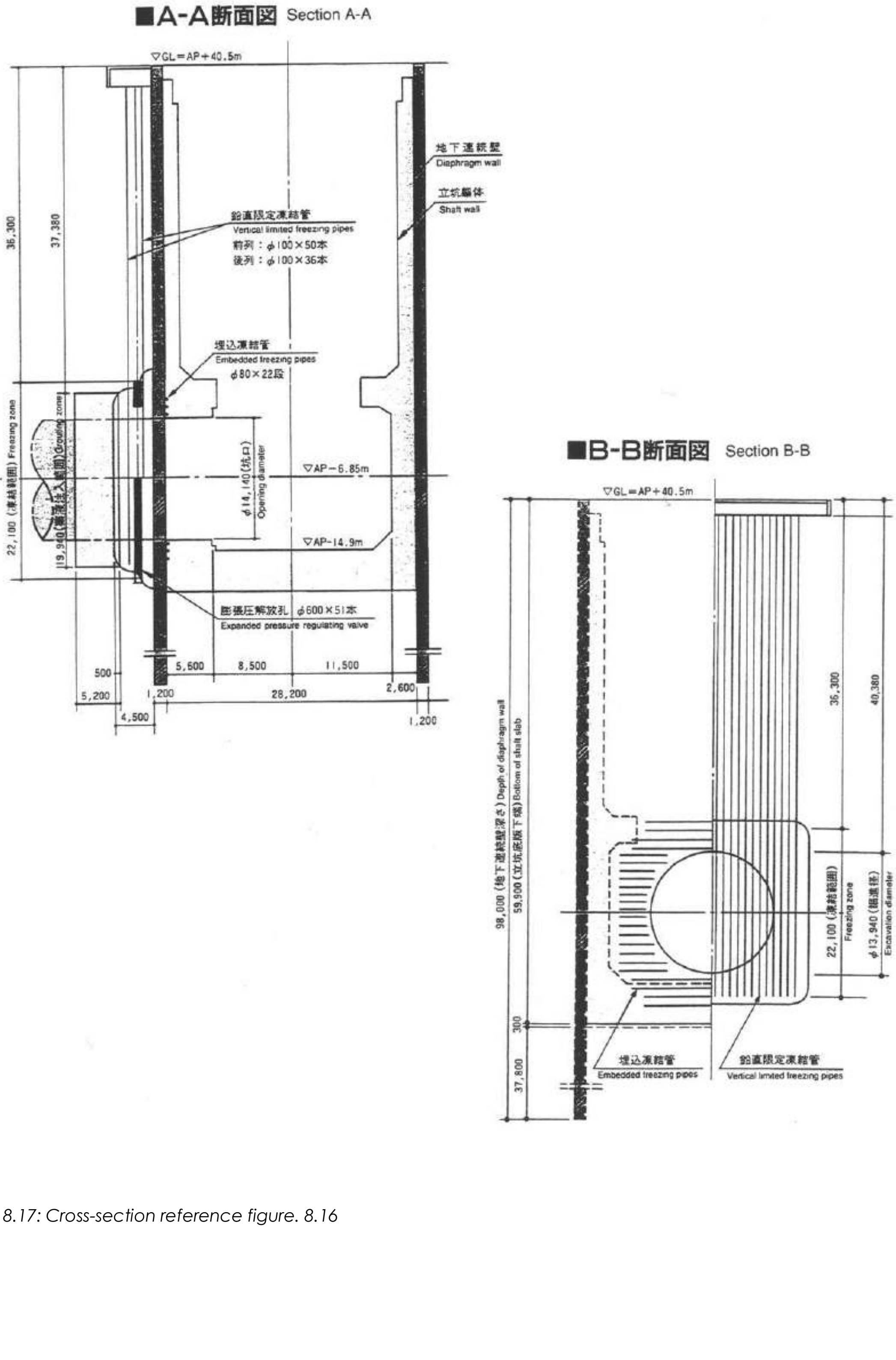


Figure 8.17: Cross-section reference figure. 8.16

8.7 Special attentions

1. Mutual influence of parallel tunnels
The boring of a tunnel is always accompanied by a disturbance of the soil stresses surrounding the tunnel. The direction of the main stresses will change directly above the tunnel. Arching will occur, which will increase the horizontal stresses and decrease the vertical stresses above the tunnel (figure 8.18). The vertical earth pressure above the tunnel will be taken to the soil layers next to the tunnel by the arching effect.

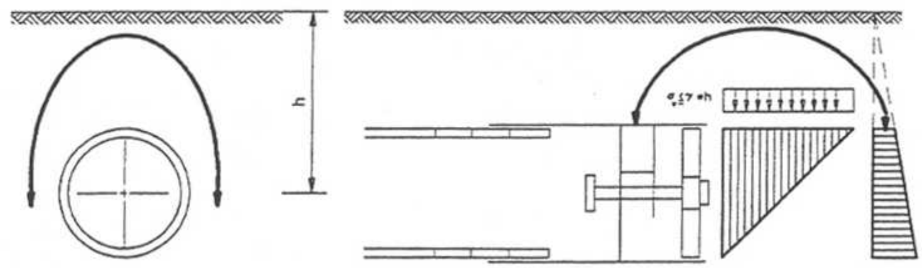


Figure 8.18: Arching

When a second tunnel is bored close to the first tunnel, the arching above the first tunnel will be disturbed and the ground deformation above the first tunnel will increase. Furthermore forces on the first tunnel will be altered by boring of the second tunnel.
Excluding the mutual influence totally, the distance between the tunnels has to be 2 to 3 times D (from wall to wall). The distance between the tunnels will decrease the mutual influence; possible additional measures will need to be determined. The minimum distance (a) is:

- Flexible lining, low shield-pressure: a = 0.5D
- Stiff lining, high shield-pressure: a = 1.0D

In specific situations the distance between two tunnels can be much smaller. This is especially common at stations or difficult passages were the distance could be as small as 0.25-0.5D. Additional measures may be necessary in such circumstances.

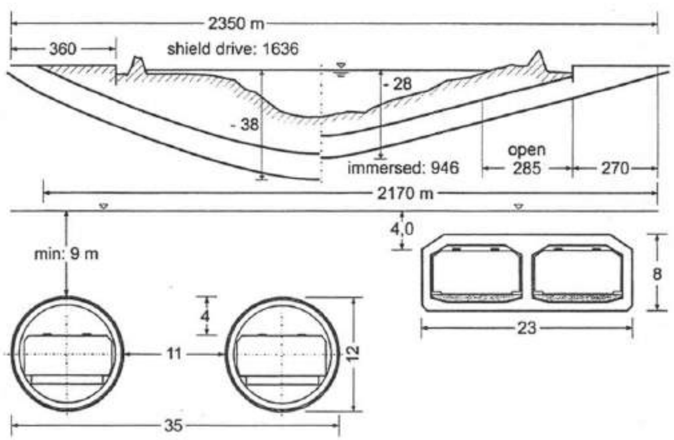
2. Influencing the foundation of the surrounding buildings

- Release of the soil in the influence zone of the tunnel will decrease the point bearing and / or the shaft bearing of the foundation piles.
- Extra negative friction on the foundation pile will be generated by soil level transformations.
- Inadmissible (horizontal) transformations by soil transformations will be forced onto the foundations-piles.
- As a result of the reduction of the bearing capacity and / or occurrance of inadmissible transformations, damage will occur on natural foundations.
- Detection and prediction methods with respect to the construction of the bored tunnel can give valuable information regarding potential soil deformations and the optimal bore method.

3. Vibrations
Nuisance caused by vibrations can occur during the boring of the tunnel and in the operational phase. Nuisance during the operational phase will (unfavourably) differ from the nuisance created during operational phase of a conventional rectangular tunnels because (i) the different shape of the tunnel, (ii) bored tunnels have less mass, (iii) the depth, and (iv) the foundation method.

4. Depth
The required minimum depth will be determined by the demands regarding the bore-front stability and / or the overpressure used in the bore chamber and the vertical stability of the tunnel in the final stage. With respect to the stability of the tunnel in the final stage one has to take into account: (i) the relatively low mass of a bored tunnel (by the same horizontal and vertical loads, the thickness of the lining of a round tunnel can be smaller than the lining of a rectangular tunnel and the prefabricated concrete is qualitatively better and stronger than not prefabricated concrete, so the thickness of the lining can be smaller), and (ii) the behaviour of the segment joints as a result of the joint working of the

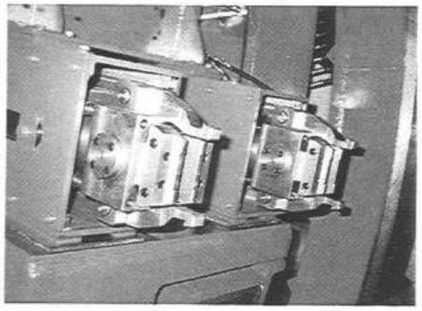
tunnel. Figure 8.19 shows a comparison of the required depth of a conventional rectangular tunnel and a bored tunnel.



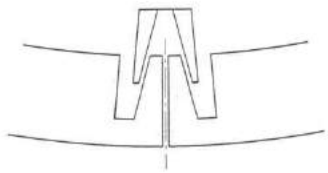
As a (conservative) rule of thumb 1D as minimum depth measured from the top of the tunnel would be used, in which D is the outside diameter of the tunnel. For a tunnel constructed with an EPB-shield the demanded depth is smaller due to decreasing demands with respect to the overpressure in the bore chamber.

8.8 Robotisation and computer control

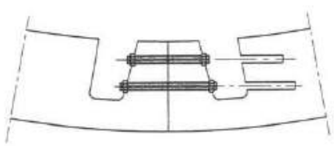
Efficiency and quality during the construction of a bored tunnel can be improved by robotisation and application of computer control. Some examples of this development are: “Automatic Segment Assembly” (figure 8.20), “Automatic Segment Transport and Erection Systems” (figure 8.21), “Automatic Surveying and Directional Control Data”, “Control and Management Systems for the Automatic Segment Assembly and for the remote monitoring of using public telephone lines” developed by Kawasaki, and the “Multi-arm erector” (figure 8.20d).



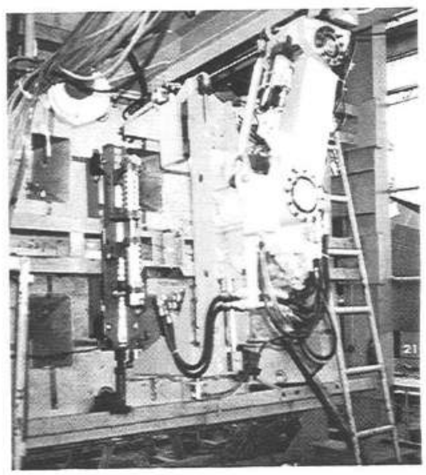
① Automatic assembly of cotter joint segments

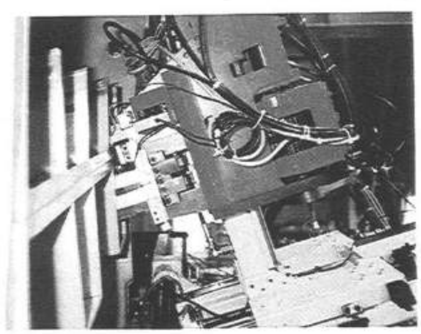


② Long bolt joint segments



Since several years ago, Kawasaki has carried out research on the automation of shield machines. With respect to automatic segment assembly, in particular, R&D efforts have been concentrated on segment clamping and positioning systems for various types of segments.





③ Short bolt joint segments

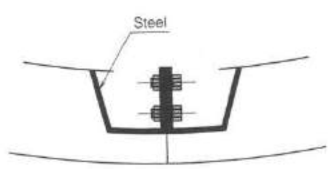


Figure 8.20a: Automatic Segment Assembly

• **Application to superlarge diameter shields**

With the increase in segment weight to cope with the increase in the number of tunnels of larger bores, it has become indispensable, especially with shields of very large diameter, to assemble the segments accurately and safely. Over the past years, Kawasaki has carried out research on segment clamping and positioning systems for various types of segments. As a result, it has an automatic segment assembly system for the first time for superlarge diameter shields. This system has proved very effective in actual tunneling operations.

Automatic segment assembly flow

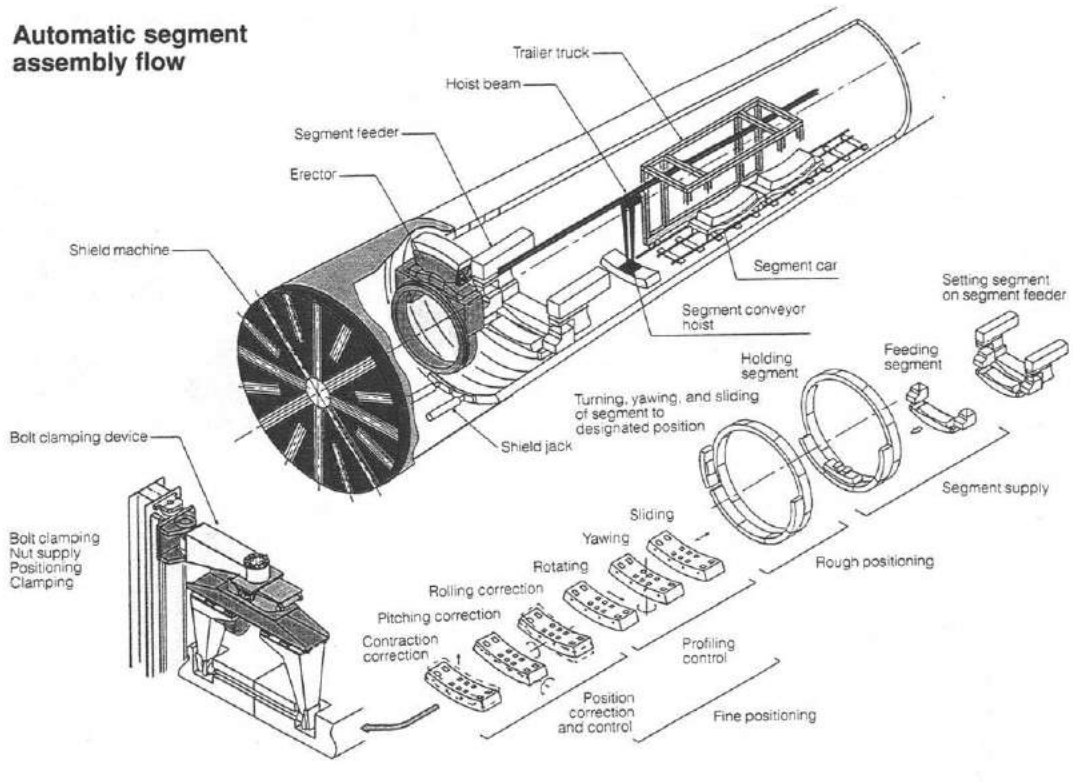


Figure 8.20b: Automatic Segment Assembly Flow

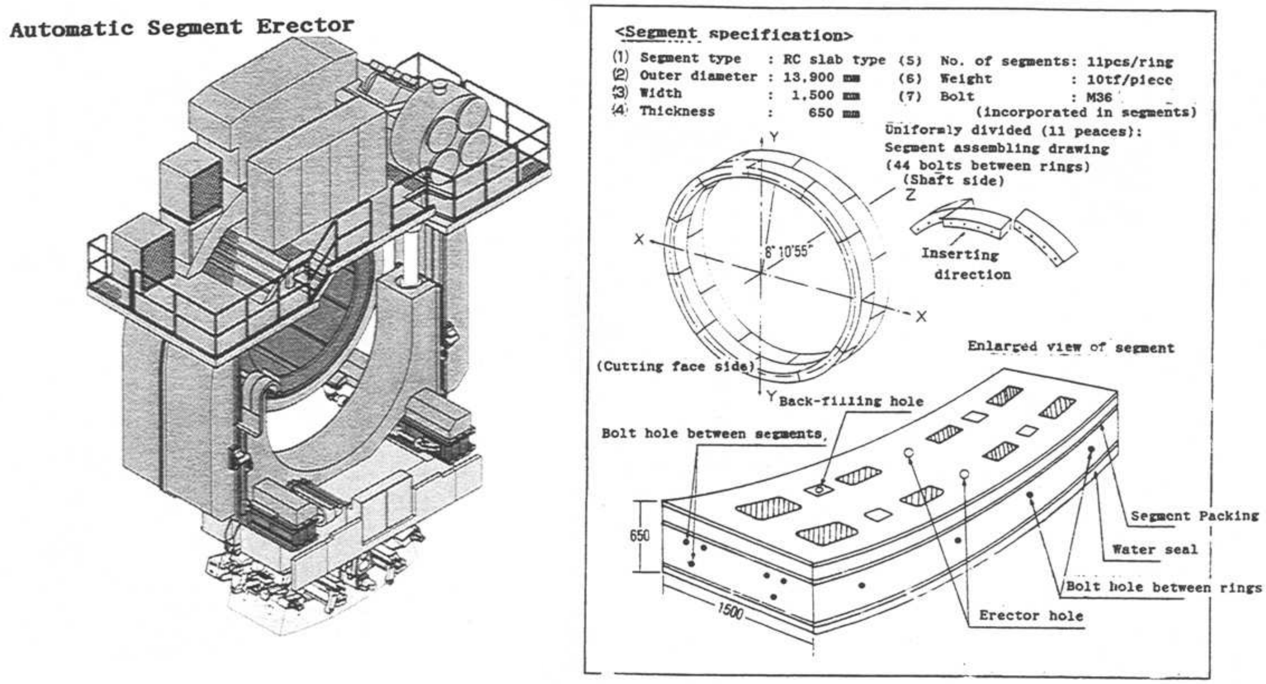


Figure 8.20c: Automatic Segment Erector

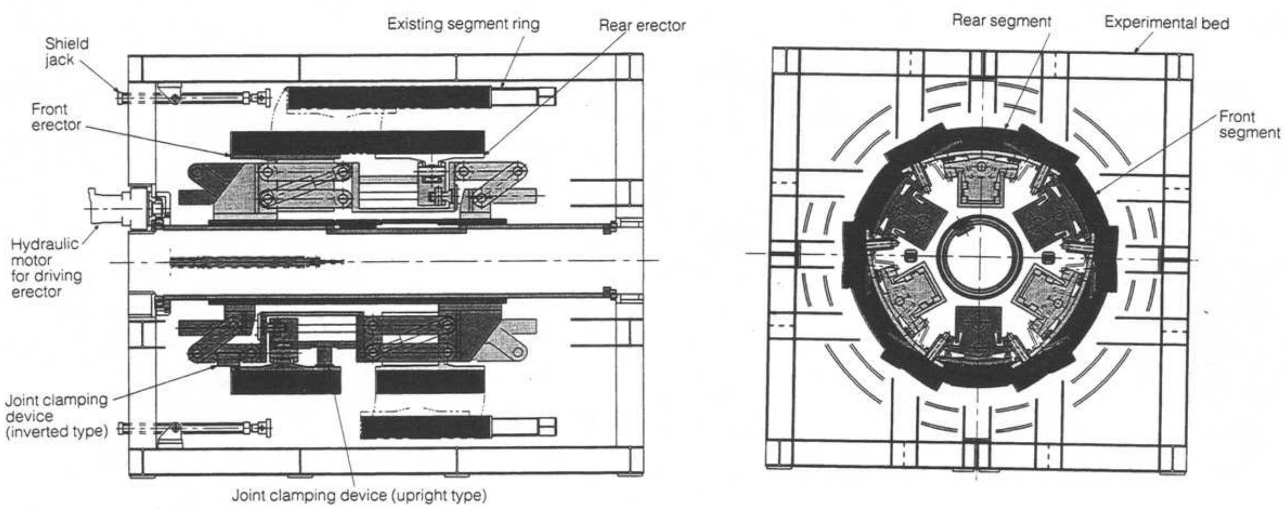
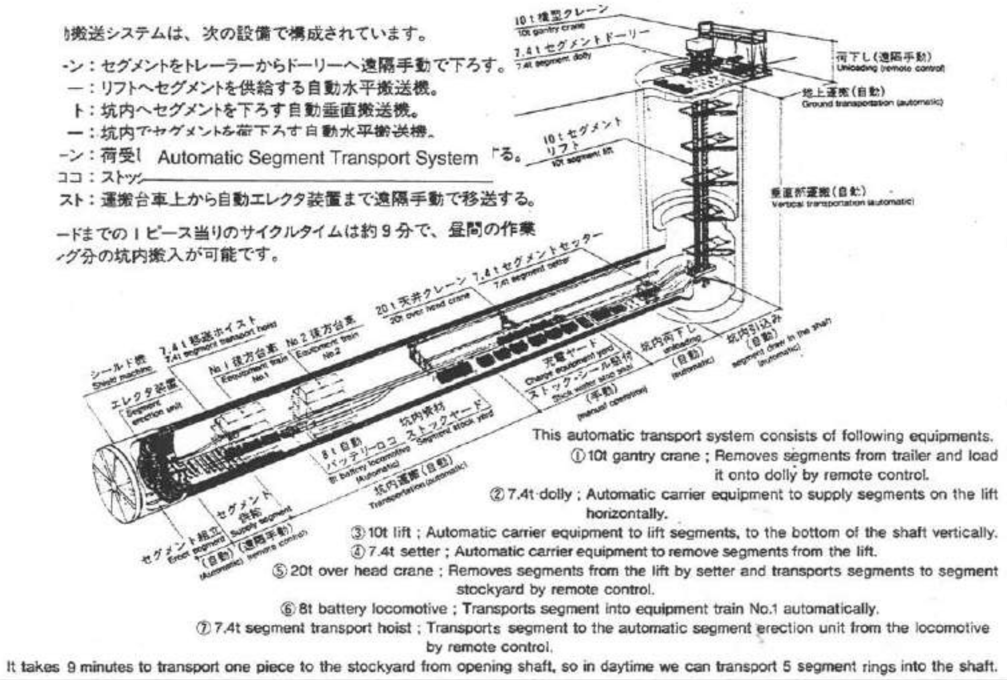


Figure 8.20d: In order to cope with the increase in excavation speed, Kawasaki has devised a new erector aimed to curtailing the time required for segment assembly



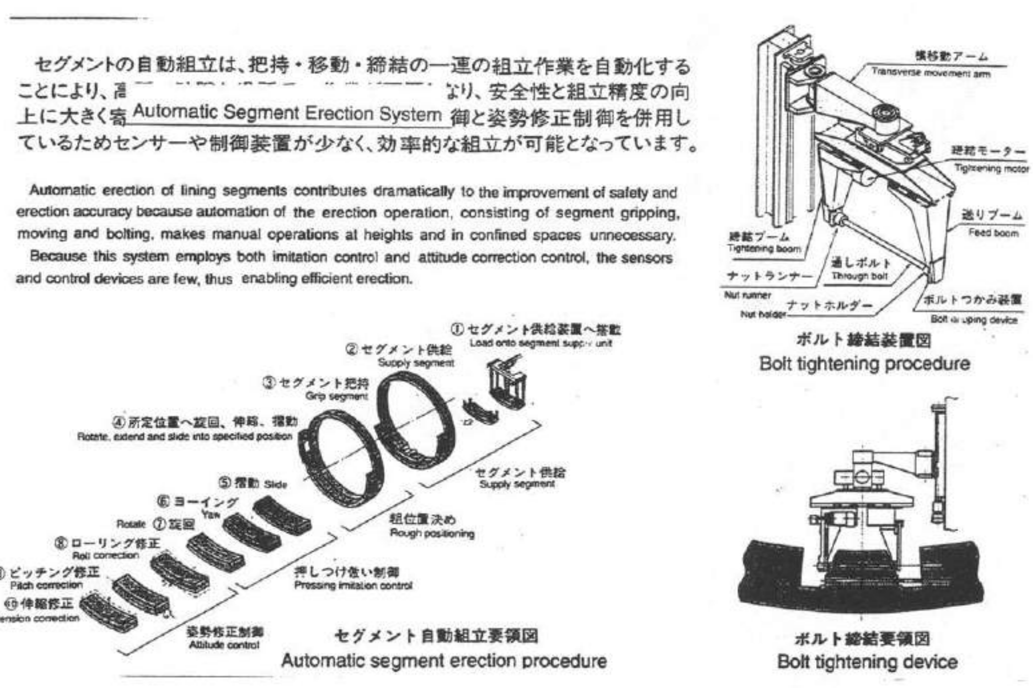


Figure 8.21: Automatic Segment Transport (top) and Erection Systems (bottom)

8.9 Costs and Risks

Bored tunnels require large investments, as table 8.1 shows. Note that the values are given in guilders and not Euros.

Total costs (* fl.1,000.-)

	Bore diameter [m]			
	6	8	10	13
Construction site				
Fixed	1150	1300	1500	2200
Variable	9006	12892	18933	27402
Bore installation				
Buying	12000	17500	26000	40000
Mobilisation	1250	1650	2100	3000
Change	900	1100	1300	1700
Demobilisation	400	500	650	950
Remaining value	-1500	-2000	-2500	-3500
Transport ground	3535	6280	9815	16585
Separation installation				
Buying	1200	2000	3100	5000
Mobilisation	750	1000	1500	2500
Demobilisation	350	450	600	1000
Remaining value	-600	-1000	-1550	-2500
Lining	36250	56850	91150	132500
Grout-injection	1770	2355	2945	3825
Pipes and cables	3000	3750	4750	6250
Bentonite	1555	2765	4320	7295
Energy	3495	4230	5225	6195
Maintenance, reparation	3535	6280	9940	16580
Labour costs	22175	25210	29990	36640
Total	100221	143112	209768	303622
Profit and risk rise	20 %	20 %	20 %	20 %
Costs rough structure	120265	171734	251721	364346
Price per m^1 tunnel	24000	34000	50000	73000

The amounts above are the costs for the structure of the tunnel only. Other costs could include costs for research and design.

- 2 tunnels, each with a length of 2.5 km
- the machine will be changed one time
- price level 1992 (in The Netherlands)
- subsoil: Pleistocene sand with clay
- top of the tunnel on 16 to 20 m below ground level

Table 8.1 Costs bored tunnel
(Source: KivI report "Boren van Tunnels voor Weg- en Railverbindingen", august 1993)

An analysis was carried out by W. Broere in his final project report "Risks and disturbances at bored tunnels" regarding the influence of disturbances and changes on the costs of bored tunnels. This analysis was carried out from the point of the indicative survey of costs, like presented in the rapport of the department Tunnel technique of the KIvI in 1993 (boring of tunnels for rail- and road connections)

Broere has divided the costs in three groups: fixed costs, length-dependent costs and time-dependent costs (see table 9.2). The causes of the disturbances were not considered during the formulation of the cost survey. The given structure of costs (only a rough indication to check tendencies) is representative for a standard tunnel with the following features:

(1) two parallel tunnels of 2500 m each;
(2) diameter outside 10 m;
(3) an average progress of 10 m/day;
(4) a single casing constructed from prefab concrete segments;
(5) a single machine for the construction, which is turned over one time in a period of 50 days.

In his analyse he varied the progress, the cost price of the tunnel casing and the labour costs and concluded that in the "best case" scenario, the total costs can decrease up to 30 %, while in the "worst case" scenario the total costs can double. The interest that had to be paid by the contractor or the client was not included in this research.

Some examples regarding the savings versus the risks:

- *Savings on the fixed costs will be searched often in the choice or the equipment of the tunnel bore machine (TBM). The direct saving that is achieved this way is relatively small and the possibilities to absorb disturbances during construction usually are decreased. The chance disturbance will lead to delays and will increase the costs of the project are increasing then very strong.*
- *Saving on costs of the casing of the tunnel can be an interesting possibility for reduction of project costs. One often thinks to realise such a saving by application of extru-concrete. The quality of such a tunnel casing is relatively low and unreliable, which can have undesirable consequences. Furthermore the construction speed of such a casing is many times shorter than a tunnel with a prefabricated casing. In order to keep the costs of a tunnel as low as possible, it is important to design the tunnel as much as possible with one type of prefabricated concrete casing.*
- *The influence of the labour saving measures, by economising the quantity or the quality of personnel, is small. The chance of disturbances, which can come into being by human mistakes, increases disproportionate. This increases the chance on higher total costs.*

The assumed combinations of setbacks are certainly not unthinkable. It appears that for the time being risks associated with boring tunnels are huge and that savings on the standard situation often introduce new risks instead of offering improvement. Therefore, efforts to improve boring projects should first of all be concentrated on reduction of risks.

An analysis regarding the influence of the diameter and the length on the costs, like shown in the above-mentioned KIvI report as result of the TEC/Mott Mac Donald study on assignment of the Buildingservice (1991), shows the influence of the diameter is especially large (figure 8.22).

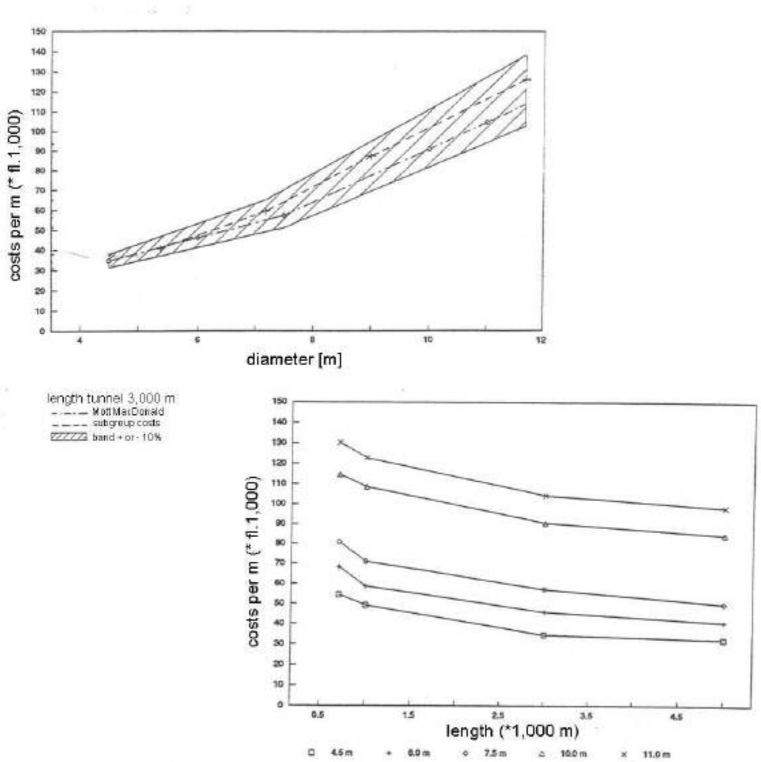
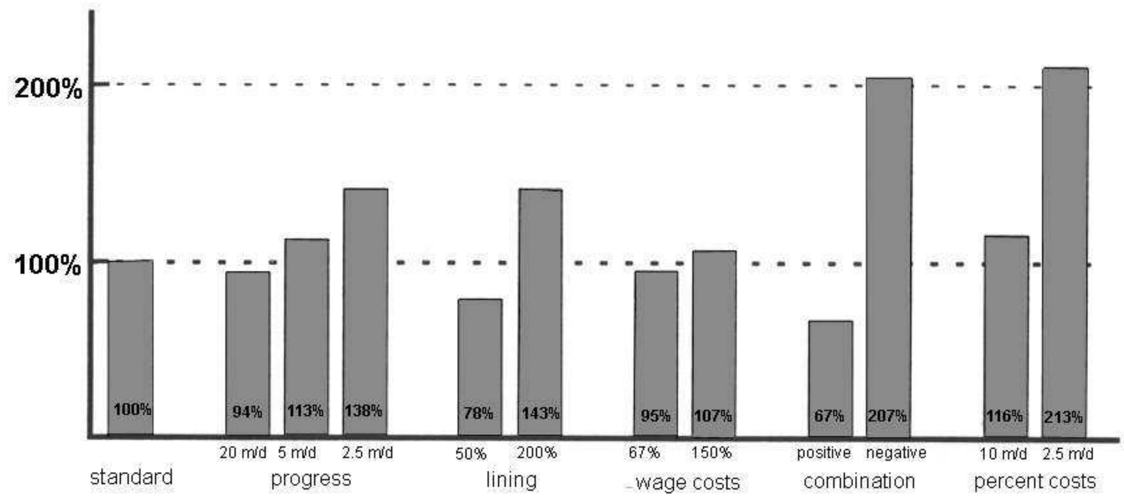


Figure 8.22: Influence of diameter and length on costs

Based on the previously mentioned, one can conclude that by reducing the diameter as much as possible and striving for drastic reduction of risks is the only way to optimise costs of bored tunnels. Development of innovative transport systems in other countries also point towards tunnels with small diameters.

TBM	14%	
rest	5%	+
Total standing charges		**19%**
Tunnel lining	42%	
Ground-transport	4%	
Construction site general	9%	
Rest	12%	+
Total length dependent costs		**67%**
pays	13%	
Rest	1%	+
Total time dependent costs		**14%**
Total costs general tunnel		**100%**

Table 8.2: Costs analyse of bored tunnels.



standard: *2 * 2500 m, Ø 10 m, 10 m/day,*
single lining, prefabricated concrete,
single machine

Figure 8.23: Influence of failures and changes on the costs of bored tunnels.

8.10 The Dutch situation: the Heinenoordtunnel[1]

8.10.1 General

One of the connections between the Randstad and the province of Zeeland is the Heinenoordtunnel. With the increase of traffic intensity, an increase in the tunnel capacity was also necessary. This was made possible by rebuilding the tunnel tubes to allow for 2 x 3 traffic lanes for fast traffic. The first phase was completed in 1990, in which the eastern tube was transformed such that it could hold three traffic lanes. All slow traffic was diverted through the western tube during the construction of the bored tunnels. An alternative cross-river connection was created for slow traffic. This was done using two bored tunnels, one for cyclists and pedestrians and one for agricultural traffic. This was the first time a tunnel was bored for other than utilitarian purposes. Because of this the project has become a large study project in order to learn more about possibilities for tunnels in The Netherlands.

[1] Source: Het boren van tunnels in Nederland, A.J. van Kessel, 1996 and Keuze Tunnel-Boor-Machine 2[e] Heinenoordtunnel, ir A van der Put, 1995

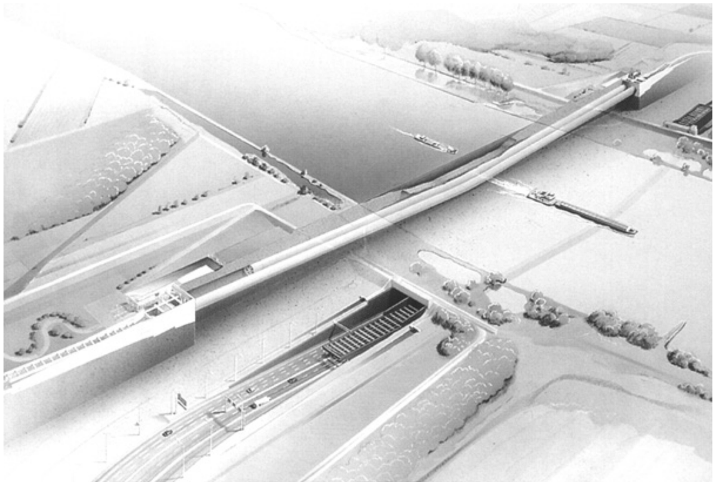


Figure 8.24: Heinenoordtunnel

8.10.2 The tunnel boring machine

The type of shield which was used for boring the Heinenoordtunnel was a hydro-shield, from the German company Herrenknecht GmbH. The diameter of the TBM is 8.55 m and the length of the shield is 8.49 m. The total weight of the machine amounts to 640 ton. The tunnel consists of two tubes and has a length of 941 meters. Beneath the river the minimum distance between the bottom of the river and the tunnel is 1 x the diameter of the tunnel. In the centre of the navigation channel the tunnel reaches the deepest point; at this point the bottom of the tunnel lies at –26.47 m NAP.
The cutter wheel can be moved forward up to 40 cm. The rotation velocity of the cutter wheel had a maximum of 2 rotations per minute during boring of the tunnel. It was also possible to tilt the wheel slightly, up to a maximum gradient of 11 degrees. The machine was moved forward by 2 x 14 jacks, which had a maximum propelling power of 50.4 MN. The velocity of the machine during boring was 3 to 5 cm / min.

8.10.3 Geotechnical parameters

GeoDelft has done extensive ground research on the location of the tunnel. The tunnel lies mostly in a Pleistocene sand layer. Thick Holocene clay and sand layers are present at the shaft site on the northern shore. Under the Maas the tunnel lies partially in a Pleistocene clay layer. The shaft on the southern shore is situated among thin layers of clay, peat and sand.
Therefore along the entire route no cross-sectional profile is the same; for every cross-sectional profile the loads on the TBM are different. This meant that many different load situations had to be calculated.

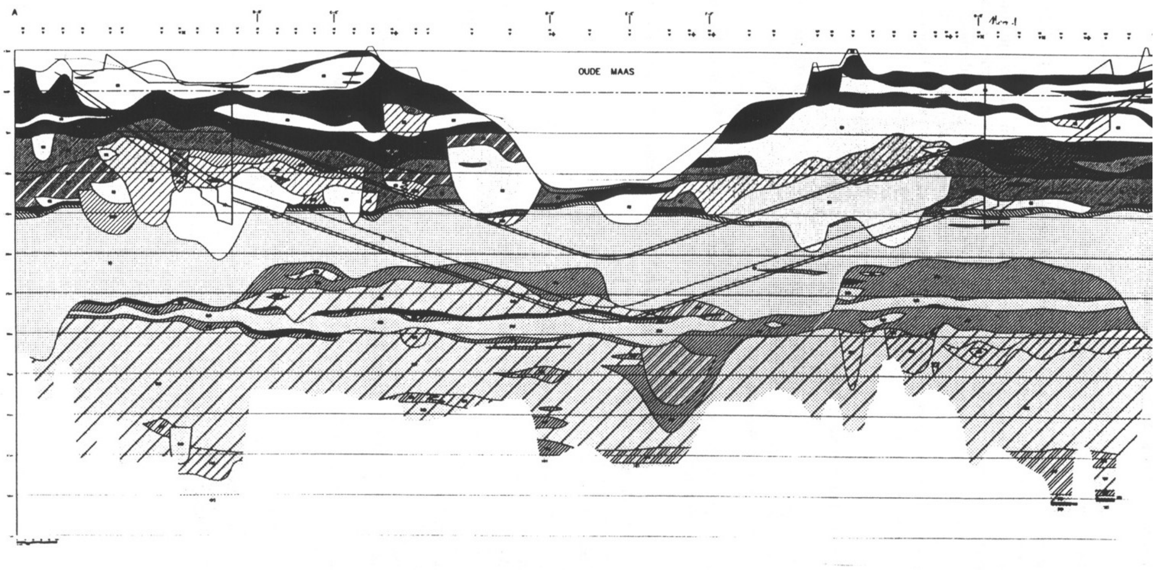


Figure 8.25: Cross section of Heinenoordtunnel

The TBM should satisfy the different demands that result from operating in certain types of soil. The suitability of a TBM-type is determined by:

- Bore front subsidy
- Excavation mechanism
- Ground removal system
- Other factors: driving force, ground tillage and experience

The hydro-shield was eventually chosen because it is easy to use without many auxiliary measures in different soil layers. The necessary use of installations for the benefit of the hydraulic transport and suspension separation were equal to the lesser risk of entering the excavating chamber, small driving forces and a clean ground transport by the tunnel tube.

9. Immersed tunnels

9.1 Introduction

Immersing a tunnel is a method by which the tunnel elements are built in a construction dock and floated to their final destination, where they are immersed. It is a well developed field of study in The Netherlands. Almost all river crossing tunnels have been realised with this method (an exception in the Netherlands is the Velser tunnel).

The immersed tunnel method is especially suitable for crossings of rivers and canals, but it does not have to be restricted to these. The immersed tunnel can also be implemented on land. A large advantage of the immersed tunnel method is the limited hindrance to shipping traffic, compared to the execution in phases of the building pit methods. The hindrance is restricted to the dredging of the immersion trench, the transportation of the elements, and the immersing operation of the tunnel elements. An advantage of immersed tunnels compared to bored tunnels is that they are situated at a shallower depth. This means the sloped access roads are at shallower depth and the length of the entire tunnel can be much smaller.

9.2 Building method

9.2.1 Immersing

In the immersed tunnel method, tunnel elements are prefabricated in construction docks. Subsequently these elements are floated to their destination and immersed into a trench, which has been dredged between the tunnel's shore sections. Transportation via waterways is made possible by closing off the open ends of each element with (temporary) watertight bulkheads. When the construction dock is filled with water these “boxes” have enough buoyancy to stay afloat. Usually the height of the “box” above the water is not more than about 100 millimetres.

The floating elements are taken to their final location by tugboats. Load is added to the construction and the element is submerged into the trench; there the elements are connected to each other and to the shore sections by using watertight rubber seals. Backfill material is placed next to and on top of the tunnel in order to fill the trench and permanently bury the tunnel. After this phase the original bottom profile of the river is restored and shipping can continu.

The phases of execution are shown in figure 9.1 and figure 9.2.

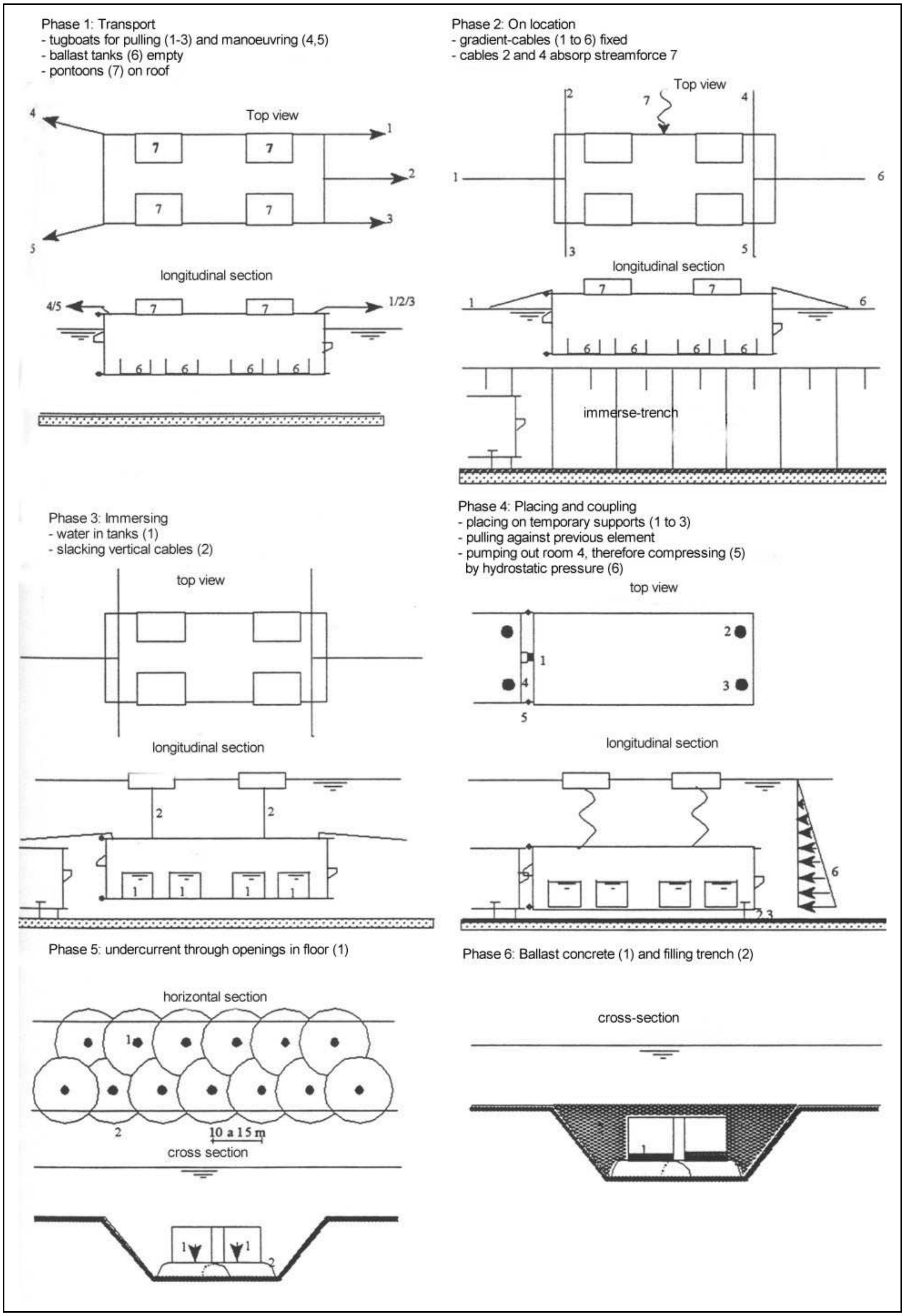
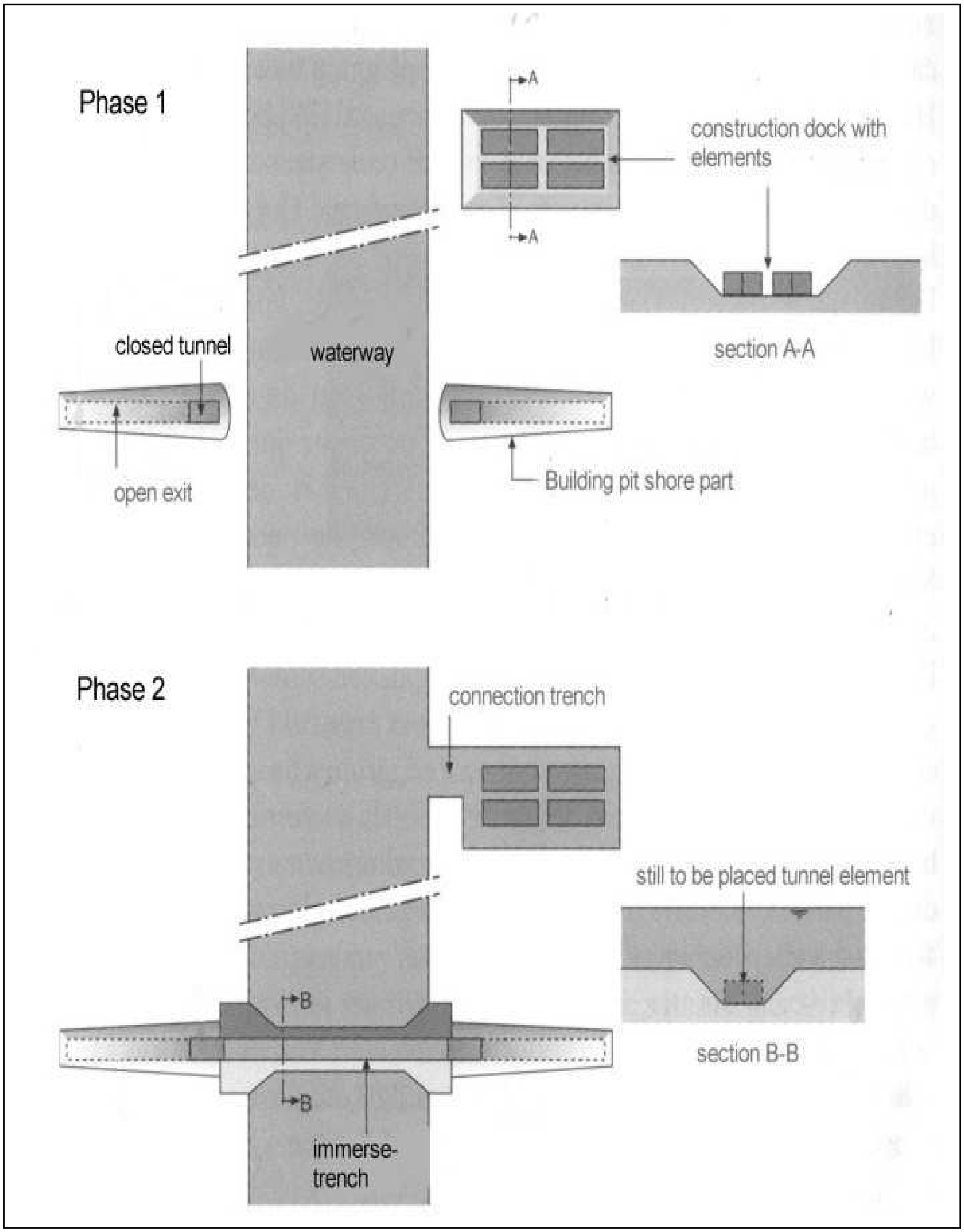


Figure 9.1: Phases of execution of an immersed tunnel



Phase 1: *Tunnel elements and shore sections*
Phase 2: *Dredging the trench, filling the dock, dredging the connection trench and completing shore sections*

Figure 9.2a: Works before immersing

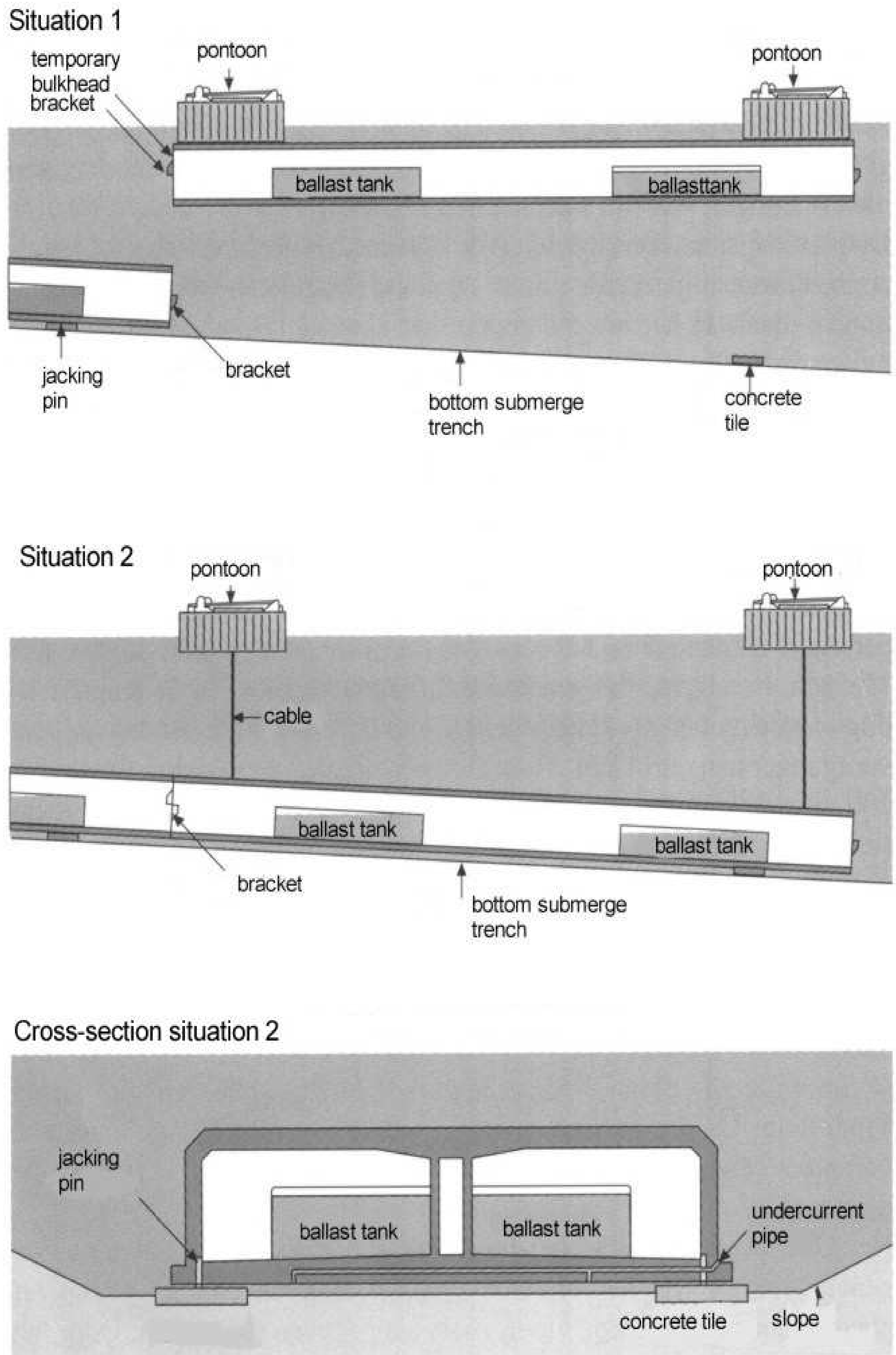
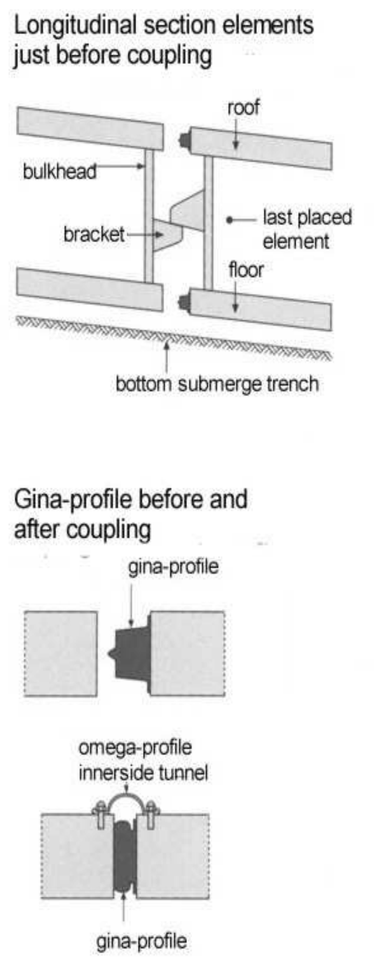


Figure 9.2b: Immersing

9.2.2 Coupling elements

In order to couple an element with a previously immersed element or the shore section of a tunnel, great accuracy is needed. A detail of how this is realised is shown in figure 9.3.



The element is pulled (with a horizontal cable) against the previously immersed element. This requires only a small force, because the overweight of the element is little and therefore the friction, which has to be overcome, is too.

The force is just enough to deform the soft nose of the rubber Gina-profile. The Gina-profile is placed around the perimeter of the element during construction in the building dock. By deforming the Gina-profile a space is created between the two bulkheads. The space is filled with water, but sealed off from the surrounding water. Subsequently the water is pumped out of this space. This means there is no longer water pressure against these bulkheads. The bulkhead on the other side of the new element still has water pressure acting on it. The difference in force pushes the new element against the previously placed element, thus increasing the pressure on the rubber strip. This results in a watertight joint that is created between the two elements. For extra safety a second watertight profile – the Omega-profile – is placed on the inside of the joint between the elements.

Figure 9.3: Coupling of elements

9.3 New development

Traditional immersed tunnelling results in a tunnel being buried beneath the waterway it traverses. A new development, the submerged floating tunnel (figure 9.4), consists of suspending a tunnel within the waterway, either by tethering a buoyant tunnel section to the bed of the waterway, or by suspending a heavier-than-water tunnel section from pontoons.

This technique has not yet been realised, but one project in Norway is currently in the design phase. The submerged floating tunnel allows construction of a tunnel with a shallow alignment in extremely deep water, where alternatives are technically difficult or expensive. Likely applications include fjords (for example: Norway), deep, narrow sea channels, and deep lakes.

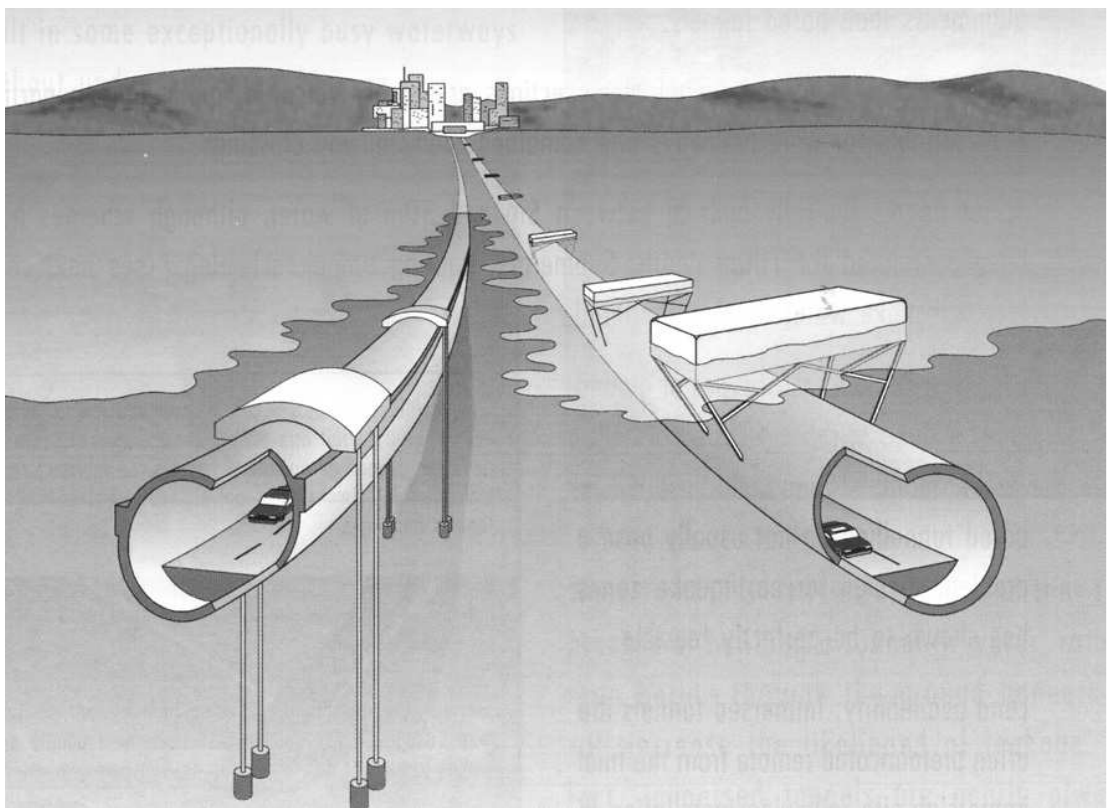


Figure 9.4: Submerged floating tunnel.

9.4 Execution problems

9.4.1 Immersing

For a well executed connection of the elements it is important that the elements lie accurately in each other's extension. A twisting of one of the elements in the cross-direction, or a difference in height close to the connection can cause difficulties. Because of this, the trench is dredged a little deeper than necessary (for example 0.5m under the bottom of the element) and the element is first placed on three temporary supports (concrete tiles) as shown in figure 9.2b. The free space is later filled up with sand. This happens with the undercurrent pipe (figure 9.2b Cross-section); through this pipe a mixture of sand and water is jetted into the free space. The sand settles, while the water surplus washes away.

9.4.2 Interference with shipping

To reduce the possible hindrance to shipping on busy waterways, the immersion operation has to be executed as quickly as possible. For this reason it is recommended that the transportation distance between the dock and the final location is kept as short as possible.

9.4.3 Dredging of the trench

While dredging the trench unfavourable effects can appear like:

- Huge dredging work required for the immersed trench and the subsequent refilling of the trench.
- Possible pollution of the sludge, which can be very expensive.
- Possible crossing of layers with increased water tension during the dredging of the trench. Disturbance of the balance (grain tension / water tension) can have unfavourable effects on the surrounding area; and collapse of the trench itself.

9.5 Execution time

The execution time is very important in regard to the hindrance created for shipping, as described in section 9.4.2 above. The hindrance is limited to the dredging of the immersion trench, and the (partial) obstruction caused during transport and immersion. The hindrance caused by an immersed tunnel is therefore much less than the construction of a tunnel using the open building pit method.

9.6 Building costs

To reduce the building costs it is attractive to use one dock to build several tunnels. The negative consequences of this method are:

- The need to have enough depth in the channel for the transportation route;
- A longer transportation route, which may result in hindrance of shipping and higher transportation costs.

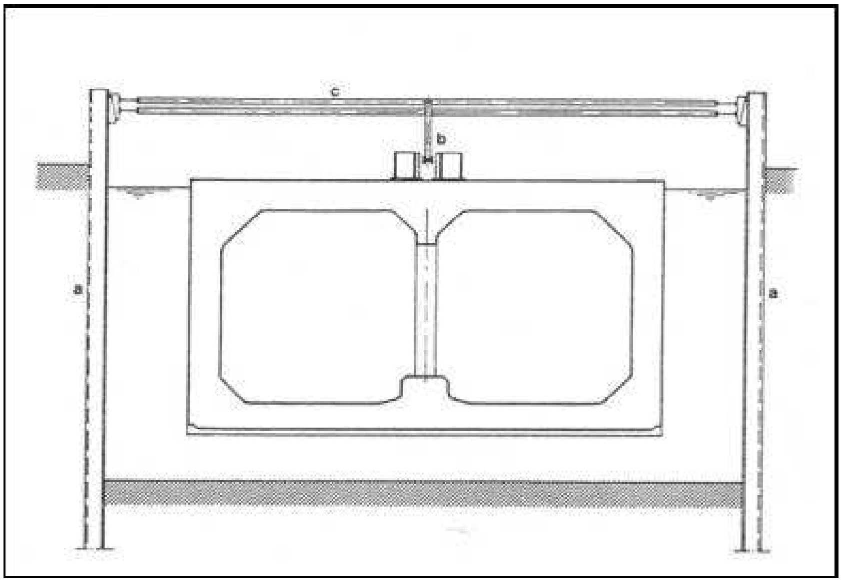
9.7 Dutch situation

The execution process of concrete immersed tunnels was developed in the Netherlands. Below is the Dutch situation regarding immersed tunnels (in 1978) shown.

Figure 9.5: Situation Dutch immersed tunnels.

Implementation of immersed tunnels does not have to be restricted to river crossings. The subway tunnel of Rotterdam (North/South line) is an example. In this case the implementation of the immersed tunnel was not restricted to the part under the river, but was also implemented underneath the north shore (city centre part). The tunnel elements (figure 9.6) were immersed in an excavated canal (created between sheet-pile walls), with a strutting above the waterline. The building pits of the subway stations were used as building docks.

Reasons for using this building method were lower costs and easy crossings of the canal with temporary bridges during excavation.



a. Sheet pile
b. Guide rail
c. Struts

Figure 9.6: Rotterdam subway construction; tunnel unit floating in trench

After immersing (on piles with adjustable pile heads) the sheets were pulled out and the canal was filled up with soil. The foundation (figure 9.7) of the tunnel on adjustable pile heads was an alternative for the foundation on a sand bed.

a. concrete tunnel structure
b. foundation piles

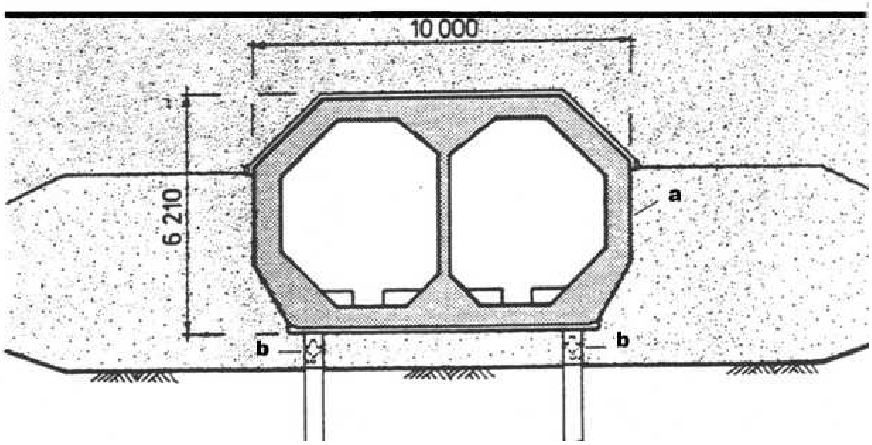


Figure 9.7: Rotterdam subway construction, foundation on pile heads

The reasons for a pile foundation were the following:

- The stiffness of the subsoil varied considerably along the tunnel line and uneven settlements were unacceptable.
- The mass of the tunnel was rather small in relation to the dynamic loads of the trains passing trough the tunnel. Therefore it was feared that the tunnel might be subject of vibrations, which again would be transferred to the subsoil and result in unacceptable settlements, had the tunnel been founded directly on the sand.

As it would be impossible to drive the piles to exactly the required level, a special type of pile with an adjustable head was developed.

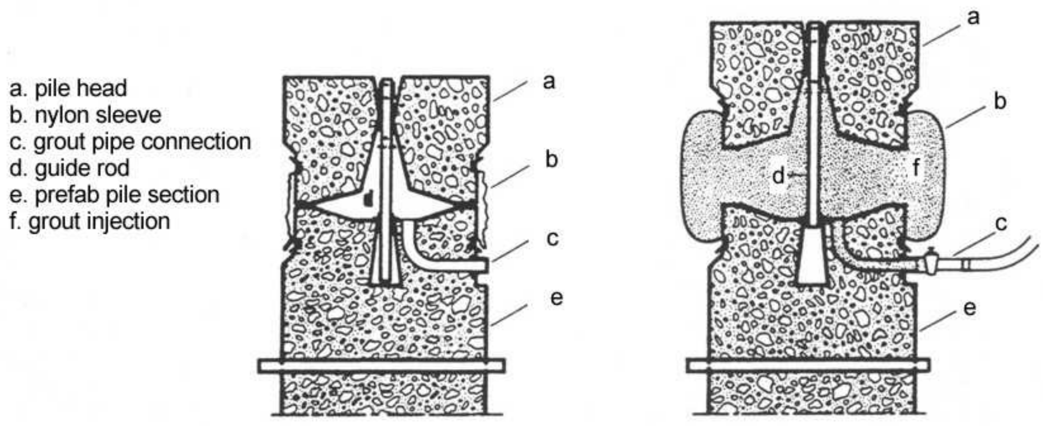


Figure 9.8: Adjustable pile head

The piles were constructed in the following way. First a steel tube, outer diameter 0.62m, with a cast iron toe was driven into the soil. At the bottom of the tube $0.5m^3$ of grout was cast on the iron toe. Now a prefabricated concrete pile was lowered into the steel tube pushing aside the grout thus forming a good connection between the pile and the cast iron toe.

The steel tube was withdrawn afterwards and as a result the enlarged pile toe contributes considerably to the bearing capacity of the pile. The prefabricated piles were provided with an adjustable pile head consisting of a separate concrete part connected to the rest of the pile by a nylon sleeve (figure 9.8). The tunnel units were immersed and temporary placed on an alignment beam, fixed to four special piles. After placement of the tunnel unit on the temporary structure and ensuring an accurate position, the adjustable pile heads were pressed up against the tunnel bottom by a cement grout injection into the sleeve, carried out by divers. Slight deviations of the pile from the vertical were taken up by the rotation capacity of the pile head. A felt layer on the head of the pile provided for uniform load transfer.

10. Open-trench constructions

10.1 Introductory

When comparing direct costs, building of underground infrastructure is very expensive compared to building on ground level. Deepening is a compromise, in some cases this can be a good alternative. Over recent years new construction methods have been developed for deepening (rail) roads, mainly to reduce the building costs. A number of disciplines are, more or less, in the experimental stage, like membrane solutions, the U-polder, the V-polder and the TOMAS method.

The covered alternatives to open-trench construction, with the covering-over just beneath or above the ground level, is called a land tunnel. Covered trench construction can be used over deep, or ground level, laid (rail) roads, such as the "hollow dike" concept shown in figure 10.1.

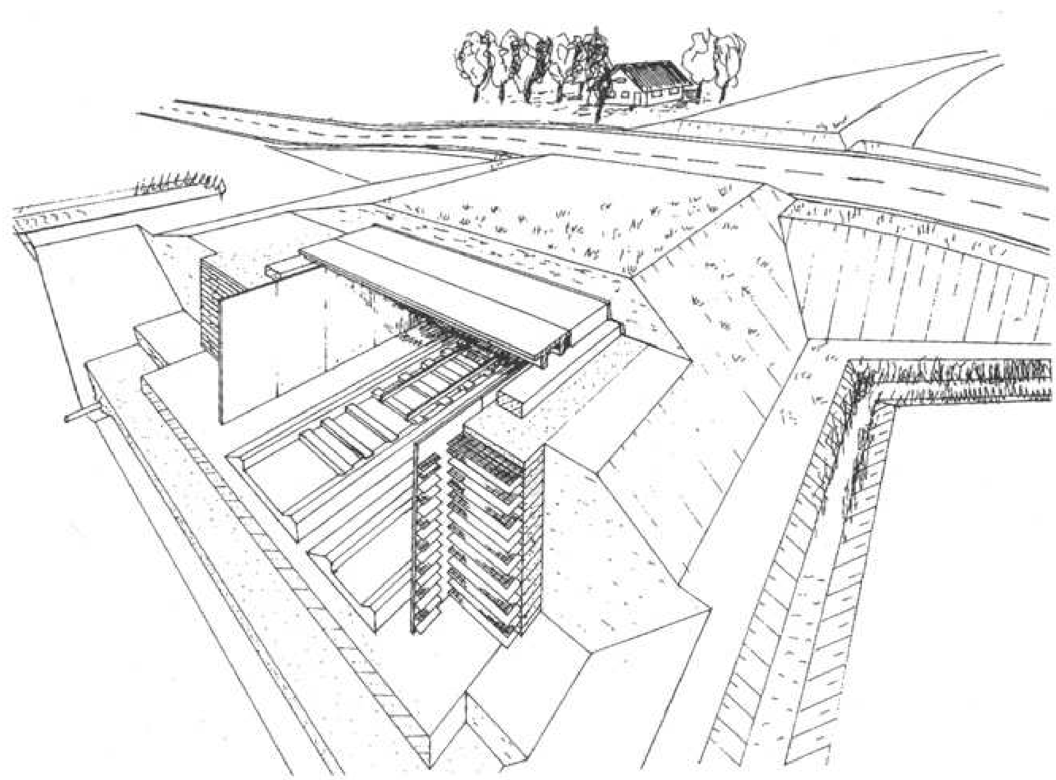


Figure 10.1: The hollow-dike

10.2 Supported membrane-polder

In traditional membrane constructions foil is laid at such depth, that the foil, with the ground above it, cannot be pushed up by the ground water. Therefore it is necessary to make slopes (slope 1:3 to1:4), which results in a deep, wide trench.

The principle of the supported membrane-polder is shown in figure 10.2. The supported membrane-polder concrete circle-elements activate the weight of the ground, which is put above the foil in the bench, next to the deeply laid road. This way, the trench can be designed with less depth and width than the traditional membrane constructions.

Figure 10.2: Supported membrane-polder.

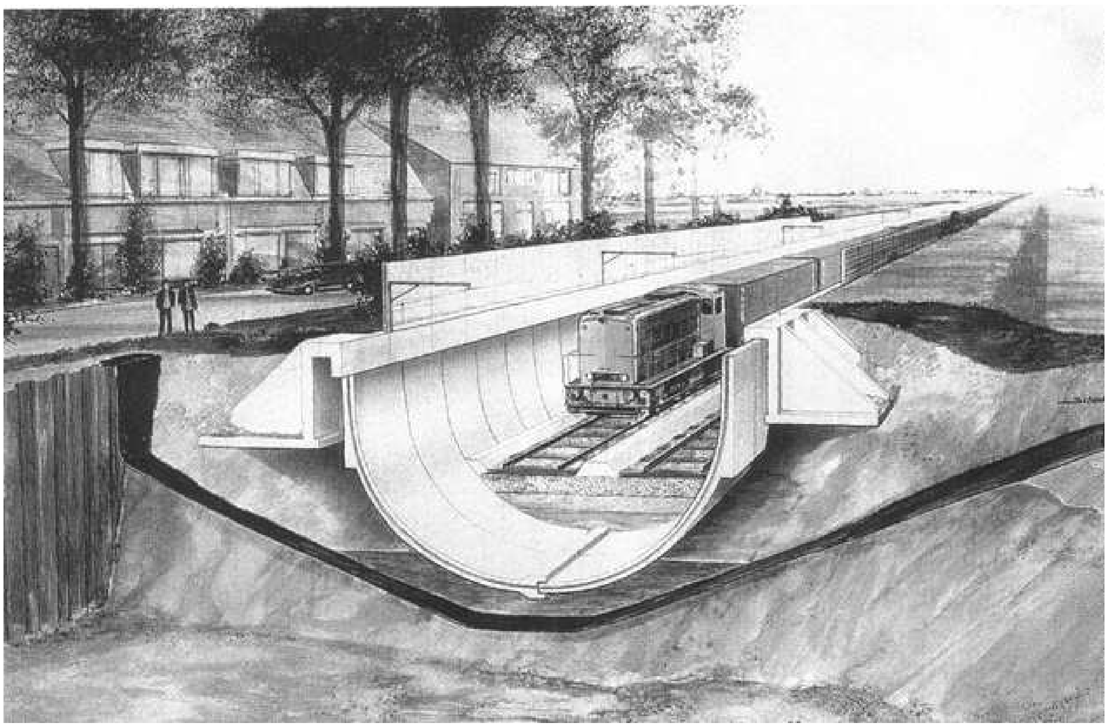


Figure 10.3 shows the various phases of the construction:
The foil is submerged in the groundwater before the prefabricated circle-elements are installed and the trench is filled with sand. This ensures that the groundwater system won't be disturbed during and after construction.
The temporary sheet- pile wall is only used in situations with little free space.

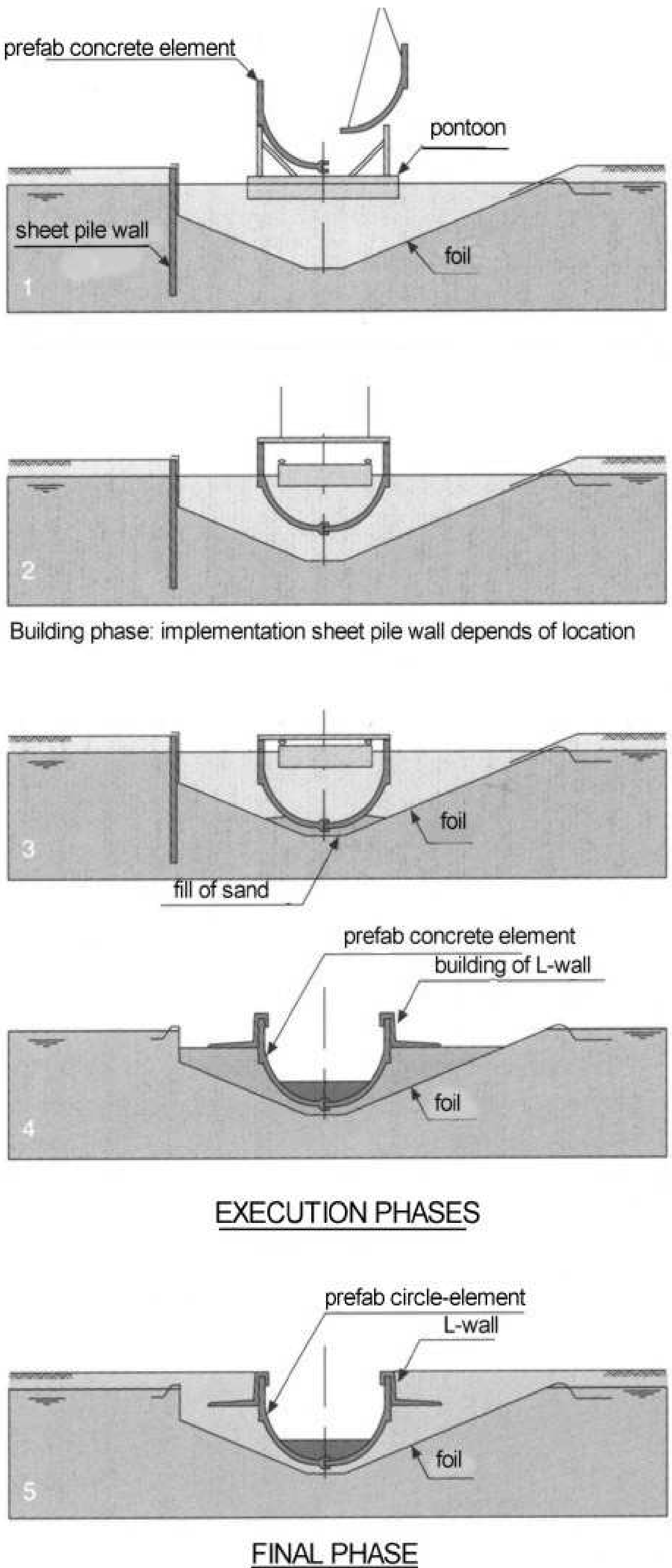


Figure 10.3: Phases of execution supported membrane-polder

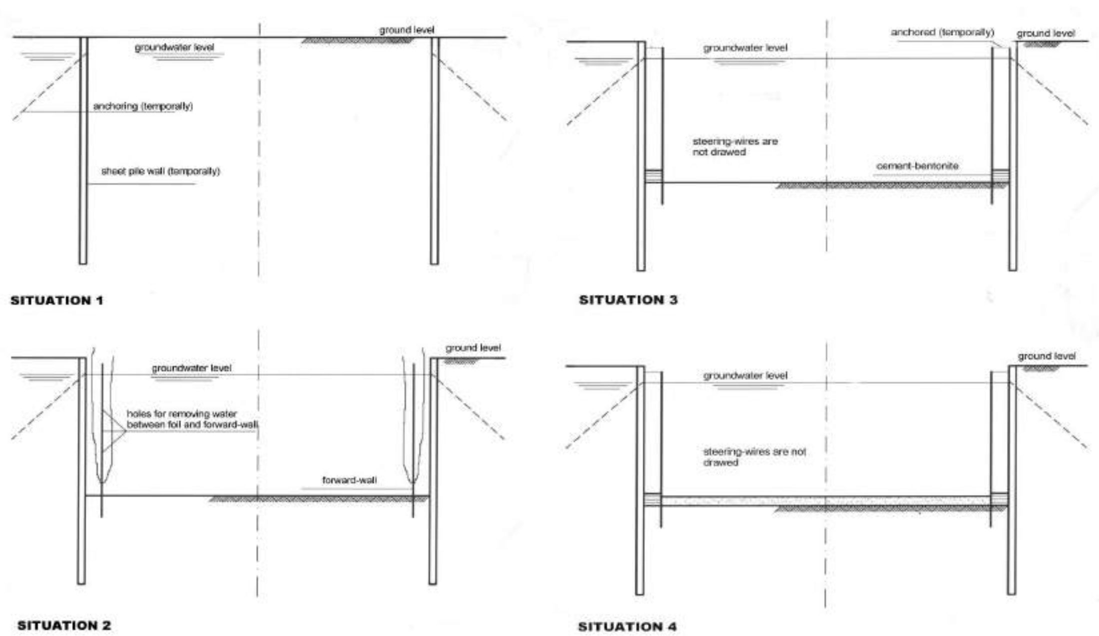
10.3 The U-polder

The principle of a polder was discussed in Chapter 5 “General Construction Methods”. The U-polder is based on the principle of implementing a foil construction in the shape of an U. The speciality of this principle, compared to the traditional foil constructions, is the limited work width that is established with the vertical implementation of the watertight foil.

Temporary heavy sheet-pile walls with anchors make the building pit. In the building pit socket shaped secondary walls (build of light sheets), a welded steel plate and a bottom plate are added. The forward-walls come complete with a drainage system and steering wires.

The phases of construction of the U-polder are shown in Figure 10.4. This illustrates the building sequence of the U-polder construction per situation.

First a spreading bed and a watertight cement-bentonite layer is put down. Then the foil package becomes submerged. The still vertical part of the foil is pulled up along the secondary wall by the steering wires. Enclosed water and eventual leak water between foil and secondary wall is discharged by the drainage system inside the forward wall. Then a ballast bed is put onto the foil. The water level inside the building pit is decreased until it is below the topside of the ballast bed. Inside the now dry pit retaining walls are made. At the same time the space between the secondary wall and the main sheet-pile wall is filled. After uncoupling the anchors, the heavy sheet-pile can be pulled out.



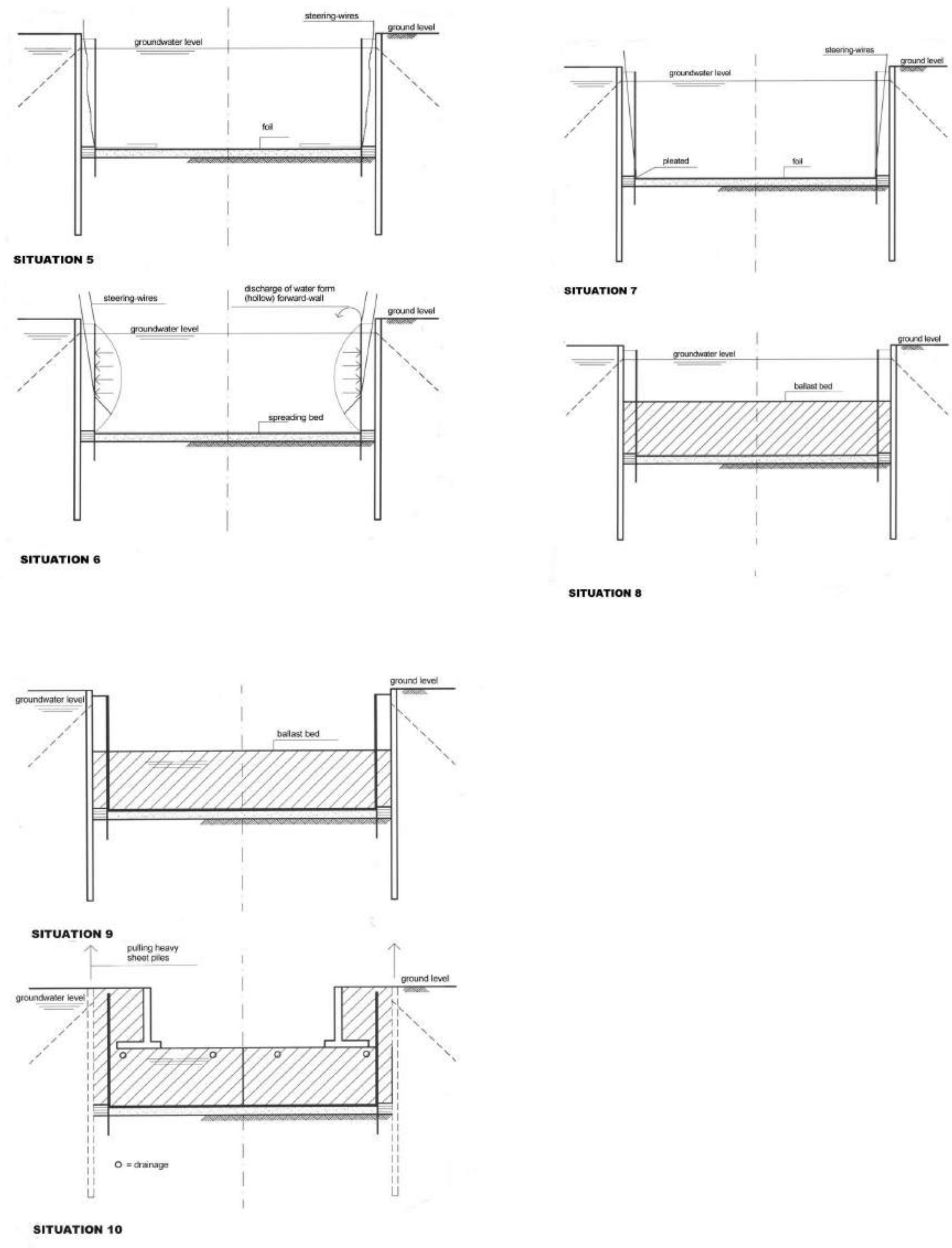
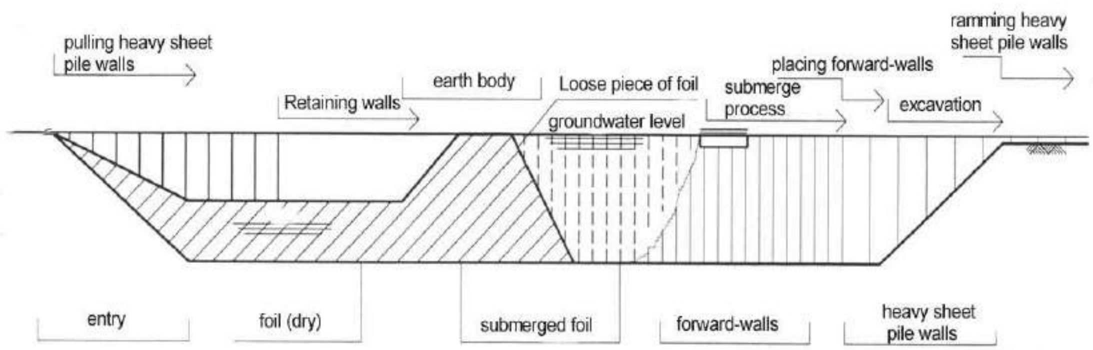


Figure 10.4: Phases of U-polder construction

The execution of the U-polder is a continuous process, as shown in figure 10.5. After putting enough ballast on the foil to keep the foil in place when the water level is decreased, a water-retaining dam is made which is higher than the present building pit water level. The slope of the ground dam is supplied with a loose piece of foil on one side. This dam creates a separate building pit, where the water level inside can be decreased, so that completion can start.

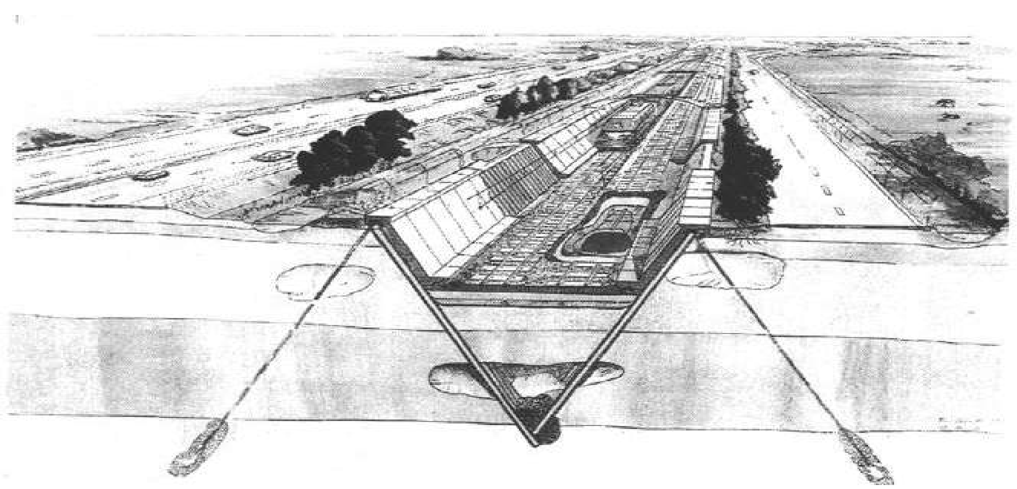
Figure 10.5: Execution by a continue process



10.4 The V-polder

The V-polder is a technique used for deep railways or roads and is shown in figure 10.6. The building pit boundary both temporary and permanent and is formed by the vibrated or driven sheet-pile wall and soil-injection in the toe. The sheet-pile wall is supplied with tension anchors. A drainage bed is created beneath the railway or road.

Figure 10.6: V-polder



The V-polder is especially suitable for the deep application of railways and roads. For highways the system is less suitable. Because of the increased width of the road, the sheets have to be brought in too deep.
Sometimes the deep sheet-pile wall forms a barrier for natural groundwater flow. For these situations the V-polder throughbeam (figure 10.7) was developed. With this method a trapezium-shaped open box of reinforced concrete is built inside the temporary pit. After this, the sheet pile wall is removed.

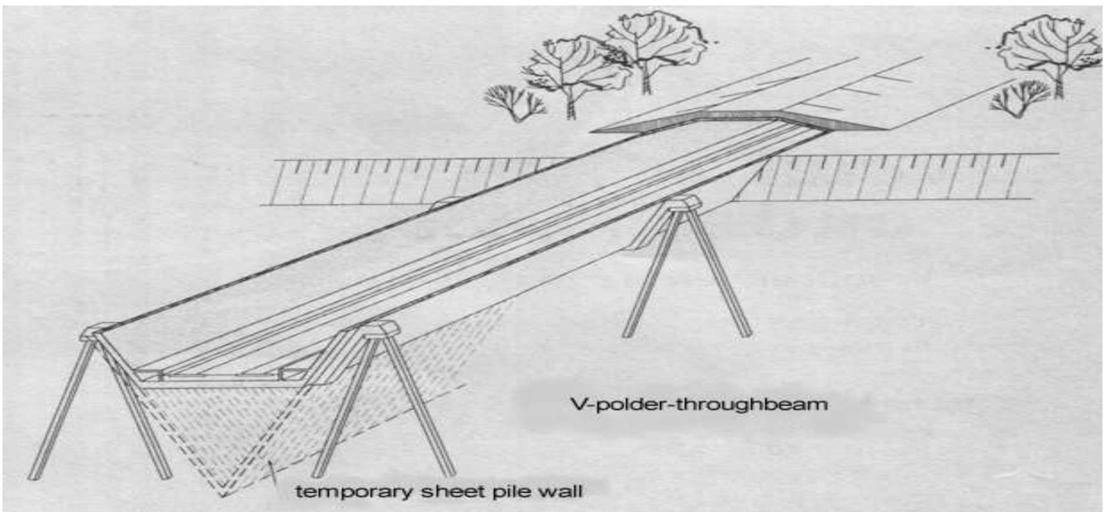


Figure 10.7: V-polder-throughbeam

10.5 The TOMAS technology

TOMAS is a building method for continuous industrialised construction of an U-shaped box, which is located completely below ground level and whereby de-watering is not required.

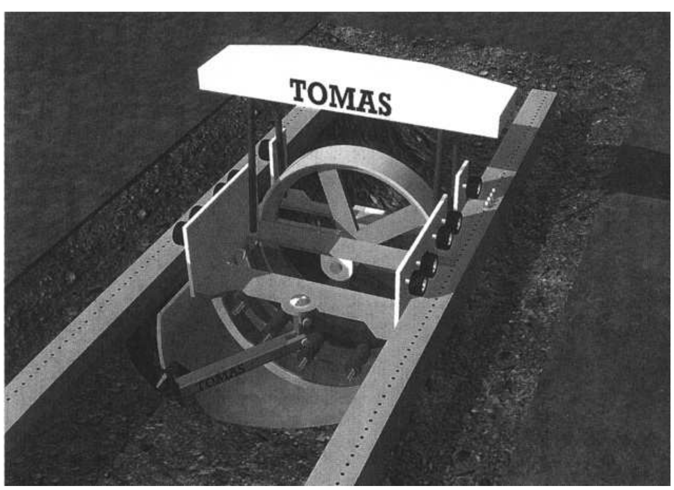


Figure 10.8: The dredger

For this building method a special machine was developed, the so-called “dredger” (figure 10.8). This machine combines dredging and assembling of the prefabricated shell-elements. A cutter suction dredge is placed on the front, which is followed by several hydraulic installations and at the rear an assembly wheel and a crane.

There are two different designs of the TOMAS-method, to meet different soil characteristics:

A. For soft soils (the west of The Netherlands).
B. For sandy soils (the east of The Netherlands).

The construction of design A is shown in figure 10.9. As can be seen a concrete and / or steel pile on the existing firm ground layer provides a foundation for the box. In design B (see figure 10.10) the construction is placed on a natural foundation. Different construction methods exist for A and B.

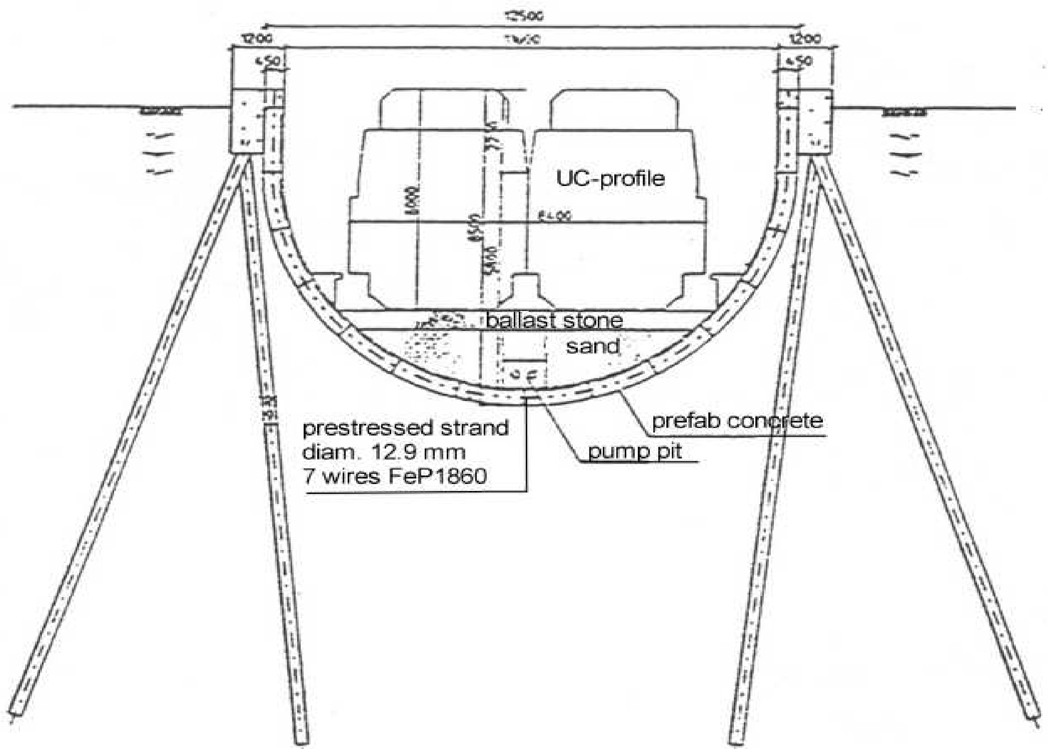


Figure 10.9: Design A

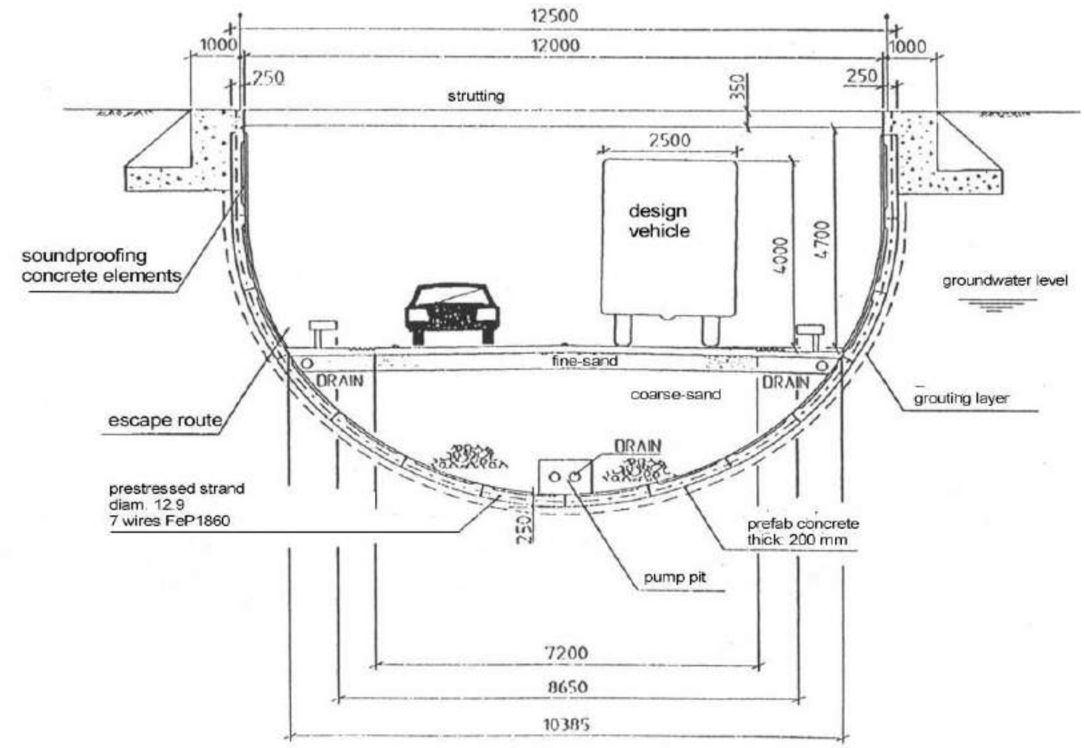


Figure 10.10: Design B

The phases of execution for design A are shown in figure 10.11. In the first phase concrete edge beams are placed on piles. These edge beams conduct the dredger in the second phase, when excavation takes place and the assembly wheel places prefabricated concrete shell-elements. In the next phase the deep laying (rail) way can be completed. The groundwater pressure is partly compensated by the weight of the construction; the rest is transferred to the piles. When using this system the groundwater system will not be disturbed during construction or in the final situation. In the last cross-section a solution of a crossing is shown. A tunnel roof can be poured onto a prefabricated concrete sheet.

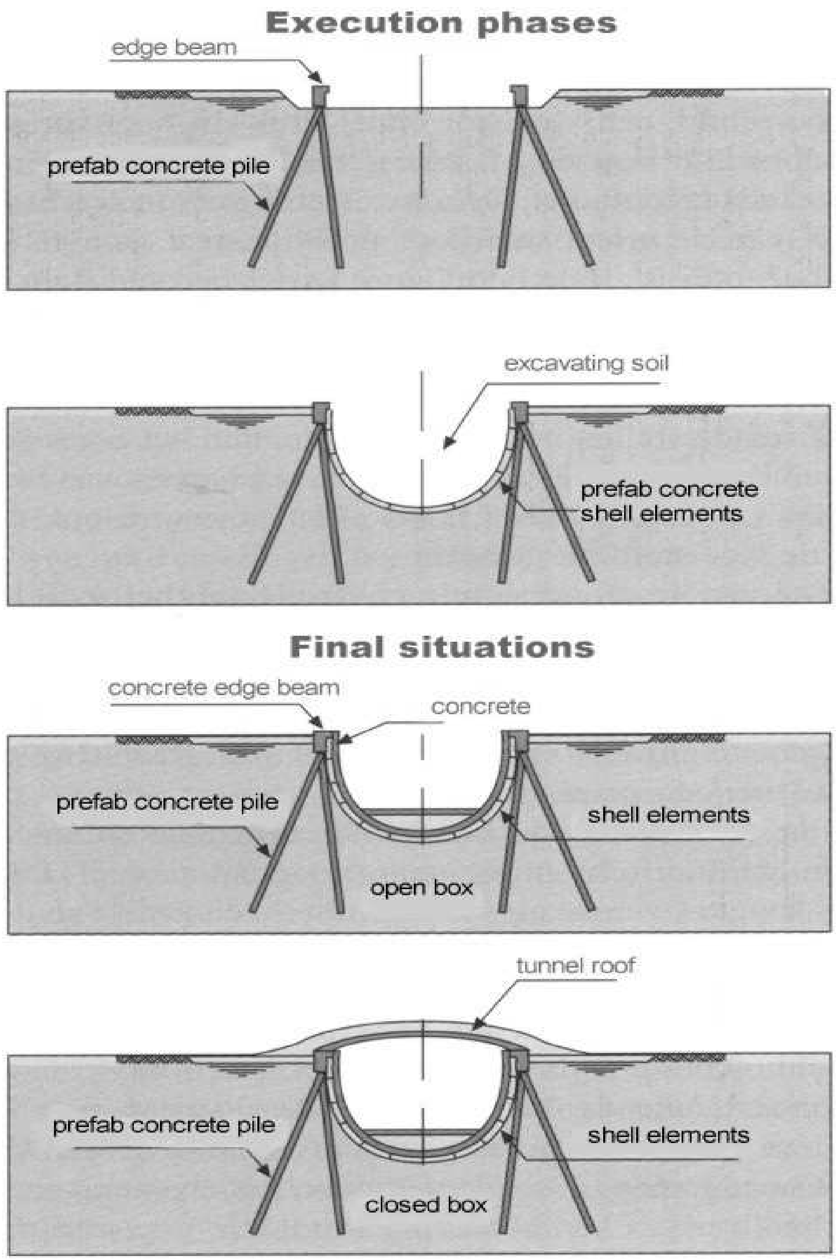


Figure 10.11: Phases of execution TOMAS technology

10.6 Building costs

The U-polder is a foil construction, which combines the advantages and eliminates the disadvantages of traditional construction as much as possible. The traditional constructions are the concrete box with tension elements and foil construction with slopes (figure 10.12).
Compared to the traditional foil constructions the U-polder can be cheaper because of the cost saving made by excavating less soil.

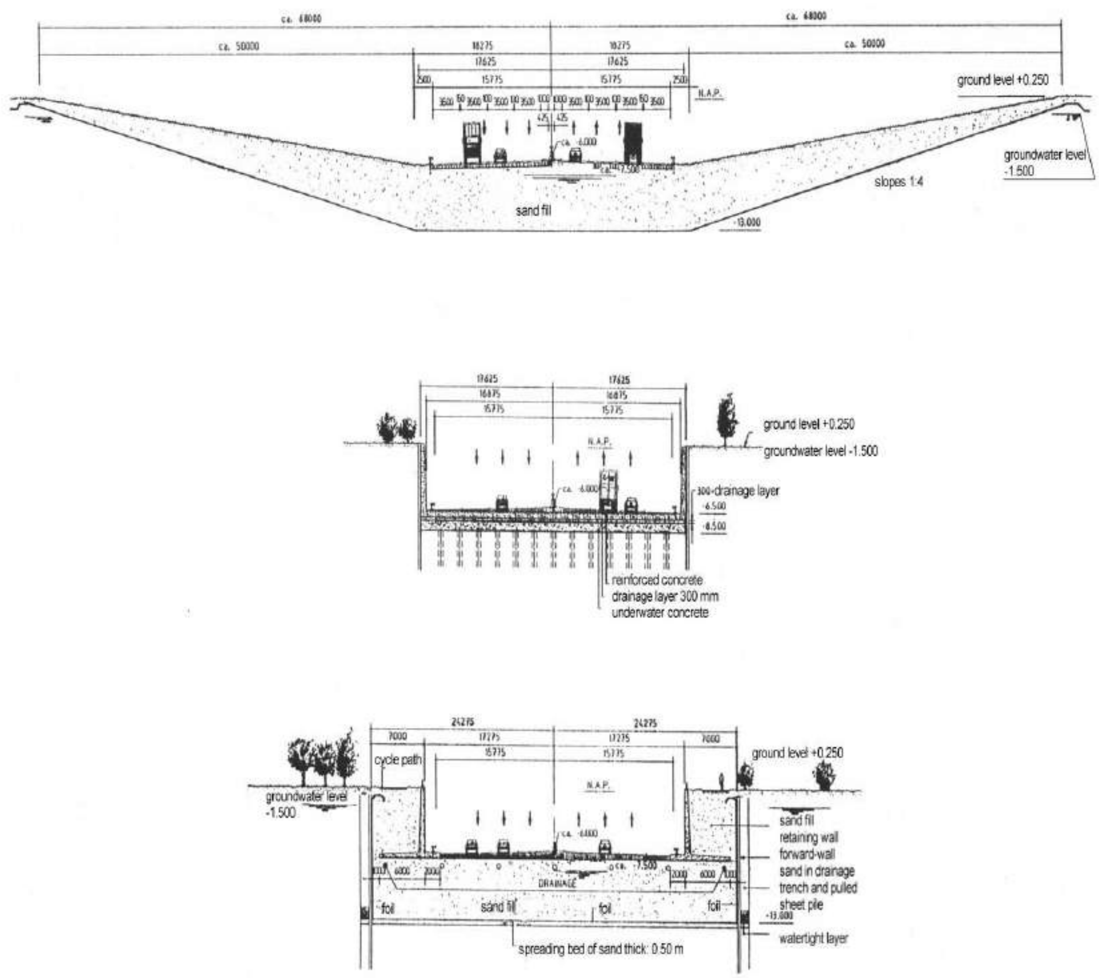


Figure 10.12: Traditional concrete box and foil construction

Compared to the traditional concrete box it is possible, depending on the width of the road, to make large cost savings using the U-polder principle. This is shown in figure 10.13. At a road level of 6 m below ground level and a width of 10 m the building costs are similar.
At a width of 25 m the U-polder is circa 20% cheaper than the concrete box. It is clear that the savings will increase with increasing width. The costs of tension piles, the underwater concrete, and the concrete construction floor are compared to the costs of the extra excavation, the foil and the ballast bed.

The shallower the road is, the higher the cost savings will be, because the tension piles, the underwater concrete and the construction floor are always necessary. The recycling of the heavy sheets also contributes greatly to the cost savings, which makes the U-polder very suitable for long distance traces.

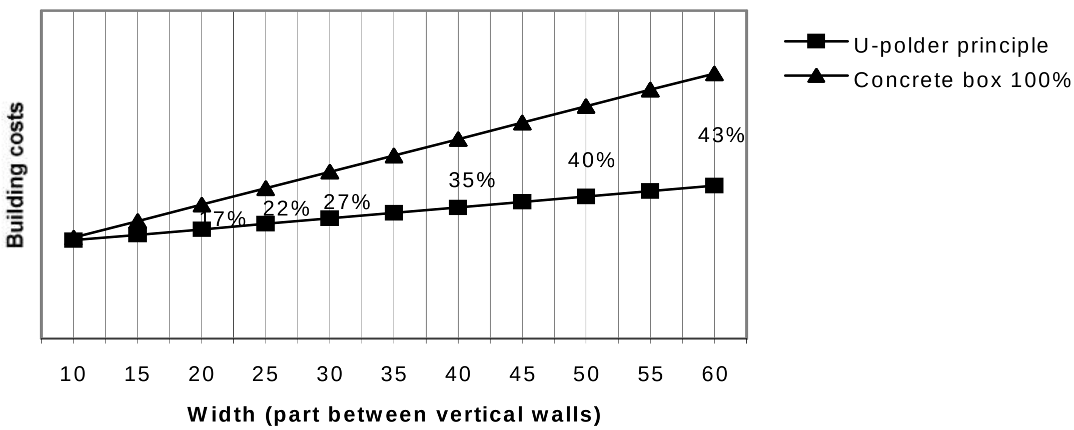


Figure 10.13: Road level 6 m below ground level

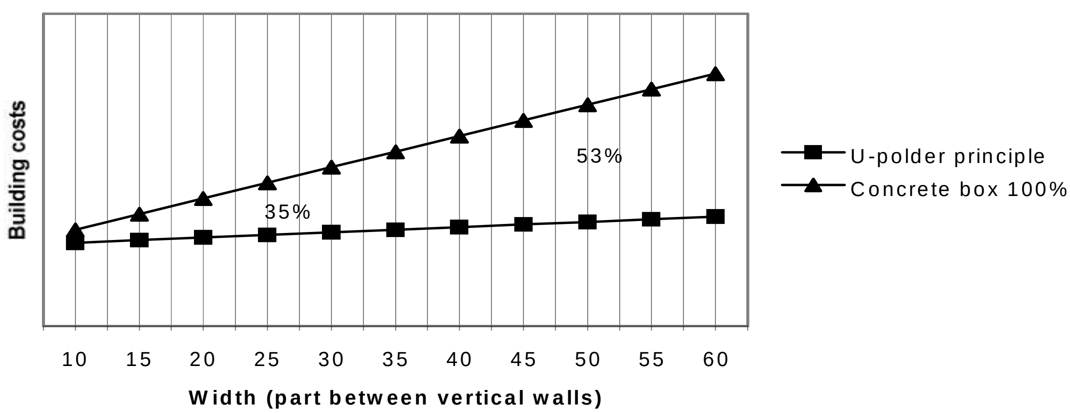


Figure 10.14: Road level 4 m below ground level

With the U-polder method a lot of earth moving takes place. Sometimes the excavated soil is of such bad quality that it cannot be used for ballast beds. This soil needs to be disposed and treated, which raises the costs of the project.
The full integration of the temporary building pit boundary within the final construction of the V-polder makes this method very attractive with regard to building costs.
To implement the method TOMAS successfully it is necessary to have projects with long distances or projects that require a high construction speed.

10.7 Dutch situation

The Dutch government supports the development of innovative construction methods. This is why Dutch companies have developed and designed the building methods discussed in this chapter. Through experimental projects the methods will be further developed, in order to make them more competitive to the more traditional methods. The techniques are of interest to the Dutch market, because of the increasing restrictions for de-watering in several areas.

11. Trenchless technology

11.1 Introduction

In the past every cable or main could only be placed by continuous, open-cut excavation. This method gives a lot of disturbance directly above and next to the hole. In present times the consequences for the environment around these open cuts have become unacceptable. The trenchless technologies offer an alternative for these situations in many cases. Since the 1950s, it has been relatively common to use jacking and rotary boring methods to bore horizontal holes to install pipeline and utility crossings under rights-of-way such as highways and railroads. The last decades the use of these techniques in the Netherlands expanded rapidly.

The goal of this chapter is to give an introduction to the trenchless technologies. It shows when and where it can be used and it gives the principles of the different techniques. Furthermore, the advantages, disadvantages and important parameters will be discussed. Also the reparation methods, the open-front technology, closed front drillings and the horizontal directional drilling methods will be discussed.

11.2 Small infrastructure

The use of underground space looks very attractive. But after a century of using this underground it is already very complex in some areas. Figure 11.1 shows a realistic situation of today. Often it is absolutely not clear which pipe belongs to whom, or even worse, if it is still in operation, or not.

Figure 11.1: The complexity of the underground

So what makes the underground so complex? The traditional small diameter infrastructure in Dutch cities consists of:

- sewers
- water mains
- gas mains
- electricity mains
- telephone cables

Nowadays the following services are added:

- networks for cable TV
- district heating
- separated sewerage systems for drainage and wastewater

Outside the cities there are complex networks of mains and cables for:

- Transport of natural gas and oil
- Transport of water
- Pressure pipelines for sewerage
- Transport of electricity
- Telephone
- Transport of heat
- Transport of chemicals or non-fluids

It is clear that the total length of these pipelines consists of hundreds of thousand of kilometers. In the Netherlands we are used to put almost all small infrastructure in the underground. In other countries this is often quite different. In Germany en Belgium electricity mains and telephone cables dominate the landscape. All this makes excavation for the expansion of existing systems or the building of new systems in the Netherlands very complicated. There are two main reasons for using trenchless technologies. First of all there is the growing resistance against open-cut excavation (see next paragraph), and secondly the complex use of the upper meters in the underground.

11.3 Comparison between conventional and trenchless technologies

Open-cut excavation has been used for a long time, but this conventional technique of using trenches causes more and more problems like:

- Space restrictions
- Deformation of the surrounding area
- Difficulties with groundwater control
- Caving in / silting up
- Bank protection works
- Excavated polluted ground

Besides that, when filling up the trench the following potential problem areas appear:

- Quality of the fill / soil
- Required rate of fill compaction
- Protection of the installed pipe against damage

Above-mentioned problems are in fact problems for the companies who do the work. But they are not the only ones who suffer from (potential) problems. The surroundings of the work will often be confronted with problems too. Some examples of problems are:

- Hindrance to shipping at crossing of waterways
- Fulfilling of safety requirements at the crossing of bank protection works
- Hindrance to traffic at the crossing of roads
- Damage and / or lack at the crossing of agricultural or nature area

Many of the drawbacks can be prevented, or reduced, using trenchless technologies because of the following features:

- No open trenches

- No inverted siphons in waterways
- No open dikes or other bank protection works
- No excavated polluted ground
- Less damage to the landscape and environment
- Free depth installation, therefore no interference with other existing systems
- High production speed
- Favorable cost-benefit ratio

Of course there are also consequences when using trenchless technologies. The installation depth of the pipeline can make repair work very difficult or only possible from the inside. Also after repair work there is a possible reduction in the profile of free space. Besides that some types of trenchless technologies need a larger dimensional tolerance compared with conventional techniques. This is caused by the accuracy of the existing steering and measuring systems.

11.4 Parameters for trenchless technologies

When trenchless technologies (especially the non-reparation orientated) are considered, one has to take into account some parameters. To choose the optimal technique, or even to make the decision to use trenchless technologies, one needs information about the following critical parameters:

- Geotechnical circumstances like:
- Deformation of the soil
- Friction qualities
- Cohesion
- Earth moving qualities
- Deformation behavior
- Ground settlement sensitivity
- Super load situation (filling up, lowering or erosion)
- Quality and compounding of the groundwater
- Groundwater tension

- Obstacles in the subsoil like:
- Stones in glacial sediments
- Remainder of fundaments
- Sunken ships
- Explosives
- Fossilized trees

- Risk for damage to above ground structures

- Availability of above ground space needed:
- Pressure and receiving shafts at microtunnelling
- Pipe string space for Horizontal Directional Drilling (HDD)
- Space for eventual bore slurry treatment
- Accessibility

- Transport medium to install
- Pipe casing construction
- Possibility for corrosion protection of steel pipes

- Reversion scenario, when something goes wrong with the underground structure
- Treatment / removal of bore (bentonite) slurry

Every trenchless technique has its own characteristics and each project has other forcing preconditions, therefore all involved parties will need to take these described parameters into account when creating a project. If this does not happen, then there is a risk that technical problems may occur, bringing unnecessary cost as a result.

11.5 Classifying Trenchless Technologies

Trenchless technologies can be divided into 5 different techniques. In this paragraph every technique will shortly be presented. For details and more information one should see the following chapters.

1. Air-percussion boring techniques
   The techniques which use air-percussion can be divided into two variants. First there is impact moling. In this technique soil is displaced by the percussion tool, the pipeline follows the tool. Secondly there is impact ramming. The difference with the first technique is the position of the percussion tool. With impact ramming the tool pushes the pipe or casing into the ground. The front of the pipe is open with larger diameters and closed with smaller diameters. If open, the soil will be pushed or washed out afterwards.

2. Open-front technology
   Out of a start shaft steel pipes are jacked horizontally into the soil. This technique can also be divided into two different variants: *Open front non-man entry size* where an auger drill removes the soil and *Open front man entry size,* where people can enter the pipe to remove the soil. Because the front is open, this technique is normally used above the groundwater level.

3. Closed front boring techniques
   Characteristic of this technique is that the installation of pipe sections is preceded by a tunneling-machine. A cutting head or shield forms the hole. Hydraulic jacks push the machine and the pre-formed sections into the soil. With the closed front it is possible to bore below groundwater level.

4. Horizontal Directional Drilling, HDD
   HDD is a technique that pulls a pipe from ground level through a drilled hole. Execution of HDD can be distinguished into 3 phases. The first phase consists of making a pilot drilling. In the second phase the pilot hole must be enlarged. This can be accomplished by reaming the hole with a reamer that is pulled back through the pilot hole. In the third phase the diameter of the hole is big enough and the pipeline can be pulled through.

5. Methods for repair or replacement
   Trenchless methods for repair or replacement are used more and more instead of traditional replacement end repairing methods. To improve a pipe system there are three types of activities possible: reparation, replacement and renovation.

11.6 The Use of Trenchless Technology

Yearly the TU Delft and the NSTT (Netherlands Society for Trenchless Technology) collect data regarding the use of trenchless technology in the Netherlands. The results are reflected below.

The growth in the use of the HDD technique (table 11.1) is caused by two main reasons. (1) Increased use for the installation of the rapidly growing glass fiber net for IT purposes and (2) the use of the technique in more complex situations, for example in town centers or in more unfavorable soil conditions.

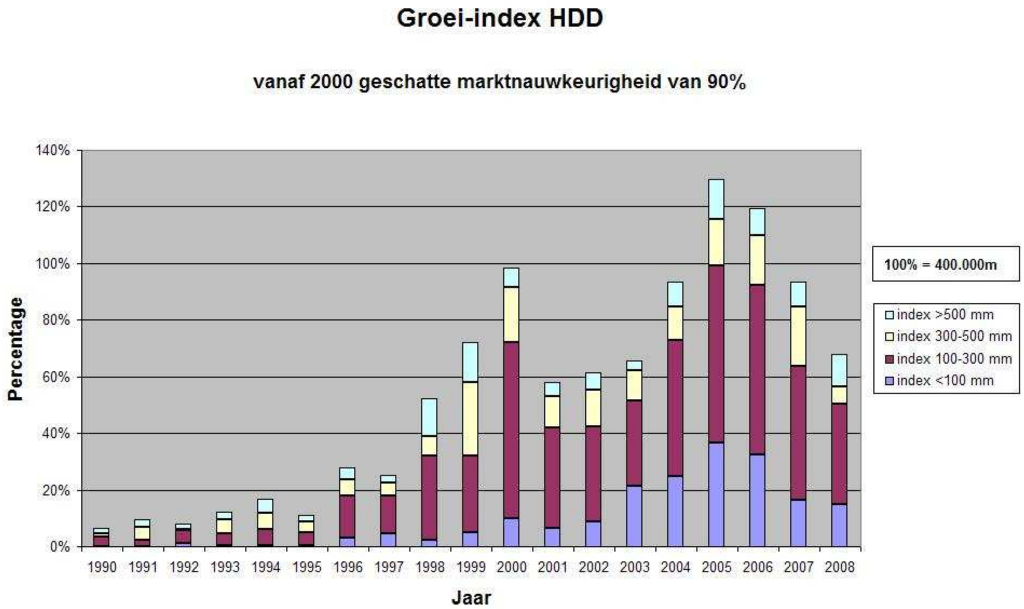


Table 11.1: index categories HDD

Remarkable is the drop in use of the microtunnel technique (table 11.2). Lack of major projects in recent years in combination with a low use factor in city centers (this is similar to experiences in other countries) is the main reason.

The increasing resistance to construction hindrance and more efficient use of the underground will no doubt lead to an increased use in the coming years, not only for the conservative utility systems, but as well in the fields of soil cleaning, drainage, freezing, transport of non bulk goods, etc.

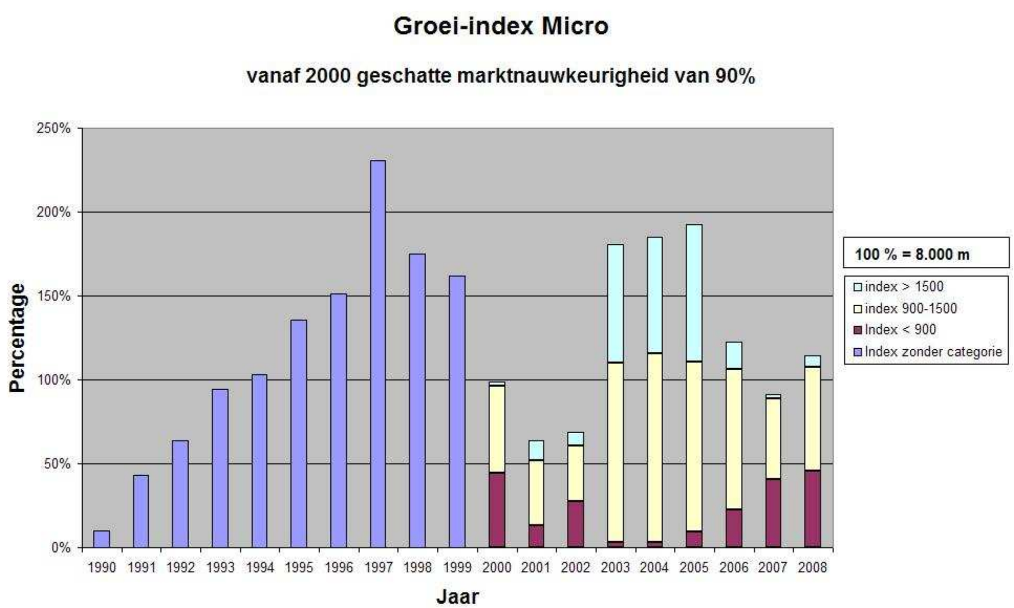


Table 11.1: index microtunnelling

11.7 Reparation methods

Many constructors have developed their own methods to repair existing pipeline systems. Most techniques are designed for commonly used pipeline materials such as concrete, steel, and plastic. Many of the existing reparation systems are known under their own name and classification. A division can be made into three main groups. These are:

- Carbonising of the inner wall.
- Installing of a new lining (relining).
- Removing of the existing pipeline and installation a new at the same time.

Figure 11.2 Carbonising steel pipe

11.7.1 Carbonising

Carbonising is used for existing steel pipes. This is a condition where a concrete layer is attached by spraying it to the existing inner wall. The inner wall therefore will usually be cleaned very well. For various applications several cement mortars are combined, which fulfil the requirements (for example for drinking water).
The big advantage of this method is that the existing system won't be destroyed, so there is no loss of capital.

A major parameter is the quality of the existing system. It must be possible to move an inspection camera, cleaning devices and cement installations through the existing pipeline and the inner wall (after pre-inspection and pre-treatment). A disadvantage of the system can be the slight reduction of the usable cross section area.

11.7.2 Relining

Relining consists of installing a new inner pipe (lining) into the current pipeline system. Just like carbonising different methods are on the market, ranging from bringing in (pulling or pushing) new pipelines of steel or plastic, to pulling in or unfolding of, eventually hardening, stockings.

Just like carbonising, there are some requirements dictated to the pipes. For the pulling-in of a “hard” lining, sufficient free space is required. So before the lining work can begin, it is necessary to carry out a thorough investigation, similar to an inspection for collapsing and narrowing of the profile.
Pushing or pulling of the new lining into the old pipeline will cause friction, which should be taken into account. A solution can be to do the pull-in operation while the pipe is filled with water. This will reduce friction and the new lining will be pulled in while more or less floating.

This technique will also cause a reduction of the free profile, but the existing pipeline will stay in use.

11.7.3 Removing and reinstalling

The methods that do exist for this are known under different trademarks but are based, in general, on one of the two principles:

- The existing pipe is destroyed and remains behind in the ground while at the same time a new pipe is installed.
- The existing pipe is destroyed, sucked into the drilling machine, and is transported by the new pipe, which is installed at the same time (pipe eating).

An advantage of these methods is the installation of new pipes along the existing lines. The pipe-eating method allows for new pipes with a greater diameter than the original to be installed.

Because this technique is executed with use of pipe jacking technology the new pipes, in principle, consist of concrete or glazed stoneware. Like mentioned before, many repair methods exist. The most are typically bound to specific companies. For more information reference is made to the course Trenchless Technology (CT5741).

11.8 Open-front technology

Open front technology has been used for a long time. Far before our lifetime tunnels were made, especially for water supply and defending works. The methods used today are split into:
- Jacking with open front, non-man entry size
- Jacking with open front, man entry size

For the general execution prescriptions for this technique a reference is made to "*Richtlijn Boortechnieken*" Rijkswaterstaat, Dienst Weg en Waterbouwkunde, Delft 1995.

11.8.1 Open front non-man entry size

From a start shaft a pipe (usually steel) is jacked ahead using jacking devices. The soil is removed with a twist drill, which is installed in the pipe. The function of the twist drill is not only excavation, but also transportation of the soil.

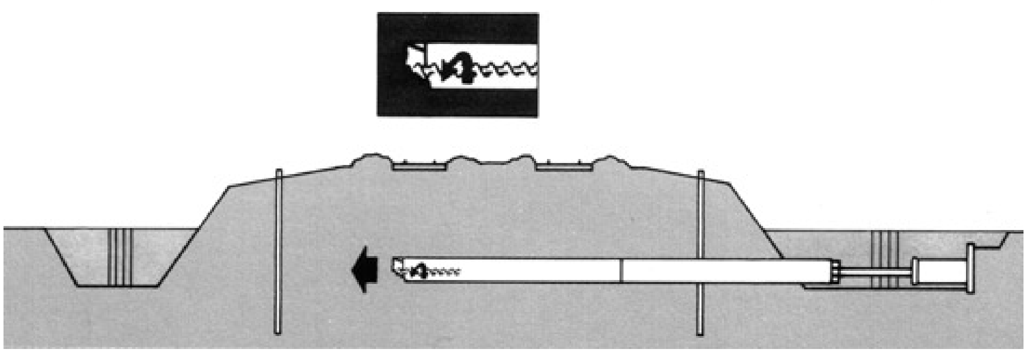


Figure 11.3: Drill technology non-man entry size

Due to the increasing friction and the minimal control possibility, the length of these drillings is restricted.

Although the technique can only be used above the current groundwater level, it is often used because it is relatively fast and economical. Nevertheless the microtunnelling systems with closed fronts are used more and more because of the larger drilling lengths and the increasing restrictions on the lowering of the groundwater level.

11.8.2 Open-front man entry size

The parameters of this method are similar to those for the non-man entry size. Of course there must be a minimum diameter; this depends on the specific regulations of a country.

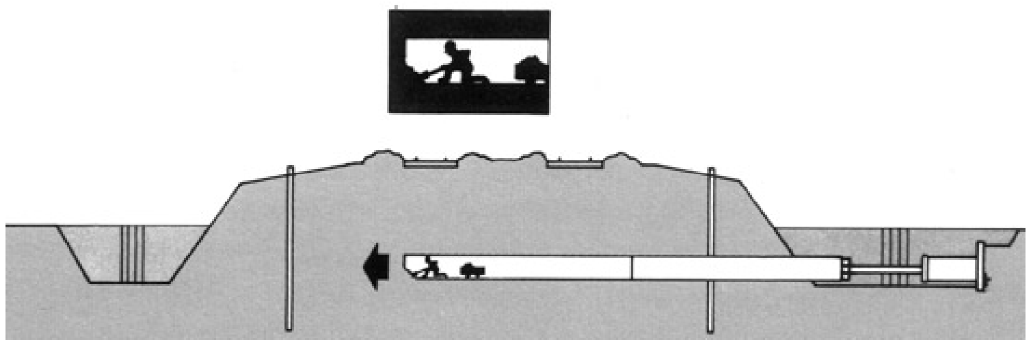


Figure 11.4: Drill technology man entry size.

A special application of this method is the excavation of the soil by water jetting under very high pressure (for example 400 bar). This application is especially interesting in hard clay grounds or moderate hard rocks. Because the soil is mixed with water suction trucks instead of wagons or conveyors can transport it.

With this technology and especially with the water jet method there is danger of settlement. However the groundwater level is decreased, therefore no supply flow appears, it is possible that more ground is disposed than is justified by the proceeding movement of the pipe.

11.9 Air-percussion drills

As the name indicates, these techniques use air-percussion. The methods used can be divided into two groups:

- Impact moling
- Impact ramming

For the technology and the general execution regulations you are again referred to “Richtlijn Boortechnieken”.

11.9.1 Impact moling

From a small start shaft a percussion tool forms a horizontal hole by compacting and displacing the soil. These tools have a cylindrical or torpedo shape and are powered by air or hydraulic power. The compressed air or hydraulic fluid drives a piston within the piercing tools against a cutting head or anvil at the front of the tool. The pipes follow the tool. Piercing tools are also known as moles.

The control possibilities are limited and the system is usually used for short distances (< 30 m) for installation of small diameter flexible pipelines for gas, electricity, telephone et cetera.

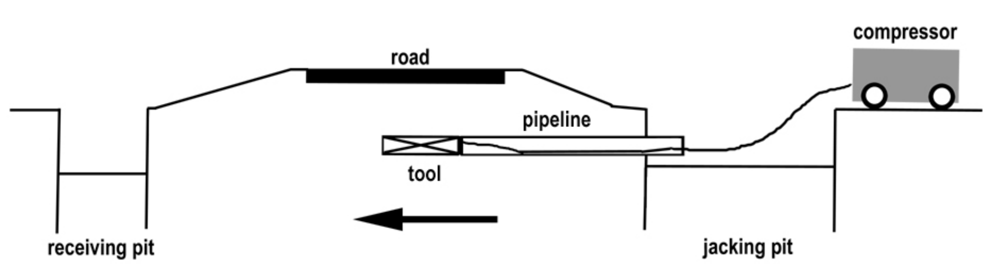


Figure 11.5: Impact moling.

Compacting and displacing the soil forms the hole, therefore deformation of the soil and prevention of obstacles has to be taken into account. The best use of the system is in rock-free compressible soils, like clay soils.

Controlling is somewhat possible by so called Electro-Magnetic (EM) home to target tools. With this tracking system the magnetic field, generated by a solenoid coil mounted on the boring tool, is detected by a receiver containing three mutually orthogonal sensing coils located at the retrieval point. Output of the receiver coils is proportional to the angle between the axis of the tool and the axis of the receiver. Further processing generates the tool co-ordinates, which can be displayed digitally in typical units relative to the launch location.

11.9.2 Impact ramming

Impact ramming uses a piercing tool that operates as an impact device to drive a pipe or other conduit into the ground. The pipe installed by ramming equipment is typically used as casing for other pipes or cables to be installed at a later time. The next section of pipe is inserted into the launch pit and welded to the first section.

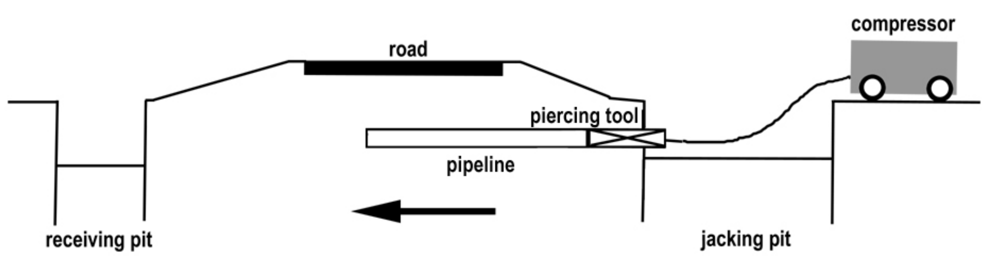


Figure 11.6: Impact ramming.

The piercing tool drives the pipe up to the length of the entry pipe and then is returned to its original position to add each new section of pipe.

Often an open-end pipe is driven through the soil. Soil in large open-end pipes (< 1400 mm) is pushed out with compressed air, or washed out with water jets, to prevent the pipe being forced up and possibly bursting. With closed-end pipes the soil will be displaced and compacted. This technique tends to limit the diameter of the pipe (<150 mm) because of the danger of being forced up and possibly bursting.
The method can be used in many soil types, even in gravel and soil which holds boulders. However, because controlling is impossible the length of the boring is generally limited (40 meters).

11.10 Closed front drillings

A characteristic of closed front drillings is that the installation of pipe sections is preceded by a tunnelling-machine. Closed front drilling can be described as the principle of using hydraulic jacks to push pre-formed sections in order to line the hole formed by a cutting head or shield.

Over the last twenty years the technology has developed very quickly. First only straight drillings were executed, but nowadays curves (within certain restrictions) are also possible. A wide range of tunnelling machines is available at present, which work, partially or completely, along the same principles as the larger TBM's.

The pipes are installed using the “pipe jacking” system, this is different to the tunnels where the pipe wall is built from the inside by reinforced concrete elements or extrusion concrete. Using this system with increasing diameters (incidentally to 5 meters) means that the difference regarding diameters with the large infrastructure tunnels is disappearing. In this text the term microtunnelling is used to describe the technique of using a tunnelling machine in combination with pipe jacking.

First a tunnelling-machine is jacked ahead through the wall of the dry start shaft. For this a hydraulic jack-construction is put in the shaft. After the tunnelling machine is jacked far enough ahead a pipe element (usually of reinforced concrete) is coupled to the machine and the whole line is jacked further forward, after which the cycle of coupling and jacking is repeated.

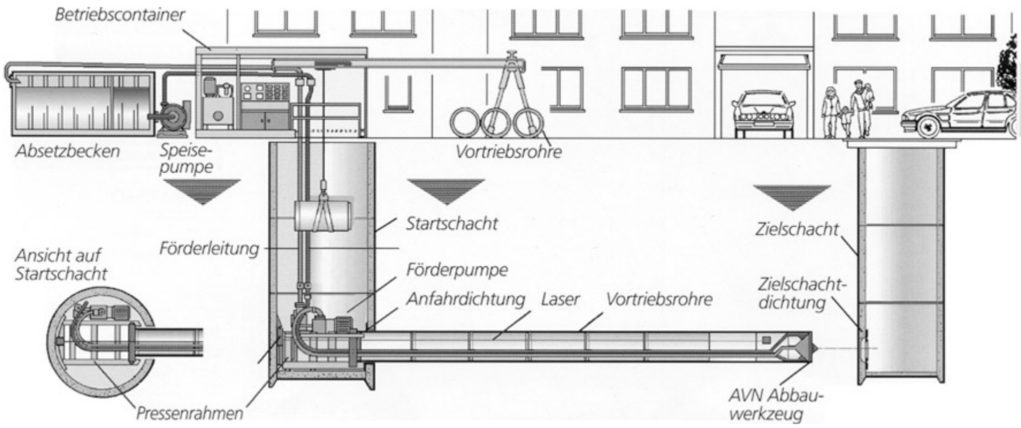


Figure 11.7: Principe of closed-front drilling in general

The system is normally used for diameters between 0.15 and 3.50 meters, but in some specific cases diameters up to 5 m have been proved possible. During the process, the friction on the pipe wall will increase with increasing length of the pipe. After a certain length the necessary jack pressure will become so high that the permitted concrete-tensions or the maximum jack pressure will be exceeded, so the maximum length is then reached. In pipes which are accessible to construction workers it is necessary to build in and out “interjack stations”, which can greatly increase the possible drilling lengths. The whole line moves like a caterpillar through the soil.

For several regulations a reference is made to “Richtlijn Boortechnieken”.

Although several types of tunnelling-machines are on the market, and developments are still continuing a distinction can be made in:
- Slurry shields.
- Earth Pressure Balance shields (EPB).
- Mix shields.
- Compressed air shields.

The differences between these machine types are described in chapter 8.1.

11.10.1 Radius of curvature

Usually the permitted radius of curvature is 300 times the diameter of the pipe. Recent practice experiences have shown that a conservative approach to the radius of curvature is necessary (certainly when the drilling takes place through soft soils). Research must show what the actual safe radius of curvature is under given circumstances.

Normative factors are:
- The length of a pipe section
- The power transmission
- Freedom of movement of the couplings
- Remaining water tightness of the couplings
- Sufficient resistance sideways of the encasement bottom against the buckle power

The use of special shortened and banked pipes could increase the possibility of a smaller radius. For this further research is necessary.

11.10.2 Length and dimensions

The maximum length at which microtunneling can be used depends on the diameter. Because the jacking resistance increases with the length of the tunnel, the axial power will become too high at a certain point. The possible jacking lengths will depend on the geotechnical circumstances, but will not be more than 200 meters for diameters up to 750 mm. With greater diameters interjack stations can be installed. The maximum length between the jacking shafts can be increased normally until about 1000 meters. Power supplies, discharge, buckle length, and correct control will become normative factors. Longer lengths between the jacking shafts are possible under specific circumstances, for example the Europipe land accretion on the German Wads with jacked length of 2500 meters (at once), with an inner diameter of 3.00 meter.

Figure 11.8: Interjack station

The diameter of pipe-jacked elements in The Netherlands has not exceeded 3.50 m so far. Incidentally diameters of 5.00 meter are used in Germany. These are however special cases because normally such diameters would be built using segmented tunnels.

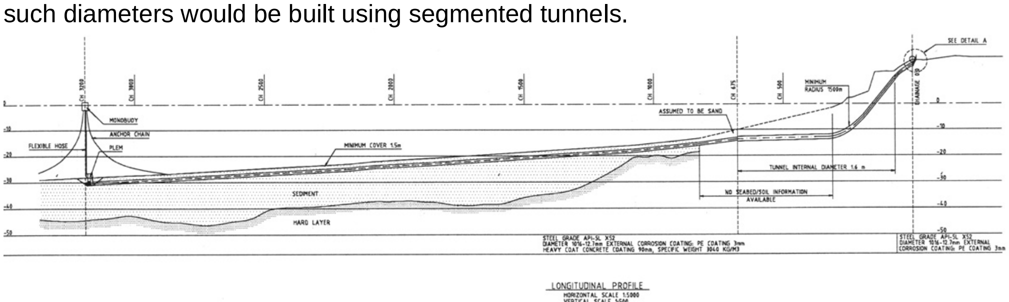


Figure 11.9: Land accretion oil company Petrogal, Portugal

11.10.3 Required jacking forces

The required jacking force depends in principle on:

- Possible appearance of shear stresses between the pipe wall and soil

– Required pressure for the forward movement of the drilling machine

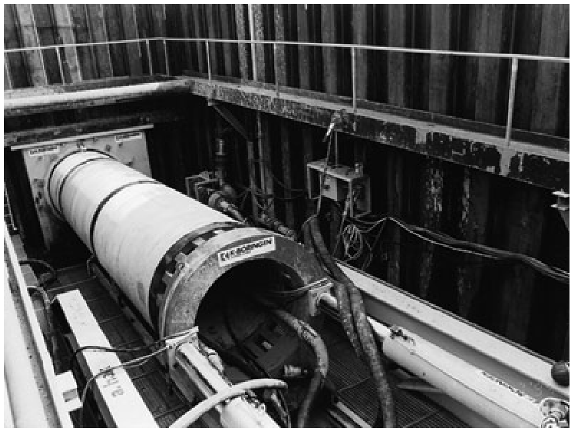


Figure 11.10: Jacking shaft with hydraulic rams

Both factors depend on the local soil parameters. The appearance of shear stresses between pipe wall and soil is also influenced by the “lubrication” with bentonite, which is usually applied. The effect of the lubrication determines the level of friction to a large extend. It depends on the geotechnical circumstances whether interjack stations will be installed. To prevent jamming, the distances between two interjack stations should not exceed 80 meters (conservative). Just like the permitted radius of curvature more study is needed to make a more accurate prediction.

During drillings with a diameter up to 3.00 m, the jacking forces can increase up to 500 or 600 tons, depending on the project specifics.

11.10.4 Steering and positioning

Steering

Rams placed behind the cutting head are used for steering. By pushing out one or more of the rams the head can change direction up to 3 degrees. With the turning of the cutting head, the direction of the drilling will change. The steering possibility is not just for following the trace, but also to correct mistakes when the bore unit loses course.

Positioning

For both steering and positioning the co-ordinates (x, y and z) and angles of rotation of the cutting head are important to monitor.

For microtunnelling Laser Targets are used. A laser is installed in the starting shaft and is pointed at a target in the shield, this provides a reference point. There are passive and active targets for laser systems. In a passive system, a closed circuit TV (CCTV) system transmits information about the location and direction. Active systems detect a distortion of track and correct this. Laser target systems have become the system of choice in microtunnelling because they are highly accurate and made of proven design. The work length depends on the diameter of the pipe and the chosen system.

The curved trajectory drillings demand special attention. When the target is not visible from the starting shaft any more, special systems are required. These systems follow the drilling from fixed points in the pipe. They move forward altogether (including the laser). As long as the system is in a known position it works the same when it is based in the starting shaft. Regular control (for example with land surveying) of the position of the pipeline is necessary because when the position is altered, the cutting head is automatically wrongly positioned as well. This control is necessary because the pipeline can move in a cross-wire direction after installation. The curved laying of the pipe and the non-axial jacking force causes this.

11.10.5 The reinforced concrete pipe

Normally reinforced concrete is used for constructing pipes, however for smaller diameters other materials (e.g. stoneware) are also used. Because of the required high-pressure strengths, the accuracy of dimensions, and the finishing, high restrictions are dictated to the fabrication process. Inaccuracy in the finishing process directly alters the shaft friction and power transmission between the mutual pipes for example.
The concrete quality will normally be at least B45. Because of this the concrete will have a high level of water tightness. A spigot and socket joint contain the coupling, where a rubber seal provides a tight water barrier. Because concrete is not completely watertight, in special cases “steel core” pipes will be used. Following the steel core installation in the couplings, they can be welded to each other from the inside.

Figure 11.10: Hoisting of a concrete pipe

After the required geotechnical research the depth and length of the elements, along with the diameter dimensions are calculated. For this the requirements dictated in Euronorm PR-EN 1916 can be used. This standard also gives guidelines for reduction of the permitted tensions in case of curved drillings. Rings of wood are used as stops between the pipes (made with special types of wood, of mono- or multi-layer construction). The purpose of these rings is to achieve a uniform transmission of power. This is very important because it prevents peak pressures. The pipes cannot stand up to these pressures and can be permanently damaged.

In the regulations and execution method calculations a small angle rotation is taken into account. A rotation of half a degree per coupling is possible. However it appears from practical experience (and especially with soft soils) that the pipeline is not always rotating at each couple. It does appear that angle rotations can occur abruptly. For example two couplings do not rotate and then one rotates twice the calculated rotation. This can cause leaks in the couplings or worse, the pipeline can buckle out.
Further research into this phenomenon is taking place, but especially in soft soils the radius of curvature must not be too small.

To reduce the friction on the pipe wall during the jacking, lead-throughs are made in the pipe wall at regular distances. During the jacking lubricants (usually bentonite) are dispersed using these lead-throughs. After the installation the lead-throughs are filled to prevent leaks.

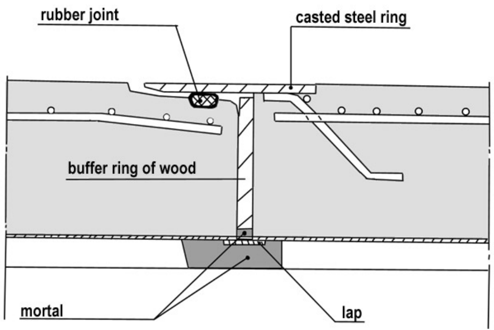


Figure 11.12: Joint drill pipe

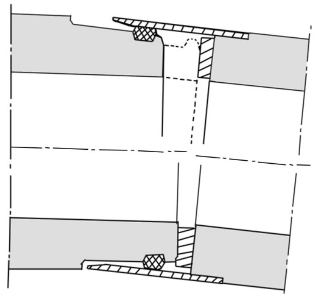


Figure 11.13: Joint with transversal slope

Figure 11.14 Bore pipe with bentonite – injection points

11.10.6 The jacking shaft

The jacking shaft is an essential part of construction in more than one way. In The Netherlands sheet-pile pits are usually used. In other countries (and sometimes in the Netherlands) immersed or bored / jacked concrete drop caissons are used.

The dimension of the shafts is determined by the necessary works, which have to take place in the shaft. A certain freedom of dimensions of the shaft does exist.

The tunnelling machine and the pipes have to be led through the wall of the shaft. This is only possible when there is no inflow of water into the shaft. The lead-through has to contain a water retaining construction or the groundwater level has to be decreased. This last option does not often take place any more. Usually one makes a dry lead-through with a double construction (for example a double sheet-pile wall) filled with an impermeable material. The drilling pipe is covered with a rubber gasket, which is also attached to the sheet pile wall.

Figure 11.15: Jacking shaft for drilling under railway

The building depth of pipeline systems is usually far below the groundwater level and because the work must be executed from a dry shaft, the shaft needs a watertight floor, which can also withstand the groundwater force. A special back wall construction has to be made to withstand the high-pressure powers of the jacking pumps.

Experiences with the Dutch soft Holocene soils show that the necessary reactive forces can cause large deformations in the shafts, which results in large leaks.

Because the start of the drilling often takes place in soft soils, it is important that the tunnel-boring machine does not dive down due to its unevenly divided weight, after leading through the wall. A solution often used is the welding of one or more pipe sections to the machine, which results in a better stiffness and a better dividing of the weight.

In case the starting and receiving shafts have to be removed after the pipe installation, one has to take into account that because of the removal techniques used (like vibration blocks) settlements can appear. This can also effect the horizontal alignment of the pipeline, which can lead to big tensions in the pipes. To estimate such technical problems an adequate soil study is also indispensable.

11.10.7 Use under Dutch circumstances

The use of closed-front drilling systems started slowly. First drillings were only executed with small diameters over relatively short distances and with long elongated traces. One of the reasons, other than technical caused by the usually soft soil and the high groundwater levels, was the variety of the Dutch soil. A bought tunnelling machine cannot be used universally, so some Dutch companies were concentrating on EPB machines, while others used slurry shields.

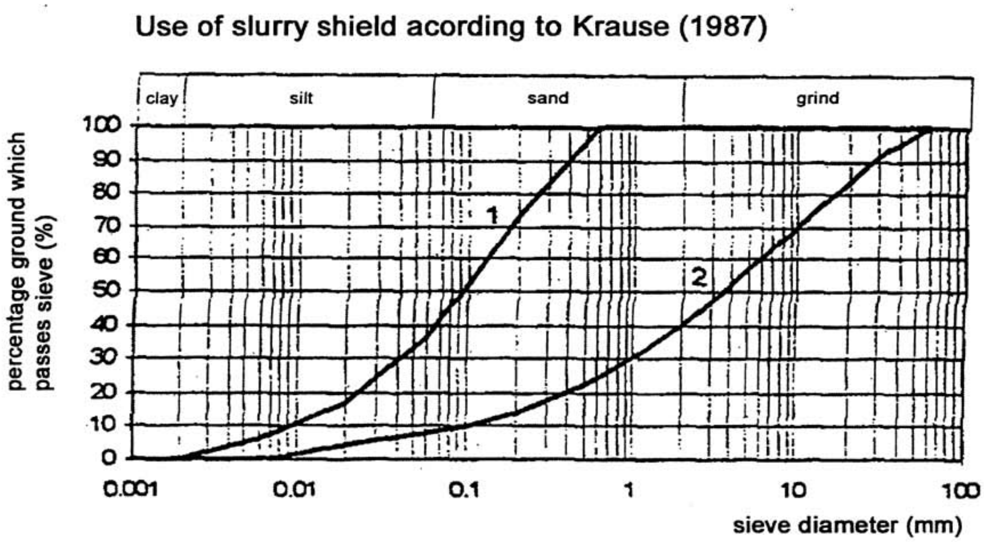


Figure 11.16: Slurry shield use

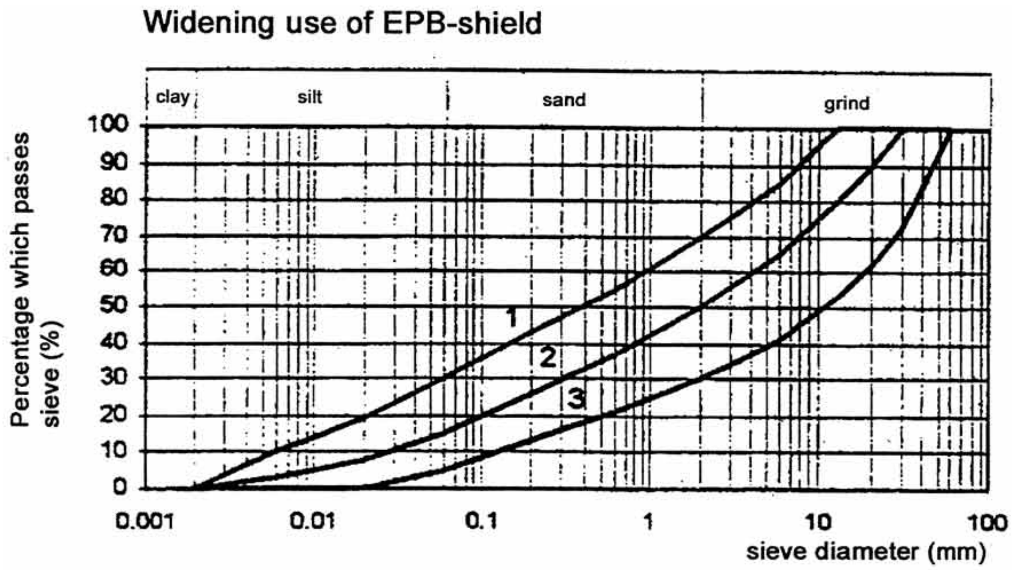


Figure 11.17: EPB-shield use

The use for small infrastructure dates from the 1970s; the real development started in the late nineties however.

The slurry and EPB machines are not suitable for all Dutch soil, as the grading curve shows. Over recent years, many companies and institutions have studied and experimented with additions to make the soil suitable for the chosen tunnelling machine.

A circumstance that cannot be overlooked with the use of microtunnelling machines is the potential presence of large stones. Even when there are no stones found during the geotechnical study, it is important to collect geological information. Glacial soil especially poses a danger with regard to possible boulders and stones. EPB tunnelling machines cannot transport bigger stones than permitted within the auger. Slurry machines, when supplied with the right bore construction, can process stones of one-third the total diameter. A special crusher in the mix chamber is then used.

11.10 Horizontal Directional Drilling

Horizontal Directional Drilling was developed in America. It was basically an adaptation of oil-field technology. Directional drilling was applied in mining, gas exploration, and construction. The most recent application has been for drilling beneath rivers, streams, and long crossings. Since the beginning of the eighties the system has also been used in the Netherlands. The initiative came from the NV Gasunie, which had to install many gas pipelines. Because of this a couple of Dutch companies had a large influence and will continue to have in future developments.

Nowadays the system is not only used for gas pipelines, but also for oil, chemical products, water, telecommunication, electricity cables, and city heating. Meanwhile many crossings of rivers, roads, scenic areas, and difficult to reach terrain etc. have been created.

New developments are the use for drainage and soil clearing systems and the investigation of soil at vertically inaccessible places. The HDD system is very flexible and has a favourable cost benefits ratio.

Figure 11.18: Midi-rig site

An interesting field of study is the combination of HDD and microtunnelling. The technique is developed to build pipelines underground over long distances without digging. For this a drill rig is used, which is installed under an angle of about 10 degrees.

The drilling of a horizontal directional drilled crossing can be divided into three phases:

- Pilot drilling.
- Pre-reaming.
- Pulling-back pipe.

11.11.1 Pilot drilling

Initially a pilot hole is drilled along a pre-determined profile. Drilling is accomplished by either a mud-motor and drill bit or by simply using a jet bit. To control the desired drill direction, a steering element is installed, with which the drilling can be checked and steered continuously. As drilling progresses a wash pipe is connected to the pilot pipe to support the pilot string, prevent hole collapse around the pilot pipe, and provide a passage for return.

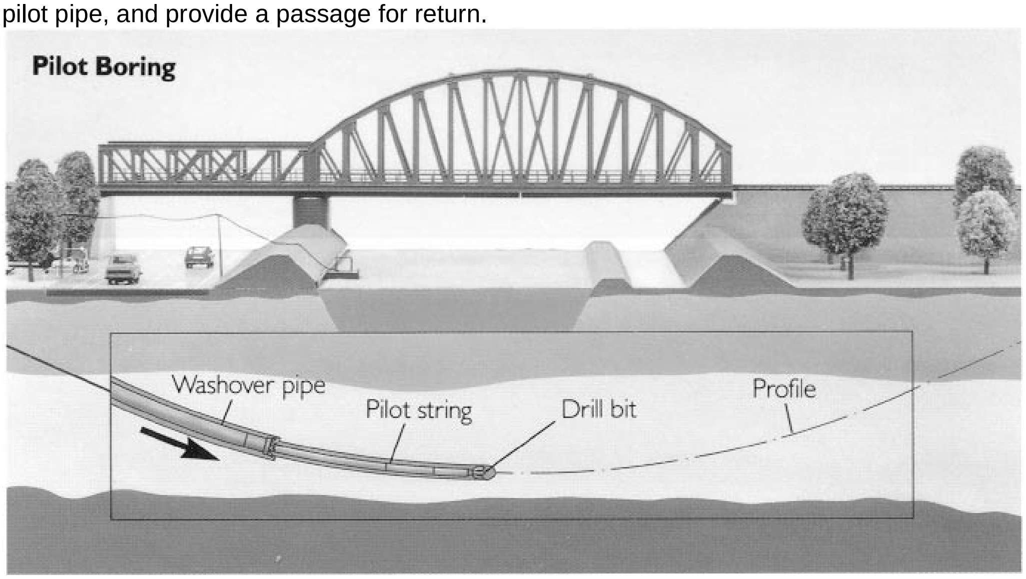


Figure 11.19: Pilot drilling

The drill fluid for the motor, or the fluid jet, is provided through a hollow drill pipe. This pilot pipe normally has a diameter of about 7 cm. The excavated soil is disposed along the outside of the drill pipe to the rig location. The soil is transported by drill fluid (which possesses some characteristic qualities for this).

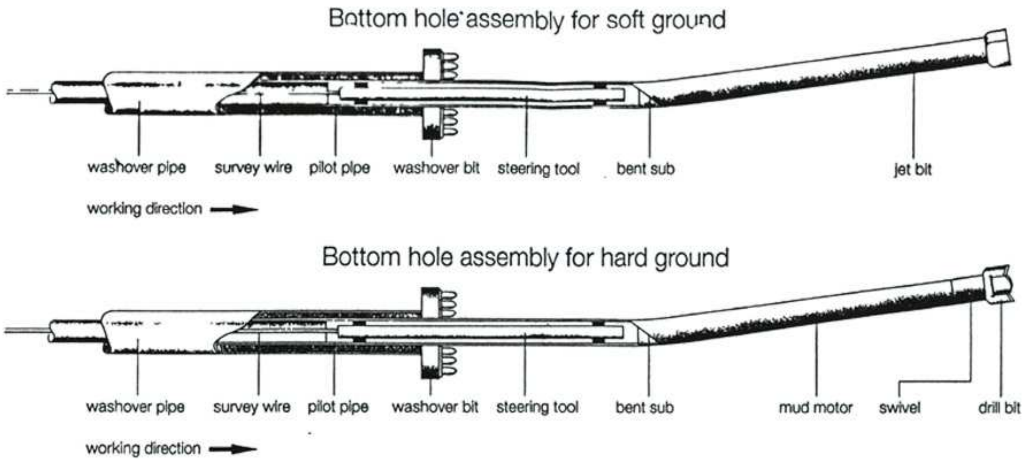


Figure 11.20: Bottom hole assembly for soft and hard grounds

In many soil types it is possible to drill directly with the wash-over pipe. This takes less time, so there are lower costs. This does imply working with a bigger drill motor or the use of a bigger jet.

11.11.2 Pre-reaming

After arrival on the other side, the pilot pipe is pulled back out of the wash over pipe. A reamer is then added to the wash over pipe at the exit side. The reamer is then pulled toward the drill rig while rotating through the drilled hole. While pulling the reamer through, the reamer removes any excess cuttings or formation materials that may have sloughed into the pilot hole to the desired diameter.

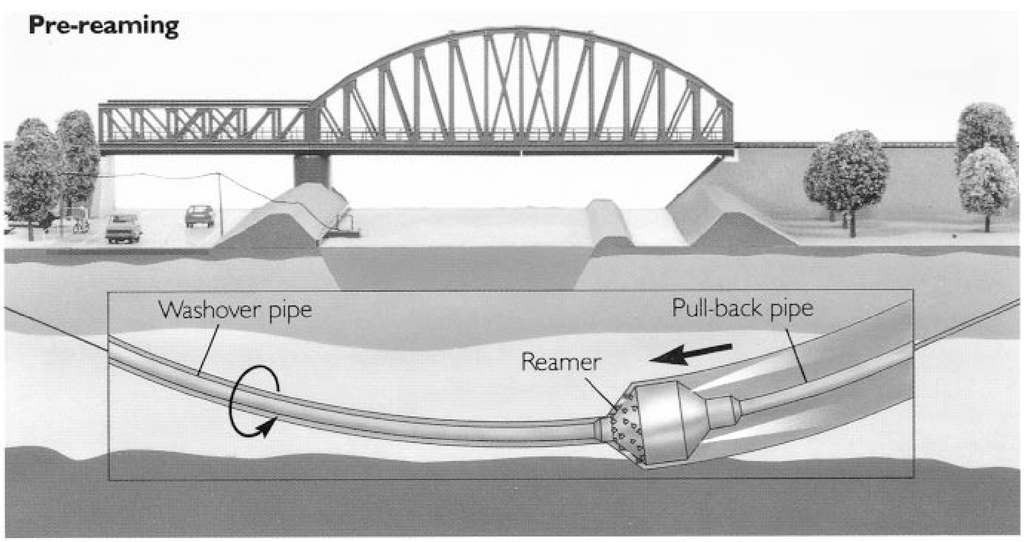


Figure 11.21: Pre-reaming

11.11.3 Pull-back pipe

Simultaneously with the drilling operations, the product pipe, sleeve pipe or pipe bundle at the pipe site (opposite from the rig) is welded up and tested. At the front end of the pipe a pullhead is welded and then connected along a swivel and a reamer until it reaches the wash-over pipe that remains in the drilled hole. Pullback commences by rotating and pulling the wash pipe and reamer assembly towards the rig. The inclusion of the swivel allows rotation of the wash pipe whilst the product pipe remains free from rotation.

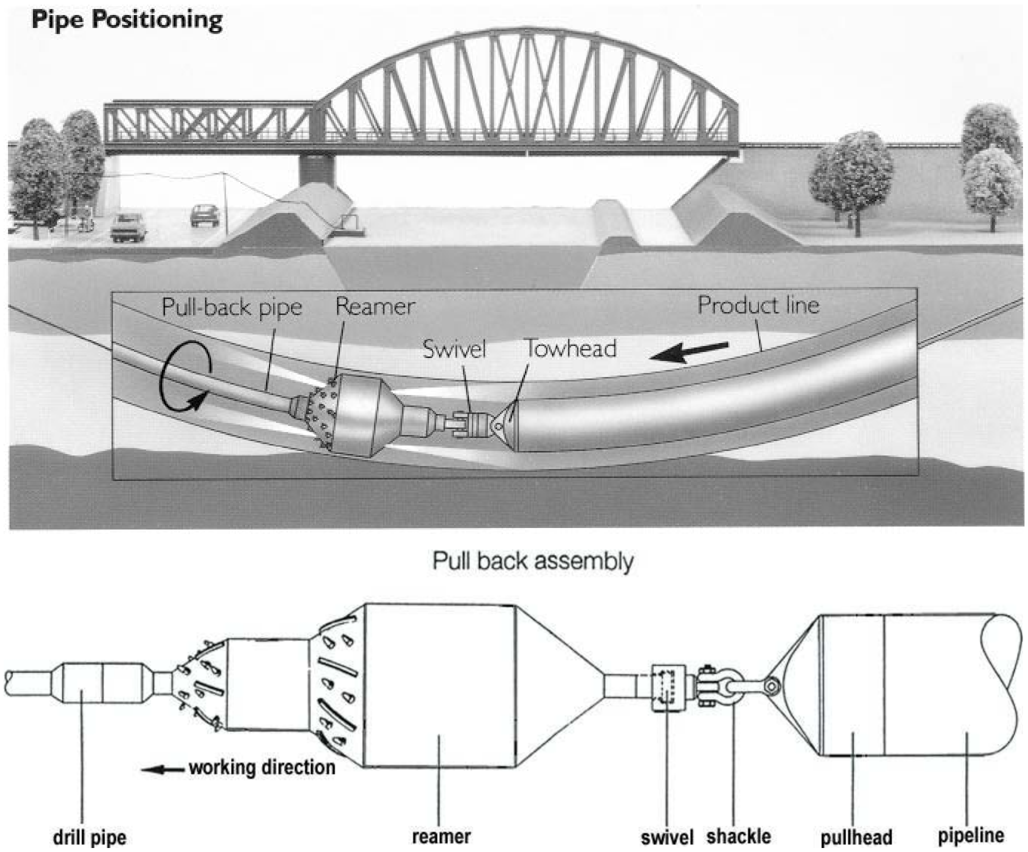


Figure 11.22 Pull back assembly used during pipe positioning

11.11.4 Drill fluid

Normal drill fluid is a suspension made out of water and bentonite. The functions of the drill fluid are:

- Hydraulic cutting with the jet.
- Energy transport for the drill motor.
- Lubrication of the cutting head and the wash-over pipe.
- Transport of drilling cuttings from the borehole through the annulus to the surface.
- Stabilisation of the bore hole against collapse.
- Build up of a filter cake to avoid loss of drill fluid.

Depending of the situation, natural additives may be included for the improvement of the drilling process. Another reason to choose bentonite is that it is easy and relatively cheap to get.
Despite the large advantages of bentonite there are also some restrictions, such as:

1- With salt water the working of the suspension decreases without special measures very quickly;
2- Because of the lubrication working of bentonite, it is less suitable for installation in drains as they can get blocked.
3- With clay soils, the forming of clay balls can cause complete jamming of the drill system.
4- With very rough soils, like grind nests, and also in Dutch soil shell banks are often found, a very big volume and pressure loss appears;
5- The remaining mixture of soil and bentonite cannot be dumped until it is cleaned first, which is very expensive.

Solutions to the problems mentioned above are the development of various polymers, which are nevertheless expensive and are not always ecological.

Large infrastructure tunneling and the increasing costs for cleaning the mixture of soil and bentonite are reasons why a lot of study is being done to improve the drill fluid.

11.11.5 The machines

The choice of drill machine is important when planning HDD-projects. In this section three kinds of machines are discussed (see figure 11.23):

1. Maxi rigs
2. Midi rigs
3. Mini rigs

Classification of the machines is very difficult. The following values and qualities are therefore just indicative. The pull force of the mini rigs will normally be under the 15 ton and of the maxi rigs normally more than 100 ton with a maximum (currently) of about 350 ton.
Mini rigs are often used to install small cables and pipelines. It is possible to steer and monitoring takes place with detection methods from the ground level.
Maxi rigs are used for the largest and longest pipelines in all kinds of soil types (including rocks). Steering is very advanced and various monitoring methods are possible.

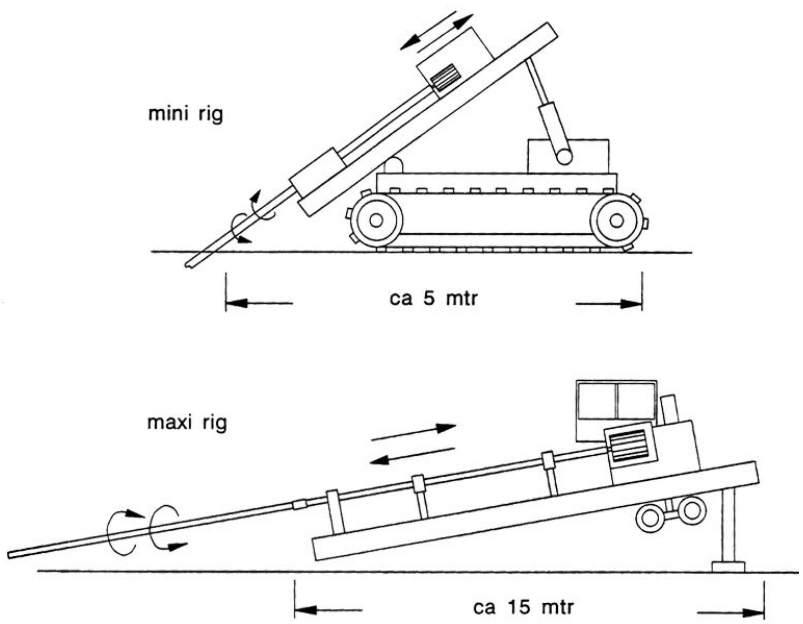


Figure 11.23: Mini- and maxi rig.

Midi rigs are used in the area between the two mentioned before. This strongly depends on the geotechnical circumstances and the various steering techniques that are used.

Due to the high transport costs and installation all over the world it is important to make the whole machine as compact as possible. If the unit fits into a couple of containers, the mobility will be high and the machine can be economically used for various projects.

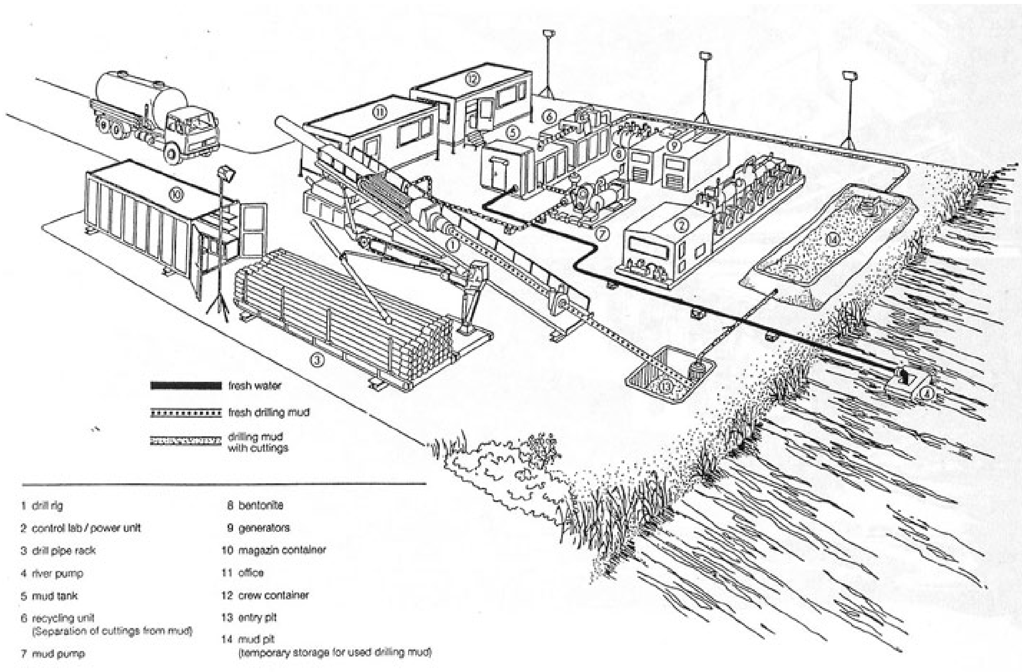


Figure 11.24: Layout rig site

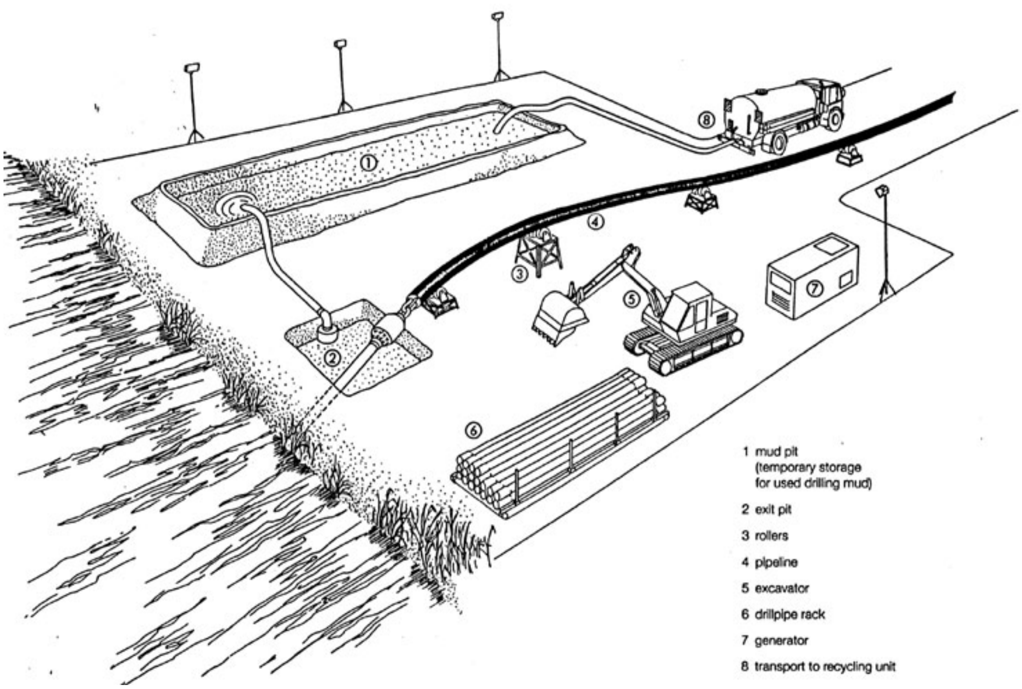


Figure 11.25: Layout pipe site

11.11.6 Recycling Installation

Recycling or separation installations are necessary units for larger drilling projects and when bentonite drill fluid is used. These are used for:

1. Cleaning the drill fluid of soil parts. This way the drill fluid can be used again.
2. Treatment of the residue drill fluid, so that simple disposal and dumping is possible.

The fluid returning from the drilling operations is passed through mud cleaning machines and then returned to the mud tank for re-use with the freshly mixed mud. A typical mud cleaning process consists of various steps for filtering the different fractions of the cuttings. The used mud, for example, will pass through a series of shaking sieves, de-sanders, and de-silters.

Figure 11.26 : Separation installation

Upon completion of drilling the remaining drill fluid can be:
1. Used at another directional drilling project
2. Left on farmland for recommended soil improvement
3. Evacuated to a dump

11.11.7 Length and dimensions

The use of this technique is very broad because many different size drill machines do exist. Ten years ago the first midi machines came on the market followed by the mini.

When using mini rigs the length is limited to about 100 m and the diameter to about 30 cm.
The maxi rigs do have a competitive struggle with the midi rigs and are currently only used for drillings longer than 200 - 300 meter or diameters larger than 40 - 50 cm. The maximal possibilities nowadays are about:

- Length: 1500 a 2000 meter
- Diameter: maximum 150 cm

The above mentioned dimensions are very indicative because the borders of all possibilities have not yet been reached. There are some uncertainties in the combination of the length and diameter because both parameters have a direct influence on the time, which the borehole is obliged to stay open. With larger diameters the stability of the borehole may be debatable at a certain stage. What really happens inside a borehole is a field of study, which takes place at several locations.

Curves
In general two parameters are important:
- The permitted tensions in the bore pipe
- The permitted tensions in the pulling pipe

This restricts the use of the system. Using steel pipes the radius of curvature is 1000 times the diameter. However, the regulation is less strict when using plastic HDPE pipes (depending on the application).

11.11.8 Required forces, steering, positioning

Forces
There is a great variety in dimensions of the machines and the scale of projects. A couple of factors will determine, more or less, the required forces. These factors are:

1. Drilling

Preconditions are:
- Geotechnical circumstances.
- Diameter of the borehole.
- Length drilling.
- Curves in the trajectory.

2. Pulling in of the string

Preconditions are:
- The above mentioned preconditions.
- The pipe material types.
- The finishing of the pipe wall.
- The thickness of the pipe material.

There is a difference between the forces (powers), which are always necessary and the powers that can be necessary for the stability of the borehole.

For example the required pull force for a maxi rig drilling. Theoretically the calculated force will be about 500 kN. In practice the maxi rig can supply a pull force of about 3000 kN. In case of instability of the borehole the pull force has to be increased, to keep the pipe string in motion. It is important that the forces don't exceed the permitted tensions of the pipe material. This can appear very quickly with plastic pipelines, such as HDPE.

An interesting aspect appears when several pipe strings of different materials are pulled in at the same time. The required pull force will possibly be within the margins of the steel pipe, but will cause deformations at the HDPE pipeline. In general technically correct designed and executed drillings use less power than incorrectly prepared or executed drillings.

	Nacap RIG-1	Nacap RIG-2	Nacap RIG-3	Nacap RIG-4	Nacap RIG-5	Nacap RIG-6
Pull force [kN]	200	2000	2500	1000	300	100
Jacking force [kN]	150	500	500	1000	120	50
Rotation torque [kNm]	14	58	58	50	15	4
Bore motor [RPM]	130	55	55	125	50	150
Installed power [kW]	74	2x300	441	320	47.5	100

Min. Bore angle [°]	4.5	7.5	8	10	8	13
Max. bore angle [°]	30	20	15	18	46	30
Stroke rig [m]	4.0	10.5	10.5	10.1	3.5	1.65
Type	Cater-pillar chassis	Cater-pillar chassis	Cater-pillar chassis	Heavy duty truck	Cater-pillar chassis	Cater-pillar chassis

Table 11.1: Various rigs

Steering and positioning

There are several steering systems on the market that make use of sensors behind the cutting head. These sensors:

- are located at the end of the drill rod;
- provide the azimuth and inclination of the bottom-hole assembly;
- provide the orientation of the drill face (bent subassembly)

This information, combined with the measured length of the drill pipe, can be used to calculate the position of the drill face: Measurement While Drilling (MWD). The most common guidance systems are magnetometer- accelerometer systems, gyroscopes systems, and electronic beacons.

A disadvantage of this system is the use of an earth magnetic compass. A disturbance of the earth magnetism causes incorrect observations.

Disturbances can be caused by:
1. changing of the earth magnetism itself;
2. influences due to variable voltages of the cables in the ground;
3. ships at crossings of waterways;
4. sheet-pile walls and other metals in the ground.

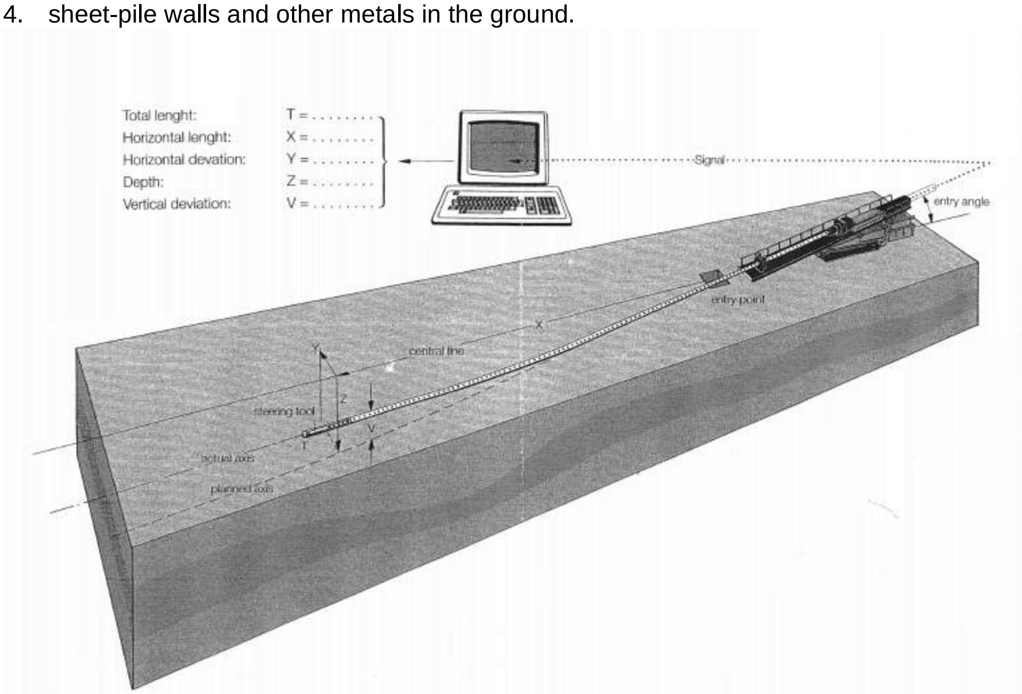


Figure 11.27: Parameters steered drilling (True-Track system)

To control the pre-determined location various systems can be used. Like the “True-Track” system where an electromagnetic field of known intensity and size is inducted.

With small rigs pipe locators are usually used. A small transmitter is located just behind the drill face, while a receiver on the ground level calculates the position and depth. This method is often called the "walkover method" because a technician carries the surface unit over the trajectory of the drill face. The system is rather accurate to a depth of about 9 meters and cannot be used in areas where surface obstructions prohibit access above the drill face.

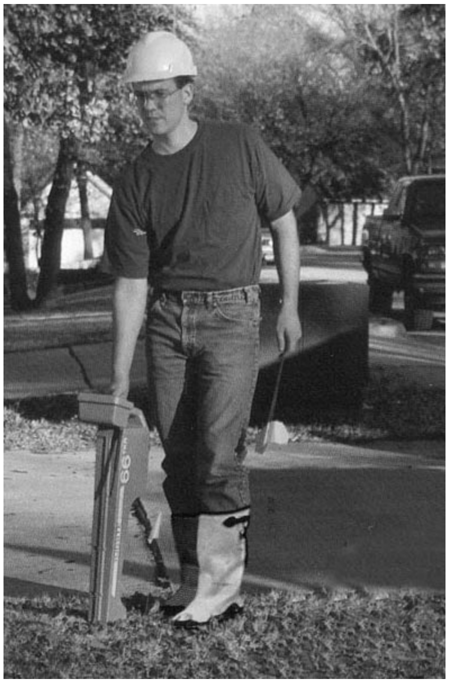


Figure 11.28: Detection from ground level

Special applications, like installation of drains, need special steering methods. The system showed below of Mector Magnetics is an example.

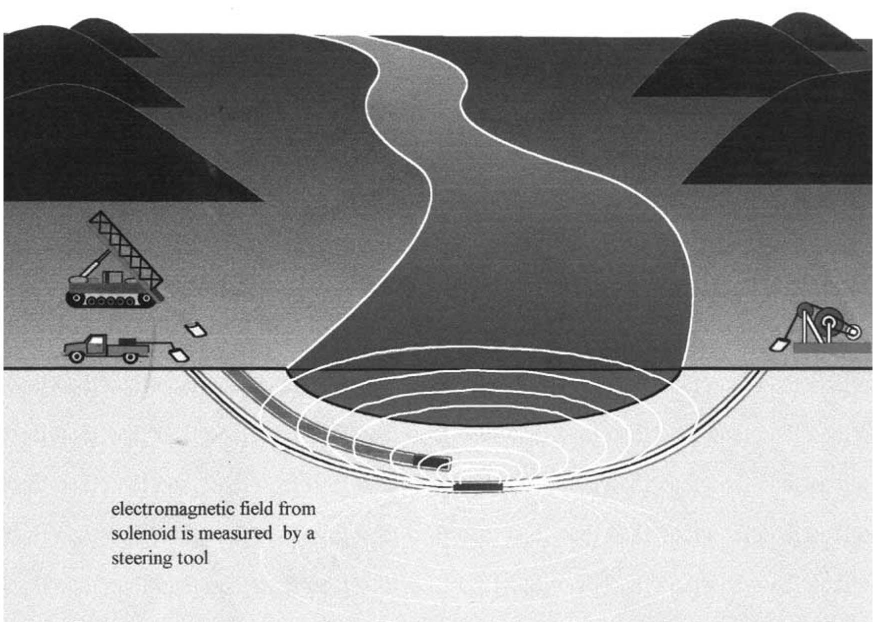


Figure 11.29: Navigation with existing pipelines

11.11.9 Use under Dutch circumstances

At first this technique was used especially for the installation of gas pipelines under rivers, streams, and long crossing. Initially maxi rigs were often used with American prescriptions and experiences. Drill fluid outbreaks and large deviations (up to 1% of the pre-determined length) often appeared. With the increasing Dutch requirements regarding steering techniques, calculation technique prescriptions were developed. A reference is made to “Richtlijn Boortechnieken”. For the specific requirements of drill fluid pressures and installation depths a reference is made to the article of ir. H.J.A.M. Hergarden. This article is a part of the PAO lecture 1996 “*Waarom en hoe bouwen we ondergronds*” pages 10-17.

11.12 Geotechnical aspects

The importance of a good geotechnical investigation has been mentioned in previous paragraphs. The type of soil and the ground conditions found at a site will help determine the preferred drilling machine for the job. As the complexity of the job increases, lack of knowledge regarding soil conditions can create delays and become costly.

In practice it often happens that the available geotechnical research does not fit with the chosen technique, or worse when there is no information at all.

It is essential for all geotechnical research undertaken that the soil is investigated to a sufficient depth and the screen of investigation is sufficiently tight. Along with soil borings (preferably with non-stirred soil samples), laboratory research to composition, grading, c-values, and soundings, it is often necessary to have geotechnical and / or historical reports available.

With trenchless technology in general, the following questions are asked:

Microtunneling:
- At which depth is it possible to have good dimensioning and stable positioning?
- What can be said about the friction of the pipe wall?
- Which is the best technique, a Slurry shield or an EPB shield?
- Are special restrictions necessary with regard to drill fluid?
- Is the soil polluted?

Horizontal Directional Drilling:
- Which soil layers are best suitable to drill through?
- What is the composition of the drill fluid?
- What are the required drill fluid pressures and what is the maximum permitted slurry pressure on the surrounding soil?
- Is there water tension beneath sealing layers?

Starting and receiving shafts:
- These shafts have to be dry to execute microtunnelling and reparation works. The question whether there are sealing layers in the bottom, which can be used to create a dry shaft without long lasting de-watering, is extremely important. Another aspect that deserves attention is the question whether temporary constructions such as sheet-pile walls can be removed, concerning the eventual (salt) oozing through the created holes.

11.13 Economical aspects

The following aspects are important:

- Direct cost of the project (preparation, design and execution)
- Social costs because of hindrance towards the environment
- Building speed

The direct costs of trenchless technology are often higher than the costs of an execution using the classic open building pit method. In many cases an objective estimation of the social costs and building speed will be in favor of the trenchless technology. Therefore it is important that all cost factors (direct, social, environmental) are taken into account in order to make the best choice.

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