14th European Conference on Soils Mechanics and Geotechnical Engineering

Geo-engineering in the Netherlands and Belgium

The GeoQ ground risk management process

Foundation Options for LNG-Tanks

Different applications for soil nailing in soft soils

Existing structures govern building methods near Rotterdam Central Station

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Spain and the Netherlands have a common history that dates back from more than 400 years ago. And although that common history consists of 80 years of war, for the Netherlands the end of the war has been the start of a very prosperous period named ‘Golden Age’. The city of Amsterdam was growing fast in that period, and in many cities the economic growth was expressed by building beautiful houses in well-developed areas, very often in combination with the digging of new canals.

The cultural heritage of that period has to be preserved, and this is an enormous task. Most of the buildings have been founded on wooden piles, and are vulnerable to influences by activities that could not be imagined by anyone in former times. The traffic has changed from horses to a lot of horse power, and as a result the mobility of the ever growing population has stagnated. To relieve the pressure on the narrow streets, underground parking facilities for private transport and tunnels for public transport were constructed at the border of and in the densely built urban areas.

Spain has experienced an exceptional change in social, economic and political areas for many years now. These changes have brought a high development in infrastructure. Parallel to these developments, this period has seen a worldwide change of views with an increasing sensitivity to the interaction with the environment. The main topic selected for the 14th European Conference ‘Geotechnical Engineering in Urban Environments’ by the Spanish Society reflects that sensitivity, and is also appropriate for the present situation in many Dutch cities.

Since the 16th International Conference in Osaka the Netherlands have made the step to the boring of tunnels in urban areas:
- Two bored tubes for the Hubertustunnel in The Hague for road traffic have been successfully completed;
- One of two bored single-track tunnel tubes in the urban area of Rotterdam for the realisation of a light-rail connection for RandstadRail has been completed this year;
- The construction of a bored tunnel underneath the old inner city of Amsterdam for the North-South subway line will follow soon.

Is it a coincidence that the venue of the Conference, the Palacio de Congresos de Madrid is situated next to the Estadio Santiago Bernabéu? In that stadium a Dutch football player cooperated with the Madrilènes to become the national champions in 2007. Madrid hosts another great friend of the Netherlands, although he will be difficult to find: St Nicholas. Every year, on the 5th of December the Netherlands celebrates the feast of St Nicholas on which presents are exchanged. The story tells that the presents come from Spain, brought along by St Nicholas in November.

Since 1997 the periodical Geotechniek issued by Educom appears quarterly in the Dutch language. It is only in exceptional cases that Geotechniek appears in English. This special edition is a tribute to the cooperation between Spain and the Netherlands that exists nowadays. The Dutch geotechnical industry facilitated this edition and presents a number of innovative and interesting on-going projects.

Ir. G. Hannink
Chairman of the Editorial Board of Geotechniek

R.P.H. Diederiks
Publisher
Geo-engineering in the Netherlands and Belgium

Peter van den Berg, Geerhard Hannink and Koenraad Thooft
Editors Geotechniek

Delta areas

More than half the world’s population live in low-lying areas near the coast, and almost 80% of the major urban areas are located in delta regions. Deltas have always held a great attraction for man, partly because of the fertile soil, but also because of the possibilities they present for trade and transport. As in ancient times, life in a delta area calls for extra attention to safety. At the same time, consideration must also be given to the quality of the living environment.

Alongside the risk of flooding, a number of other problems also face delta inhabitants. The Dutch and Belgium delta, for example, was created by alluvial sand deposits from the sea and clay from large rivers after annual flooding. Peat packets formed in the intervening periods, on top of which yet more clay and sand were deposited at a later date. The result is an underground patchwork quilt of soft and less soft layers with an (extremely) high groundwater level, where (rail) road foundations deform, where cities are built on piles, where underground construction presents a major challenge, and where contamination can spread in an unpredictable way. Parking garages, cellars and other underground facilities must be watertight constructions, designed to keep out groundwater. To prevent damage to buildings, (rail) roads and sewerage systems, measures such as under-piling are required, or the soft peat soil must be excavated and replaced with firmer sand.

Similar problems face all those living in delta areas throughout the world. Floods caused by rivers and the sea occur in numerous places each year and, if no further steps are taken, the frequency will undoubtedly increase as a result of climate change. Sea level rises combined with land subsidence urgently demand our attention. Climate change can also result in more rainfall, which when combined with an increase in the amount of hardened surfaces (roofs, roads, parking place), must be carried away more quickly. But more and more people also want to live and work in a way that has a qualitatively higher value. As a result, the demand for mobility is certain to increase in coming years. New residential areas, smoother roads, faster metro connections, and a cleaner environment all have a direct relationship with the subsoil. This is also generally true for constructions in existing urban areas, both above and below ground.

Importance of geo-engineering

The field of geo-engineering is not yet a century old, and although much has been achieved in this relatively short period, the uncertainties involved in this extremely practically-oriented subject are still greater than 50%. These uncertainties are covered in practise by high safety factors. Partly because of the unusual foundation (‘soft soil’), this therefore represents an important cost component in the realisation of construction projects, specifically those concerned with soil, road and hydraulic construction.

Despite using high safety factors, failure costs are high; these are mostly related to uncertainties associated with the subsoil. The challenge is to ensure that uncertainty margins also become clearer outside the geo-engineering field, to develop tools that will deal more effectively with these uncertainties; to develop new materials that will improve soil properties; and to guide development of the field that will systematically reduce the uncertainty margins from a financial and social perspective. To substantially reduce the knowledge gaps and uncertainties that are currently still representative of the geo-engineering field, three spearheads of research can be distinguished.

Data-driven model development

In the first place, an important step can be made by continuing theoretical and numerical model development and to bring this into direct interaction with field experience and experimental research. For data-driven model development accessible databases containing structured relevant data are a first prerequisite. In this respect, artificial intelligence can play a supportive role. This will ensure that the predictive power of models will increase considerably. Inverse modelling is an important component of this. The possibilities currently offered by ICT can fulfil an important role. Re-
results from measurements and experience can be introduced in a joint learning- and work-environment, where numerical models also have a place. This integrated environment is not only relevant for the development of knowledge, but can also play an important role in education.

Risk management
A second important line is risk management, aiming to reduce uncertainties about the structure, behaviour, and use of the subsoil. There are still large uncertainties concerning the behaviour of soft soil (humus-like clay and peat). This is also true for the behaviour of objects, such as dikes and hydraulic structures (particularly in conditions of extremely high and low water), for the management of construction processes in urban areas (including underground construction and foundation engineering), and settlement behaviour of the subsoil (including roads and railways). A dedicated risk-assessment approach is needed in order to reduce risks during each phase in the construction process, for instance to handle obstacles in the subsurface during construction works in urban areas. Current developments in the field of sensor technology (monitoring) make it possible to closely watch behaviour while a project is being carried out and during its lifetime. By placing this information online, the correct decisions can be taken at the right time and mitigating measures initiated where necessary (the ‘observational method’).

The use of knowledge from geophysics plays an important role in this. This is not only true for the behaviour of objects, but also to gain better understanding of the heterogeneous structure of the subsoil.

Soil as a construction material
A third line is the in-situ modification of soil. Developments in the field of biotechnology, among others, provide understanding about a fundamentally different approach to the subsoil in relation to construction. In the past, the properties of soil were seen as constant. It has only recently become clear however, that it is possible to actively guide natural processes in the subsoil, and thereby the physical and mechanical properties of the soil. For instance, modifying the strength or permeability of the soil (for example, dredged soil) so that it can be used as a construction material. This also includes the development of specific grouts and slurries. Alongside knowledge in the fields of geohydrology, biotechnology, and geochemistry, fundamental knowledge about micro- and nano-structures in the soil plays an important role (pore space engineering). Many uncertainties also still remain regarding the use of ‘non-improved’ soil as a construction material, which still regularly results in over-sizing or unexpec-
ted failures.

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Table 1 Presented papers at the 14th ECSMGE in Madrid, and in this special edition ("published in this special")

**Recent research**
For an overview of the research carried out in those fields, during the last, say, four years, reference is made to the set of Dutch and Belgium papers, published in the proceedings of the 14th ECSMGE Conference in Madrid (see table 1).
**The GeoQ ground risk management process**

**M.Th. van Staveren**
GeoDelft

**Abstract**

How could we live without ground: any construction needs a foundation. Incorporating engineering and maintenance activities, construction provides us with houses, schools, hospitals, industrial plants and infrastructure. Unfortunately, the ground is a major driver of risk in many construction projects, as reflected in the relatively high failure costs. The GeoQ risk management process aims at a structural way of handling with these risks.

**Introduction**

There is no construction without ground. Any construction, whether very small or extremely large, needs a foundation and so has some form of connection with the inherently uncertain ground. Our ability to cope with this uncertainty will make a difference between our foundation settling or not, between excess groundwater in our basements or not, or even whether our structures collapse during an earthquake, or not.

Until now, the ground has been a major driver of risk in many construction projects all over the world. This is reflected in the relatively high failure costs and often small profit margins in the construction industry. Many projects are completed at a higher cost than estimated, as well as much later than scheduled. This causes serious additional expenditure for clients, reduced profitability or even losses for contractors and a lot of irritation for the public. For many years, risk management has added value in a lot of sectors and industries, such as the financial sector, the chemical industry, and the offshore industry. In construction, however, risk management has not been entirely incorporated and exploited, in spite of the inherent uncertainties and high risks. The application of well-structured risk management, during all project stages from feasibility through to construction and maintenance, needs to be started or extended to many more projects. This situation is particularly apparent in ground-related engineering and construction activities. A serious obstruction to the introduction and application of risk management is the people factor. Together, we are that people factor. Typical human attitudes and behaviour, driven by unawareness and fear, often prevents us to consider risk in a timely and effective way. As a result, we will miss opportunities to optimise projects and benefits for our organisations, our clients and our societies as a whole remain hidden and untouched.

**GeoQ**

We present GeoQ, where Q stands for quality, as a vehicle to meet two objectives. The first is to contribute to the application of cost-effective ground risk management in order to reduce failure costs and improve profitability. Besides this, ground-related innovations in engineering and construction are urgently required to gain competitive advantage. The secondary objective is therefore that adequate ground risk management should act as a sort of airbag against the inherent business risks of innovations.

GeoQ is an easy-to-use and flexible framework for ground risk management during the entire life cycle of all types of construction projects. It is independent of the type of ground conditions expected and can reveal many hidden and ground-related opportunities, such as cost savings, tighter schedules, improved project quality and increased profitability for a lot of stakeholders. Anyone can make GeoQ fit for purpose, to meet the specific requirements of any small or large construction project, anywhere in the world.

![Figure 1: The six cyclic steps from project phase N to project phase N+1 (after Van Staveren 2006)](image)
**The GeoQ ground risk management process**

Applying GeoQ on a construction project starts with dividing the project in appropriate phases – generally the 'normal' project management phases. In each of the project phases we apply six generic GeoQ steps, depicted in figure 1, starting with collecting the available information, including in particular the risk portfolio of the former project phase, and ending with the transfer of the risk portfolio to the next phase.

For each step many tools have been developed by different competent parties and we are not aiming at developing just more of these tools. Instead, we focus on designing a process of risk management rather than tool development.

Within a project phase we discern six different GeoQ risk management steps. The steps as tabulated are fixed and should be applied one by one in a structured way. On the other hand, the GeoQ risk management phases are much more flexible. Normally we discern six phases: the feasibility phase, the pre-design phase, the design phase, the contracting phase, the construction phase and the operation and maintenance phase (figure 2). The position of the contracting phase depends on the type of construction contract. Contracting will occur just before construction in case of conventional contracts. For design and construct type of contracts, the contracting phase is before the design phase or even before the pre-design phase. For very large or rather small projects the number of project phases can be extended or combined. This does not effect the GeoQ process, as long as the six steps within each project phase are strictly performed.

Existing ground risk management tools can be applied at will within the framework of the GeoQ process. Examples are site classification and scenario analysis in the feasibility phase, team-based risk identification and classification in the pre-design phase, and risk-driven site investigations in the design phase, as well as tools as Fault Tree Analysis (FTA) and Failure Mode Effect and Criticality Analysis (FMECA). In the phase of contracting, contractual allocation of the risk of differing ground conditions by the Geotechnical Baseline Report (GBR) is recommended. During the construction phase application of the observational method, supported by online monitoring, can be fit into the GeoQ framework. Also for the operation and maintenance phase appropriate tools for ground-related risk management are ready available.

Many tools have their proven benefits well beyond ground-related risk management. An example where the people factor is used advantageously, is team-based risk identification and classification, by support of information and communication technology. Figure 3 shows a typical setting, in which a team of professionals, either mono-disciplinary or multi-disciplinary, participate in a risk management session in a so-called electronic board room (EBR). The laptop computers and easy to use risk management software allows them to brainstorm anonymously on risk identification and classification. These individual professionals can build forward on the results of their team members, while unfavorable team effects are limited because their input remains unidentified by team members. From a people point of view, we consider education in risk management as a crucial factor. We are happy that since 2007 GeoQ forms part of the standard curriculum in geotechnical engineering at the Delft University of Technology in The Netherlands.

**Literature**

SmartSoils® - Soils on Demand

M. Blauw
GeoDelft

Abstract

Soil has always been a very important building material, but it was never possible to change it the way it was desired. GeoDelft has developed a new concept “soils on demand”, with the name SmartSoils®. SmartSoils® has developed innovative techniques to change soil properties on a natural way in-situ. The aim of SmartSoils® is to engineer macro parameters based on micro reactions. The techniques include BioGrout, reinforcement of ground; BioSealing, blocking the ground; and BioSlurry, reuse of waste-materials.

Introduction

Soil has always been a very important building material, but it has been assumed that the soil “as a building material” is always there and that its quality cannot be provided to order, in contrast with other building materials such as wood, steel or concrete. Since a few years the idea has risen that soil can be engineered. GeoDelft has introduced the concept of ‘soils on demand’, with the name SmartSoils®. This concept has been derived from biotechnology, where bacteria are used to clean the polluted soils in-situ. GeoDelft has developed techniques that are as natural as possible to influence the physical, chemical and biological properties of the ground in-situ. By using bacteria the strength, rigidity and permeability of the soil can be influenced. All these techniques are characterized by the fact that they work at the level of the soil pores, therefore this is called pore-space engineering, meaning that the desired properties are achieved by bringing changes on the pore-level (nanotechnology). The first techniques have been demonstrated in the laboratory and in pilot-scale studies.

BioGrout

BioGrout is an in-situ cementation process to strengthen the soil using calcium carbonate or silicate crystals, depending on the type of soil.

Sand-soil

To strengthen sand-soils microbial induced calcite precipitation (MICP) is used. For this process a lab-culture of soil-bacteria is injected into the ground together with a solution of urea and calcium. These bacteria convert urea into carbonate, which will precipitate with the calcium forming calcite. The calcite crystals precipitate on the sand grains and will form “bridges” between the grains causing cementation (figure 1), and thus the increase in strength and stiffness. The strength of calcite-precipitated sand is adjustable between 250 kPa and 30 MPa, without causing a decrease in the porosity. The remaining of porosity is one of the main advantages of BioGrout. Another advantage of BioGrout is a side effect where heavy metals are immobilized. At the moment BioGrout has been applied on several types of sand in the laboratory. Upscaling experiments and pilot-cases are being set up.

Peat

In many parts (especially the densely populated part) of the Netherlands, the subsoil is peat. This gives many construction problems, caused by a high rate of subsidence of the peat. By being able to increase the strength of peat settling-problems will be less. First experiments to increase the strength and stiffness of peat by precipitation of silicate crystals, this is through geopolymerization and biological crystallization, were successful (figure 2).

BioSealing

BioSealing is a natural method that enables soil permeability to be influenced on site. Leaks in water retaining structures are easily and efficiently sealed. In addition, natural water-retaining layers like peat and clay layers can be sealed. Compared with traditional repair methods, BioSealing does not require injection at the exact location of the leak but the injection has to be situated in the area where the groundwater flow is directed towards the leak. The main application areas for BioSealing are excavations, tunnels, wells and (salty) seepage and leaking of dams.

To initiate the BioSealing process, nutrolase will be injected into the ground that is transported to the leak with the groundwater flow. The nutrolase mainly stimulates the microbial activity in the soil at the leak. This is because at the leak the flow is the highest, causing a continuous replacement of nutrients, thus a higher concentration of nutrients. This results in the formation of bioslime and mineral deposition in the leak, so blocking the soil particles.
BioSealing has been proved successful on lab-scale as well as in the field, where in a period of 4-6 weeks, the flow of groundwater decreased with a factor 5-20. In 2005, it was used for the first time on practical scale to salty seepage near the HSL-aqueduct Haarlemmermeer in the High Speed Railway Amsterdam-Paris (figure 3). Because of the fragile and complex ecosystem at the Haarlemmermeer polder, only BioSealing was the feasible solution, due to the environmentally-friendly principle. Further practical developments will be executed in co-operation with different international parties, while further scientific research is planned by the Delft University of Technology and the University of Utrecht.

**BioSlurry**

There is an increasing demand for soil-like construction material. Many residual materials from the soil, hydraulics and road sector that have been traditionally regarded as waste, are ideally suited for recycling as building materials. GeoDelft has developed techniques to convert residual materials into building materials. To reuse a waste material, they must comply with environmental hygiene and meet construction requirements. With BioSlurry, it is possible to adjust the properties of sludge that it becomes a useful building material. An interesting application was tested recently in a pilot-experiment: the Dredge Sludge Mattress (figure 4). By adding fibers, binding agents, foam and a hardener to the sludge, it is possible to create a sustainable, strong, permeable and lightweight building material. This makes it an ideal material for use under roads and railways. Since the main part of the Netherlands has a weak underground, it is important to have lightweight construction material. The Sludge Mattress is lighter than sand, therefore reduces settings by a quarter. The Dredge Sludge Mattress is also designed to clean up polluted sludge. To the sludge, straws are added making it porous. The rainwater filtering through ensures that in a few years the pollution will be carried off and stored in an ecological zone next to the road. BioSlurry can also be used to reinforce water-retaining constructions, nearby sludge-rich areas.

**Conclusion**

The three methods described above are innovative SmartSoils® concepts. They provide solutions for the construction field and yet are environmentally friendly. GeoDelft is still investing in development of other innovative methods for the construction sector.
N242 Bridge Abutments on geogrid reinforced soil near the city of Alkmaar in the Netherlands

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Abstract

The capacity of the provincial road N242 and all the junctions lead to huge traffic problems. To solve these problems the contractor Heijmans Infrastructure BV is constructing two fly-overs including four bridge abutments on geogrid reinforced soil. Designs are in accordance with BS 8006. Varying with the type of fly-over and the bridge abutment there are 7 to 9 layers of geogrid reinforced soil under every bridge foundation. After finishing the reinforced soil is covered with soil for protection. The settlement of the reinforced soil construction after constructing the concrete foundation and placing the bridge deck was less than 10 mm.

Introduction

The provincial road N242 has a crucial role in the attainability and development of the region Heerhugowaard, Alkmaar, Langedijk and Schermer. At this time the limited capacity of the road and all the junctions lead to huge traffic problems. To solve these problems the contractor Heijmans Infrastructure BV is constructing the next items:

• All the driving lanes of the N242 will be separated;
• Three junctions of roads with the N242 will be combined into one fly-over;
• Two junctions at the same level will be fly-overs;
• Separate bicycle roads and tunnels for bicycles;
• A separate bus lane from Alkmaar to Heerhugowaard for public transportation.

In this project fly-overs KW B and KW O will be constructed including four bridge abutments on geogrid reinforced soil.

Calculations

Figure 1 shows the principle cross-section of the construction with geogrid reinforced soil. Figure 3 shows a more detailed drawing as the result of the calculations. The geogrid reinforced soil structure is built in 0.5 m compacted fill layers reinforced with Fortrac® geogrids. The fill material is sand and at the front facing granular material (0/40) to get better compaction. The construction is built with a gradient 2:1 in order to optimise the Fortrac® geogrids in strength and length. Later the construction is covered with soil at the front so it can be protected against UV-radiation and vandalism.

Designs are in accordance with BS 8006. In figure 2 a graphic presentation of the overall stability is given. Different cross-sections were calculated with different heights and loads in order to optimise the geogrid strengths. Geogrids used are Fortrac R 300/30-30 MP, Fortrac R 150/30-30 MP and Fortrac R 110/25-20/30 MP. Fortrac M (made of PVA yarns) is used because of the high tensile stiffness in combination with the high chemical resistance and very low creep. The high chemical resistance is important since the geogrids may come in contact...
with the concrete of the bridge foundation, which may imply an environment with pH > 10. Varying with the type of fly-over and the bridge abutment there are 7 to 9 layers of geogrid reinforced soil under every bridge foundation.

**Construction of the geogrid reinforced bridge abutment**

For this project the contractor Heijmans produced a formwork allowing every layer to be built in one operation. After constructing the layer the formwork was pulled away with a crane and placed on the finished layer. Figures 4 and 5 show the construction method. Every layer was compacted to a minimum proctor density of 98 %. At the front side the layer of 0.5 m is compacted in 2 runs of 0.25 m with a plate vibrator. The sand layer behind is compacted in one operation with a heavy roller compactor. When necessary water was added to get optimal compaction. The compaction was measured every 1 or 2 layers with a nuclear device on 3 different places. Figures 6 and 7 show the activities. Every 3 layers the height is checked so that if necessary the height can be compensated in the next fill layer.

The Fortrac geogrids are placed with an overlapping of 0.20 m. For each bridge abutment and fill layer an installation plan was made. With this plan everybody on the job site could see which geogrid was needed in length and strength. Figure 8 gives a corner view from the top of the reinforced bridge abutment after fi-
Figure 9 shows the reinforced bridge abutment from the side after finishing.

**Reinforced soil KW O eastside**

At the eastside of fly-over KW O a small waterway for recreation was foreseen at the foot of the bridge abutment. It was anticipated to be built with wooden sheet piles but due to the new location it had to be built with steel sheet piles and anchors. By making 3 extra reinforced fill layers just behind the sheet pile construction the wooden sheet piles were made possible again. These extra layers also carry the soil above eliminating ground pressure on the wooden sheet piles (see figure 10). Figure 11 shows the 3rd fill layer just behind the wooden sheet piles.

**Fly-over KW B**

After finishing the reinforced soil is covered with soil for protection. The concrete construction of the foundation was built and settlements were measured. Figure 12 shows the bridge foundation after construction. The final slope was made with stabilised sand and stones. After that the bridge deck was placed (see figure 13). The settlement of the reinforced soil construction after constructing the concrete foundation and placing the bridge deck was less than 10 mm.
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Quality is the foundation
Terracon: an expert and resolute partner in foundations

R.A. Schiphouwer, S. Doornbos, Terracon

ABSTRACT
Terracon is an expert in the field of special foundations, and has extensive know-how and modern equipment to its disposal. Priority is given to quality and security. Terracon has a quality system according to ISO 9001 and has a policy plan for better working conditions. Terracon operates throughout the Benelux. Germany, France, Great Britain and Scandinavia are part of its field of operation. Terracon has developed pile systems like Terracombi piles, a method to counteract the negative skin friction along the pile shaft, and Terrason piles, a vibration free installed, prefabricated concrete pile. Terracon is able to offer a great number of foundation systems.

INTRODUCTION
A company which specializes in foundation techniques is naturally expected to have both feet firmly on the ground. But also to keep an open mind to the most advanced techniques. Terracon is fully aware of that and combines the best of both. The extensive know-how, the personal effort, the problem-solving capacity and the modern equipment make Terracon an expert in the field of special foundations.

Priority has been given to quality and security. Terracon has a quality system according to ISO 9001 and also has a policy plan for better working conditions. Terracon is one of the first companies in the Netherlands who became National Authorised Foundation company ("L.E.F."). Thanks to its favourable geographic location Terracon operates energetically and efficiently throughout the Benelux, while for instance Germany (from our Branch office in Werder OT Plötzin), France, Great Britain and Scandinavia (from our Terracon International subsidiary) are also part of its field of operation.

Terracombi piles
Terracon has developed a method to counteract (if applicable) the negative skin friction along the pile shaft with an efficiency of approximately 90%.
The Terracombi pile consists of a prefab prestressed concrete core which is surrounded with grout in the layers where positive skin friction is expected (photo 1). In those layers where negative skin friction occurs, the pile shaft is covered with bentonite. By this method an economic solution is possible because a high net bearing capacity will be obtained.

Vibro piles
The Vibro pile is a cast in situ driven pile which is mainly in the heavier sizes compatible with the prefab concrete pile. If a client cannot wait for production of prefab piles, Vibro piles can offer a solution. Furthermore there is no chance for damaging the piles during driving if heavier earth layers have to be penetrated. In those cases where pile point levels vary strongly the cast in situ pile provides an excellent solution.

Terracon owns technically advanced equipment, like hydraulic IHC S70 type hammers which are friendly for the environment as they produce no exhaust and less noise. The whole pile driving process is monitored by computer and printer.

Geotechniek ECSMGE
Terrason piles
Terracon has developed a vibration free installed, prefabricated concrete pile (photo 2). The prefab pre-stressed concrete cores are surrounded by grout in the layers which offer positive skin friction. By using a high grade concrete for the prefab shaft and combining this with a grout cover under high pressure a system can be offered which has a high quality and is attractive for the environment.

Bored piles
Terracon applies drill tables, which have a high torque (photo 3). Even if high soil resistances have to be passed, the high torque combined with a vertical pressure on the casing (pull-down) cause a minimum amount of soil transport. Terracon’s bored piles are full soil displacing and vibration free.

Traction piles
Terracon specialized itself in the installation of traction piles with a high bearing capacity (photo 4). These piles are applied for example for foundations for overhead transmission lines, quay walls, docks, basements, windmill foundations etc. The piles are steel tubes or H-beams which are surrounded with grout during the driving or drilling procedure. Bearing capacities are granted from 500 kN up to 2,500 kN. Pile diameters up to Ø 2,200 mm have been installed.

Double drilling
Terracon offers the double drilling method for example for secant pile walls (photo 5). Two drill tables have been placed above each other; the lower drives a temporary casing, the upper turns a continuous auger which empties the casing and fills the casing at the same time with a cement bentonite mix or concrete. After the casing has been removed steel beams or reinforcement cages are inserted.

Terracon is also able to offer you:
• Diaphragm walls
• Slurry walls
• Secant pile walls
• Complete building pits, if needed with anchoring
• Jet grouting
• Piling in limited headroom and space
• Micro piles
• Freezing of soils and soil injections
• Pile load tests (photo 8)

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Information
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Introduction
LNG (Liquefied Natural Gas) is natural gas that for storage has been turned into a liquid. When natural gas is cooled to minus 162 degrees Celsius it condenses and its volume is reduced ca. 600 times. This makes it easier to transport over long distances by ship and to store it in large quantities. Thereafter, the fluid is processed in a gasification plant to the gas phase and is distributed to consumers. An LNG terminal generally includes a jetty with mooring and unloading facilities (figure 1). LNG storage tanks, the liquidising/gasification unit and other facilities necessary to feed the natural gas efficiently into the gas grid.

LNG is stored at atmospheric pressure in special, low temperature cryogenic tanks. LNG storage tanks have double containers, where the inner contains LNG and the outer container contains insulation materials. The inner tank is made of high nickel steel alloy suitable for low temperatures. The outer tank is made of pre-stressed concrete as well as the roof. Tanks can be constructed in ground or above ground. The most common tank type is the full containment tank. Tanks are roughly 25 to 50 m high and 80 m in diameter.

Typical Geotechnical Aspects
Basic characteristic design issues are a relatively large foundation load and restricted differential settlement criteria. Secondary issues are load variation during time, groundwater level and construction schedule requirements. LNG storage plants are located in coastal areas. Soil conditions are most likely to be marine and alluvial deposits to great depth. The groundwater level is close to ground level.

Common foundation loads are 70 to 140 kPa for the empty tank, 200 to 400 kPa for the operating conditions filled with product and 250 to 500 kPa during hydro testing. The high foundation pressure applicable to the full tank area results in a stress increase to great depth, up to 120 m (1 to 1.5 times the width of the tanks). Therefore settlement of clay and sand deposits are of great importance. Moreover, the rigidity of the concrete tanks demands relative strict (differential) settlement requirements.

Structures on sandy soil prone to water saturation may be subject to liquefaction, i.e. water-saturated soil behaves as a fluid rather than as a solid. Driving force for liquefaction can be earthquakes or (tidal) waves. An analysis of the expected earthquake intensity and wave impact should therefore be part of the investigation.

Geological information of the project site is important in relation to the presence of over-consolidated soils.

Foundation options
In general there are two commonly applicable foundation types: above ground and in ground foundations.

Above ground level
Above ground tank foundations require extensive settlement analyses and/or construction techniques that reduce the settlement amplitude (figure 2). Several options are available:
- Preloading with a preload up to permanent load
- Ground improvement
- Pile foundation or piled raft foundation

A combination of options can be selected. Selection of options is dominated by local soil conditions, schedule requirements and cost.

Abstract
LNG tanks are very specific structures with high loads and severe requirements on allowable soil deformations below the foundation. In general there are two commonly applicable foundation types: above ground and in ground foundations. Above ground tank foundations require extensive settlement analyses. The basic idea of in ground tank foundations is reduction of the foundation load. For this type of foundation the construction method below ground level is a key factor. Soil investigation should basically consist of Cone Penetration Tests (CPT’s) and boreholes up to the depth of influence of the foundation.
Below ground level
The basic idea of in ground tank foundations is, from a geotechnical point of view, reduction of the foundation load. Also this option may be chosen for environmental, operational or economical reasons. For this type of foundation the construction method below ground level is a key factor. Construction of the tank in a dry excavation under high groundwater conditions require temporary or permanently lowering of the groundwater table, under water concrete or caisson like foundations. As required excavation depth increases temporary and permanently closing off groundwater may become not feasible.

Partially below ground level
Reduction of foundation load can also be met with a foundation partially below ground level. On application of a partial buried foundation an optimum construction method can be selected. Often, disadvantages for both an above ground as well as in ground foundation can be avoided. Therefore a partial in ground foundation is to be included in preliminary design studies.

Eventually, the ultimate favourable condition regarding settlement reduction is a floating tank. From structural point of view this is not so strange as it may sound. Construction in a dock, similar to submerged tunnels, and floating to the final destination may be feasible.

Soil investigation
Soil investigation for LNG storage tanks should basically consist of Cone Penetration Tests (CPT’s) and boreholes up to the depth of influence of the foundation.

The CPT’s performed with cone resistance and sleeve friction measurement provide a good identification of the soil by means of the friction ratio. CPT’s with measurement of the pore water pressure are recommended for more accurate identification of compressible clay/peat layers and geohydrological conditions.

CPT’s with sleeve friction measurement equipped with geo-phones (seismic cone) are carried out to determine the dynamic properties of the underlying soils/rock to be used for earthquake analysis.

Geotechnical boreholes with field classification and laboratory test of (un)disturbed samples will provide information in addition to and to support the CPT results. Circumstances and possibilities for execution of geotechnical soil investigation may vary depending on the location (see figure 3). It is very important to use the adequate drilling and sampling technique in order to obtain high quality samples. The additional cost of such techniques is largely compensated on the cost savings on the foundation design.

Oedometer tests with unload-reload steps are essential to determine the (isotachen) compressibility parameters, the preconsolidation stress and the Over Consolidation Ratio (OCR).

Conclusion
LNG tanks are very specific structures with high loads and severe requirements on allowable soil deformations below the foundation. Therefore various foundation options, also deep foundation levels below surface should be considered. A tailor made soil investigation should support the decision-making of the foundation type and provide all relevant data for the foundation design.
Design and validation of jet grouting for the Amsterdam Central Station

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ABSTRACT

Beneath the Amsterdam Central Station is an excavation created within so-called ‘sandwich walls’ to be able to immerse a tunnel. The sandwich wall is a composite wall consisting of two rows of steel piles with a body of jet grout columns in between. In order to establish whether the requirements could be achieved a number of trials were carried out in advance of the main jet grouting to ensure that risk of gaps in the wall or inadequate strength were avoided. Significant advances have been made in improving the quality control of the jet grout process. The use of column callipers, hydrophones and spoil density measurements gave confidence to the actual diameter of jet grout column produced.

INTRODUCTION

Beneath the Amsterdam Central Station is an excavation created of the North/South Line, within a tunnel is immersed. This is characterised by the application of a particular technology in the form of, inter alia, the so-called ‘sandwich wall’. This is a composite wall consisting of two rows of steel piles with a body of jet grout columns in between. This wall acts both as an excavation support wall and also provides vertical bearing. The installation of the wall, within these specific conditions (limited height, sensitive historical building, train station in service), within the design requirements set in terms of construction tolerance and water and soil retention, may be regarded as being a pioneering achievement. Especially for the jet grouting an integrated design and construction approach, including an extensive monitoring programme was needed.

Work commenced on the sandwich wall in 2003, when the wooden piles were extracted at the locations where the sandwich wall was to be constructed. In 2004, the steel piles for the southern wall sections were installed. From May 2005 to February 2006 for the southern part of both walls jet grouting was carried out (2007/2008 the last northern parts).

This paper is the second part of two papers. The first paper deals with the design and construction philosophy of the work following the observational method (Langhorst et al. 2007). This second paper will describe the validation of the jet grouting. The requirements for the jet grouting may be to achieve the design diameter within limits of ± 20% of the diameter, a positional tolerance within 1% of the design location at any point of each column, a minimum strength of 1.5 MPa. If the above requirements are achieved then the risk of any leakage of water or soil through are minimised and structural capacity is acceptable. In order to establish whether the above requirements could be achieved a number of trials were carried out in advance of the main jet grouting to ensure that risk of gaps in the wall or inadequate strength were avoided. Following completion of the trials, the main production jet grouting commenced in May 2005 with ongoing quality control and validation using a number of techniques that are described below.

JET GROUT DESIGN LAYOUT

The design of the sandwich wall consists of two rows of steel Tubex piles of diameter around 450 mm surrounded by jet grout material. The column layout consists generically of 800-1,000 mm diameter single system columns formed between the Tubex piles and 2,000-2,200 mm diameter double system columns to infill the gaps between the two rows of piles and jet grout perimeter columns. The jet grout columns were jetted full height from a depth of around 29 m (NAP –28 m) to within 1 m of ground level. Figure 1 shows the schematic arrangement of the wall in plan. The two lines of Tubex piles are around 2.5 m apart and spaced at around 1 m centres.

Difficulties associated with the achievement of the design were the achievement of the positional tolerances and also the design diameters. In addition to these problems, a number of relic wooden piles remained within the footprint of the sandwich wall which would also complicate and potentially compromise quality. Because of the historical importance of the Central Station building and the construction programme, it was absolutely vital that the sandwich wall functioned correctly without causing unacceptable movements or distortion to the building. It was therefore considered paramount that the quality of the wall could be validated during the works to provide sufficient confidence for the following excavation.

TRIAL WORKS

The first trial was executed between February and April 2004 and consisted of a total of 6 single and 5 double system columns to investigate the two generic types of column (perimeter and infill) that were to be used on the project.
The columns were jetted to a level of NAP –28 m, approximately 29 m below ground level. The results of the trial suggested that there was some scatter in diameter and that the required strength might be difficult to achieve. The main philosophy of this trial was to carry out the jet grouting with both a pre-cut or pre-washing phase followed by a further jet grout phase. The initial pre-cut phase was to theoretically enlarge the hole to around a diameter of 40 cm and thus allow for improved spoil return and less material to be cut with the follow on jet grout phase. The measurements of diameter by both column callipers and the hydrophones gave some confidence that the required diameter had been achieved but strength was on the low side. Following this trial the design of the sandwich wall was re-evaluated and a lower side. Following this trial the design of the sandwich wall was re-evaluated and a lower design strength resulted. This assisted the jet grout process but ultimately it was decided by the steering group that the most satisfactory solution could be obtained by carrying out a pre-cut with significantly higher energy to actually construct the column diameter with this phase. The jet grout phase was then used to create a high cement content by the injection of a low water cement ratio grout. This methodology has the benefit that lower pump power is required for the pre-cut phase to achieve the high pressures and flows required and that the heavy jet grout grout injected was more liable to displace the lighter pre-cut spoil and give an enhanced strength through displacement rather than mixing. Following this change in methodology it was concluded that a further small scale trial was required to validate the new approach and in May 2005, five further columns were constructed using the higher energy pre-cut with grouts of differing density. The column calliper, spoil density and hydrophones were used again to validate diameters achieved. The results of this trial indicated that the high energy pre-cut was successful but that a lower water cement ratio grout was needed to ensure that the clay material was lifted out of the columns.

**Column Sequence**

Because of the length (around 28 m) of each column and the necessity to pre-cut and then jet grout, it was considered that the column had to be pre-cut in three sections. This was to ensure that the time between the start of pre-cut and the start of jet grout was kept to a sensible limit which would allow the jet grouting to be carried out without the risk of excessive sedimentation or initial grout set. Measurements of diameter were also carried out following pre-cut and this sequence assisted with maintaining free access to the bottom of the column for the calliper device. Because there were a number of differing parameters in use, control of sequence was very important and within some sequences, parameters would be changed depending on soil type or density, see figure 2.

**Column Jetting Parameters**

The jet grout parameters for each type and diameter of column were established from the previous trial works and also updated as the works proceeded. The use of hydrophones and the column callipers allowed a high degree of confidence of the diameter achieved and the reliability of the jetting parameters in use. With the hydrophones it was also possible to adjust the parameters in real time if the feedback from the testing during jetting was unfavourable (this is discussed in more detail below). Figure 3 gives an example of the parameters used for a 1,000 mm single system column.

**Column Diameter Measurement**

One of the most difficult aspects of jet grouting in the past has been the verification of column
diameter as this has often lead to design problems when insufficient diameter has been formed. Three methods have been developed on the Central Station project which is discussed below.

**Column Calliper System**

The contractor provided a hydraulically activated column calliper for use on the project. A schematic illustration of the device is given as figure 4. Considerable work was required, prior to the start of, and during construction to enable a more accurate interpretation of the results. Figure 5 shows a typical result of a diameter measurement. The calliper operates by applying a pressure to a hydraulic cylinder which expands the arms as shown on figure 4. The displaced volume and pressure of the cylinder are measured at the surface. Before an actual measurement is carried out, a calibration of the device is required. This is carried out by extending the arms and measuring the resulting pressure and volume change within the system. On figure 5, curve A is the calibration of diameter against displaced volume and curve B is the calibration of applied pressure against displaced volume. To interpret the actual column measurement the applied pressure is plotted against displaced cylinder volume (curve C). Because the behaviour is slightly different in the ground the device does not follow the calibration line and the final portion of curve C is projected back to curve B. The intersection with curve B then defines the volume at which point the arms touch the sides of the column and then the diameter can be estimated from curve A as shown. A further correction (not shown) is required for the expansion of the hydraulic hoses under pressure but surface calibrations with the arms placed between concrete and clay blocks proved that the measurements are repeatable and accurate. In a final development, digital inclinometers were added to the arms which gave a better clarity in the measurements. It is considered that this device gives good indication of actual column diameter and is an important advance for the jet grouting industry.

**Hydrophone System**

In addition to the use of the column calliper, a hydrophone system was also deployed. Figure 6 shows the schematic diagram of the operation of hydrophones. In operation a number of small diameter holes are drilled around the periphery of the column to be tested. These can be 50-75 mm in diameter. During the jet grouting process, microphones placed at a depth close to the level of the jet grout nozzle(s) are used to measure the noise resulting from the impact of the jet on the hydrophone tubes. Placing the tubes at differing distances from the centre of the column allows an estimate of the diameter range depending on the response of the system. Furthermore, the hollow Tubex piles were also used to carry out hydrophone measurements during the jet grouting works. Here, the main purpose was to verify that closure between the perimeter column and steel pile was achieved. Figure 7 shows the resulting display used during jet grouting. The amplitude of the

![Figure 3](https://example.com/figure3.png)

**Figure 3** Typical jet grouting parameters 1,000 mm column

![Figure 4](https://example.com/figure4.png)

**Figure 4** Schematic section of column calliper

![Figure 5](https://example.com/figure5.png)

**Figure 5** Diameter measurement plot
waves matches the passage of the jet and thus the diameter can be proved. It is also possible to adjust the jet grouting parameters if the results of the hydrophones are not conclusive thus for example the lift speed can be reduced or increased and the response on the hydrophones noted. It is therefore possible to match the jet grouting parameters to the required diameters more efficiently.

**Spoil Density Measurements**

In addition to the use of the column calliper and the hydrophones, the density of the spoil returns from the borehole was measured at 1 m intervals during pre-cut and jet grouting. In principle this is a very low cost option for diameter measurement as it does not delay the operation and is simple to carry out. At Central Station a number of methods were investigated including hydrometers and mud balances. The interpretation of these was found to be difficult if the highest accuracy was required and finally a sample was measured by filling a 1 litre container and using a digital balance to weigh it. At a later stage a 1 litre container with a close fitting lid was manufactured to give more repeatability of volume. The theory of relating spoil return density to column diameter has been reported in a number of papers (Kauschinger et al. 1992) and (Croce & Flora 2000). Essentially a mass balance approach is adopted to the material within the jet grout body and the excess material ejected from the borehole. Assumptions are made that either the column composition is identical to the spoil ejected or that certain percentages of the original material are retained within the column. Usually for sands the first relationship is used but as larger particles or clay are present then the mass balance approach becomes more complex. Figure 8 shows the results of a measurement by both spoil density and column callipers for a column. Because of the overlap of the column with previously constructed columns, the calculation of spoil density is more complicated as an assessment of the actual column volume being cut is required. For the perimeter columns the areal percentage cut was around 80–85 % whereas for the infill columns this ranged from 40–55 %. This change in column volume has a profound effect on calculation of spoil density or conversely back calculation of areal percentage and predicted diameter is required. However the results can give an indication of column diameter to within 20 %.

**Conclusions**

Significant advances have been made in Amsterdam in improving the quality control of the jet grout process. The use of column callipers, hydrophones and spoil density measurements all give confidence to the actual diameter of jet grout column produced and it is expected that with further development in all three techniques a better accuracy can be obtained. The use of a two stage process of a pre-cut and jet grout phase allows the separation of column diameter creation and column strength. It is considered that this approach will allow the use of higher design strengths in clays than was previously considered.

**References**


Different applications for soil nailing in soft soils

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ABSTRACT

Soil nailing is successfully used in some recently realised projects in soft soils in the Netherlands. In Gouda, new buildings are built with underground parking facilities. Because of the very critical vertical balance of the subsoil during the excavation phase, soil nailing was used to resist uplift of the soil body. In the framework of an innovation project for dikes the installation of soil nails in the inner slope of a dike was investigated in a series of large scale direct shear tests. The research has demonstrated that dike nailing can be regarded as a satisfactory dike strengthening technique. In the city of ‘s-Hertogenbosch soil nailing was applied for the restoration of the medieval city walls.

INTRODUCTION

The technique of soil nailing is used all over the world for reinforcement of steep slopes or walls. Because of the unknown behaviour of soil nailing in soft soils like clay and peat, the method is not commonly used in the Netherlands. As a member of the consortium INSIDE-Squad, Grontmij investigated the behaviour of soil nails in clay. Also Grontmij was responsible for the design of some recently realised projects where soil nailing was successfully used for different applications in soft soils.

Excavation Gouda: soil nailing for uplift resistance

In Gouda, the Netherlands, new buildings are built with underground parking facilities. Grontmij was the geotechnical consultant for the contractor and was responsible for the design of the foundations and the excavation works (figure 1). Because of the very critical vertical balance of the subsoil during the excavation phase, the contribution of the pile foundation in the vertical balance was taken into account. In this way soil nailing was used to resist uplift of the soil body.

Gouda is located in a region with very soft subsoil. Down to 10 m below surface level the soil consists of very soft peat and clay layers with an average undrained shear strength $c_u$ of 9 to 12 kPa. Under these Holocene layers a sand layer is found which is used as the foundation layer for most of the structures. The buildings are founded on prefab concrete piles which are also temporary used as tension piles during the construction of the parking facilities. The vertical effective stress on top of the sand layer after the excavation is 70 kPa. The water pressure on top of the sand layer is 80 kPa so even with a limited excavation depth of 3 m, without preventative measures uplift will occur.

Possible solutions investigated were a wet excavation with an underwater concrete floor or a dewatering system in the sand layer. The first option was found to be too expensive and dewatering was not allowed as it can cause settlements in the soft Holocene layers. Therefore the contribution of the pile foundation on the vertical balance was examined. The principle of this system is that the soft soil is anchored by the piles. An important parameter in the calculation was the adhesion between the soft soil and the pile. As the critical excavation phase is very short, it is likely that the adhesion is dependent on the undrained shear strength. The relation between $c_u$ and adhesion is described by many authors and varies from 0.5 to 1.0. Taken an adhesion of 0.5 $c_u$, the contribution of the piles to the upheave resistance was calculated to be 4%. Together with a staged excavation procedure this was just enough to reach the required safety factor of 1.1.

Research project INSIDE Squad, soil nailing for dike improvement

The densely populated western part of the Netherlands is located several meters under sea and river level. Dikes are needed to protect us against flooding. Adjustment of the dikes is needed because of rising water levels, increasing river run off and ongoing settlements. If raising of the crest is required, the slope stability is best increased by widening the dike. However, sometimes this is not possible, for example in the case of existing buildings on the land side. Within this framework the project INnovations on Stability Improvement enabling Dike Elevations (INSIDE) was started in 2001. The objective of INSIDE is to develop, test and stimulate applications of new and sustainable methods to strengthen dikes that will be safe, space saving and cost effective.
By installing soil nails in the inner slope of the dike, the slope stability can be significantly increased. This is caused by anchorage of the sliding section, shear connection of the sliding section and an increasing contact stress at the shear plane. The contribution of anchorage to increasing the stability factor is most significant. The contribution of shear connection is less but essential for the effect of soil nailing.

The old dikes are commonly constructed with clayey soils. Since the behaviour of soil nailing in clay was not very well known, it was decided to investigate the shear connection in a serie of large scale direct shear tests. Pre and postdiction finite element calculations were made to understand the behaviour and to improve the design model (figure 2). The research has demonstrated that dike nailing can be regarded as a satisfactory dike strengthening technique. Furthermore the project has resulted in the development of a design method and guidelines for the quality control in the execution and user phases.

Restoration of the City walls of ‘s-Hertogenbosch

The city of ‘s-Hertogenbosch initiated the restoration of the medieval city walls. For the repair works innovative techniques were applied such as soil nailing. Grontmij was responsible for the design of the restoration works.

The city wall was built in the Roman’s time and greatly extended in the Middle Ages. From then on the wall was strengthened in every new era. This was carried out using new layers of brickwork, locally buttressed and in later periods by making a supporting embankment behind the wall consisting of sand, clay and a waste material of antropogenic origin. A great deal of the wall showed a serious amount of decay to the foundations and brickwork.

The goal of the restoration was the strengthening of the entire wall without substantial replacement of the existing brickwork with new stones and at the same time to rearrange a durable foundation structure under the wall. The structural assessment of the brickwork with the buttresses showed that a part of the wall could be restored using injection techniques (strengthening) combined with anchoring of the buttresses. This approach was only possible on those sections where the brickwork between two buttresses had sufficient thickness and strength to allow development of the arching mechanism. However a major part of the wall was in such a bad condition that the above mentioned restoration method could not be applied. Instead therefore soil nailing was envisaged to take into account the brickwork’s structural condition (figure 3). The philosophy of this approach was the possibility of developing a self supporting mass of earth behind the wall without a prior need to strengthen the weak unreachable brickwork parts that were mainly under the ground and water levels. The soil nailing results in a decrease of the lateral pressure directly at the “back” of the weak masonry structure. To increase the friction between the nail and the soil, all nails were injected with a cement grout. The chemical content of the injection mixture was such that the pH of the masonry environment will not change.

The chosen innovative approach to the city wall restoration using soil nailing offers a low impact environmentally friendly solution to a challenging engineering problem in an urban area.

References


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Some different applications for soil nailing in soft soils
Existing structures govern building methods near Rotterdam Central Station

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Abstract

Extensive building activities mark the area around the Central Railway Station of Rotterdam, the Netherlands, during the period 2005 - 2012. A number of projects is under construction, others are still in the design stage. The building methods of these projects are governed by the presence of nearby structures. The geotechnical challenges that are encountered during the realisation of the projects are discussed, and the influence of these projects on the densely built environment.

Introduction

The development of six new key projects in and around the high-speed train stations in the Netherlands is in full swing. Work has started at three locations, including Rotterdam Central Station. The investment in the development of the station area will give the economic position of the city a significant boost.

The extensive reconstruction of the area around Rotterdam Central Station requires a great deal of juggling. It means realizing many new constructions in a very confined space, and trams, buses and underground trains must keep to their schedules, passengers and passers-by must be able to go on their way, cars and bicycles must not be held up and taxis must remain visible and accessible.

The project 'Rotterdam Centraal' consists of a number of projects. Some of them are presently under construction, others are still in the design stage (figure 1):

• reconstruction of the Central Railway Station of the city of Rotterdam, including a new large Public Transport Terminal to facilitate passenger transfer between (inter)national trains including the high-speed train to Paris and regional and local public transport like trams, buses and underground trains;
• construction of the new RandstadRail underground line, a high-quality public transport system that will provide connections from the centre of Rotterdam to the towns and cities in northern direction. RandstadRail will be linked to the existing Erasmus underground line at the underground metro station CS;
• construction of the new underground metro station CS that has to be enlarged to provide sufficient passenger transfer capacity;
• construction of an underground parking facility for about 5,000 bicycles;
• doubling of the existing Weenatunnel for road traffic;
• construction of the new underground parking facility Kruisplein;
• construction of a tunnel between the new underground parking facility Kruisplein and the existing underground parking facility Schouwburgplein.

The construction of the new RandstadRail underground line, two single-track shield tunnels with each a length of 2.4 km and an outer diameter of 6.5 m, started in 2004. The first tunnel has been completed in spring 2007. The second tunnel is presently being bored. The reconstruction of the underground metro station CS started in 2005, and the doubling of the existing Weenatunnel in 2006. The other projects are expected to follow soon. All projects are planned to be completed in 2012.

This paper discusses the geotechnical challenges that are encountered during the realisation of the projects that are currently under construction, and the influence of these projects on the densely built environment of Rotterdam Central Station.

Soil and groundwater conditions

The ground level in the area is situated at about NAP (sea level). The phreatic groundwater level is about NAP –2 m. The geotechnical profile of the Rotterdam city area consists of anthropogenic layers (from NAP to about NAP –5 m), and soft Holocene peat and organic clay layers (from about NAP –5 to NAP –17 m). Below this level Pleistocene coarse sand layers are encountered up to 35 to 40 m below NAP. These sand layers are underlain by overconsolidated clay and sand layers called 'Kedichem'. Figure 2 shows the soil profile at the underground metro station CS.

The environment

During the extensive reconstruction of the area the following structures may be influenced (see figure 1):

• Groothandelsgebouw, an office building, opened in 1955. The building is a post-war architectural monument and has been founded in the top of the Pleistocene sand layer on concrete piles with an enlarged tip. The foundation is vulnerable;
• Existing Central Railway Station, built in 1957. Although it will be pulled down, it has to maintain its function during the adjacent reconstruction works of the underground metro station CS;
• Existing underground metro station CS, built in the period 1962-1967. This station has to maintain its function during the reconstruction works;
• Office building Delftse Poort. The tallest office building in the Netherlands opened in 1992, and has been founded on concrete piles into the Pleistocene sand layer. Parts of the temporary supporting structures and ele-
Typical building methods for new underground constructions

The possible building methods comprise of a number of options. Common practice for the soil conditions in Rotterdam is an excavation up to about 8 m deep that is realised by using sheet piles in combination with a dry or a wet excavation. For excavations up to 8 to 12 m deep a combined wall of steel pipe piles and sheet piles is needed together with a dewatering system for a dry excavation. For deeper excavations a diaphragm wall or a prefabricated wall placed in a slurry trench is required.

Dry excavations may be realized by means of dewatering or by using the deep almost impermeable ground layer ‘Kedichem’ as a natural water barrier. This latter method creates an ‘into the ground’ polder. A polder construction ensures that the construction pit can be excavated under dry conditions. The advantage of this method is that the pumping of water out of the construction pit does not affect the groundwater in the vicinity, thus minimising the risk for the structures in the neighbouring areas.

Negative influence on the surroundings may be caused by settlement due to dewatering, and deformations due to the excavation. Another important criterion during the selection of a building method is the expected nuisance for the environment. Especially in inner cities nuisance by vibrations and noise are hardly accepted. Building activities normally make a lot of noise, for example during the driving of foundation piles. These activities also cause vibrations that may be harmful to computers and other hardware in the nearby offices.

The selection of the building method for the projects that are currently under construction will briefly be discussed in this section: the RandstadRail project, the extension of the underground metro station CS and the construction of the new Weenatunnel.

**RandstadRail**

Because of the limited room and the many building activities that take place near the Central Railway Station, both single-track tunnels are bored from the construction site at the St. Franciscus Gasthuis at the north side of the city. This means that unnecessary building traffic in the city is avoided. The tunnel boring machine (TBM) ultimately arrives in the Conradstraat, west of the Central Railway Station, where the end shaft is constructed. Here the TBM is dismantled (figure 3).

The construction of the end shaft is being made with the aid of the “polder construction”. This is realised by constructing the diaphragm walls down to the low permeability clay/peat/loam layers of the Kedichem formation below NAP –35 m.

**Existing Underground Metro Station CS**

The existing tunnel of the “Erasmus” underground line was assembled from prefabricated segments, which were built in dry docks. The tunnel segments were floated to their final destination through a canal. Once arrived on the spot, the segments were immersed onto their permanent foundation which consists of pre-installed concrete ‘oppers’-piles. It is typical for this foundation concept that tension loads cannot be transferred through the pile-tunnel connection. After construction of the tunnel, the canal was filled with sandy material.

**Existing Weenatunnel**

The original two-lane tunnel dates back from about 1950. It has a limited height, and the tunnel part is relatively small. The tunnel has been founded on prefabricated concrete piles.
Underground Metro Station CS
Governing design condition is that regular underground traffic and passenger transfer at the existing underground station CS is not affected during the construction works, thus no damage (e.g. cracks, water leakage) to the tunnel due to the works is allowed.

The extension of the underground metro station CS is being realised with the aid of diaphragm walls constructed around the current station to a depth of approximately NAP –38 m. The building pit covers about 7,500 m². The dimensions of the required excavation are: length 230 m, width 30 to 50 m, and a maximum excavation depth of 14 m. Diaphragm walls cannot be constructed at the eastside of the excavation, due to presence of the existing underground tunnel and underground obstacles such as abandoned sheet pile elements and anchors from ancient projects. For closing this gap in the cut-off wall the ground freezing technology is applied for retaining the soil and water pressures by means of a collar construction around the underground tunnel (Thumm & Haß 2007). The ground will be frozen all the way down into the layer of Kedichem. The curved shape of the frozen block of ground will resist the pressure from the surrounding soil strata during the excavation of the construction pit. Together with the layer of Kedichem, the diaphragm wall and the frozen soil ensure that the construction can take place in a dry construction pit. The excavation is done from underneath the roof of the new station, that has been built during the very first stage of the project. This allows more or less normal traffic at the ground surface.

Weenatunnel
The new Weenatunnel will consist of two double lane tunnels. The tunnel part will create space for a large pedestrian area at the ground surface. For the two stages of the construction two building pits are created surrounded by combined walls of steel pipe piles and sheet piles and by only sheet pile walls. The combined wall with the future parking facility Kruisplein consists of a diaphragm wall up to a depth of NAP –42 m. Dry conditions in the building pit are provided by drainage of the Pleistocene sand layer between NAP –17 m and NAP –35 m.

Influence on adjacent structures
The new RandstadRail underground line, the reconstruction of underground station CS and the doubling of the existing Weenatunnel are currently under construction (figure 4). The adjacent structures are monitored during the execution of the projects. The extensive monitoring plan was based on the risks involved (Berkelaar et al. 2007). Some of the expected and measured influences of the construction works on the surrounding structures will be discussed briefly.

Groothandelsgebouw
Diaphragm walls for the building pit of metro station CS have been installed at a minimum distance of 2 m from the pile foundation (figure 5). An almost uniform settlement of a few mm’s was measured at the corner of the building during the execution. No damage was caused to the building.

In the design stage the driving of piles within the building pit for metro station MCS was restricted to a distance of more than 25 m. At a shorter distance a low vibration system was used to prevent damage to the Groothandelsgebouw. During the driving of the piles, the vibrations of the building were monitored.

Since the start of the drainage for the building pit of the Weenatunnel monitoring data showed that the settlement of the building is limited to a maximum of 5 mm in the first half year of 2007.

Existing Underground Metro Station CS
In order to reconstruct the station without disturbing the metro exploitation, a new floor with a thickness of 2 m was designed below the existing station. To construct this floor a dry excavation of 4 m below the existing metro tunnel to NAP –14 m is necessary. Because of loss of buoyancy additional bearing capacity for the existing metro tunnel has to be provided in advance. This was done in two different ways:
- holes with a diameter of 200 mm were drilled
through the roof, the intermediate floor and the tunnel floor, and about 20 jet grout columns with a diameter of 1.000 to 1.200 mm were installed from the ground surface to a depth of NAP –20 m; • holes with a diameter of 252 mm were drilled through the roof, the intermediate floor and the tunnel floor, and about 60 steel pipe piles were driven from the ground surface (NAP) to a depth of NAP –31 m.

The driving of piles through the station was a challenging activity. The steel piles have an outer diameter of 244.5 mm and a wall thickness of 20 mm. The bottom consists of a massive steel point with a length of about 480 mm. Before driving some dry concrete was brought into the steel pipe. The piles were driven by dropping a weight of steel, length 16 m, on the bottom of the pile. The piles were, without major problems, installed against the water pressure, through ‘preventers’. Although the base level of the piles was much deeper than of the existing ‘oppers’ piles, the existing piles only settled 2 to 3 mm.

Underground metro tunnel below the office building Delftse Poort
One of the reasons that freezing technology was opted for here, was the fact that the foundation of the underground tunnel under the Delftse Poort office building was not designed to cope with a large drop in the groundwater level. Dewatering of the deep Pleistocene sand layer is also causing some side effects. This is due to the Holocene layers that contain local inclusions of sand layers, with a thickness varying up to several meters. These so-called ‘donken’ are suspected to cause a hydraulic connection between the top sand layers (including the fill around the metro tunnel) and the Pleistocene sand formation. To avoid the risk of loss of buoyancy due to the lowering of the groundwater table, an infiltration system was installed in the perimeter of the tunnel. This system functioned well during the drainage for the construction of the new Weenatunnel.

Water main adjacent to the new Weenatunnel
The sheet pile wall for the building pit of the Weenatunnel was installed by vibration. Settlements of the ground surface and of the water main at the south of the building pit have been predicted, and were considered to be acceptable. A monitoring programme had been set up to check the behaviour of the water main. Installation of the sheet pile walls started at the end of 2006. In the period of the installation of the sheet piles a maximum settlement of the water main at a distance of 8 m from the building pit of about 45 mm was measured (figure 6). Next to the water main the maximum settlement amounted to 35 mm. Settlements continued after the installation and amounted 50 and 40 mm respectively at the end of January 2007. Drainage for the building pit started at the end of January 2007. The effect became visible in February 2007 by an increase of the settlement in the time from about 0.125 to 0.25 mm/day at the most settled measuring points. To date more than 70 mm of settlement has been measured. The stresses in the water main have been calculated. So far the stresses are within acceptable limits, because the differential settlements are relatively small.

Conclusion
Building in inner cities is a major challenge, not only from geotechnical point of view. Designs may be well-thought-out, the timetable for the construction of the different project is not as accurate as that of a train. Realizing many new constructions in a very confined space, each with its own timetable leads sometimes to conflicting interests. The construction period until 2012 will therefore pose sufficient challenges.

Building in inner cities needs direction to create added value for the city. A station equipped with new facilities, attractive office locations and additional greenery for the creation of pleasant and safe residential areas is expected to do so.

References

The Rotterdam Central Station project is funded by Rotterdam Municipal Authority, the Ministry of Transport, Public Works and Water Management, the Ministry of Housing, Spatial Planning and the Environment, NS Dutch Railways, ProRail and Stadsregio Rotterdam.
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