Project Name and Location
Amsterdam Noord/Zuidlijn
Amsterdam, Netherlands

Overall Project Value
EUR 3.1bn

Geotechnical Value
EUR 350mn

Please outline scope of the overall project (243 words)
The Noord/Zuidlijn metro project will ensure accessibility of Amsterdam´s city centre, which is considered to be essential to sustain economic development. The line will transport 185,000 passengers quickly and comfortably, straight through the heart of the city. As the name says, it will connect Amsterdam North with South. The first shows a variety of developments for new businesses, shops and housing, while the latter is an important business district and a primary location for multinationals. By connecting these two rapidly expanding suburbs, the Noord/Zuidlijn will contribute to trade and industry growth.

From Amsterdam North the line runs above the ground and passes the IJ-canal through a submerged tunnel before arriving underneath Central Station. From there onwards the line continues below ground towards the RAI exhibition centre, from where beyond it rises to the surface again and connects to the already existing station Amsterdam South. It covers a distance of 9.7km over 8 stations and reduces travel time from 31 to 16 minutes.

The Noord/Zuidlijn is the paramount example of the use of modern geotechnical engineering expertise and major ground engineering innovations to make the impossible possible: creating a metro line underneath the historic city centre of Amsterdam - a world heritage site and remarkable tourist hot spot floating on piles in soft and waterlogged ground - without damage to the ancient buildings directly above. This required the highest level of quality possible in ground engineering and construction, which is unprecedented in the world.

Please outline the overall project costs and the value of the geotechnical elements (30 words)
The ground engineering elements that are considered for this award entry – the bored tunnel and aspects that have been successfully completed by 2013 – constitute a total value of EUR 350mn.

Please explain the geotechnical elements of the project and the challenges of this aspect of the work (291 words)

Key element of the Noord/Zuidlijn is the bored tunnel section. It covers a distance of 3.6 kilometres, thereby crossing the three cut-and cover stations that divide the tunnels into four subsections. It consists of twin tube, one-lane, unidirectional tunnels with a 5.82m internal diameter. The tunnels mainly follow the street pattern, therefore requiring curves with extremely short radii of 190m. At depths between 20m to 33m below sea level, it is located in soft soil, either sand or clay. For almost the entire route the tunnel is driven close to, and at one specific section underneath, the wooden pile foundations of mostly ancient buildings.

During the design phase in the mid-nineties, experience with tunnelling in the weak Dutch subsoil was limited. Damage to historical buildings was considered to be the greatest risk. Average volume losses of 2% were estimated on the basis of international experience, whereas a maximum volume loss of 0.5% was required. Centrifuge tests indicated initially that the tunnels would have to stay away from the pile tips at least twice the TBM diameter in order to maintain existing stress levels, which would lead to extremely deep cut and cover station boxes. Therefore, new levels of TBM control and understanding of structural behaviour of buildings were required, creating numerous challenges in engineering and design innovation.

TBM and tunnel design had to be optimised for manoeuvrability, soil conditions, and process controllability. In addition to that, on seven specific locations compensation grouting had to be applied prior to, and during, the tunnelling process, in order to compensate for excessive settlement effects. Finally, every single building within the tunnel influence zone needed careful investigation of foundation and construction conditions. To keep an eye on their movements, a large-scale monitoring system was required.

Please outline the main achievements of the project, such as delivery time, within budget, or delivery of a new technique (380 words)

The Noord/Zuidlijn will not win a price for keeping budget or finishing on time. Main reasons of stretching out the project schedule and exceeding the budget were the overheated construction market at time of tender and permit issues in the inner city. On top of that, the project faced tremendous difficulties with the construction of the cut and cover stations along the central underground section of the line, due to leakage incidents in the diaphragm wall of Vijzelgracht station. Shortly prior to the tunnelling phase, the project was largely shut down for almost a year. It was uncertain whether the project would ever be finished. As a result, it carried an increasingly built up public mistrust. If bored tunnelling would go wrong, most certainly the project would be aborted.

However, the tunnelling phase went exceptionally well. Besides the outstanding performance of the contractor, this is highly attributable to the meticulous engineering and preparation phase. Tunnelling started in March 2010, took 587 days, and was completed within budget and ahead of schedule in December 2012. High quality, super clean tunnels have been delivered, without any considerable damage to buildings. Settlements remained significantly below the maximum allowable limits of typically 15 to 25mm. Surface settlements on the centre line of the tunnel were generally in the range of 5 to 10mm, often less. Building settlements were even smaller or close to zero.

Integral part of controlled tunnel boring was the feedback of settlement performance to the tunnelling process. With a network of 70 robotic total stations and more than 10,000 measurement points, the Noord/Zuidlijn had the largest monitoring system in the world. By finding the correlation between the tunnelling process and the subsequent settlements that were detected by the monitoring system, adjustments could be made for optimal performance, e.g. minimal ground settlements.

Although compensation grouting wasn’t something new, using this technique below pile foundations was ground-breaking. At the aforementioned seven locations it has been applied successfully. Since settlements due to tunnelling were even less than anticipated, some of these buildings are now slightly higher than originally measured.

These geotechnical masterpieces of the Noord/Zuidlijn serve as the state of art in engineering and construction, paving the way for future projects where high quality underground infrastructure needs to be integrated in challenging urban settings.

Please explain how your company contributed to the overall success of the project (520 words)
The design philosophy developed by Witteveen+Bos to overcome the aforementioned ground engineering challenges was based on the strategy of *Value Engineering* and *Design by Testing*. Desk research was conducted on the effects of tunnelling to its direct environment, and innovative 4D FE models were developed to predict the interaction between tunnels and nearby pile foundations, so the impact on the stability of each building could be accurately assessed.

The 4D FE models were validated by full scale pile trials (EUR 2.5mn) at the construction of the 2nd Heinenoordtunnel, the first bored tunnel in the Netherlands. About 38 wooden piles and 18 concrete piles were subjected to settlements and after thorough research it was derived that the distance between tunnel and pile toes in Amsterdam could be reduced to 0.5D, when pursuing a volume loss of 0.5%. This led to a major Value Engineering achievement as construction depths of the station boxes could be significantly reduced while maintaining an acceptable settlement risk profile for the buildings that are influenced by the bored tunnels.

The requirement of 0.5% volume loss resulted in the development of an innovative TBM with an extremely short articulated slurry shield, comprehensive measurement and control systems, and a customised cutting wheel capable of dealing with sand, sticky clay, and concrete.

A major survey and extensive FE analysis of building response was used to classify 1500 buildings. The foundation depth, type, and condition aspects of the construction were individually taken into account.

In order to prove that compensation grouting could be successful in combination with pile foundations, EUR 2.5mn was invested in a full scale trial at the bored Sophiatunnel in the Netherlands. The results proved to be promising and compensation grouting was implemented in the design by Witteveen+Bos. Within the Value Engineering approach a unique single layered interceptive TAM design was developed during the construction of the Noord/Zuidlijn, which was successfully applied with great care by the Contractor.

The concept of the integrated boring control system was highly innovative and proved to be very effective in adjusting the tunnelling process by detection of even the smallest settlements. For every building, separate performance requirements were formulated by means of settlement limits. This was also done for the so called virtual points on each meter of the tunnel centreline.

The adverse subsoil conditions and heavy asymmetrical building loads initiated a development program towards a new joint design between the concrete segmented tunnel rings in association with an innovative semi probabilistic integrated geo-concrete 3D FE modelling design approach. As the deep Eemclay is relatively soft, the state of the art of that time normally would indicate the use of expensive steel segmented rings. However, by means of the development of post-injectable concrete ring joint couplers the stiffness of the couplers was optimised and fine-tuned on the basis of another full scale trial program. This unprecedented Value Engineering approach made the use of concrete segmented rings feasible.

Many research papers (see attached) have been published in order to disseminate these innovations in ground engineering. Without the extraordinary level of geotechnical engineering expertise achieved by our company, the Noord/Zuidlijn would have been inconceivable.

List the other companies involved and their remit (34 words)
Engineering: Adviesbureau Noord/Zuidlijn, JV of Witteveen+Bos and RoyalHaskoningDHV

Client: Municipality of Amsterdam

Tunnelling contractor: Saturn X, JV of Züblin (Germany) and Dura Vermeer (Netherlands)

Monitoring contractor: Soldata-Grontmij, JV of Soldata (France) and Grontmij (Netherlands)

Total accepted number of words for the 6 questions below: 1500

Number of words used: 1498