Relevance of geo-information in designing bored tunnels in soft soils of the Netherlands

L'importance de l'information géotechnique pour le développement des tunnels forés dans les terrains non-stabilisés aux Pays-Bas

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ABSTRACT: An overview of the interaction between the geo-environment and soft ground tunnelling is given for the situation in the Netherlands. The importance of site investigation is stressed and optimisation should originate from a balance in tunnel boring process control, costs and risk. An interesting concept is the integration of site investigation and soft soil tunnelling in probing ahead from a tunnel boring machine. The challenge in this concept is the effective use of this data in the control of the bored tunnelling process. Research initiatives are given as soft ground bored tunnels are becoming a reality in the Netherlands

RESUME: Cet article présente un sommaire de l'interaction entre l'environnement géotechnique et le forage de tunnels en terrains non-stabilisés aux Pays-Bas. L'importance de la reconnaissance géotechnique est accentuée. Une recherche est faite pour obtenir une balance entre les risques, les frais de la reconnaissance et le niveau de contrôle de l'exécution du forage. Une présentation d'un projet pilote est donnée, dans lequel on trouve la combinaison de la reconnaissance et l'exécution du forage en dirigeant les instrument de reconnaissance en avancant le chantier. L'aspect intéressant de cet approche est de rendre les données utile à l'exécution du projet. Puisque le forage des tunnels dans les terrains non-stabilisés se produira dans le future bien proche aux Pays-Bas, des initiatives de recherche sont prises.

1. INTRODUCTION

The unique feature of bored tunnelling is that this type of civil engineering work is totally surrounded by the geo-environment. To reach its goal, e.g. establishing a tunnel, the construction interacts with all aspects of this geo-environment. The geo-environment in this paper refers to the total combination of influences encountered in the subsurface. It therefore comprises aspects such as geotechnics, geohydraulics, ground and groundwater contamination and natural and man-made obstacles.

These unusual circumstances require special measures to be taken in the construction process of a tunnel. Especially in soft soil the ground surrounding the tunnel cannot support itself. This makes for conflicting processes when constructing a tunnel using a tunnel boring machine in soft soil. On the one hand the soil needs to be removed, hence creating an unstable situation. On the other hand the soil must be kept stable to avoid excessive overcut of the tunnel face which can result in subsidence at the surface.

In order to reach this controlled condition of excavation, the tunnel boring process should be tuned to its surrounding geo-environment. After placing the tunnel lining, the geo-environment surrounding the tunnel should ideally retain the same features as before.

In this paper the relation between soft ground tunnelling and the geo-environment is discussed. This relation is practically determined by the tunnel boring process and the assessment of the geo-environment, or more specifically the ground investigation. Of importance in this is the accuracy of the information on the geo-environment and with this information the accuracy to which the tunnel boring process can be controlled. This results in the problem of translating the information on the geo-environment efficiently into tunnel boring process control parameters.

The relationship between geo-environment, tunnel boring, risk and costs to reduce risk is discussed. An important aspect of construction in the geo-environment is that the parameters are not only changing in three directions, but also that the data is spatially dependent. This requires special techniques of interpretation and processing of information. Obviously many correlations can be made with the geological circumstances of the area under study. However, spatial quantification of data would provide interesting options for validating the spatial models of the geo-environment.

The most intriguing concept of integrating ground investigation and bored tunnelling is when the investigation forms an integral part of the bored tunnel process. Site investigation from a tunnel boring machine is one of the most challenging developments in technological improvement in this construction process.

2. RISK AND COSTS REDUCING RISK

The reduction and control of risk in any form is becoming increasingly important in the evaluation and design of large infrastructural projects such as bored tunnels. Increasing complexity of the projects and difficult ground conditions are important factors in this area. According to a schematic outline of risk in bored tunnels by Jancsecz (1992), 75% of the risk is due to the geo-environment and approximately 15% are of technical origin. An interesting graph given in the same article is that of risk versus costs to control risk (figure 1). From this graph the conclusion can be drawn that the more you spend on risk reduction, the risk will asymptotically become zero. A similar graph by Zettler et.al. (1996) adds the component of information to the risk-costs graph. As is shown in figure 2, this component is the mirror image of risk.

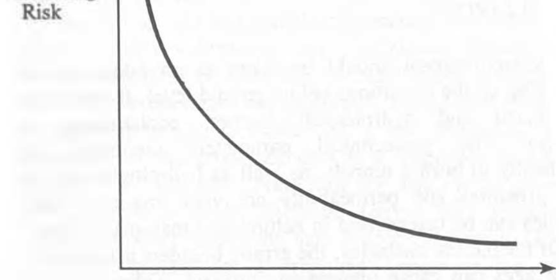

Figure 1. Risk versus costs reducing risk, after Jancsecz (1992).

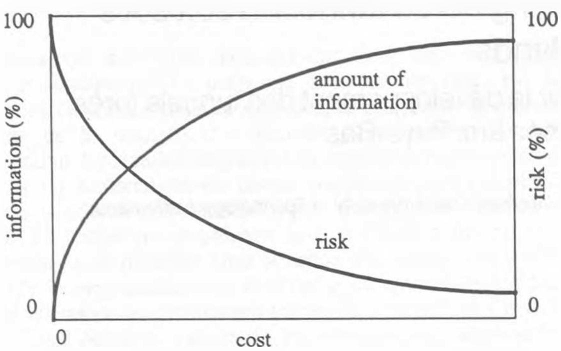

Figure 2. Risk and information versus costs, after Zettler et.al. (1996).

From these schematic approaches towards risk, costs and information the relationship between the tunnel boring process control and the amount of information about the geo-environment can be derived. As is shown in figure 3, the control of the tunnel boring process increases rapidly with a small amount of information. Hence, the difference between a soil or rock environment has a great influence on the TBM design. Extending the information of the geo-environment will prove to be increasingly less effective in the control of the tunnel boring process. The physical boundary seems to be at that stage where detailed geo-information is no longer of value to the control of the tunnel boring process or it technically cannot be implemented.

The purpose of effectively acquiring geo-information should be to reach an optimal balance in cost, risk and tunnel boring process control.

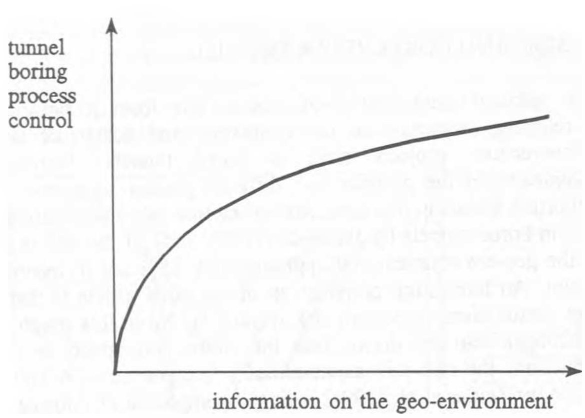

Figure 3. Tunnel boring process control versus information on the geo-environment.

3. GEO-ENVIRONMENT VERSUS SOFT GROUND BORED TUNNELLING

The geo-environment should be taken as an integrating term comprising all the conditions below ground level. It encompasses geotechnical and hydrological factors, contamination and obstacles. The geotechnical parameters obviously figure prominently in boring tunnels, as well as hydrological of which water pressures and permeability are very important factors. Obstacles can be categorised in natural and man-made, hard and soft. Of the natural obstacles, the erratic boulders associated with the ice ages can cause unpleasant surprises. Other phenomena such as natural gas, wood and cemented layers can have a detrimental influence on the tunnel boring process. Withdrawn piles or poorly filled boreholes can lead to a blow-out. The typical Dutch piles can be considered hard man-made obstacles. Bombs, infrastructure and sheet pile walls are also classified in this category. A very important possible feature of the underground in the Netherlands is pollution. The construction of the Bergambacht drinkwater pipeline showed that crossing contaminated sites requires special measures (Driessen 1996).

Soft ground bored tunnelling is considered in two main categories: design and construction. The first category is split up in tunnel boring machine design (TBM) and lining design (after Maidl et.al. 1995). In the construction stage the total of the tunnel boring process is considered. In figure 4 an indicative table is given of the relation between the geo-environment and soft ground bored tunnelling. It is shown that many factors of the geo-environment are linked to the different design and construction parameters of a bored tunnel. In this table is seen that especially the geotechnical factors are of influence on the bored tunnel process, both in design and construction phase. The same can be stated for the hydrological factors. The presence of contaminants in the subsurface can effect on the lining, cause disposal problems of excavated spoils and contaminants could seep into tunnels. Withdrawn piles or badly closed boreholes make a zone of low strength in the ground. Through these "soft obstacles" the support medium could disappear leading to instability of the excavation face.

4. GROUND INVESTIGATION AND SPATIAL INTERPRETATION

Ground investigation is the acquiring of information on the geo-environment. A well performed ground investigation should therefore include studies on all the components which make up the geo-environment. The geotechnical and hydrological parameters of the subsurface should obviously be measured. Establishing contamination is done by a combination of historic and field surveys. Historical studies are also applied on recognising man-made obstacles. A good understanding of the geological history of the area of interest gives an indication of the possible natural obstacles. The issue of erratic boulders in the Netherlands is an illustrative example of this kind. The geological setting of the Netherlands gives sufficient prior information on the occurrence of boulders. Erratic boulders are closely associated with the land ice of the Pleistocene era. The land ice never reached further south of the line Haarlem - Nijmegen. When boring a tunnel south of this geographical line, the chance to encounter such an obstacle will be considerably less than a similar project north of this line.

Another point of prior-information of the geo-environment in the Netherlands is illustrated by the method of ground investigation. In the western part of the Netherlands, the area where most of the tunnel projects are planned, nearly all ground investigations are executed by performing a large number of cone penetration tests (CPT). The fact that this specialized soil investigation method can be used on such a large scale is fully based on the geological prior-information of the area.

Nevertheless, the ground investigation strategy for geotechnical parameters is somewhat simplistic, by doing CPTs at regularly spaced intervals. In the Second Heinenoord tunnel project, which is currently underway, the spacing on land is 25 meter, over water 50. Given the large amount of prior-information (from the first tunnel) and the relative high quality of the site investigation tool, it should be possible to perform the ground investigation in a more selective way. This optimisation of ground investigation should be accomplished in combination with the interpretation of the field data.

The key to optimisation of ground investigation appears to be in quantifying the spatial interpretation of the field measurements. This can be done by using geostatistics to make a uncertainty model of the subsurface based on the data points. This model can be applied to evaluate where the uncertainty is too high and where

Soft ground bored tunnelling	Geotechnical: Soil profile	soil parameters: density	grading	plasticity	porosity/voids ratio	moisture content	strength	in-situ stress	deformability/consolidation	Hydrological: permeability	water pressures	chemical composition	Contamination: type of contaminant	concentration	dispersion	Obstacles: natural: Soft (natural gas, wood)	Hard (boulders, cemented layers)	man-made: Soft (withdrawn piles, boreholes)	Hard (piles, infrastructure utilities, ground-anchors, bombs)
TBM design																			
shield type/face support medium	X	X	X	X	X	X	X	X	X	X	X	X				X	X	X	X
external loads	X	X					X	X	X	X	X						X		
operational loads	X	X		X			X	X	X		X					X	X		X
tail sealing			X		X	X		X		X	X	X	X	X		X			
Lining																			
radial pressure	X	X	X	X			X	X	X	X	X								
axial pressure	X	X		X			X	X	X		X								
type of lining (steel, extru-concrete)	X	X	X	X	X	X	X	X	X		X	X	X	X	X				
flexibility of lining	X	X					X	X	X										
material							X	X				X	X	X	X				
grout	X		X		X	X			X	X	X	X	X	X	X			X	
Construction																			
building in/out TBM	X	X			X	X	X	X	X	X	X					X	X		
control of excavation process																			
face stability	X	X	X	X	X	X	X	X	X	X	X					X	X	X	X
conditioning	X		X	X	X	X				X	X	X	X	X	X	X	X	X	X
excavated material																			
transport	X	X	X	X		X							X	X		X	X		X
disposal	X		X	X		X				X		X	X	X	X	X	X		
wear of cutting tools	X		X	X			X						X	X			X		X
grouting	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X		X	
settlement	X	X	X	X	X			X	X	X	X							X	
foundation neighbouring structures	X				X		X	X	X	X	X								

Figure 4. Indicative table linking geo-environment and soft ground bored tunnelling.

more information is required. However, which type of geostatistics can best be applied in the Dutch heterogeneous soil conditions is as yet a subject of study. The vast amount of general prior information (though not always readily available) of the Dutch subsurface can be of help in this process.

5. GROUND INVESTIGATION AS AN INTEGRAL PART OF THE BORED TUNNELLING PROCESS

The need for information on the geo-environment can roughly be divided in two phases: information necessary in the design stage of a bored tunnel project and information that is required during tunnelling. This two-fold demand is illustrated in figure 4. It is seen that factors such as contamination are especially prominent in the design stage. Also, all factors of the geo-environment governing lining design should be known prior to the start of the construction phase. Factors such as soil profile and soil parameters are of importance in both phases. Insitu stress and deformability parameters provide in the construction phase information to control deformation of the surrounding area, for instance whether compensation grouting is applied or not.

The effective use of information on the geo-environment in the construction phase of a bored tunnel project is, especially in the Netherlands, a field of intensive study. Similar to principles used in rock tunnelling such as probing ahead and seismic forepoling (Schunnesson 1996, Inazaki 1995), methods are developed to acquire information ahead of the tunnel face in Dutch soft soils. Of importance is how this information effectively can be used in the control of the excavation face of the tunnel boring process, thereby keeping the surrounding geo-environment as undisturbed as possible. This concept of implementing a soft soil investigation tool in the tunnel boring process is studied in the context of the centre of underground construction (COB). The use of a cone penetration test type of tool is in Dutch circumstances an obvious choice. To use this sophisticated tool just for poking at obstacles would be rather simplistic. Converting the standard Dutch vertical CPT (taking cone resistance, friction and water pressure measurements) in a horizontal alignment could give the required information to gain in tunnel boring process control. The next step would be to implement sophisticated georadar or associated geophysical techniques. The leading factor in deciding the type of investigation tool should lie in the need and application of the required information on the geo-environment. Hence, a balance between the required information of the geo-environment and translation to tunnel boring process control should be found. As stated before, this is at the same time the balance between acquiring information (costs) and reducing risk.

The method of obtaining ground investigation from a tunnel boring machine is just as important as to how this information is (real time) processed and used in the tunnel boring process. First, the raw data should be processed by using a geologically based automated processes (software). For this a geostatistically based or other spatial based techniques could be used. This interpretative process should be done using also the prior information, e.g. all the available information. Once the data has been statistically validated it may be passed through various analytical programs to calculate the most likely influences they may have on excavation rate, alignment, adjustments to the slurry mix, grouting takes, to name but a few examples. For the presentation of the processed data it is important to know the demands of the end user. Presenting the data for the pilot of the TBM demands a totally different format than input for an automated process. When the data is processed for a TBM pilot it is useful to consider a graphical display of the expected excavation face. The TBM pilot should also be aware of the assumptions that are made in the acquisition and processing of the data. This demands a high understanding of ground investigation and the geo-environment. The raw data can also serve as input for a automated process based on artificial intelligence. An example of a fuzzy theory based shield tunnelling system is by Seno et.al. (1991). It shows that a fuzzy theory based control system performs better on certain parameters than manual operation of the bored tunnelling process. An example where geotechnical parameters are transferred to mechanical predictions is by den Hartog et.al. (1996). In this paper the performance of a rock trencher is predicted through a fuzzy model using geotechnical data as input. Nevertheless, these automated systems still require highly qualified personnel to control and adjust the process.

6. RESEARCH AIMS

The unique feature of bored tunnelling is that this type of civil engineering work is totally surrounded by the geo-environment and interacts with its environment in many different ways. The effectiveness of the ground investigation is determined by an optimal balance between costs, risk and tunnel boring process control. Its optimisation is reached through the quantification of spatial data using geostatistically based methods. The integration of ground investigation in the bored tunnel process could involve geostatistically based processing techniques with an artificial intelligence based translation to process parameters. To achieve these aims it is necessary to built up a database, not only of the information on the geo-environment but also on the performance and mechanical data of the tunnel boring process. Using this data and data of forthcoming projects the described systems can be developed and tested.

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