RISK MANAGEMENT IN THE GEOTECHNICAL DESIGN PROCESS OF A RAILWAY TUNNEL IN URBAN ENVIRONMENT, DELFT , THE NETHERLANDS

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ABSTRACT: Current developments show increasing risk levels in urban construction projects. Availability of public space in city centres becomes scarce. The impact to every day life is immense. Risks are even higher where complex engineering projects in soft soil environments are involved. Risk analyses starts before tenders where clients define risk levels. High level risks require proper management. Risks can be distinguished in different fields such as communication between stakeholders, environment, engineering and construction. A powerful tool for work-processes management of interdisciplinary engineering projects is Systems Engineering (SE). Geotechnical risk management following the SE approach has added value during design and construction of the Delft railway tunnel in The Netherlands.

The Delft railway tunnel project comprises the design and construction of a 2.4 km long, four track double railway tunnel, an underground station and an underground parking in the historic city centre. Monuments and historical buildings are supported by shallow foundations at very close distances from excavations. The lowest excavation level is about 10 m below ground surface. The ground water level is 1.5 m below ground surface. The cut-and-cover tunnel is retained by diaphragm walls in order to minimise ground deformations. The tunnel is constructed in two stages and the Dutch Railways requires direct exploitation of the eastern tube after the first stage. The second stage comprises the removal of the old railway viaduct and the construction of the western tube and the underground parking.

This publication discusses the general outline of the tunnel project. It focuses on selection of construction methods, the advantages of the organisation and work-processes in Design & Construct contracts and geotechnical measures and provisions in order to decrease and control risks during engineering and construction.

INTRODUCTION

Continuing growth of the intensity of railway traffic, the impossibility to double the existing tracks on a sound polluting railway viaduct in the historic city centre and the possibility for redevelopment of the outdated urban environment, the city council of Delft and the Dutch railway organisation ProRail BV decided to initiate the construction of a railway tunnel through the city of Delft. The tunnel project comprises the design and construction of a 2.4 km long four track double railway tunnel, an underground station and an underground parking. The construction of the tunnel will be mainly retained by a cut-and-cover (top-down) technique using diaphragm walls. The contract is assigned to Combination "CrommeLijn" (CCL), a co-operation between CFE NV, Mobilis BV TBI infra and Dura Vermeer Group BV. In the Design & Construct contract the engineering consultant Grontmij Nederland NV is responsible for the engineering. In June 2008 Grontmij started the final design. The construction will start in August 2009.

USE AND NECESSITY

Construction of the railway tunnel leads to a significant improvement of the liveability in the city of Delft. Daily over 350 trains pass through Delft. The track is the most frequently used railway section in the Netherlands. All trains cross Delft over a noisy viaduct which splits the city in half.

Karla Peijs, Dutch Minister of transport (2005): "The era in which the railway track splits Delft on a rigorous manner like a Berlin Wall comes to an end."

This viaduct is situated in a dense historical town centre. Three main problems need to be taken into account. First, increasing the number of train passings through Delft is not possible. Second, there is no space available for extension of the viaduct. Third, passing trains cause large inconveniences. Constructing a railway tunnel will clearly improve the atmosphere in the city and enables further growth of the railway transport by doubling the railway to four tracks. On top of this, removing the viaduct also creates space to develop new urban areas which increase the feasibility of the project. As like many underground projects infrastructural developments and environmental developments go side by side.

REDEVELOPMENT OF URBAN AREAS

After construction of the tunnel and removal of the existing railway viaduct, almost 37 hectares of released city ground can be redeveloped. According to the plan of the Catalan architect Joan Busquets the area will have a complete makeover. New condos with almost 1,500 apartments will be built and an extensive public transport branch point consisting of an underground railway station and a bus and tram platform will be realised. A new city hall, designed by the Delft architects of Meccanno, will be built on top of the tunnel. Furthermore, the public space will be enriched with a new canal, restoring the course of a medieval moat, and will have the atmosphere of a city park.

TUNNEL ALIGNMENT AND STAGED CONSTRUCTION

Interruption of the railway traffic during construction is not allowed. For this reason two main construction stages will be applied. The first two underground railway tracks in the 2.4 km long railway tunnel will be located at the eastern side of the existing railway. The removal of two city blocks at the southern and middle part of the alignment is required to create the necessary space. The proposed underground railway station will be located below the existing station square and includes an underground bike parking. The northern part of the alignment will follow the Phoenixstraat, an arterial road used by cars, trams, bikes and pedestrians. Here the tunnel will pass existing medieval to 20th century buildings supported by shallow foundations at very close distances (about 4 m). The tunnel will underpass two fragile historical monuments wind mill "The Rose" and the "Beguine tower" a former part of the medieval city's defence walls (Figure 1). Scheduled completion and exploitation of the eastern part of the tunnel is in 2013. Then the existing tracks and viaduct will be removed allowing the construction of the second part of the tunnel. This second part, the western part, consists of a two track tunnel and an underground parking for approximately 650 cars below the Spoorsingel. Tunnel construction activities will be completed in 2016.

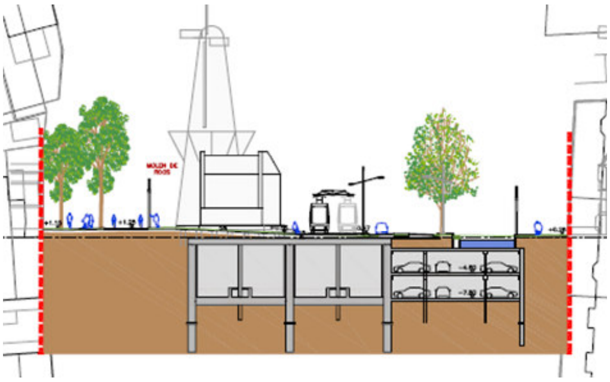

Figure 1: Cross section with wind mill "The Rose"

SUB-SHALLOW SURFACE

The sub-shallow surface in the western part of The Netherlands can be characterised by almost 20 m of soft soil of Holocene origin underlain by medium to dense sands of Pleistocene origin. North of the tunnel area a factory is situated that extracts large amounts of brackish groundwater from the Pleistocene sands. The draw down results in low pore pressures in the Pleistocene sands what is an advantage during construction as it reduces the risk of up-lift of the bottom of the excavation. Without measures deep excavations can be achieved. The final tunnel construction is designed to retain higher upward water pressures in case the extraction ends.

ORGANISATION AND CONTRACT

The project outlined above involves complex developments of infrastructure and urban regeneration. It has many stakeholders from owners of local stores to local governments and the Dutch railway organisation. Without exceptions all stakeholders see the high risks involved with the construction of the tunnel in the historic city centre. Not all assign the same weighting factors evaluating those risks. This results in a wide diversity of visions and attitudes towards the future final result.

The project organisation is typical for large public works. The main client consists of a co-operation of ProRail and the city council of Delft. After preparation of a preliminary design competition the construction of the tunnel and re-arranging the public space was awarded to CCL. In a Design & Construct contract this preliminary design is now being elaborated into a final design first and detailed design later. Grontmij is a subcontractor to CCL and produces the design documents and drawings.

The involvement of the Client did not end after contract award. The Client provided an extensive scope and a detailed structure of project specifications. During the design the design basis is discussed in regular meetings with the Client.

The Design & Construct combination is working closely together. CCL and Grontmij share offices which is favourable for development a professional relationship between the contractor and the consultant.

RISK MANAGEMENT AND SYSTEMS ENGINEERING

The design process and the construction of the tunnel are based on the method of Systems Engineering (SE). SE is a powerful tool to organise projects and to control risks in large projects. Input for the method is the full range of project specifications and requirements provided by ProRail. Those requirements have been allocated into the System Breakdown Structure (SBS) during the tender phase. The SBS breaks down the system into subsystems, components and elements. Subsystems are the underground constructions and the regeneration of the public space. Components are parts of the construction such as the underground station, the tunnel and the tunnel entrances. Elements are parts of the components like the tunnel roof, the foundation or the diaphragm wall.

The top-requirements have a rather abstract character. In the project scope these have been re-worked into more practical requirements. Supplementary requirements have been deduced from design options, quality and cost considerations, national and European standards, risk assessments, RAM-analyses (Reliability, Availability and Maintainability), HSE and additional requirements for construction activities (Figure 2). Drafting of design alternatives for the construction of the tunnel was the starting point for verification of top-requirements and generation of more detailed sub-requirements. Interfaces requirements of the tunnel and its environment were introduced to the SE-structure. The deduction of sub-requirements is often necessary to reach a level at which they can be verified. The result is a large chain of design requirements ranging from the abstract top-requirements to the practical requirements at the working-floor. The design process follows the SBS-chain which helps to systematically prepare design documents and verify the project.

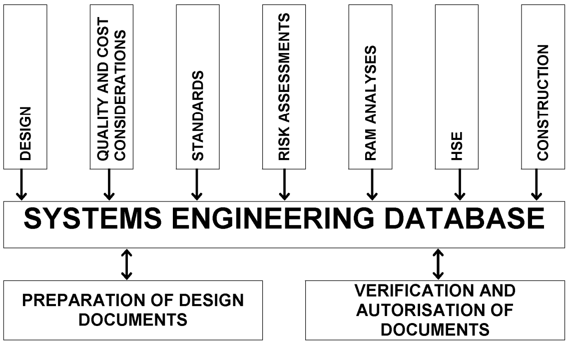

Figure 2: SE database

The introduction of risk-related requirements into SE is a result of risk assessments. These assessments help to evaluate risks. Risk can only be controlled and prioritised when the impact to the design process is known. Within the project organisation it was decided what risk can be accepted, or what risks should be decreased and further controlled. Of course, the first group will not be incorporated into the SE-database.

The above can be illustrated with an example. ProRail focuses on maintaining a positive public opinion about the tunnel. This could be achieved by having proper communication with stakeholders, by guaranteeing accessibility of the project area for access traffic and by preventing damage to buildings and monuments along the alignment as an effect of the construction of the tunnel. The latter is of primary interest to the geotechnical engineer and can be further broken down to displacement criteria of the diaphragm wall, criteria related to horizontal strain and angular distortion of foundations and the control of ground water levels.

TUNNELLING CONCEPT

The SE procedure has led to the selection of the cut-and-cover tunnelling technique retained by diaphragm walls. Diaphragm wall construction causes minimum noise and vibration disturbance. The method is believed to cause minimum damage to surrounding historical buildings. Working top-down creates the possibility to use the tunnel roof for construction roads, temporary roads for urban traffic and for tram lines. It could also be used for storage of construction material and equipment. This way minimum pressure is being put on the scarce public space.

Diaphragm walls are used for the temporary ground and groundwater support during excavation and are permanent retaining walls of the tunnel construction. The walls bottom sections penetrate the Pleistocene sands. For this reason the diaphragm walls are able to support the tunnel superstructure. Once all panels have been cast, staged excavation and construction of two 12.5 m wide tunnel tubes can start.

The first stage is excavation of the ground within to a depth of about 2 m. The concrete roof of the tunnel is casted in-situ and is directly connected to the walls. Below the tunnel roof the excavation and construction of the tunnel takes place. In order to limit deformations of the diaphragm walls temporary pre-stressed struts are installed after reaching 50% of the maximum excavation depth. Excavation continues to a maximum depth of 10 m. Groundwater is kept constant at 0.5 m below each intermediate excavation level. The concrete floor of the tunnel is casted in-situ and is also directly connected to the diaphragm walls. Finally, the temporary struts can be removed.

The construction of the underground parking is a bottom up process. Here also temporary pre-stressed struts and permanent concrete floors are applied to limit deformations. Because of the future high ground water pressures at the bottom of the 18 m wide floor, additional tension piles are applied.

The tunnel and parking garage are constructed in two main stages. The eastern tube will be constructed first. The diaphragm wall at the western side of the tube has a temporary soil retraining function. The western tube and underground parking will be constructed in the second stage.

ACCUMULATION OF DEFORMATIONS

Results of risk assessments qualified the risk of excessive deformations of buildings most important. Further detailed geotechnical engineering and verification of project requirements brought about the development of a method to analyse the behaviour of contiguities during construction of the tunnel.

Construction of the diaphragm walls near critical buildings require additional measures to limit deformations of the diaphragm walls in order to meet the criteria for angular distortion and horizontal strain of buildings along the tunnel alignment. The deformations of foundations of contiguities are an accumulation of deformations, as follows:

1. Earthworks for underground infrastructure (pipes and cables) in the narrow area between the buildings and the diaphragm wall. At some places the distance is less then 4.0 m and the excavation depths over 2.5 m.
2. Removing obstacles of the historic town defence walls at the proposed route of the diaphragm walls (excluded from the analyses, impact is negligible).
3. Trench deformations during excavation with the ground supported by bentonite mud or similar. Once the reinforcement cage has been lowered into place, concrete is tremmied into the slot, displacing the mud.
4. Deformations as a result of staged excavation of the strutted tunnel trench.

The measures taken during trenching and burial of cables and pipes are based on the historic profile of former earthworks. Where the excavation is within the historic profile the additional ground deformation is considered negligible. When earthworks are required beyond the limits of the historic profiles additional measures will be taken. Trench boxes could be applied and at some very critical locations lost pushed-in and strutted sheet pile walls are used. In order to predict the ground deformations and to verify the measures, 2D Plaxis calculations are carried out.

The diaphragm walls have thicknesses of 1.0 m and have standard widths of 7.3 m. Additional efforts to meet the deformation criteria of buildings focus on further limiting the deformations of the diaphragm walls by:

- Excavation in stages, were the groundwater in the building pit also is lowered in stages.
- The panel width can be reduced to 3.8 m during excavation of the diaphragm wall.
- More struts can be applied at two or three levels during excavation, where the first strut is located directly at ground surface.
- The struts can be pre-stress to reduce elastic shortening of the steel cross section and to pre-stress the ground at the active side of the retraining walls.

QUALITY OF BUILDINGS AND MONUMENTS

The allowable deformations of the contiguities are small. They are a combination of angular distortion and horizontal strain (Figure 3). Most buildings in Delft are supported by shallow foundations with foundation levels at about 0.8 m below ground surface. The buildings are divided in different quality classes based on the additional allowable deformation. Quality classes (Figure 4) used are slight damage (class II, yellow), very slight damage (class III, orange) and negligible damage (class IV, red). The condition of buildings was investigated with a visual inspection by a constructional engineer.

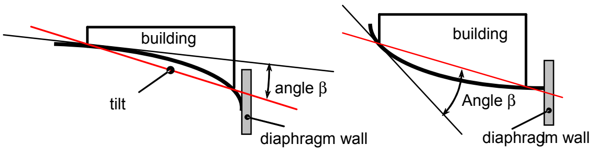

Figure 3: Definition angular distortion and horizontal strain for buildings

Comments Figure 2 - The definition of the angular distortion and horizontal strain is as follows:

- angular distortion (β) is the maximum angle between tilt and tangent line of the settlement curve;
- horizontal strain (ε) is the strain of buildings at foundation level.

When a building is in very poor condition, it is assigned to class IV (red). The combination of angular distortion and horizontal strain must fall inside the red area. Some of the (new) buildings have deep foundations. Those are classified green (class I). The method adopted is prescribed by the Client. The inspection of the buildings was and subsequent classification was also performed by the Client. Figure 4 presents the allowable deformations (the combination of angular distortion and horizontal strain) for different conditions of buildings.

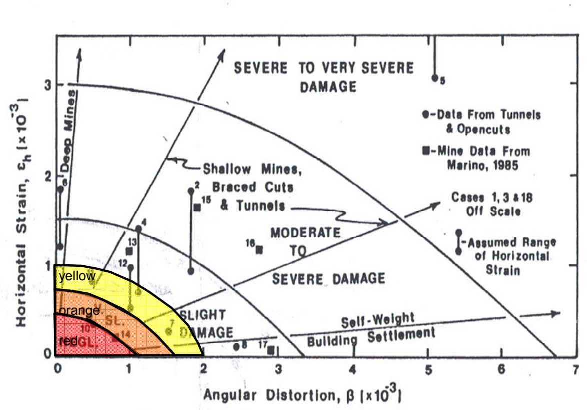

Figure 4: Allowable additional deformation of buildings (Boscarding and Cording, 1989)

PREDICTION OF DEFORMATIONS FOR BUILDINGS

Finite element models (Plaxis 2D and Plaxis 3D) were used to assess the deformations of the tunnel system. The model does not take account of interaction of soil and foundation slabs. It assesses green field deformations outside the tunnel trench. The deformations at foundation level can be extracted from the model.

The design approach outlined below was adopted for the prediction of deformations:

1. The ground deformations are assessed (SLS) as a result of the construction of the diaphragm walls for panel widths of 3.8 m and 7.3 m (Plaxis 3D)
2. The required dimensions of the diaphragm wall are determined with an elastic beam model using bi-linear ground springs in (MSheet) (ULS and SLS) in combination with structural analyses (ESA PT).
3. The ground deformations are assessed (SLS) as a result of cable and pipe trenching.
4. The ground deformations are assessed (SLS) as a result of the tunnel trench excavation taking account of detailed construction stages (Plaxis 2D). This model continues from step 3 and uses the input from step 2.
5. Finally the results of step 1 and 4 are combined. Now the verification of the deformation criteria is performed. Where the requirements are not met additional measures have to be taken, as described in section “Accumulation of deformations”. Steps 2, 3, 4 and 5 are repeated until the requirements are met.

Using a cross section over Phoenixstraat 30 and Spoorsingel 25 (Figure 5) the deformation analyses is explained. Figure 6 shows a location map with the location of the example cross section. The building Phoenixstraat 30 has an old part which is in poor conditions (class IV, red) and new part which is in fair conditions (class II, yellow). There is a basement below the building at about 2.0 m below ground surface. The building Spoorsingel 25 (class III, orange) opposite of Spoorsingel 30 does not have a basement. This building has a foundation level at 0.8 m below ground surface.

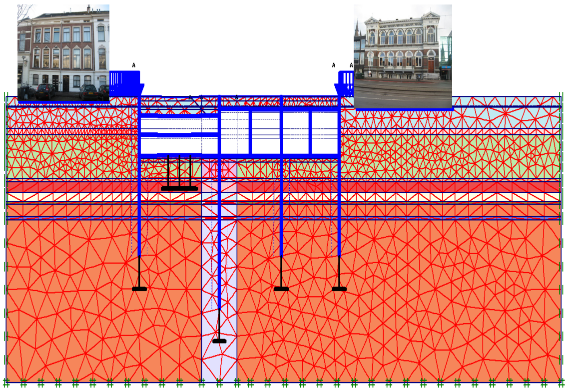

Figure 5: Plaxis 2D model with cross section Phoenixstraat 30 (right) and Spoorsingel 25 (left)

Using the calculated deformations from the different calculation steps (1 to 5 above), verification of the allowable building deformations is presented in Figure 7. Calculations proved that additional measures are required to limit the

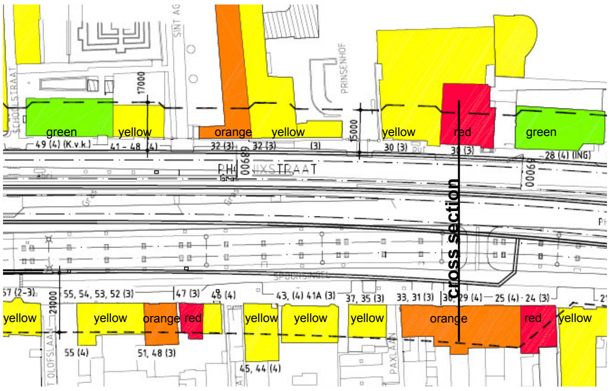

Figure 6: Location map Phoenixstraat and Spoorsingel, Delft, The Netherlands including future tunnel and underground parking

horizontal deformation of the diaphragm wall during the first excavation stages. Measures selected for this cross section are the introduction of additional struts at surface level and the use of 3.8 m wide diaphragm wall panels.

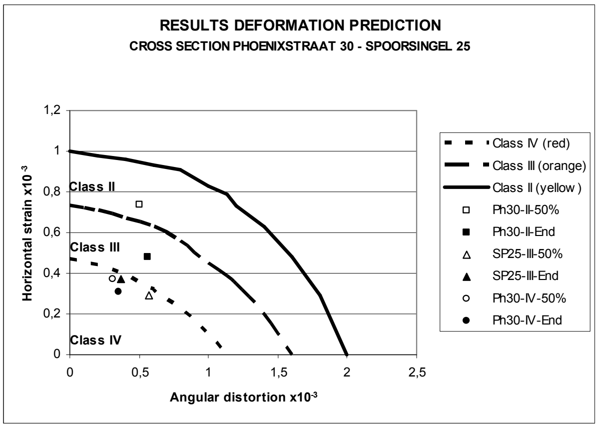

Figure 7: Verification of allowable building deformations

Comments Figure 6:

- Phoenixstraat 30, new part (class II, yellow): II-50% (construction stage), II-End (final stage)
- Phoenixstraat 30, old part (class IV, red) IV-50% (construction stage), IV-End (final stage)
- Spoorsingel 25 (class III, orange) III-50% (construction stage), III-End (final stage)

Figure 7 presents an up-scaled graph based on Boscarding and Cording (1989). It shows that the most critical construction stage for Phoenixstraat 30 is at the end of the construction of the eastern tunnel tube (about 50% the total construction period). The critical construction stage for Spoorsingel 25 is the final stage. Further, the verification of deformation criteria proves that the combination of horizontal strain and angular distortion is met during all intermediate design construction stages.

SENSITIVITY ANALYSES

Sensitivity analyses have been performed to study the impact of varying soil parameters and groundwater levels on the calculation results. This study is the basis for a calamity plan taking account of higher pre-stresses and necessary structural adjustments. A monitoring programme is being set up to record deformations during construction. Where deformations are in excess of alarm values the calamity plan will be executed.

PROCEDURE OF VERIFICATION

From the SE-database all specifications and requirements related to tunnel components and relevant to design disciplines (such as geotechnics) can be extracted into a Programme of Requirements (PR). In this document information is given about how and in what stage during the project requirements require verification. The geotechnical engineer is responsible for the verification of geotechnical requirements throughout the design process. References to documents and drawings will be added to assure that all requirements are met. At the moment of transfer from design to construction the RVP indicates that the design does not leave any omissions in the verification.

CONCLUSIONS

In combination with traditional geotechnical engineering design the Systems Engineering method serves multiple purposes.

Within the project organisation it proved to be a powerful tool for project control and risk control. Requirements and risks are embedded in the SE-database providing a platform for risk evaluation at practical levels. The method promotes structured working processes and value engineering. Application of the SE-method helps to indicate that until completion of final and detailed design all requirements have been met. The construction process continues where design stops.

For Clients Systems Engineering provides clear and easy to check output in the Programme of Requirements. This reduces efforts to control Design & Construct projects.

REFERENCES

BOSCARDING, M.D. and CORDING, E.J., 1989. Building Response to Excavation-induced Settlement. Journal of Geotechnical Engineering (ASCE). 1989 115(1), pp. 1-21.