Four-track Railway Tunnel Re-unifies the City of Delft in the Netherlands

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1. Introduction
The preparations for the construction of a 4-track railway tunnel in Delft (The Netherlands) have recently started. The 2.3 km long tunnel will run through the historic city center and replaces a fly-over, which causes major nuisance due to noise and vibrations. This paper addresses a brief history and description of the project, some main design risks (safety, vibrations, pressure waves), settlement risk assessment, the geological and geohydrological conditions and the construction methods.

2. History
The current railway line dates back to 1847. Then, it ran along the city’s western border. Since then, the city has grown substantially to the west, making the railway line a great barrier.

Figure 1: City walls and canal in 1763, view of first railway, current situation and future situation.
Because of increasing rail traffic, a two-track rail fly-over was built in the 1960’s. With its construction, the historic city canal, once bordering the historic city, disappeared. Since the 1960’s rail traffic has further increased. Daily 350 trains pass through Delft, in the rush hour even one train every 3 minutes. This creates significant nuisance due to noise and vibrations. Legal noise standards are exceeded for more than 700 buildings. The capacity of the currently two track line is almost fully occupied, future growth of rail traffic demands expansion to 4 tracks.

3. Plan development
The first studies to a tunnel started in the 1980’s. The current plan dates back to 2003. After various feasibility and environmental impact studies by DHV, TCE (Witteveen+Bos) and Benthem Crouwel it was decided to build a 2.3 km long 4-track tunnel next to the rail viaduct. The tunnel enables the development of 1500 houses and 50,000 m2 for offices. The tunnel structure will be suited for 4 tracks. In the first stage only 2 rail tracks are to be built. In the future, the expansion to 4 tracks can occur without further nuisance to the city. A new underground station will arise next to the current station, and will contain a parking facility for 5000 bicycles. Several underground car parks further add to the quality of the new developments. Part of this project is a 2-story parking for 450 cars, located underneath the re-constructed city canal.

Figure 2: Top: the project plan including public spaces and real estate developments. Bottom, left to right: aerial view of the current situation, GIS projection and GIS projection with tunnel.
The project is divided in several contracts. The largest contract contains the tunnel structure, the tunnel installations, the underground station, an underground car park and the reconstruction of the public spaces. This contract was tendered as a design and construct contract. In order to give the contractors the possibility to optimize, all specifications, apart from aesthetic specs and the development plan, are functionally described. The client, ProRail (Netherlands Railway authority) awarded this contract to the Combination Cromme Lijn (CFE, Mobilis/TBI and Dura Vermeer). The contractual date for completion of the works is July 2016.

4. Underground station and city hall
The new underground station is catered for the transport of 39,000 passengers each day. It will comprise two platforms, located at 8 m below surface and 340 m long. A lot of effort is made to create a pleasant, secure environment for the passengers. Optimal transparency is created by avoiding columns at the platforms, making the roof span 2 times 20 m. With its 9 m height, the underground station is very spacious. Natural daylight accentuates the central staircases. A special artificial light design was made to further improve the traveler’s orientation. From the platforms, stairs lead to an intermediate level, the “mezzanine”. From here, passengers can either continue to the bicycle parking at the same level or go further up, to the station hall. The hall has no columns, spans over 40 m and is integrated with the new city council building. The 6-story building is founded on the tunnel walls.

Figure 3: Top: impression of new community building and cross section of building and station (Mecanoo). Bottom: impressions of mezzanine and platform level (Benthem Crouwel Architects)

5. Safety concept
The tunnel consists of 4 separated tubes, one for each rail track. In case of a calamity, passengers flee to the adjacent ‘safe’ tube. This tube is reached through emergency exit doors that are present every 75 m. Longitudinal placed ventilators create an air overpressure in the adjacent tubes, preventing smoke to enter through the rescue doors. The rail traffic in tunnel is stopped automatically. Passengers flee through this safe tube to the tunnel mouth or to the station, which is regarded as a ‘safe haven’. Since the station has no separating walls, a different concept in chosen to create a safe and smoke-free area. In case of a fire incident in the station, a smoke and heat discharge system, positioned at the top of the station walls, will create a smoke
free situation during at least 5 minutes, which allows passengers to flee to one of the five regular or emergency exits. Glass smoke screens (downstands) protect the staircases from smoke entry. Several simulations with a 3-dimensional CFD (Computational Fluid Dynamics) model are performed to check the proper functioning of smoke and heat discharge system.

Figure 4: simulation of evacuation of train passengers (l) and smoke distribution in the station (r) during a fire incident

6. Pressure waves and draught
About 50 percent of the trains will not stop at the station, but pass the tunnel and platforms with a speed of 140 km/h. The resulting pressure waves are a possible nuisance to train passengers. Also, draughts at the platforms and the stairs to the station hall should be limited. Both aspects are studied through numerical modeling and scale tests. From these studies, it followed that several measures are necessary to create an acceptable wind climate, such as air release points in the tunnel, wind guiding structures at the platforms and airtight revolving doors in the station hall.

7. Train induced vibrations
The tunnel will ameliorate the environment with respect to noise significantly. However, train induced vibrations remain a matter of concern, not only with respect to the existing adjacent buildings, but also to the new buildings. Most new buildings are positioned a few meters from the tunnel walls, but one apartment block and the new city hall are positioned on top the tunnel. Extensive numerical and analytical analyses are performed to assess the nuisance remaining in the new situation. The vibration source of the trains was back calculated from measurements at a nearby tunnel with a comparable structure. According to the calculations, the utilization of ballast mats underneath the ballast foundation material is a promising measure to reduce both vibrations and low frequency noise in the nearby houses to an acceptable level. Therefore, the tunnel structure is prepared for this application. After completing of the tunnel structure, vibration tests will be carried out in order to validate the calculations, further assess the efficiency of the mats and optimize its properties.

8. Geological and geohydrological conditions
The geological layers encountered in the Delft region are typical for the river delta in the western part of the Netherlands. The top layer is a rather thin layer of sand and recent debris. Under this top layer, the geological profile consists of an accumulation of almost 20m of soft soil of Holocene origin underlain by medium to dense sands of Pleistocene origin. The thickness of the Pleistocene sand layer is generally more than 15 to 20m (thus to a depth of approximately 35 to 40m), however at a few spots along the project, the underlying overconsolidated clay layer (Kedichem strata) is already found at a depth of 30 to 35 m.

Three different water tables are detected within these soil strata. The phreatic water level is at about -0.40m NAP (NAP = national reference water level in Amsterdam). In the deeper Holocene layers a hydraulic head of approximately -3.75m NAP is measured, in the Pleistocene sands this
varies from –6 to –9 m NAP. This particular geohydrological situation is for the greater part caused by a factory at the northern end of the tunnel, which extracts large amounts of brackish groundwater from the Pleistocene sands. The extraction results in very low water tables in the Pleistocene sands thus forming an advantage during construction as it reduces the risk of uplift of the bottom of the excavation. As it is uncertain whether this situation will remain during the 100-year tunnel lifetime, the final structure is designed for both circumstances, with and without the present ground water extraction. Simulations with a regional geohydrological model predict that, without extraction, the head in the Pleistocene aquifer will rise to the level of approximately –2 m NAP. As the very heterogeneous Holocene formation is a sequence of peat, sandy clay and clayey sand layers, a great number of piezometers are installed to measure the water pressures.

Figure 5: Geological section along tunnel alignment

9. Settlement Risk Assessment and Building Damage Control

At the northern part on the project area, the distance between the tunnel walls and adjacent buildings varies from 3 to 10 m. It is unavoidable that, despite the application of stiff, strutted D-walls, some impact on the buildings shall occur. The foundation of these buildings varies: the old masonry buildings have shallow foundations whereas the newer concrete buildings are founded on concrete piles. The capacity (strength) of the buildings is determined on basis of measurements and inspections. The allowable deformations depend on the classification. The allowable deformations for masonry buildings on shallow foundations are based on the Limiting Tensile Strain Method (Boscardin). Figure 6 shows the results of the building quality classification. Category 1 and 2 buildings (yellow) are of good quality. Slight (additional) damage due to tunnel construction is allowed, which relates to a total strain of 0,1% in the masonry walls perpendicular to the tunnel. Category 3 buildings are of less quality. Additional damaged is restricted to the category “very slight”, which relates to a total strain of 0,075%. For the most damaged buildings, category 4 (red), only negligible additional damage is accepted, which relates to a total strain of 0,05%. Some “red” building are repaired before the start of tunnel construction. A typical repair measure is the repair of large cracks, for instance by adding armor to the masonry joints. Smaller cracks are closely monitored during construction stages. Buildings on foundation piles (crossed lines) are assessed separately on the soil loads and capacity of the piles.

The input parameters of the graph are “angular distortion” and “horizontal strain”. These parameters are determined by FEM-calculations. The model includes the tunnel and surrounding soil. The building is only modeled through its weight. No interaction between building and soil is taken into account: the assumption is that the building will completely follow the soil deformations. This is a conservative assumption. The 2D-FEM calculation includes all stages of construction, excluding the construction of the D-wall. For this, a separate 3D analysis is performed. Calculations are carried out both for average and lower boundary values of soil and structural
parameters. When using lower boundary values, more measures are required to fulfil the requirements. The tunnel construction is prepared for these measures, i.e. the D-wall armour is prepared for extra struts and/or extra pre-stressing of struts. The decision for the actual activation of these measures is taken on basis of observation and analyses of the monitoring data during all construction stages. The angular distortion and horizontal strain are translated to front wall movements. These movements are the key day to day monitoring parameters. Robotic total stations will continuously measure prisms, attached to the facades, in critical phases. For each stage of construction, limits are set. The maximum displacements depend on the classification and the exact location of the building in the settlement trough. Typically, limits are set to about 6-18 mm both vertically and horizontally.

Apart from building measurements, also water pressures and soil movements are measured. Water pressures are measured in all three aquifers, horizontal soil movements are measured through inclinometers behind the D-walls.

Figure 6: Top: Damage criteria (l) and building classification (r). Bottom: impression of wind mill “the Rose” founded on the tunnel (l), facade of typical building along tunnel alignment.

10. Windmill “The Rose”

A major challenge is the crossing of the windmill “the Rose”. This monument dates from 1679 and is right in the middle of the tunnel trace and therefore a huge obstacle for tunnel construction. It is a highly sensitive building. Due to several reconstructions over the centuries and the poor soil conditions the building has tilted 5 degrees. The presence of attached living quarters further adds to the complexity. Because of the monumental status, it was demanded to leave the entire structure intact. The windmill will be given a new temporary pile foundation and is lifted to make space for the construction of the tunnel underneath. Upon completion of the tunnel, the entire structure of the windmill and its attachments will rest on the tunnel.
11. Construction methods
Diaphragm walls form the retaining walls of the building pits. As the tunnel is often situated at hardly 3m distance from the surrounding historical buildings, this method is selected since it causes minimum noise and vibration disturbance. Moreover, as these diaphragm walls have a definitely higher bending stiffness, the deformations due to the excavation of the building pits are strongly reduced compared to traditional sheetpile retaining walls. Naturally, the diaphragm walls also serve as walls of the final structure, otherwise they would not be economically attractive.

The tunnel is constructed in two stages. As soon as the eastern tube can be exploited by train traffic, the second stage, which starts with the removal of the old railway fly-over, can be executed. Once the railway viaduct is removed, the western tube and an underground parking will be realized. Due to the scarcity of the public space where roads, tramways and pedestrian roads should continuously be assured, a top-down building method was chosen. In this way, the roof could be used for storage of construction material and equipment. Moreover, the tunnel roof can be used as the upper strut during excavation.

Figure 7: First stage of construction and detail of connection of roof and D-wall

The building sequences throughout the whole process strongly depend of the robustness of the nearby historical structures. The optimum width of the diaphragm walls is 7,30m. In such panel widths, two reinforcement cages with a maximum width of 3,10m each (transport by lorry in urban environment) can be installed, resulting in a better ratio reinforced width/total width of 85% compared to the 81% for 3,8m panels. By doing this, the amount of panel joints, risk-bearing for possible future leakage is also reduced by half. However, during the stage when the excavation of the diaphragm wall is supported by bentonite mud, wide panels produce larger ground deformations. In cases of small distances to buildings, a maximum panel width of 3,80m is chosen. Generally, as parts of the medieval city walls are expected along the tunnel, a preliminary excavation between the diaphragm walls up to a depth of 3,00m is foreseen. At critical sections, this excavation can not be done without the installation of supplementary struts above the tunnel roof. Once the roof concrete is poured and hardened, excavation under the roof can take place to an intermediate level where struts, formed by steel tubes, are installed. Finally, excavation to the final level and the subsequent pouring of the tunnel floor are realized. During all excavation works, the water table inside the building pit is lowered to maximum 0,50m below excavation level in order to reduce deformations of the retaining wall and nearby structures. After finalizing works, the eastern tube is ready for train exploitation and a similar building sequence will take place to realize the western tube and the underground parking.
The underground parking is executed simultaneously with the western tube. Therefore, the diaphragm wall between the western tube and parking space is replaced by an alternation of previously installed barettes and afterwards poured in situ walls. These in situ walls only reach from floor to roof level, thus reducing the amount of concrete works. Moreover, as the underground parking is to be built in a bottom-up sequence (due to the bigger width between the diaphragm walls, which would cause thick roof and intermediate floors), the excavation of the western tube could be done through the left open spaces between the yet installed barrettes.

**Figure 8: Second construction stage**

![Second construction stage](image)

Leakage problems with diaphragm walls are mostly related to discontinuities in the concrete works, often related to a too dense reinforcement grid, especially in the coupling area between the diaphragm wall and connected horizontal slabs. Therefore, several times, hammer headed reinforcement bars are employed, sometimes combined with coupler bars.

In the underground station area, concrete columns are foreseen at the middle of the cross section. Due to the large vertical forces, resulting from the office building on top of the station, foundations by means of diaphragm wall barrettes (points bearing in Pleistocene sand layers) are designed. As the demolition of the barrettes between floor and roof level of the station is very time and money consuming, the barrettes are filled with gravel over the height between these two horizontal slabs. To ensure the stability of the roof during excavation, steel H-beams are installed in the reinforcement cages of the barrettes. Once the total excavation is done, final concrete columns can be poured around the H-beams.

**Figure 9: Diaphragm wall barrettes**

![Diaphragm wall barrettes](image)