Design interactions of underground and surface structures

WOLTER ZIGTERMAN[1]

[1] ITC. (e-mail: zigterman@itc.nl)

Abstract: In city areas many different construction methods for tunnels have been applied. Depending on the local circumstances the tunnel may impose severe limitations to the future use of the ground above the tunnel. If a tunnel has to take up large loads from above it should be designed for this purpose. If this is not the case, special foundation methods are usually needed for the new buildings.

In The Netherlands a number of buildings, even up to 150 m high, have been constructed immediately next to or on top of tunnels, in some cases several years after the construction of the tunnel.

Also on top of U-shaped structures (tunnel entrances), constructions have been built. In one case the piled foundation that used to be under tension due to ground water pressure, was turned into a foundation under compression. For this office building only two foundation piles were driven just outside the U-shaped concrete structure.

The underground railway station Rotterdam Blaak is used to illustrate how large the variation of the surcharge on a tunnel can be. In this case it varies from 0 to almost 100 kPa.

The railway tunnels at Schiphol airport are examples of how the load from above is taken into account. The parts below the runway are capable to take up the impact forces of the largest airplanes, while on top of an other part future buildings up to four stories can be build above the tunnels, if required.

Résumé: Dans des conditions urbanisés différente méthodes de construction pour tunnels sont utilisés. Dependant a les conditions locals le tunnel peut posée des limitations importantes a l' usage en future du terrain au dessus du tunnel. Si un tunnel sera a prendre chargers grandes du dessus il est nécessaire a construir le tunnel pour cette condition. Si ce ne est pas le cas, des methodes de fondation special sont nécessaire pour les bâtiments nouveaux.

Dans les Pays Bas un nombre de bâtiments, jusque a un hauteur de 150 m, a eté construit immédiatement à côté de ou au dessus de tunnels, dans certaines cas plusieures années après le construction du tunnel.

Aussi au dessus des structures du type U (entrées de tunnels), constructions sont été fait. Dans une cas le fondation de piliers qui serait en tension par suite de pression de eau en haut, serait transformée dans un fondation en compression. Pour cette immeuble de bureaux seulement deux piliers nouveaux ont eté installé au dehors du construction de beton du type U.

Le gare sousterrain de Rotterdam Blaak est utilisé a illustrer comme grande le variation du surcharge au dessus de un tunnel peut être. Dans cette cas le surcharge change de 0 jusque á presque de 100 kPa.

Les tunnels de chemin de fer au dessous de l' aéroport de Schiphol sont examplaire pourr le methode á tenir compte des surcharges. Les parts au dessous des pistes sont capable a tenir les forces de impact de les plus lourds avions, lorsque un autre part permit le construction en future de bâtiments jusque á quatre étages, si nécessaire.

Keywords: tunnels**,** overburden, deformation, design, foundations, infrastructure

1. CONSTRUCTION METHODS FOR TUNNELS AND OTHER STRUCTURES BELOW THE GROUND LEVEL

For tunnels and similar underground constructions in soil with high ground water tables the following methods are used:

- Cut and cover method in open excavation;
- Cut and cover method between earth retaining walls with lowering of the ground water levels;
- Cut and cover method between earth retaining walls without lowering of the ground water levels;
- Wall and roof method;
- Pneumatic caisson method;
- Immersed tunnel method;
- Bored tunnel method.

The first two methods cannot be applied near to wooden piles, as these would deteriorate. For bored tunnels the minimum distance to existing piled foundations may lead to a very large depth of the tunnel. The wall and roof method and in particular the pneumatic caisson method make the removal of old wooden piles from the tunnel alignment very difficult due to the limited working height, and in the latter case the limited sizes of the air locks.

Where a tunnel has been constructed this may impose severe limitations to the future use of the ground above the tunnel. It should be noted that none of the tunnels as such is suitable to take up large additional loads from above next to those foreseen during construction. If the tunnel roof is designed in a traditional way, it cannot take up high point loads. Bored tunnels with their small lining thickness can not take up large additional loads from above. Excavation of the soil above a bored tunnel can even cause it to come afloat when it is immersed. The problem of differential load on a tunnel is not in all cases its bearing capacity, but the fear for differential settlements between adjacent sections. In the worst case this may lead to leakage. Concrete tunnels and U-shaped constructions have to be made in sections with a length of 15 to 20 m, because of the shrinkage that occurs during the hardening, and also afterwards. Between the sections a rubber sealing is placed, which allows only limited deformations. Prefabricated lining elements of bored tunnels usually have only a small rubber sealing. Tunnels which are held in position by tension anchors can not take up a large load from above without the risk for differential settlements. Above most tunnels in soil there are no buildings present.

The railway tunnels below Schiphol (Amsterdam Airport) are over a large length in equilibrium in relation to the foundation: some piles are under tension, others are under compression. The tunnel sections below a runway are adapted to the high point loads of large airplanes. Certain sections are designed in such a way that a building of at maximum four stories can in the future be realized above the tunnel.

2. BUILDINGS ON TOP OF TUNNELS

Above several tunnels in The Netherlands small buildings are present, e.g. both above the Maas Tunnel in Rotterdam, and the Velser Tunnel ventilation buildings are an integral part of the in-situ build part of the tunnel. The same applies to the Benelux Tunnel. In a part of the IJ Tunnel in Amsterdam, which was made with the pneumatic caisson method, the supporting construction for a future movable bridge was incorporated. Above one of the entrances of the Wijker Tunnel the building for the Regional Traffic Control Centre for the Highways was made. All of these structures formed an integral part of the tunnel design.

In the design of the underground railway station at Rijswijk loads due to future offices were foreseen in the design. On the south side of this station an office was built on top of the roof, extending to the east of the tunnel. The buildings planned in the central part were not realized until now.

3. BUILDINGS OVER AN EXISTING TUNNEL

The office building Delftse Poort in Rotterdam was constructed over the existing Metro Tunnel, see Figure 1 and 2.

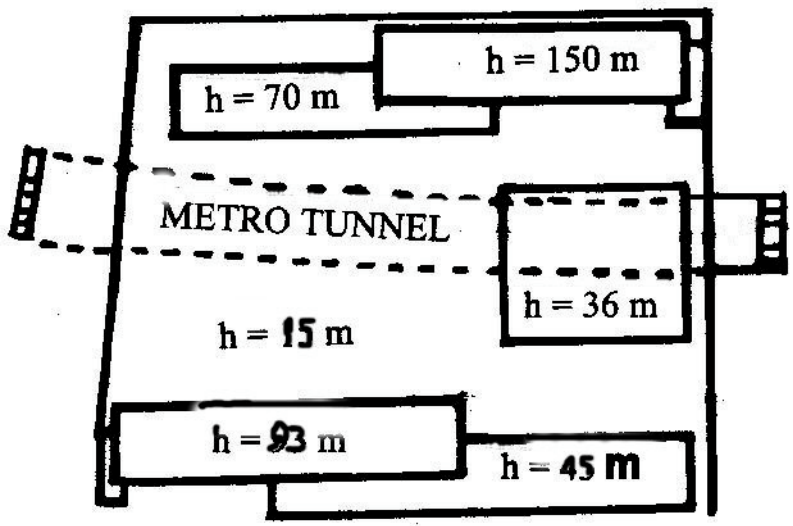

Figure 1. Lay-out of the building Delftse Poort in Rotterdam

The building part 1 (max. 150 m high) is located North of the Metro Tunnel. Part 2 (max. 93 m high) was made on the South side of the Metro Tunnel. Above the Metro Tunnel a basement and a building part 3 of 36 m high had to be made.

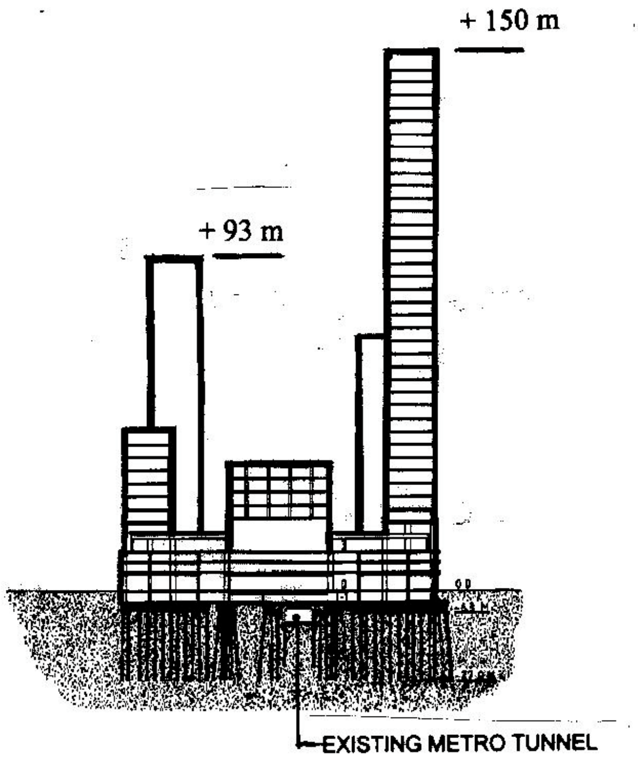

Figure 2. Cross section through the building Delftse Poort, showing the Metro Tunnel

The soil conditions at the site can be summarized as shown in Figure 3, see next page. The Metro Tunnel is located at 4 to 10 m below street level, it has been immersed on piles with a special pile head, see Figure 4, next page. The left part of this figure shows the pile head as it was installed in a temporary steel casing. The right hand figure shows the pile head after it was pushed upward against the floor of the tunnel,by pumping grout between the shaft and the head. There is no structural connection between the piles and the tunnel floor. The pile point level is app. NAP – 21 m. The bearing capacity of the sand between NAP – 18 and – 35 m is sufficient to carry the new office. Due to the clay layer between NAP – 35 and – 51 m settlements will occur to a maximum of 80 mm, which are not a problem for the structure of the office. But the Metro Tunnel would settle approximately 50 mm, which was not acceptable.

To solve this problem the following solutions were considered:

- place the office at piles to approximately NAP – 55 m;
- give the Metro Tunnel a new foundation at app. NAP – 55 m;
- make a new foundation for the Metro Tunnel at app. NAP – 27 m, with an adjustment facility to compensate the settlements.

The last solution was chosen, see Figure 5.Above the Metro Tunnel a ballast floor was made to compensate for the excavated soil. In the building structure North-South running pre-stressed walls were made to bridge over the Metro Tunnel. These are not in contact with the tunnel. It is foreseen that settlements may continue after the completion of the building. For that situation hydraulic jacks are available to adjust the position of the Metro Tunnel.

To build the basement an excavation to NAP – 7 m was needed. This was done in a closed construction dock with temporary sheet piled walls. But below the Metro Tunnel a gap existed, due to its special foundation method. From a tube placed next to the Metro Tunnel a grout injection was carried out. The Metro Tunnel and the new building are completely separated from each other by joints, which allow the expected settlement of the building to occur without any effect upon the Metro Tunnel. It is obvious that the presence of the Metro Tunnel made the foundation of the new building fairly complicated.

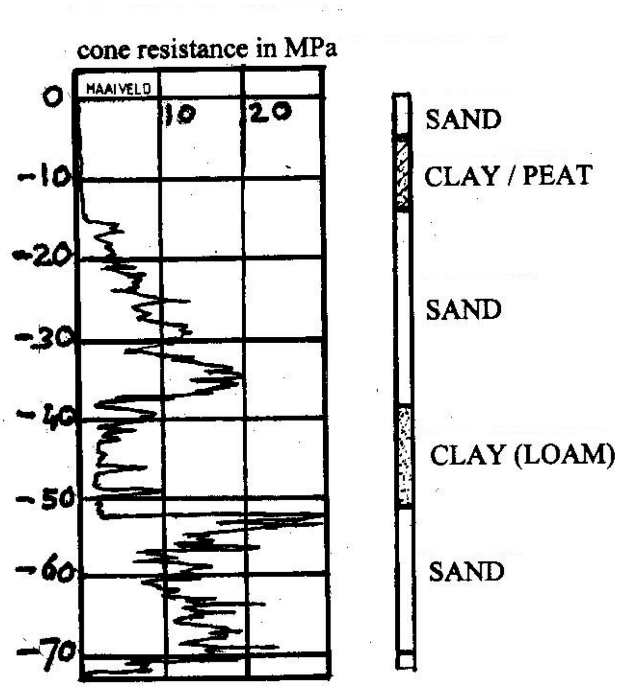

Figure 3. Representative Static Cone Penetration Test and bore hole at the site in Rotterdam

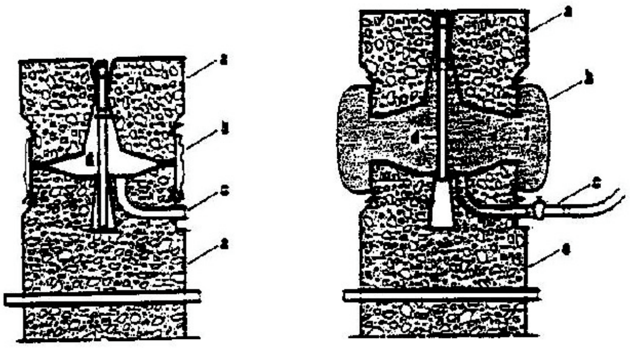

Figure 4. Pile head as used for the North-South Metro Line in Rotterdam

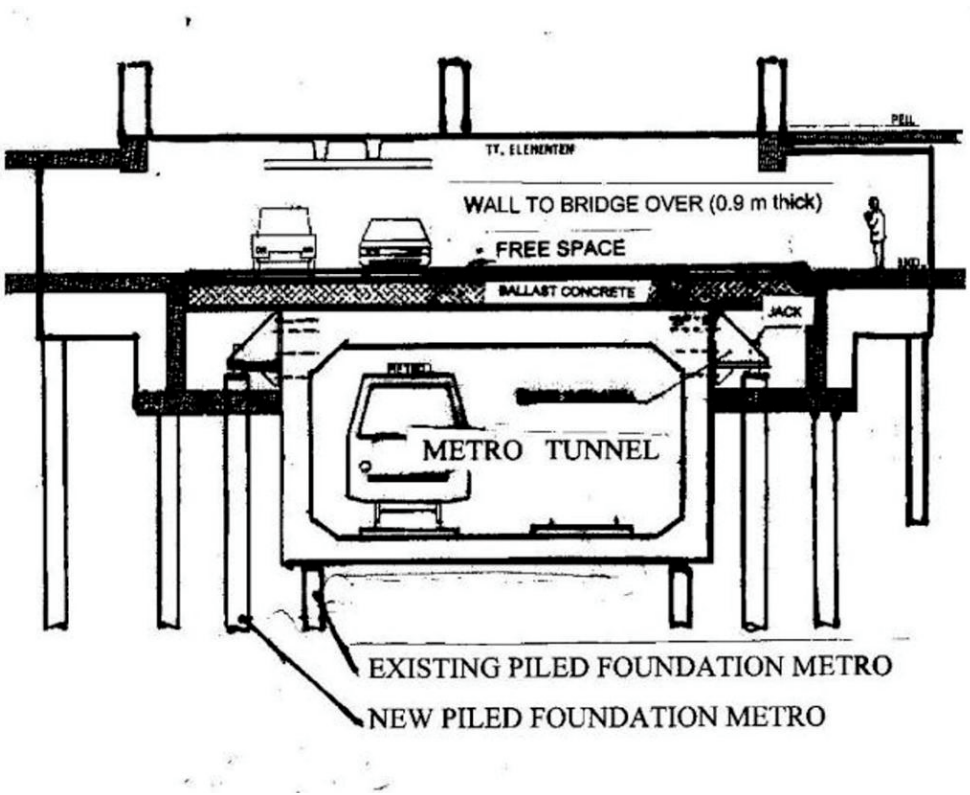

Figure 5. Cross section of Metro Tunnel with new foundation and hydraulic jacks

4. BUILDING PARTLY ON A TUNNEL

On top of the southern entrance of the IJ Tunnel in Amsterdam the building New Metropolis (NEMO) was built (Zuidwijk, 2003). In this case prefab concrete girders were placed on the tunnel entrance, to reduce the hindrance for the traffic. The tunnel entrance carries 70 % of the load of the building.

For the construction of the underground railway station Rotterdam Blaak, which is a part of the railway to the South that crosses the river Nieuwe Maas by a tunnel, a number of old merchant houses which crossed the tunnel alignment had to be removed (Municipality of Rotterdam). It was decided to reconstruct these houses after the completion of the station. This part of the station was constructed in a closed construction dock formed by diaphragm walls reaching to NAP – 33 m, into the top of the clay (or loam) of the Kedichem formation, see Figure 6. In the final situation a concrete plate was cast supported by the roof of the tunnel, by the diaphragm walls, and by foundation piles. On this plate the reconstruction of the buildings took place. Between these buildings and the concrete plate rubber blocks were installed to prevent low frequency vibrations from passing trains to reach into the buildings.

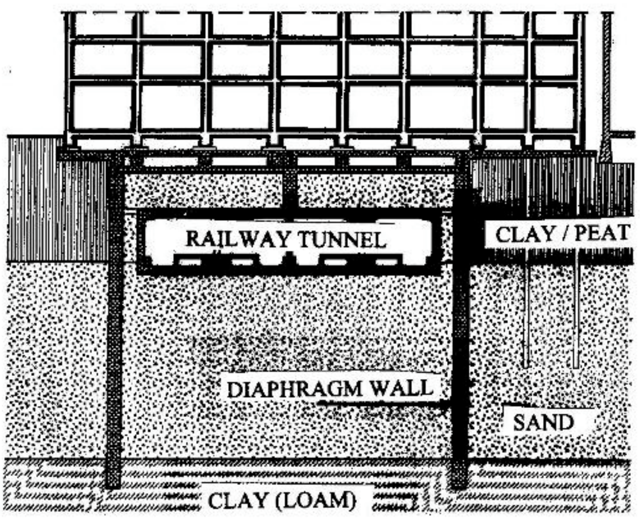

Figure 6. Reconstructed buildings partly supported by Railway Tunnel, partly by diaphragm walls, partly by piles

5. BUILDINGS OVER AN EXISTING U-SHAPED STRUCTURE

One of the few examples of double use of the ground is formed by the Utrechtse Baan motorway in Den Haag with offices above the motorway. The easternmost office building was made as a huge arch. This structure spans the motorway with an "own" foundation, not connected to the U-shaped construction in which the motorway is located.

But a bit more to the west the Equinox office was built over the Utrechtse Baan by using the bearing capacity of the existing U-shaped structure (Zuidwijk, 2003). Outside the U-shaped structure only two foundation piles were required, see Figure 7. The tension piles below the U-shaped structure changed during the construction of the building into compression piles. Calculations showed that the differential settlements between the sections of the U-shaped structure were within the allowable limits. This means that there is no risk for leakage through the joints between the sections.

Figure 7. The Equinox building above the Utrechtse Baan in Den Haag

6. VERTICAL LOADS ACTING ON TUNNELS

In the circumstances in which in The Netherlands most tunnels are made, with a very high ground water level, tunnels and U-shaped structures mostly have the tendency to come afloat if no ballast would be present. How large the variation of the vertical load on the roof of a tunnel can be illustrated with a longitudinal cut through the railway station Rotterdam Blaak, see Figure 8.

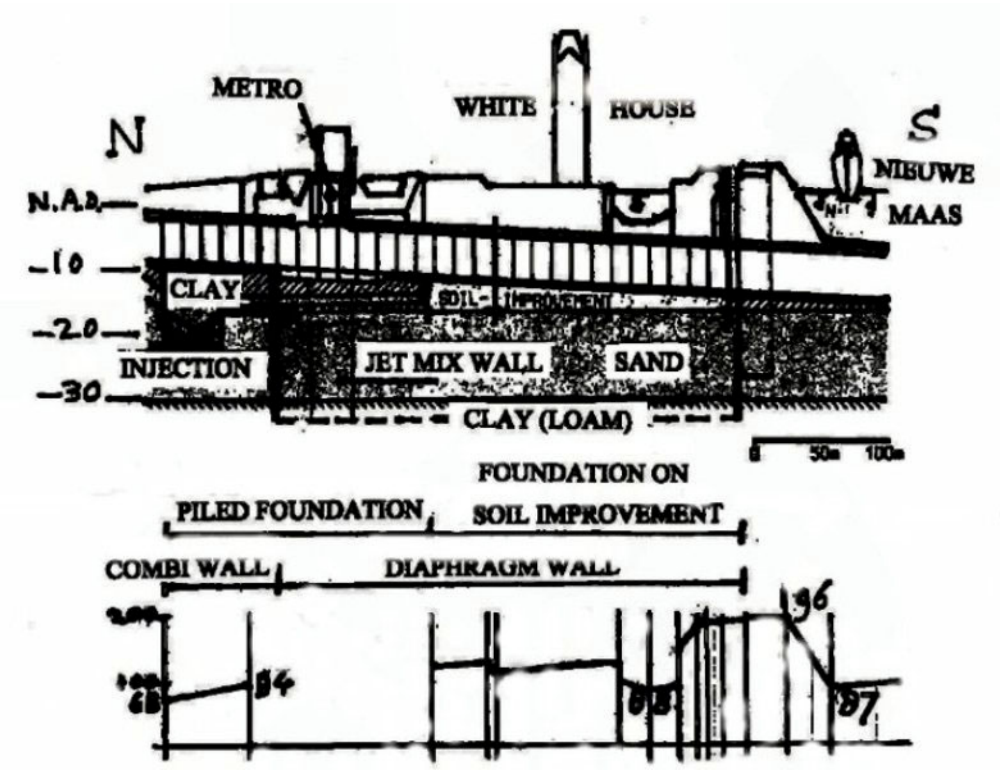

Figure 8. Longitudinal section through the Railway Tunnel around the station Rotterdam Blaak, showing the vertical loads acting on the roof of the tunnel

Below the dike along the tidal river Nieuwe Maas the stress reaches almost 100 kPa, whereas around the entrance of the station it is 0, because here is an opening in the roof, where moving staircases give access to the platforms.

South of the entrance opening the Railway Tunnel is crossed by the Metro Tunnel which was designed as an underground bridge many years ago, in the possible alignment of a future Railway Tunnel.

Acknowledgements: I thank Aronsohn Constructies for the information about the office Delftse Poort, and Mr. Hielke Zuidwijk of D3BN Civiel Ingenieurs for the information about the NEMO-building and the Equinox-building.

Corresponding author: Mr Wolter Zigterman, ITC, Hengelosestraat 99, P.O. Box 6, 7500 AA Enschede, The Netherlands. Tel: +31 53 48 74 224. Email: zigterman@itc.nl.

REFERENCES:

BOO, ir. A.J. DE and ir. D.G. MANS, 1990, Delftse Poort, hoogste kantoorgebouw van Nederland, Cement 1990, nr. 4 (Delftse Poort, highest office building in The Netherlands).

MUNICIPALITY OF ROTTERDAM, various publications.

ZUIDWIJK, HIELKE, 2003, personal communication about the NEMO building and the Equinox building, and draft text of publication in Cement about the Equinox building.