New building plans on the surface above the existing underground Willemspoortunnel in Rotterdam

Ragavan Appiah, Aronsohn raadgevende ingenieurs bv, Rotterdam, The Netherlands

The development of new projects in many cities at present deals with problems when locations of new buildings and the surface of the building area come closer to underground tunnels. When new buildings are to be realized on the surface of an underground tunnel track, some questions will show up with respect to the safety of the tunnel as well as the foundation or any restrictions for the new building design considering the tunnel safety. Both the construction phases and the final phase of the buildings may cause problems for the tunnel. In such situations it should be clear whether any problems do occur and if so, what restrictions the building design (and foundation design) should follow.

An Msc thesis project at the Technical University of Eindhoven has been carried out in association with the engineering consultant Aronsohn, to estimate the problems for the new buildings planned in Rotterdam on the surface of the existing 'Willemsspoortunnel' in the area called the 'Linker Maasoever'.

Rotterdam is a city which counts the most High-rise buildings in The Netherlands. After the Second World War the city was fully developed with new buildings and (underground) infrastructure. Rotterdam is often referred to the river 'De Maas'. The 'Nieuwe Maas' is one of the most overbridged rivers in the Netherlands and also has the most underground tunnels crossing the river. One of the most important railway tunnels in Rotterdam is the 'Willemsspoortunnel', which has been in use since 1993.

In Figure 1 a top view of Rotterdam with the track of the Willemsspoortunnel is shown. The Willemsspoortunnel has a total length of 3.4km and has a maximum depth of 19m beneath the surface. The Willemsspoortunnel was built to replace the existing railway bridge due to the need of a bigger transport capacity. The tunnel has four tracks and has therefore a rectangular shape with four tubes and a maximum width of the cross section of 26 meters. The major part of the tunnel is built using the 'cut and cover' method, which represents a dry pit using sheet pilings and constructing the tunnel in situ. The parts of the tunnel crossing the river were built using the 'Sink method'. Separate parts of the tunnel were built elsewhere in a dry dock, and then floated into place and sunk into a trench dug in the river bottom. This is a technique used in many other Dutch tunnels after the 'Maastunnel', which was the first sink tunnel in Rotterdam.

Since the tunnel has been in use, the full area above the tunnel track is kept as open area used for car parking and some sports grounds. At the moment the municipality of Rotterdam made a new urban plan for this area. The new plans are to build some apartment buildings combined with offices on the left side of the river called the Linker Maasoever (Figure 1). Aronsohn engineering,

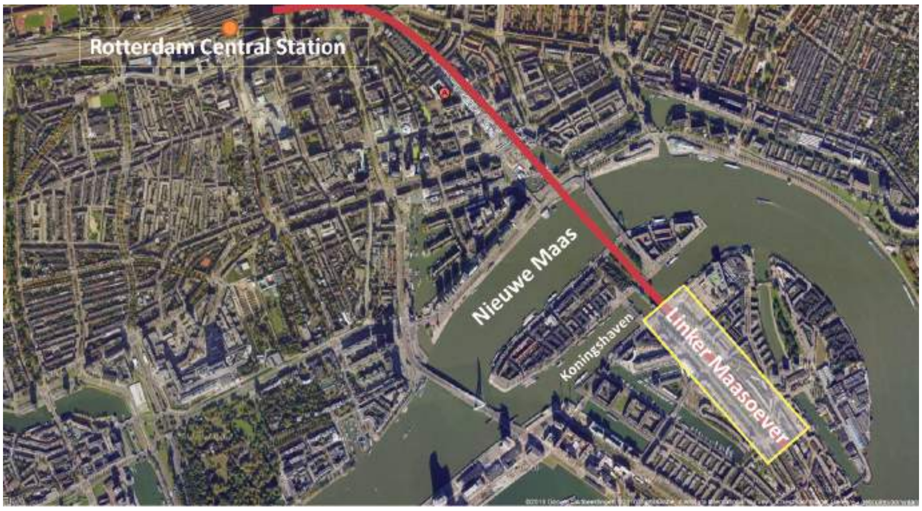

Figure 1: Top view of Rotterdam with the track of the Willemspoortunnel from the Linker Maasoever towards Central Station

specialized in civil engineering, is involved in the developments of the new buildings at both side of the river. The tunnel segments on the right side of the river were calculated on possible building loads in the future. For the parts of the tunnel at the left side of the river no extra (future) building loads on the surface were taken into account for the concrete tunnel structure. Together with Aronsohn the municipality has made a building plan for the Linker Maasoever which could be possible to build in this area. In the thesis project this urban plan has been used to make pioneering estimations of the tunnel settlements due to the new building loads, using PLAXIS 2D.

The Kedichem layer

The Kedichem layer characterizes the deeper soil structure in the Rotterdam area. This layer is situated just below the first sand layer, where most of the buildings are founded on. The first load bearing sand layer in Rotterdam is between 18 and 30m -NAP. Below this layer, the layer of Kedichem layer has a varying thickness of about 10 to 15m. Below the Kedichem layer there is a moderate sand layer followed by a soft sand layer with clay parts. In Figure 4 a soil section of the Linker Maasoever is given, with the tunnel situated in the ground. The problem of this layer is the fact that, due to heavy loads from above it will settle very slowly. Most highrise buildings in Rotterdam with pile foundations on the first sand layer show a uniform settlement of the buildings up to 200mm. For example an almost uniform settlement of 150mm was measured at the highrise building of the Erasmus Medical Centre.

For this project the soft Kedichem layer can be a critical factor which can cause settlements of the tunnel cross section. Due to the increase of the stress in the Kedichem layer, caused by the new foundation loads, the clay layers can experience some settlements as described before. When settlements of the Kedichem layer do occur it can lead to local settlements of the tunnel cross section depending on the range of the soil settlements.

In normal cases the most obvious and also the most beneficial foundation type of a building would be a pile foundation on the first sand layer, like most buildings in Rotterdam. In this exceptional situation it is maybe not obvious to choose for this solution. To make decisions regarding the total building load, foundation type and depth of piles etc, we first have to analyze whether any critical situations for the tunnel will occur. Two hypotheses of tunnel settlements depending on the behavior of the Kedichem layer are shown in Figure 2.

Hypotheses for tunnel settlements

Regarding the tunnel safety and any disturbances which could lead to traffic failure, two main preconditions have been stated for the tunnel deformations (Figure 3). It should be clear that the tunnel settlements should never lead to cracks in the concrete structure. The strength of the concrete tunnel structure was calculated on a maximum pressure corresponding to a maximum torsion of the tunnel cross section of 10mm. This means that the deformation of the tunnel should not exceed the maximum difference in settlement of 10mm between the left and right site of the cross section. According to this restriction all the construction activities as well as the final phase of the buildings should be symmetric to the tunnel cross section.

Uniform settlement of the tunnel section is limited to the maximum difference permitted at the joints between two tunnel segments. The maximum value is dependent on the maximum adjustability of the joint of the railway tracks.

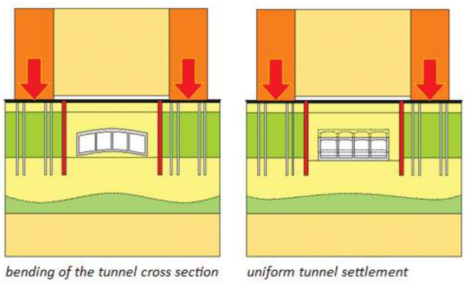

Figure 2: Predictions of tunnel settlement at symmetric building loads

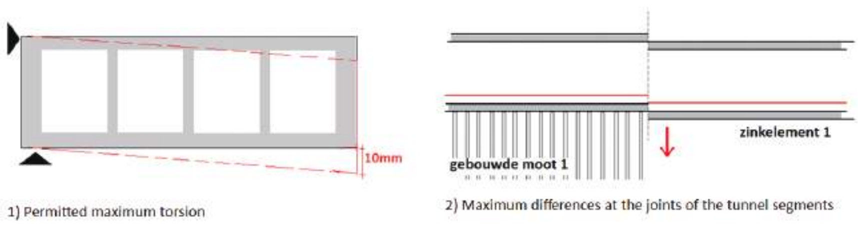

Figure 3: Preconditions to tunnel settlements

Cuurent Situation

The current situation of the cross section at the Linker Maasoever is given in Figure 4. For the tunnel two important cross sections can be discussed. Section A is the profile at the transition (joint) of the in situ tunnel segment and the first sink element. Section B is the cross section where, according to the urban planning, the largest foundation loads will take place. The in situ tunnel segments have a pile foundation which means that these segments will behave stiffer than to the sink elements which lay on the soil surface. Due to the differences in stiffness of the supporting system, big differences can take place at the joint of the two tunnel segments when soil settlements take place around this area. It is assumed that the influence on the in situ tunnel part will be much less because of the pile foundation. In Figure 4 you can also see that the existing sheet piling (combi walls), which were used for the construction of the tunnel, have been kept in the ground. These combi walls have large steel pipes of 1,5m diameters with in between sheet pile planks. Because of the large pile dimension and the pile foot located in the sand layer, these steel tubes can be used as foundation piles. A calculation of the bearing capacity of the combi-wall shows that the piles can be used as foundation for a five-storey high building.

Research Approach

To analyze the influence of the new building plans on the existing tunnel, several research models have been defined regarding the situations which take place in the urban planning. An overview of the research models are given in Figure 5.

Beside the possible soil settlements due to the building loads, excavations of soil above or nearby the tunnel area, during the construction phase, can also influence the tunnel structure. In

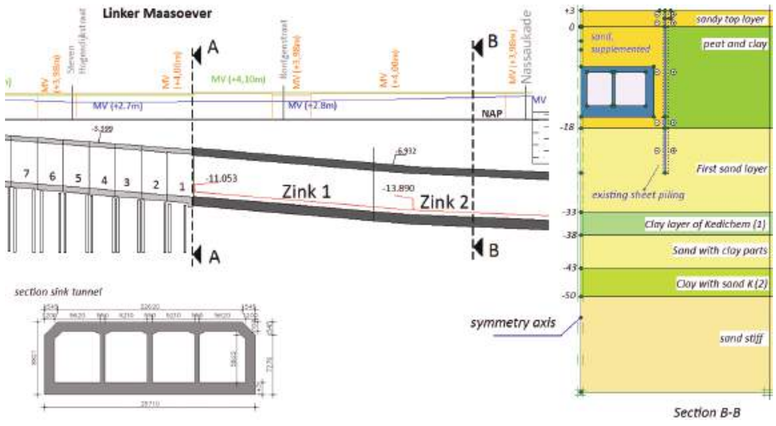

Figure 4: Tunnel section at the transition of the in situ tunnel segments and sink tunnel elements.

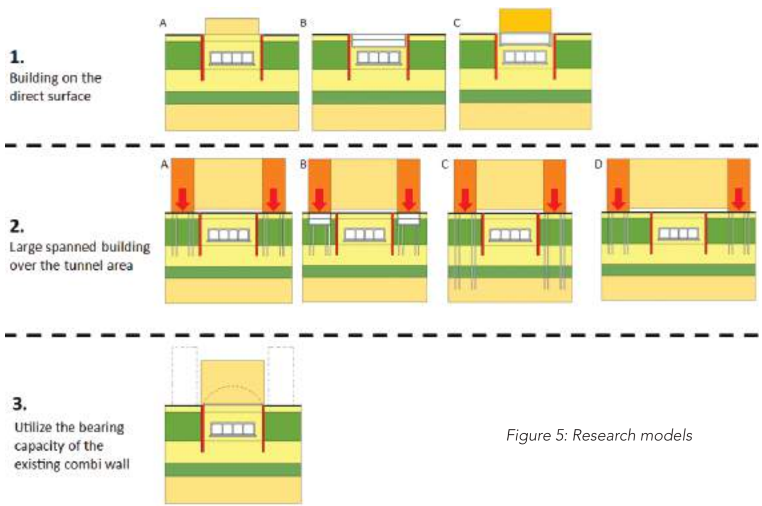

Figure 5: Research models

Parameter	HS		top sand	Clay	1st sand layer	Peat	Clay and peat	Sand with silt	Sand (plstcn)	Silt with sand
(RD/PI.index)	RD / PI (%)	(%)	40	40	50	80	20	25	80	50
Soil unit weight ab. PI	Y_{unsat}	kN/m^3	16.6	16	17	12	16	16	18	17
Soil unit weight bel. PI	Y_{sat}	kN/m^3	19.6	18	19.8	19.8	19	19.4	21	19.8
Hor.izontal Permeability	K_x	m/day	0.1	0.001	0.2	0.002	0.01	0.1	0.5	0.2
Vertical permeability	K_y	m/day	0.1	0.001	0.2	0.002	0.01	0.1	0.5	0.2
Secant Stiffnes for CD triax	E_{50}^{ref}	kN/m^2	24000	2500	30000	1250	4000	15000	48000	30000
Tangent eodometer stiffness	E_{oed}^{ref}	kN/m^2	24000	1250	30000	625	2500	15000	48000	30000
Unloading/reloding stiffness	E_{ur}^{ref}	kN/m^2	72000	10000	90000	5000	16000	45000	144000	90000
Power for stress depend.stiffness	m	-	0.575	1	0.54	1	0.8	0.62	0.45	0.54
Reference stress	P_{ref}	kN/m^2	100	100	100	100	100	100	100	100
Poision's ratio	v_{ur}	-	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Lateral stress coefficient	K_0^{NC}	-	0.4554	0.55	0.55	0.61	0.48	0.485	0.3843	0.44
Cohesion	c_{ref}	kN/m^2	0	3.5	0.2	5	1	0.2	0.2	0.2
Friction angel	φ	o	33	27	34	23	31	31	38	34
Dilantancy angle	ψ	o	3	0	4	0	1	1	8	4
Interface reduction factor	R_{inter}	-	0.7	0.6	0.7	0.6	0.65	0.65	0.7	0.7
Reference shear modulus	G_0^{ref}	kN/m^2	87200	94000	94000	10900	35000	77000	114000	94000
Shear strain at Gs=0.772 (77.2%)	$V_{0,772}$	-	$1.60E^{-04}$	$1.50E^{-04}$	$1.50E^{-04}$	$2.30E^{-03}$	$2.60E^{-04}$	$1.75E^{-04}$	$1.20E^{-04}$	$1.50E^{-04}$

Table 1: Model parameters PLAXIS 2D Hardening Soil

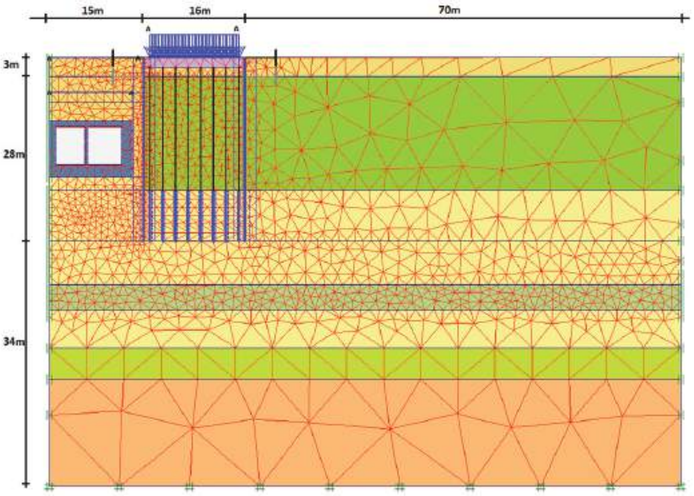

Figure 6: 2D model; Foundation on the first sand layer

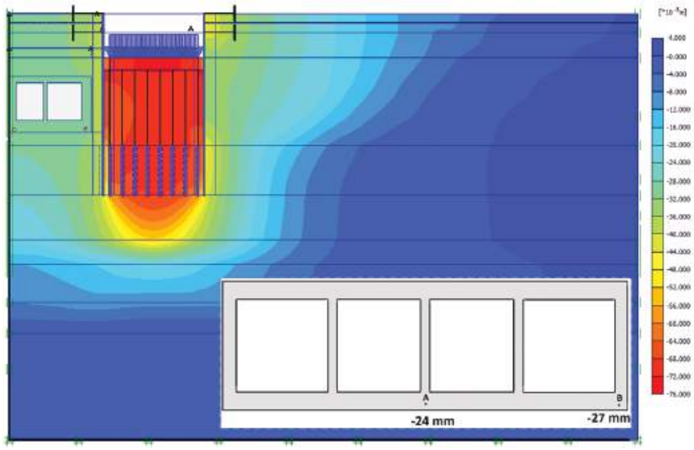

Figure 7: Results settlement tunnel, deformation tunnel section; foundation on 1st sand layer

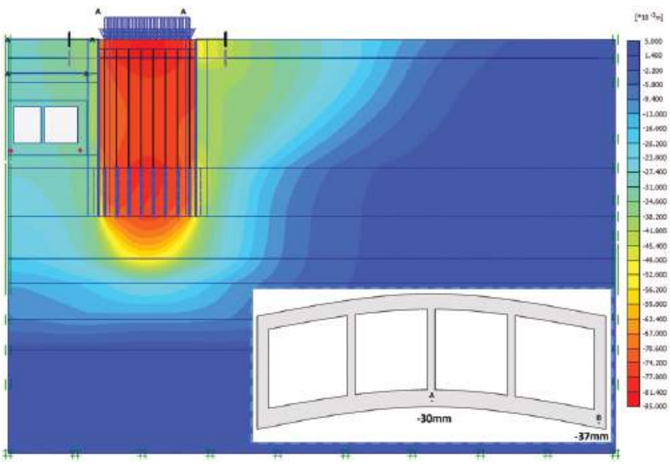

Figure 8: Results settlement tunnel, deformation tunnel section; foundation on 1st sand layer with 9m excavation

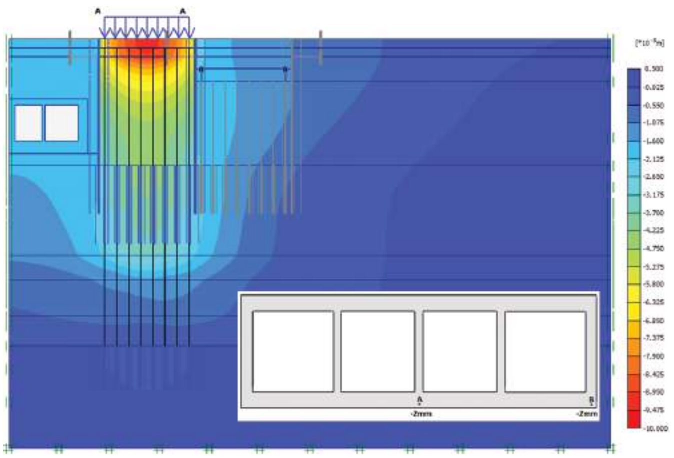

Figure 9: Results of settlement tunnel floor; foundation on 2nd sand layer

order to analyze these models FE modeling was undertaken using PLAXIS 2D V8.2. In this article only some main issues will be discussed, focusing on the settlements and deformations of the tunnel caused by the settlement behavior of the Kedichem layer.

Description of the model

Based on CPT's and the use of the validated empirical formulas for deriving model parameters for sand [1], a parameter set was made. The model parameters used for this project are given in Table 1. The soil structure has been modeled as shown in Figure 6. As discussed earlier in this article the building plans and the construction activities are determined to be symmetrical to the tunnel cross section. As you can see in Figure 6 the symmetry properties are also used in the 2D model.

The tunnel has been modeled as a soil body with linear elastic concrete properties. The building loads at the foundation levels are introduced by using a thick underwater concrete slab with linear elastic properties. This stiff concrete slab spreads the load over the foundation piles which reach the sand layer. The foundation piles are partially modeled as node-to-node anchors. At the levels where pile friction is allowed the piles are modeled as plates. The combi wall is modeled as a plate with the corresponding stiffness properties. Figure 6 shows one of the models which is used in this project. The model is made 100m wide and 65m deep so that the spreading of loading and unloading will take place without significant influences of the boundaries. To measure the settlements of the tunnel there are two 'points for curves' added in the middle of the tunnel floor and at the outer edge of the tunnel floor.

Influence of the Kedichem layer

For the analysis of the influence of the Kedichem layer on the tunnel three major foundation designs can be discussed. These are the models with foundation load at the first sand layer, foundation load at the first sand layer with a deep excavated basement pit and the deeper pile foundation beyond the Kedichem layer with pile friction in the first sand layer. The friction loads in the first sand layer, when choosing deeper foundation, can have effect on the Kedichem layer as well. To analyze this interface values (Rinter) values between 0.7 and 1.0 have been used for the piles which are modeled as plates. The maximum foundation load can be compared with a nine-storey building with a minimum span of 35meters above the tunnel. The results of the three models can be found in Figure 7, Figure 8, and Figure 9.

The model with the foundation load distributed in de first sand layer, shows a significant settlement of the Kedichem layer. This leads to a certain spreading around the foundation area. The range of this spreading of the soil settlement does reach the tunnel. At the middle of the tunnel a maximum settlement of 30mm is measured. The maximum settlement at the outer edge is 37 mm.

In a second model the effect of decreasing the final load by using an excavated basement pit is tested. By using an excavated pit the final pressure above the Kedichem layer will be reduced by the weight of the excavated soil and the buoyancy force on the basement floor. In this model an excavation of 9m deep pit with ground water flow calculations have been carried out. When we look at the results a reduction of almost 10 % of the tunnel settlements is found. This is similar to the excavated soil weight.

When the foundation at the first sand layer would be considered as critical, the solution can be found by distributing the foundation loads at the deeper sand layers beyond the Kedichem layer. In this case only the friction of the pile shafts along the first sand layer may have any influences on the Kedichem layer. The load distribution along the first sand layer is dependent on the friction factors of the piles. For the calculation the friction is modeled with interface factors as described before. The results show that the shaft friction does have a certain influence on the Kedichem layer but the values are considerably less than the two models discussed before. For this model a uniformly distributed settlement of the tunnel floor of 2mm is found.

Conclusions

The results of the models discussed in this article can only be used to conclude if the Kedichem layer will have any influence upon the tunnel elements or not. In that case the answer can be given as yes. But when we look closer to the real situation there are many other factors which also will have major influences on the behavior of the tunnel parts. In reality the whole situation should be analyzed in 3D, because a lot of 3D factors of the tunnel can have (positive) influences on the tunnel. For example the stiffness of the tunnel in the longitudinal direction compared with the spreading of the soil around the foundation in 3D directions. In the calculations there are also many assumptions made to make first estimations of the problem. Because of the lack of any laboratory tests of the soils, the soil data have been obtained by using the empirical formulas for deriving model parameters [1]. The properties of the Kedichem layers are obtained with the assumption that the soil layers are normaly consolidated.
In reality the Kedichem layer is expected to be overconsolidated due to ice loads in the past, which could mean that it could lead to lower settlement values. A recommendation for this project is to obtain the real stiffness values of the Kedichem layer by using laboratory test. For the design part of this thesis project a (structural) building design was made with pile foundation in the second sand layer, 60m below surface. Figure 10 gives an architectural impression of the final building design.

Reference

- Brinkgreve, R.B.J, Engin, E,Engin, H.K, 'Validation of empirical formulas to derive model parameters for sands'; Numerical methods in geotechnical engineering 2010, Edited by Benz, T. & Nordal, S.; CRC press; Balkema
- PLAXIS 2D Material models manual, V8.0 Plaxis b.v 2006
- PLAXIS 2D Reference manual, V8.0 Plaxis b.v 2006

Figure 10: Architectural impression of the building design at Nassaukade, Rotterdam

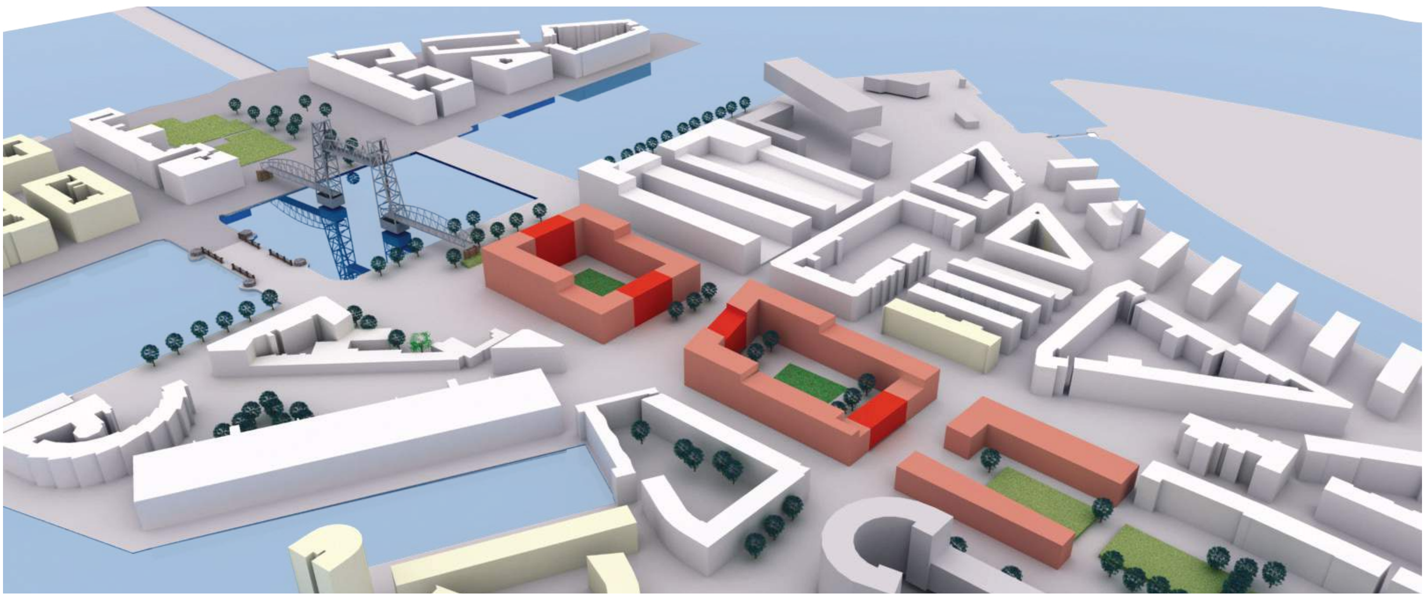

Figure 11: Urban planning for the Linker Maasoever, along the surface of the Willemsspoortunnel track