Evaluation of the up and down movements of the Vlaketunnel with cyclic analysis using PLAXIS 2D

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As part of the InfraQuest research into the sustainability of Immersed tunnels in the Netherlands, a study was carried out at Delft University of Technology to analyze the up and down movements of the Vlaketunnel. InfraQuest is a joint research program of the Ministry of Infrastructure, Delft University of Technology and Delft TNO. The research was done by N. Benhaddou as a final MSc. Project.

The Vlaketunnel is a highway tunnel under the canal through Zuid-Beveland in the A58 road, connecting the city of Bergen op Zoom with Vlissingen.

In Figure 1 a top view of the canal with the track of the tunnel is shown.

The tunnel sections beneath the canal were built with the immersed tunnel technique. The concrete elements of the tunnel were built in a dock situated just beside the canal. After finishing the construction, the dock was inundated to allow floating of the elements and transportation to the immersion site over water. The elements were immersed into a pre-dredged trench of about 10 m deep. The free space between tunnel and bottom trench was filled up with sand, that was dredged from the Western Scheldt, and formed a foundation layer. Also on either side and on the top of the tunnel sand was deposed; backfill material. To protect the roof of the tunnel against damage caused by falling or dragging ship's anchors, a stone-asphalt-mattress was installed on the top of the tunnel, see Figure 2.

To improve the maritime traffic flow through the canal, in 1993 it was decided to remove the lock at the north side of the canal that closes the canal of the Eastern Scheldt estuary, and as a consequence tidal movements from the North-sea were introduced into the canal.

The executive department of the Dutch Ministry of Infrastructure (Rijkswaterstaat) is responsible for the functioning of tunnels in the Netherlands. Deformations and settlements of the tunnels are frequently monitored. An evaluation of the data which has been delivered for the Vlaketunnel indicates that the tunnel clearly shows up and down movements, two times daily, coinciding with the tidal movements.

Besides the immersed section, the tunnel consists also of access ramps. To prevent the access ramps from floating or shifting upwards, the tunnel sections were provided with tension anchors. Mainly due to brittle fracture by pitting corrosion of the anchors and in a certain extent to tide effect, floating of one of the sections of the eastern access ramp is occurred in 2010.

The results described in this article are based on the research conducted on the submerged section of the Vlaketunnel. The aim of the research was to determine the physical cause behind the measured up and down displacements of the submerged section.

Figure 1: Top view of the location of the Vlaketunnel

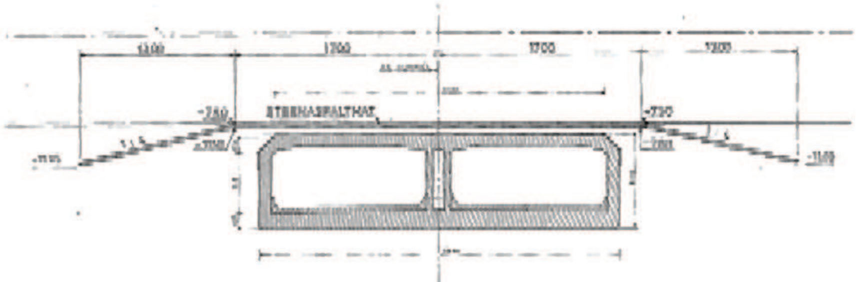

Figure 2: Cross section of the immersed section of the Vlaketunnel

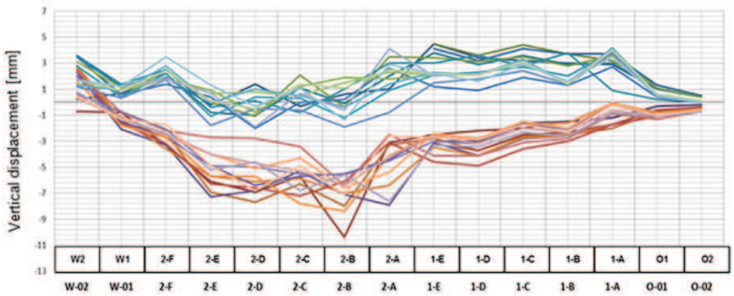

Figure 3: Graphical view of the measurements performed during high and low tide on March 27 - April 12, 2002

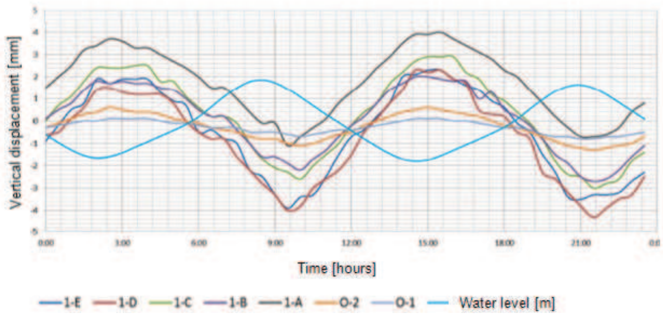

Figure 4: Graphical view of the daily measurement, April 3 2002

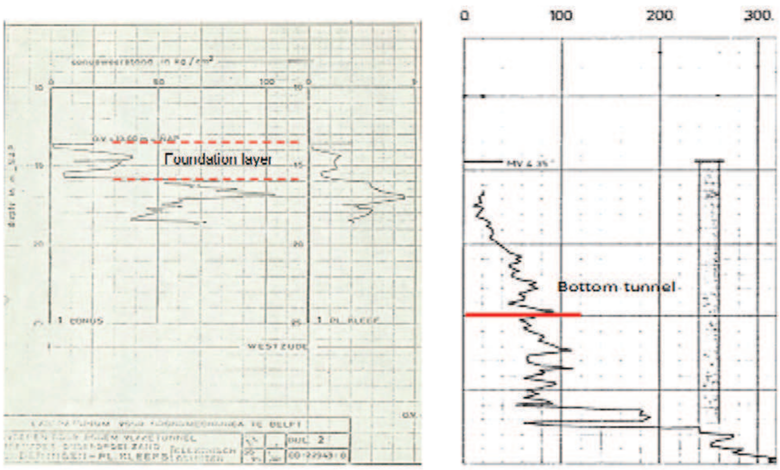

Figure 5: (a, left) CPT carried out through the floor of the tunnel in 1975. (b, right) CPT carried out before the realization of the tunnel; (please note that the graph is in kgf/cm², and not in MPa, such is customary nowadays).

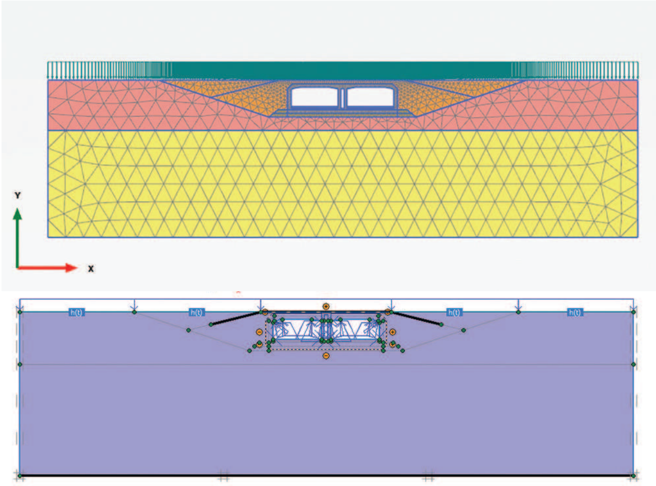

Figure 6: 2D Model, cross section

Measurements

In the context of a monitoring program that was carried out by Rijkswaterstaat, as previously mentioned, measurements had been performed in the tunnel in order to determine the movements of the tunnel as a result of water level changes in the canal. The measurements were performed during high and low water periods on March 27 to April 12, 2002. The results of these measurements are graphically represented in Figure 3. The graph shows the ultimate position of the tunnel during a complete tidal cycle. The horizontal axis represents the location of the measurement points along the longitudinal axis of the submerged section.

The vertical axis shows the vertical displacement. Figure 4 shows the daily variation in time of tunnel element 1 on April 3, 2002; the blue line in the graph indicates the water level in the canal, on this scale in [m]. The other lines indicate the displacement of fixed points of the tunnel element 1 (which consist of 7 tunnel segments) in [mm].

The graphs shows clearly that the submerged section of the Vlaketunnel experiences vertical motions that are related to the water level changes in the canal. During low tide the submerged section comes up and during high tide it settles down. An average subsidence and uplift of between 4 and 8 mm respectively, is registered.

From the measurements shown in Figure 4 it can be deduced that the tunnel movement and water level changes are not in phase. Maximum water level and maximum subsidence occurs not at the same time. This indicates the presence of a certain resistance by means of (low) permeability of the foundation and the back fill material. A phase shift of up to 1.0 hour is observed.

Soil survey

In order to infer soil parameters for the sand foundation layer, penetration data, that was realized by CPT testing through the bottom of the tunnel direct after the realization in 1975, was re-evaluated. The CPT data, see Figure 5, shows that the cone resistance of the foundation layer - consist of sand which has been filled into the free space between the bottom of the tunnel and the trench - is about 3 MPa. Below this layer the soil profile mainly consists of loosely packed sand of about 5 meter, followed by the Pleistocene sand. A typical behaviour of loose sand under cyclic loading is contraction and dilatancy.

Hypothesis

After analyzing the measurements and the soil survey a hypothesis regarding the physical cause of the motions of the immersed section is formulated. It is assumed that the soil beneath the tunnel exhibits elastic behaviour. Directly after the high water peak the saturated subsoil just beneath the immersed section experiences an increase in effective stress. This causes compaction in the loosely packed sand layer and the water is discharged from this layer into adjacent soil profile. After dissipation the tunnel section tends to settle. Directly after the low tide the opposite effect takes place. The now slightly denser sand layer experiences some decrease in effective stress that results in a small expansion of the soil skeleton. Water from the adjacent soil profiles is attracted and the tunnel tends to move upwards.

Model

Based on the soil survey, which consisted of CPT's a parameter set was established. The parameters are assumed based on overall experience with soil materials and NEN9997-1. The parameters used are summarized in Table 1. The topology was been modelled as indicated in Figure 6. In order to minimize the effects of the boundaries the geometry has been chosen 100 meter wide and 50 meter deep.

The essence of the model is that it describes the deformation of the soil layers beneath the tunnel due to time-dependent variation in the water level. So an integrated Geo hydro mechanical model was established, that includes the time dependent loading on one hand and on the other hand describes the effects of this loading on soil deformation.

The tunnel has been modelled as a soil body with linear elastic properties (for concrete).
To simulate the interaction between tunnel lining and soil, interface elements were applied.

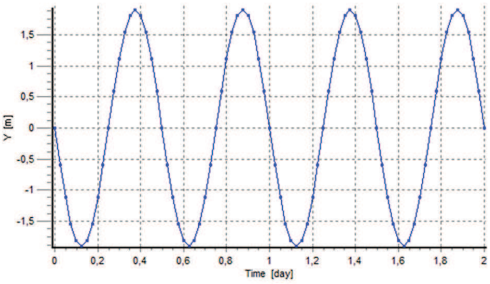

Figure 7: Used hydraulic boundary condition in PlaxFlow

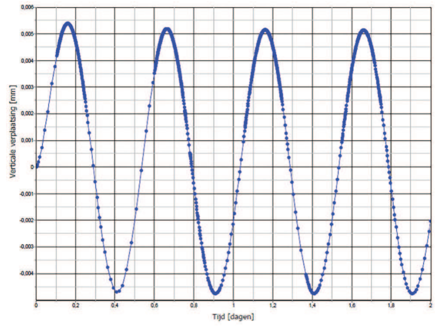

Figure 8: Predicted up- and downwards movements

	Backfill material: sand	Sand, loosely packed	Foundation material: sand	Pleistocene sand
Model	MC	HSSMALL	HS	HSSMALL
γ_{sat} [kN/m³]	16	17	15	19
c' [kPa]	1	1	1	1
φ'[°]	30	30	22,5	35
ψ' [°]	0	0	0	5
K0,nc [-]	-	0,500	0,617	0,426
$E_{50;ref}$ [kPa]	1,5E+04	2,0E+04	5,0E+03	5,0E+04
$E_{oed;ref}$ [kPa]	-	2,0E+04	5,0E+03	5,0E+04
$E_{ur;ref}$ [kPa]	-	6,0E+04	10,0E+03	15E+04
ν_{ur} [-]	-	0,2	0,2	0,2
$\gamma_{0.7}$ [-]	-	0,1E-03	-	0,1E-03
$G_{0;ref}$ [kPa]	-	50E+03	-	125E+03
k_h [m/day]	0,5	1,0	2,5	10
k_v [m/day]	0,5	1,0	2,5	10
POP [kPa]	-	10	10	10
OCR [-]	-	1	1	1

Tabel 1: Model parameters PLAXIS 2D

The stone-asphalt-mattress on the top of the tunnel is modelled with plates and interfaces and assumed to be impermeable.

In the first calculation steps the trench excavation and the initial construction of the tunnel was modelled. Afterwards the impact of the tidal wave was added by means of coupled Geo hydro-mechanical analyses with transient hydraulic boundary conditions along the bed of the canal.

The pressure profile representing the wave is described by an harmonic time dependent boundary condition with H_s = 3,8 m, as illustrated in Figure 7. To graphically display the results of the analysis, two stress and deformation points are chosen in the middle of the tunnel roof and floor.

Results

The results of the 2D analysis showed that the immersed section of the tunnel experiences an harmonic upward and downward movements due to the variation in the water level in the canal. During low tide the tunnel comes up, and goes down during high tide, according to the measurements. The calculated displacements are in the order of 9.5 mm between the lowest and highest position. Figure 8 indicates the movements predicted with PLAXIS 2D.

The aim of the analysis was not so much calibrate the exact same value of the displacement as well as to explain the physical principal that is behind the displacements. For that matter the results of the analysis largely confirmed the hypothesis. The supply and discharge of water mainly takes place through the Pleistocene aquifer sand package (Figure 9 and Figure 10).

What also leads to the movements is the infiltration of water from the bed of the canal - through the back fill sand next to the tunnel - to bottom tunnel. Infiltration is caused by pressure differences above and beneath the tunnel during high and low tide. Approximately 15% of the total vertical displacement is due to this mechanism.

A snapshot of the plasticity in the loosely packed sand layer implies that the presumption that this layer is subject to compression during high water is correct. Due to compaction of the grains, the pore water extruded from this layer. The maximum stress state is then reached, as depicted in Figure 11.

The failure points that occur during high tide at the interface between tunnel and soil, implies the up movement of the tunnel. High shear stresses occur on both sides of the tunnel, which means that the soil retains the tunnel to go upwards (Figure 12).

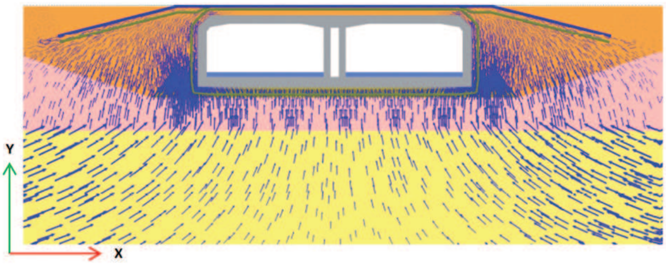

Figure 9: Illustration water flow towards the tunnel during low tide

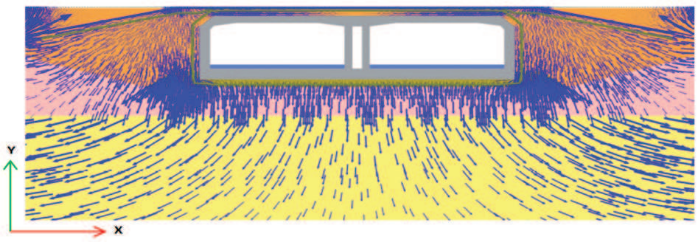

Figure 10: Illustration water flow off the tunnel during high tide

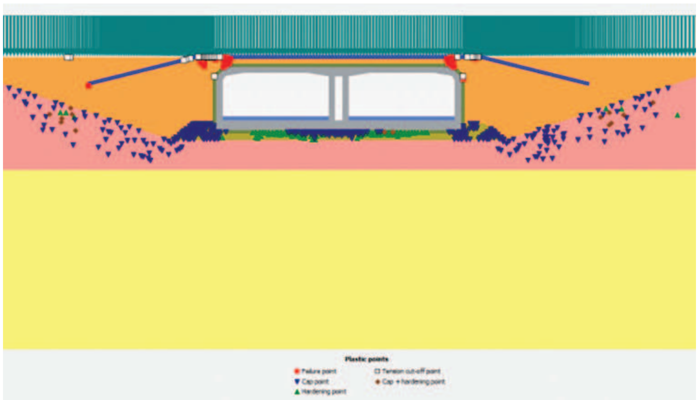

Figure 11: Occurred plastic points during high tide

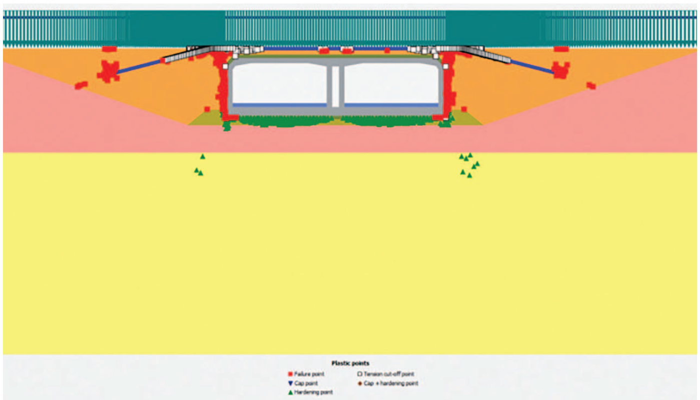

Figure 12: Occurred plastic points during low tide

The order of magnitude of the movements is strongly influenced by the permeability of back fill sand material and the stiffness of the foundation layer. Whereas the phase shift between tide and movements is mainly influenced by the permeability of the loosely packed sand layer. This has been shown by mean of a sensitivity analysis, whereby the strength, stiffness and permeability parameters of the soil layers were incrementally varied.

Removing the stone-asphalt-mattress on the top of the tunnel leads to a slight reduction of the vertical displacement of the tunnel. This has been shown with a calculation where the stone-asphalt-mattress is removed.

Effect of the vertical movements on the tunnel as a construction

The submerged section behaves under influence of tidal movements in the canal as a long beam with two support point at the end; the maximum displacement occurs in the middle. The up and down movements of the tunnel primarily affect the rubber expansion joints between two adjacent tunnel elements.

The movements leads to settlement differences, which results in rotations. For immersed tunnels, the requirement regarding allowable rotation in the joints is determined at 0.0025 rad.
The calculated maximum rotation in the joints is 0.001 rad and complies with the requirement.
The calculated rotation is determined based on the upper limit for closure level of the Eastern Scheldt Barrier.

Conclusions

The opening of the canal through Zuid-Beveland to the tidal movements in the Eastern Scheldt Barrier has triggered a soil water interaction that makes the tunnel move up and downward twice a day. The maximum displacement is limited by the level at which the Eastern Scheldt Barrier is closed. The maximum rotations in the tunnel joints stay below the critical limits. The influence of the tidal movements on the tunnel joints on a long term time frame has not been evaluated.

Acknowledgments

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