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LIEFKENSHOEKTUNNEL
PROTECTION OF THE TUNNEL AGAINST DAMAGE CAUSED BY SHIP ANCHORS BY MEANS OF ASPHALT MATTRESSES

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INTRODUCTION - RISK OF ANCHOR DAMAGE

On 10 July 1991 the Liefkenshoek Tunnel has been opened. It is the third road connection under the Scheldt in the Antwerp area. The River Scheldt is a tidal river with an average tidal range of approximately 5 m, going to 6 m at spring tides. The river is the maritime entrance to the port of Antwerp, the second largest in Europe, with an annual throughput of 100 million tons.
The existing tunnels (Waasland and Kennedy) are both situated near the city centre upstream of the harbour area, while the new Liefkenshoek Tunnel is further to the north, in the middle of the Antwerp port (e.g. fig. 1). Intensive ship movements can be expected in this area, so special attention had to be paid to potential damage caused by anchors of seaships.

The tunnel consists of an abutment of 50 m at the left bank, 8 sunken elements of 142 m and an in-situ built part of 185 m at the right bank (e.g. fig. 2). In order to limit the length of the tunnel, a minimum cover of 2.5 m is applicated.

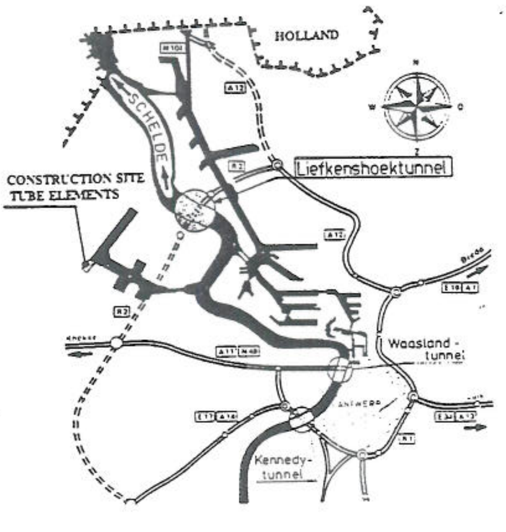


FIGURE 1 LOCATION OF THE LIEFKENSHOEKTUNNEL

ANCHOR PROTECTION - CROSS-SECTION

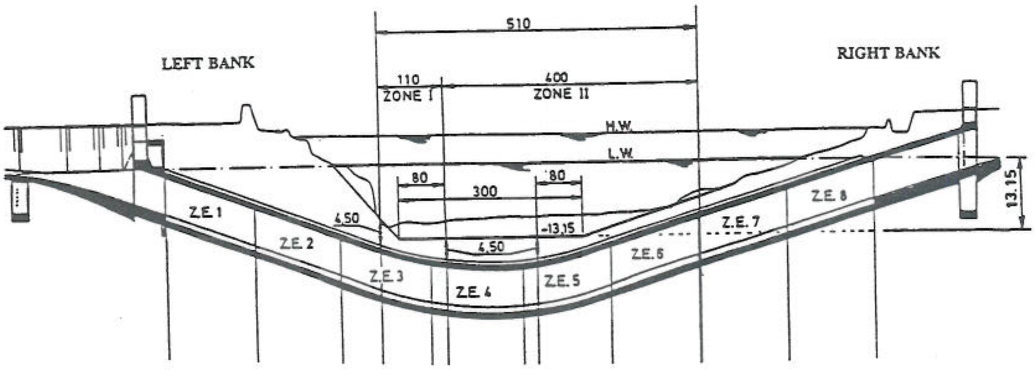


FIGURE 2 INDICATION OF THE ZONES OF ANCHOR PROTECTION

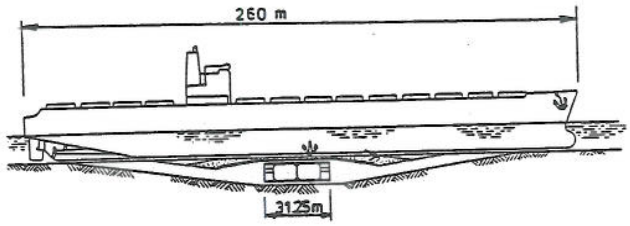


FIGURE 3

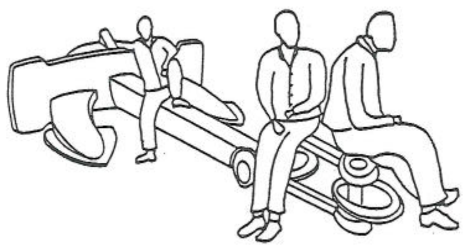


FIGURE 4

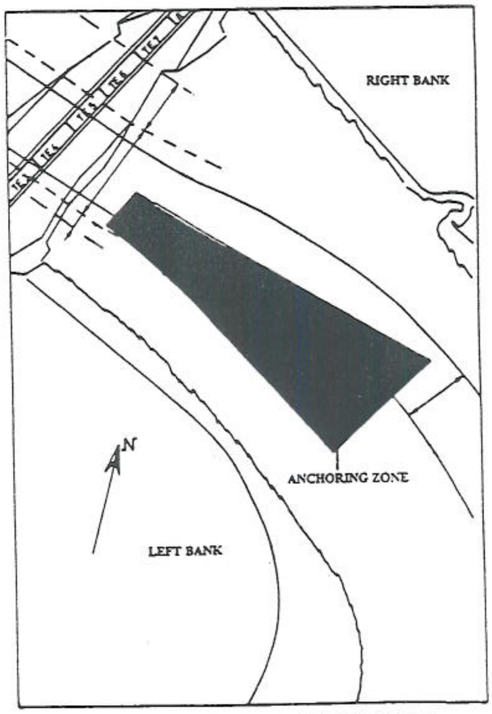


FIGURE 5 SKETCH OF ANCHORING ZONE

The tunnel is situated under a busy shipping route that is maintained to allow vessels up to Panamax size. Figures 3 and 4 illustrate the relative sizes of a Panamax vessel, its anchor, the tunnel and a human being.

A risk-analysis showed that an anchor of max. 18 tons, with a dropping rate of 7 to 8 m/sec when reaching the bottom, should be considered as maximum impact.

According to the relevant literature, such anchor enters some 3 m in good sandy soil when dragged.

An anchoring zone for ships is situated near the tunnel area. This zone is the regular anchoring area for ships waiting to enter the locks (e.g. fig. 5). Hence, the risk for grabbing and dropping anchors above the tunnel is higher than normal.

Mathematical approaches indicated that the damage caused by an anchor impact of the unprotected tunnel, especially in the area where the cover is limited to 2.5 m, can be important. The probability of important damage due to grabbing anchors is minor, but the loss of an anchor should be considered as a significant cost.

The area above the tunnel has been devided in 2 risk zones (e.g. fig. 2 and 6) :
zone I : being the access route to the anchor area, is considered a high risk for the occurrence of as well grabbing as dropping anchors ;
zone II : in this zone the risk of damage due to grabbing anchors is considered acceptable. Hence, the tunnel is only protected for the impact of dropping anchors.

PROPOSED SOLUTION

In order to protect the tunnel efficiently against the harmful effects of anchors the Contractor suggested to install a protection system, based on asphalt mattresses (thickness 30 cm), covered with gravel. When necessary, soil replacement was anticipated.

The following elements have been considered in the design stage of the protection system :

a) at Liefkenshoek Tunnel the river is silty. Therefore, there is at some places a lot of silt in the backfill material. Especially in the shipping channel area, silt had accumulated. An asphalt mattress can be placed on this silt-rich subsoil. Not-membrane systems would sink in the subsoil ;

b) especially in offshore environment, bituminous mattresses are for some time now successfully used to protect pipelines against anchors and fishing year and to keep them in place at the sea-bottom ;

c) a guiding system is required in order to allow a grabbing anchor to travel over the tunnel ;

d) protection systems based on rubble stone are expensive because of the long distances between Liefkenshoek and the yielding places.

The proposed protection system aims at the following effects :
- a dug-in-dragging anchor is worked up by the gravel package and guided over the tunnel by the mattress ;
- the impact of a dropping anchor is spread over a larger surface by the mattress ;
- when dredging the Scheldt the gravel has a signal function, so that one should not dredge any deeper than the top of the protecting gravel.

The above mentioned properties of this protection system had been awarded to it intuitively. Hence, prior to putting it in place, these properties needed confirmation by desk study and appropriate research.

IMPACT OF DROPPING ANCHORS - THEORETICAL APPROACH

For estimating the effect of a dropping anchor a linear mass-spring damper simulation model was set up. The impact is supposed to take place above the centre line of a driving duct. The hypotheses used for the building of the model are mentioned hereafter.

When the anchor drops on the bottom of the river it penetrates into the subsoil and sinks to a certain level. The experienced resistance of the anchor, integrated over the total penetration depth must correspond with the dropping energy.

The resistance the anchor experiences originates from the elasticity of the gravel bed, the shifting within the gravel mass (plasticity), the pushing away of porewater, energy needed to accelerate gravel and water and other undistinguished phenomena. Hence, it is difficult to deduct this resistance-law pure theoretically.

Therefore, as a first approach, a linear law between resistance and penetration depth was adopted. This hypothesis determines uniquivocally the course of penetration, speed and acceleration in time.

The shape of the massif, supposed to be interested in transmitting the impact to the tunnel roof, is shown in fig. 7.

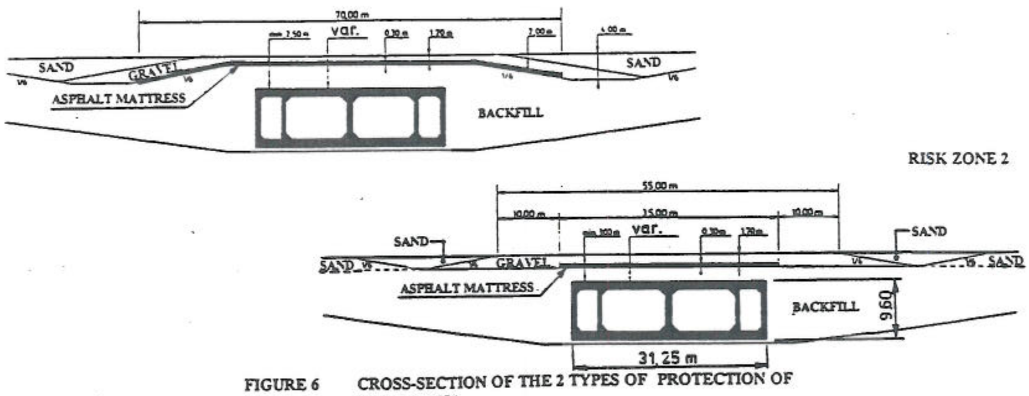


FIGURE 6 CROSS-SECTION OF THE 2 TYPES OF PROTECTION OF THE TUNNEL

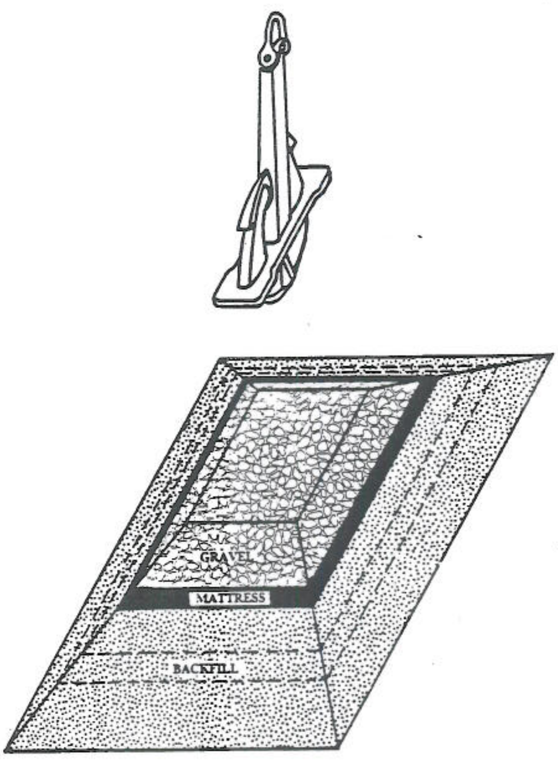


FIGURE 7

As criterion for acceptability the calculated deflexion of the tunnel roof is used.

As shown on fig. 8, different penetrations of the anchor body in the gravel result in important differences of the deflexion of the tunnel roof. In these calculations backfill of 2.5 m of sandy soil is supposed. The simulated roof deflexions can fluctuate between acceptable and completely unacceptable, depending on the supposed penetration of the anchor in the backfill.

In order to learn more about the behaviour of the gravel during impact and to assess the other elements of the above described simulation model, it was decided to set up an extensive testing program.

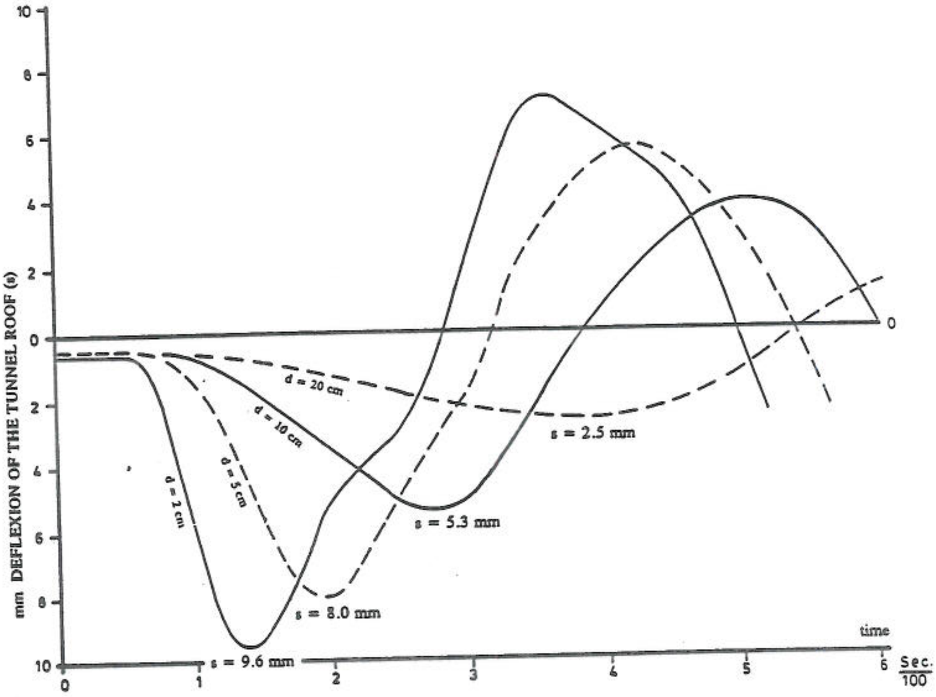


FIGURE 8 SIMULATION OF THE DEFLEXION OF THE TUNNEL ROOF (s) FOR DIFFERENT PENETRATION DEPTHS (d) OF THE ANCHOR (M = 18 tons Vo = 8 m/sec)

IMPACT OF A DROPPING ANCHOR - SIMULATION BY TESTING

Model tests on a reduced scale require a good knowledge of the phenomena one wants to examine and of the mechanisms involved in order to be able to translate test results into reality. As both conditions are not satisfied for the anchor impact process, model testing on reduced scale is not appropriate.

Fullsized tests in the middle of the Scheldt with an anchor of 18 tons are also unrealistic because of the costs and the hinder of the shipping traffic.

These considerations led to a series of tests, executed with a 6 tons weight above the in-situ tunnel part on the right bank. At the test area, the backfill, asphalt mattress and gravel are placed and immersed for the tests. They were chosen and realized with care in order to approximate as near as possible the situation that will be realized in the river. Hence, the differences between test and reality are reduced to the following factors :

	Reality	Test
Body impact	18 tons anchor	6 tons testing weight
Tunnel	sunken element	in-situ tunnel part

Walls, roof and floor of the in-situ tunnel part are thicker than most of the sunken tunnel elements which makes the whole stiffer.

Two series of tests were proposed, one with and one without asphalt mattresses. At each test the dropping height is systematically raised to a previously determined allowed bending of the tunnel roof.

The test results must allow to re-build the mathematical model in such way that the realistic results are being simulated.

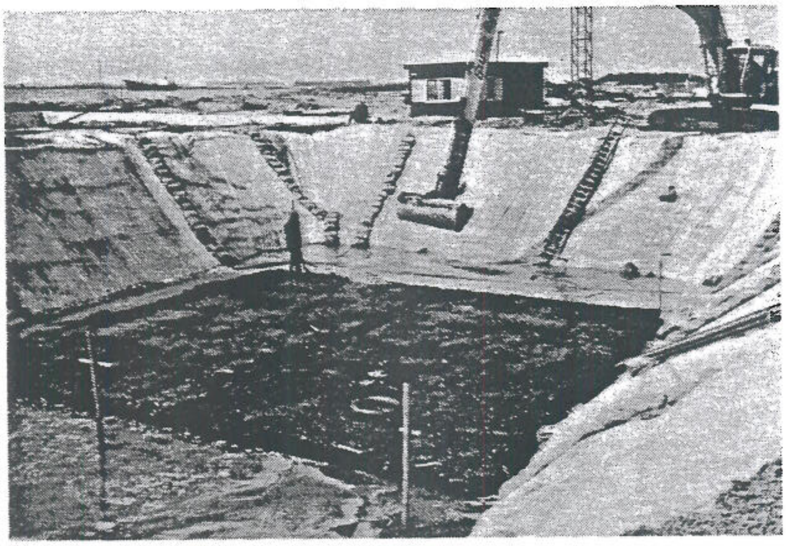
Besides investigating the effect of anchor impact, there was also examined if the mattress offered sufficient resistance to guide a grabbing anchor over the tunnel.

Below are some pictures of the investigation.

Picture 1 : Asphalt mattress at the testing site, prior to backfilling with gravel

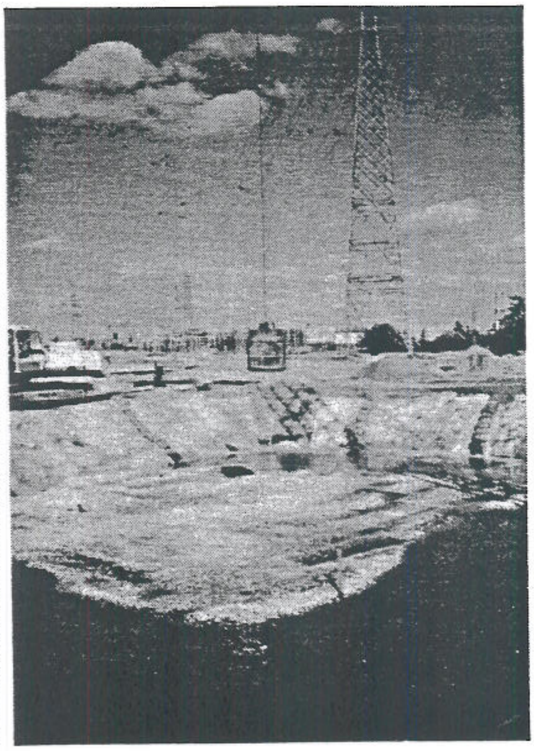
Picture 2 : 6 tons testing weight diameter 1 m

Picture 3 : Testing weight ready for impact test



Picture 1 : Asphalt mattress at the testing site, prior to backfilling with gravel

Picture 2 : 6 tons testing weight diameter 1 meter



Picture 3 : Testing weight ready for impact test

Results of impact tests - Hole marking of the simulation model

Initially, a lineair increase of penetration resistance of the anchor with penetration depth was assumed. Such lineair law results in a sinus law of the deceleration of the anchor in time. The measured deceleration of the testing weight did not correspond to this prediction (fig. 9). Only by giving much more importance to the damping of soil masses than usually mentioned in literature, calculated results could be brought in correspondance with the test results (e.g. fig. 10 and 11).

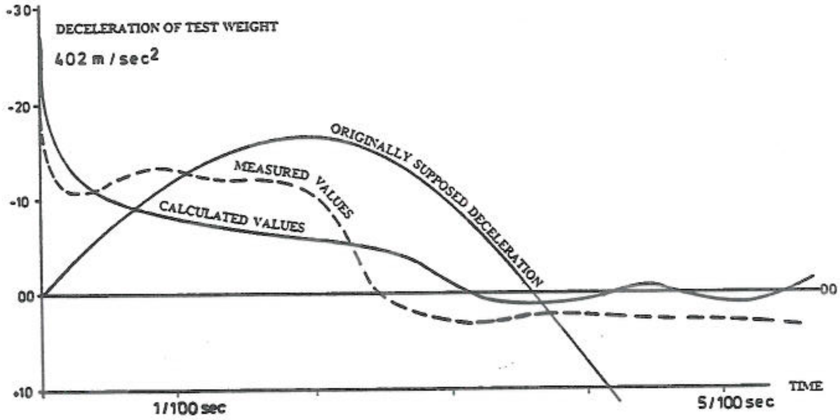


FIGURE 9 TEST NR 6 WITH MATTRESS

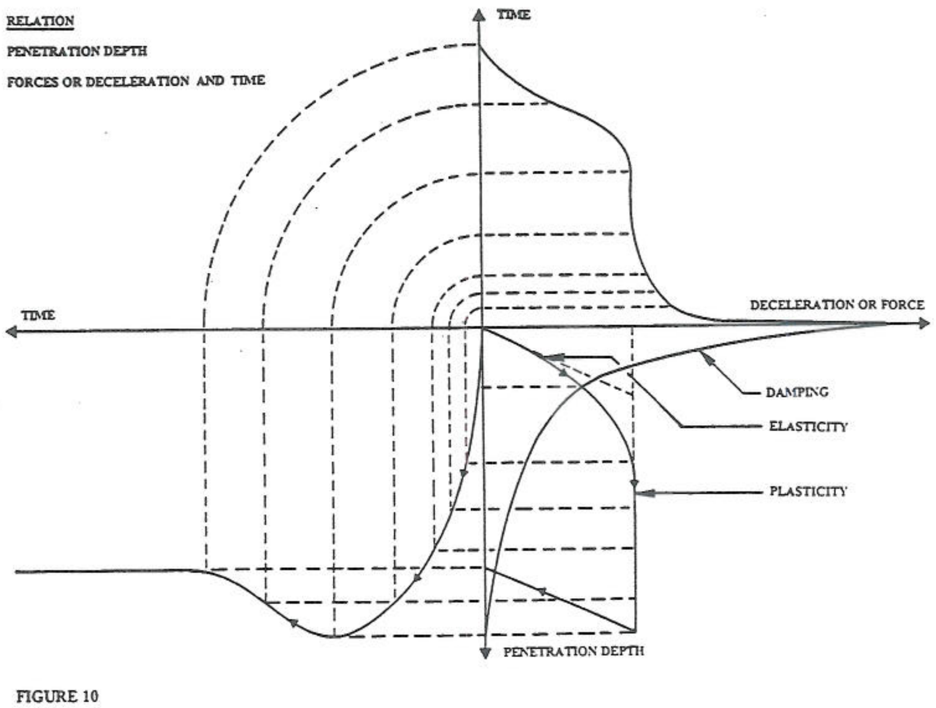


FIGURE 10

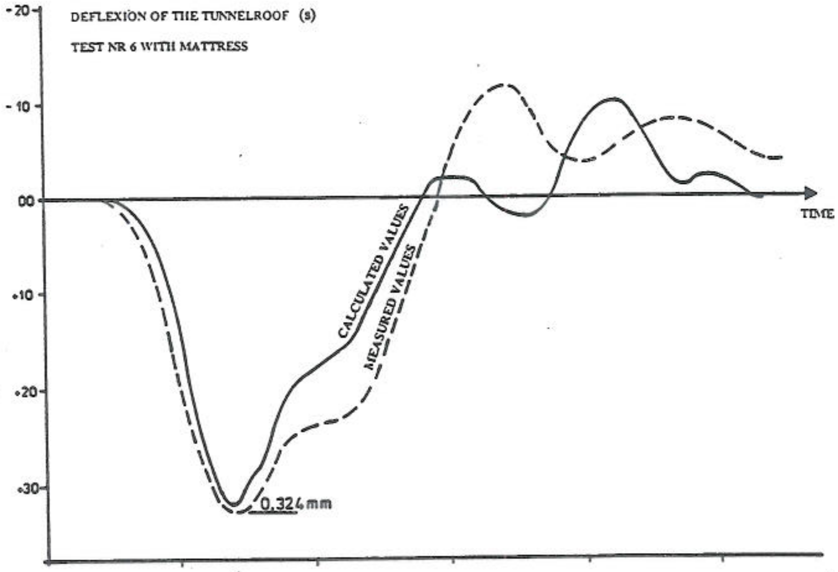


FIGURE 11

Effect of the mattress in the backfill

Soil pressure measurements on the tunnel roof during the tests showed that the mattress spread the impact force in time so that lesser pressure occurs over a longer period (e.g. fig. 12).

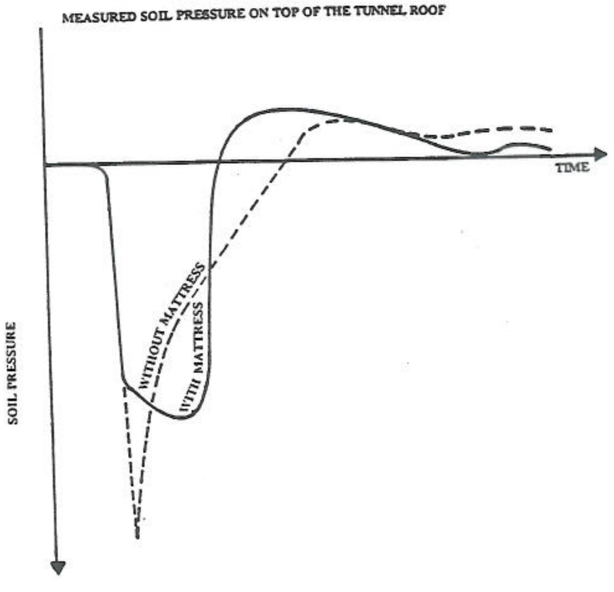


FIGURE 12

For the Liefkenshoek Tunnel the calculated beneficial result of incorporating the mattresses into the backfill is illustrated on fig. 13 and 14. However, it should be stressed that these results should not be generalized. One very important factor that influences these results is the own frequency of the tunnel roof. One could immagine a situation (and own frequency of the roof) where a mattress creates greater deflexion of the roof.

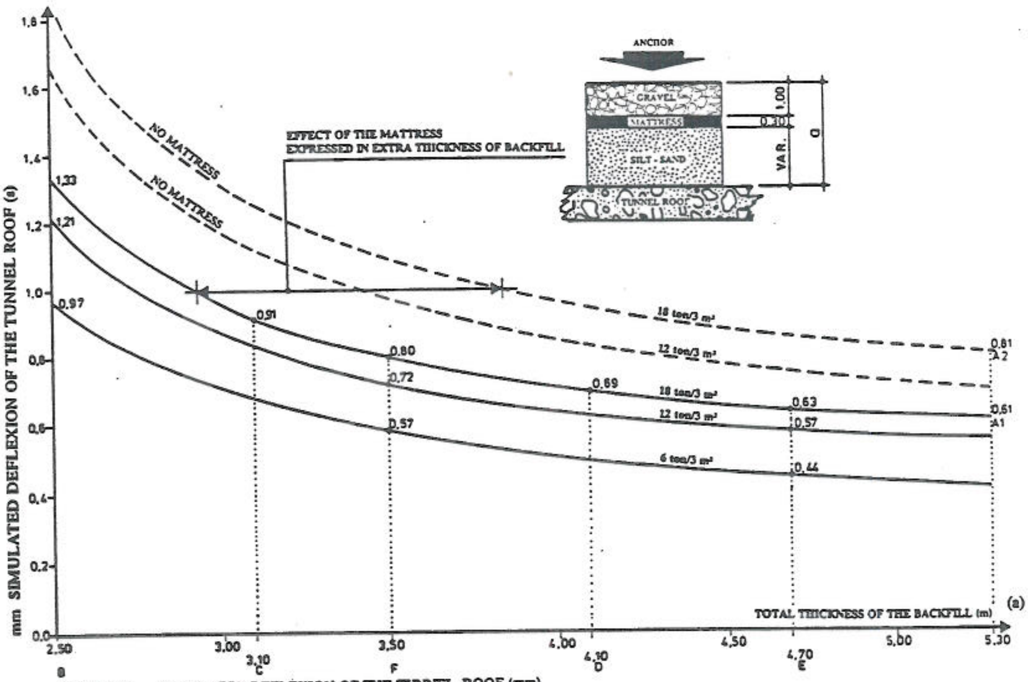


FIGURE 13 SIMULATED DEFLEXION OF THE TUNNEL ROOF (mm) FOR DIFFERENT ANCHOR MASSES AS A FUNCTION OF THE THICKNESS OF BACKFILL ABOVE THE TUNNEL

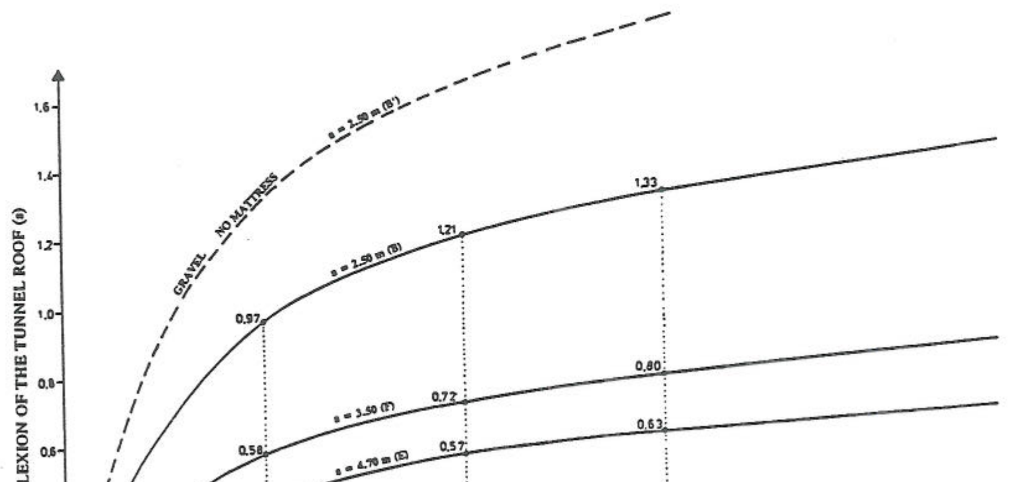


FIGURE 14 SIMULATED DEFLEXION OF THE TUNNEL ROOF (mm) FOR DIFFERENT THICKNESSES OF THE BACKFILL AS A FUNCTION OF THE MASS OF THE ANCHOR (SPEED OF IMPACT 8 m/sec)

DESCRIPTION OF THE MATTRESSES

The mattress is designed in order to incorporate the following functional requirements :

- spreading and attenuating the effects of heavy falling anchors ;
- having enough flexibility to follow differential settlements of the underlying bottomlayers ;
- guiding sliding anchors over the tunnel without damage.

Also a series of practical requirements during execution had to be taken into account :

- the use of an asphalt that was liquid enough during placing to fill in one phase the complete mattress (from thickness 30 cm with 2 reinforcement grids and supporting beams in it) ;
- sufficient strength to handle the mattress with limited additional reinforcements ;
- limited deformation when stock piled for a short period.

The exceptional loads on the mattresses can be devided into two categories :

- short term, with limited repetitions, resulting from falling or sliding anchors ;
- deformations resulting from irregular (slow) settlement of the ground.

The bending and shear force resistance of the mattress should be sufficient in order to resist the impact load of a falling anchor without damage.

Thanks to the viscous properties of the asphaltic overfilled mixture (plastic movement), no permanent stresses are introduced in the asphaltic mattress if forced to deform due to settlements of the subsoil.

The overfilled stone asphalt will act as an elastic material for the short term loads (anchors) and as a plastic material for the long term loads (settlements) (picture 4).

The mattresses have the following basic structure :

- fibrous overfilled stone asphalt
- 2 steel reinforcement grids
- a series of steel supporting beams with lifting hooks
- a base geotextile.

The overfilling technique and addition of cellulose fibers to the mix was selected in order to create long term flexibility for absorbing differential settlements of the subsoil.

The steel supporting beams were chosen to give a rigid structure during transport.

The geotextile was used to cover the joints in order to give a continuous structure which is groundtight.

The mattresses measuring 10 m by 35 m and 30 cm thick were prefabricated on a site on the left bank harbour of Antwerp, where a series of 10 mattresses could be made at once. The stone asphalt was fabricated in a normal two-phase procedure. It was put in place at a temperature of 170°C.

On average two mattresses were produced daily, each requiring approximately 250 t of asphalt. A peak production of 3 mattresses per day has been achieved.

TRANSPORT OF THE MATTRESSES

After 2 to 3 days the mattresses cooled sufficiently for removal and transportation. This transport was done on 2 pontoons carrying 6 mattresses each. The mattresses were eased down into position by a floating derrick (lifting capacity 400 ton) equiped with a purpose-built frame (picture 5).

PLACEMENT

Before each mattress would be put into its correct position, the tunnel trench had to be dredged to profile and the silt deposits removed.

The dredging works were done in two phases. First the rough removal of the bulk material. A few hours before the placement of the mattress, precision cleaning with a bucket dredger with a tolerance of 0.10 m (picture 6) took place.

After clearance of the dredging works by detailed survey and a final control by divers, the floating derrick "Norma" placed each mattress using a frame equiped with 270 hoisting slings. The final positioning of the mattress was done during slack tide. On the frame 2 positioning towers were built. They were reaching to the surface. The position of these towers could be located very accurately from two shorebased stations. After a final control by divers the hoisting slings were located and the frame hoisted for another positioning.

The mattresses are placed next to each other with a gap of less than 15 cm. The joint was covered by the geotextile of the neighbouring mattresses.

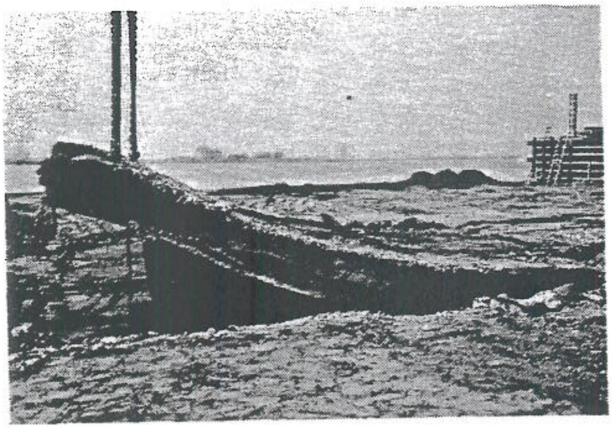
One mattress was put into position each slack tide.

Afterwards the mattresses were covered by 1 meter layer of gravel.

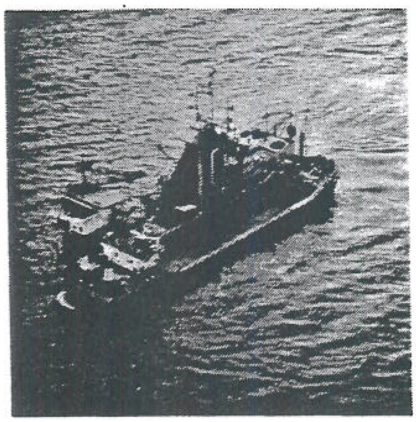
Picture 4 : Elasticity of the mattress for short term loading

Picture 5 : Floating derrick and purpose-build frame transporting a mattress (35 m x 10 m x 0.3 m)

Picture 6 : Precision clearance prior to the placement of the mattress



Picture 4 : Elasticity of the mattress for short term loading



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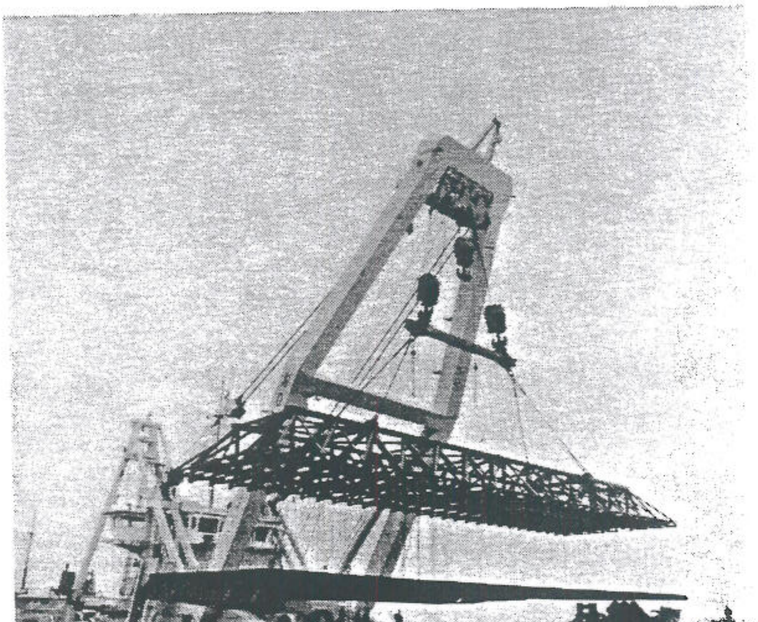

Picture 5 : Floating derrick and purpose-build frame transporting a mattress (35 m x 10 m x 0,3 m)

QUANTITIES

- preparatory and maintenance dredging	300.000	m^3
- mattresses (65 pieces)	22.750	m^2
- fibrous stone asphalt	17.000	ton
- steel reinforcements and beams	550	ton
- geotextile	25.250	m^2
- sand fill	100.000	m^3
- gravel protection layer	180.000	ton

CONCLUSIONS

- Sufficient protection against anchor damage is a prerequisite for every tunnel in a busy navigation channel.
  As long as no satisfactory theory is available for analysing dynamic impacts on a combination of soil masses and concrete construction, in-situ tests can help to provide a better understanding of the phenomena concerned and to finalize design of the protection structures.

- Asphalt mattresses combined with an underlying layer of sand and a protecting layer of gravel proved to be the optimal solution for the Antwerp situation. However, each case should be studied separately. The same protection system could prove inadequate if applicated for protection at other structures.

- In spite of the severe technical and nautical constraints, the placement of the asphalt mattresses was completed without major difficulties and ahead of schedule. However, the mobilization of an important plant was needed.

- Existing tunnels might need additional anchor protection, especially if the navigation channel above the tunnel has been deepened or if the size of the ships has increased during recent years.

- The Liefkenshoek Tunnel application will serve as an important reference for similar works in offshore situations where marine structures will have to be protected. This technique offers many advantages in very difficult situations with currents, wave and tides.