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Air Pressure Reducing Shafts on Immersed Tunnels

Summary

The narrow and long closed cross-section of the tunnels in the High Speed Link in the Netherlands, and the high speed itself of the trains require special air pressure reducing shafts to prevent unwanted air pressure variations during driving through the tunnels. Each airshaft is fixed to the top of a tunnel segment. The motions and deflection of the tunnel and shaft, caused by temperature and other factors, resulting in asymmetric soil pressure against the airshaft, required the use of an additional soilshaft. An advantage was that the airshaft could be now built in the dry. The soilshafts were partly prefabricated and floated in. The top of the airshaft was designed such, that loud noises, caused by the in and out going air, were prevented. A special shaped cone was developed, based on aerodynamic studies. The installation method of the cone determined the detailed design of it. Because of the complex shape and loads, use was made of a Finite Element Method program to determine the stresses and strains in the airshaft, the tunnel and the connection between them.

Keywords: Immersed tunnel; High Speed; Train; Railroad; Shaft; Ventilation; Air Pressure

1 Introduction

In the High Speed Railway link in The Netherlands immersed tunnels are foreseen at the Oude Maas and Dordtsche Kil rivers. They are realized by Drechtse Steden, a joint venture of Ballast Nedam Infra, HBG Civiel, Strukton Betonbouw, Van Hattum en Blankevoort and Maasdiep v.o.f. The Principal is Projectbureau HSL Zuid Zuid-Holland Zuid.

To limit air pressure waves, the long tunnels are equipped with three airshafts at each shore on top of the tunnel segments and air pressure relieve openings between both tubes at each segment. These airshafts are located on the cut and cover segments as well as on the immersed tunnel elements (Figure 1). At the second locations special soilshafts were needed to allow the construction of the airshafts.

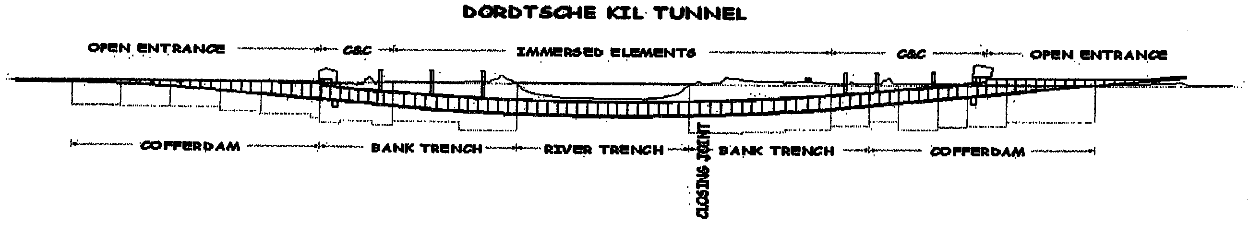

Fig. 1 Vertical alignment of Dordtsche Kil tunnel with airshafts

2 Description of the structure

2.1 The necessity of air pressure reducing shafts

The internal dimensions of conventional railway tunnels are governed by the dimensions of the trains using the tunnel. Following the Dutch requirements, the open cross section required for a train is about 6.5 m high and 4.5 m wide. Based on these data, the internal cross section for an ordinary railway tunnel is about 30 m^2.

For high-speed train tunnels a larger cross section is required to reduce the variation of air pressure. At the front of the train there is high pressure and behind the train there is low pressure. Because of the high velocity of the train, the extreme values of the air pressure vary strongly and the change from high into low values occurs within a period of several seconds. As a result, passengers in a high-speed train will experience pressure on the ears when they pass through a conventional tunnel when no preventive measures have been taken. To reduce the pressure to an acceptable level, the change of air pressure must be reduced to 1.25 kPa within 3 seconds.

The cross section requires an open area of 70 m^2 for each tube, to reduce the effect of air pressure variations to an acceptable level without special provisions. Investigations have shown that by applying the so-called "airshafts" and air pressure openings at each 25 m between both tubes, the necessary open cross section can be reduced to 45 m^2. The Oude Maas Tunnel and Dordtsche Kil Tunnel are based on these dimensions.

2.2 Shape and locations of the shafts

The Oude Maas and Dordtsche Kil Tunnels are provided with three cylinders with an internal diameter of 5.3 m. The distance between two airshafts is approximately 100 m. The definitive location is based on aspects as dikes, crossing infrastructure and joints of the tunnel.

Each airshaft is fixed to the roof of the tunnel and divided into two halves by a wall, each half connected to one tunnel tube. With the 5.3-m wide internal diameter, the maximum velocity of air stream in one half of the shaft is expected to be 45 m/s. As the air is not allowed to leave the shaft with a velocity larger than 15 m/s, the opening on the top of the shaft is widened to 4 m height all around the shaft and covered by a grating, which prevents access to the shaft. Special architectural attention is paid to the top structure.

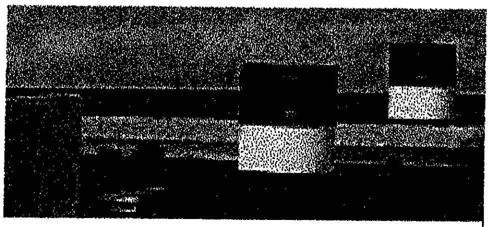

Fig. 2 Airshafts behind entrance building

Like most parts of The Netherlands, the ground level in this region is lower than the river water level. Dikes are needed to prevent the land to be inundated by the rivers. The tunnels have to cross the dikes, so the tunnel and the shafts are part of the primary water barrier. The open top of the shafts must be above the highest water level to be expected, which is at this location NAP +3.6 m, plus 0.5 m reserve (NAP = New Amsterdam Level). The lowest ground level around a shaft is NAP +1.0 m. The shaft will look like a cylindrical concrete building with an external diameter of 6.3 m and a maximum height of about 7 m above ground level (Figure 2).

In case of fire in the tunnel, the shafts can be closed, to prevent spreading of the fire.

3 Structural challenges

3.1 Airshafts on cut and cover parts

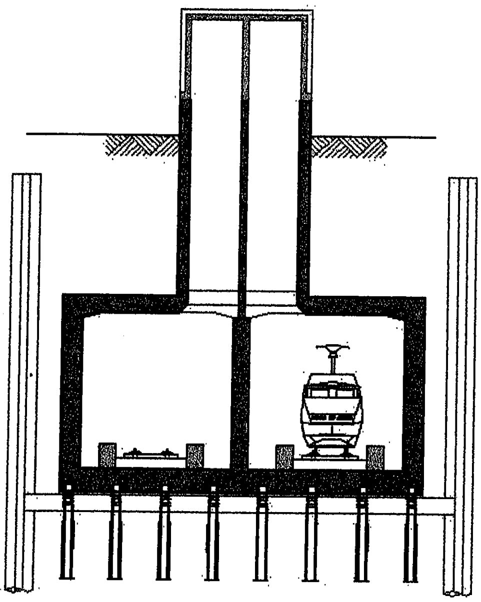

Fig. 3 Airshaft on c&c segment

Five out of the twelve airshafts are situated on the cut-and cover parts of the tunnels. These tunnel segments are built in the dry in a cofferdam, consisting of under water concrete and sheet piles. After completion of the tunnel, the sheet piles are removed till 2.5 m below ground level (Figure 3).

The most important loads are the weight of the subsoil (about 8 m) and the horizontal soil pressure against the airshaft. These loads will cause vertical tension in the airshaft over the lowest part because the tunnel roof will "hang" from it and because the horizontal soil pressure causes a global bending moment in the shaft.

In normal cases the horizontal soil pressure will be radial and equal around the airshaft, so that there will be no resultant horizontal load. The only effect is pressure in the airshaft, which is positive for the concrete. But if the tunnel element under the airshaft tends to move because of temperature variations and the shaft will not follow the tunnel segment completely, due to resistance in the soil, bending moments will occur in the shaft and in the connection with the tunnel segment. This case is even more complex because of the water tightness requirement of the structure.

The asymmetric horizontal soil pressure against the airshaft also affects the tunnel's floor. The intern wall of the airshaft is fixed to the internal wall of the tunnel segment. A reaction force to the shaft will tend to rotate the tunnel segment. This results in high bending moments, shear and pile reactions on both sides of the middle wall.

3.2 Airshafts and Soilshafts on immersed tunnel elements

Seven airshafts are located on the immersed tunnel elements, are not piled, but founded on a sand bed. The maximum subsoil is about 15 m. The loads mentioned for the airshafts on the cut and cover segments also act on the airshafts and tunnel segments of the immersed tunnels. They are however, larger, because of the following reasons:

- The surcharge on the tunnel roof and the length of the airshaft are much larger than on the cut and cover part. That means a two times larger weight hanging on the shaft. The horizontal soil resistance against the airshaft when it tends to move is also higher.
- For the immersed tunnel with no pile foundation, the segments are pre-stressed to each other by water pressure, and only at the element joint a rubber Gina allows space for extensions. This means, that the shaft may be forced to move over a larger distance than compared to a c&c shaft. On the lifetime of a hundred years, it may be possible that movements have accumulated and do not return for the full 100%. This results in a steadily increasing displacement.

individual bar. As can be seen in Figure 6, stresses peak at certain local areas in the roof around the airshaft. Additional rebar was added in these areas.

At he location with a soilshaft on the sliding plate, other loads, stresses and deflections occur, depending on the construction sequence of placing the soilshaft, the soil, dewatering the soilshaft and constructing the airshaft.

5 Construction methods

5.1 Construction of the airshafts on cut and cover segments

The cut and cover tunnel segments are built in cofferdams. The airshafts are simply built on top of a tunnel segment, before backfilling the cofferdam.

5.2 Construction of both shafts on immersed tunnel elements

During marine operations, the air openings in the roof of the tunnel are closed by a temporary concrete slab. The lower part of the soilshaft is prefabricated and floated in. Because of transport conditions it is not possible to install a complete finished soilshaft at once. After the lower part is installed, the soilshaft is extended from a level 1 m below average water level to the required height.

As the airshafts can only be built after the tunnel elements are immersed, the connection must be realised some 14 meters below the water level. Thanks to the application of soilshafts, it is possible to build the airshaft in the dry within the soilshaft, after the tunnel element is immersed and the soilshaft is dewatered. For this purpose a special rubber closure ring is foreseen between soilshaft and tunnel roof.

5.3 Installation of the top structure

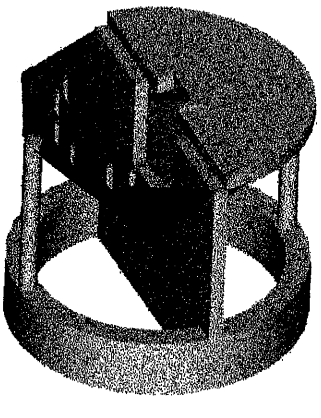

Fig. 7 Top structure of airshaft

On top of the airshaft a prefabricated roof will be installed and fixed. It supports on the middle wall and one column on each side. The steel cone, for guiding the in and out going air, is divided in 8 sections. Each section is designed as a flat orthotropic plate, composed of plate steel and profiles, welded together in a factory. By moving it in and rotating it, each cone section is fixed to the roof and middle wall. Small strips are added to close the joints. Figure 7 includes a three-dimensional impression of the structure.

different loads requires an adequate method of determining the forces and deflections, especially when strict water tightness requirements are governing. For this purpose many finite element calculations were made with the program Staad Pro. Only in this way the loads in different directions in each part of the structure, and the interactions between them can be investigated precisely.

When the tunnel element is immersed, a part of the loads (e.g. water pressure) already acts on it. After finishing the airshaft, the structural behaviour of the integrated structure changes completely. Additional loads will then be taken by the airshaft and tunnel cross section together. The tunnel with airshaft will behave much stiffer, resulting in an increase of structural forces at and near the connection. Structures always tend to take loads at the stiffest areas. The expectation is, that after 100 years, creep will have caused the tunnel element with airshaft to carry about half of the loads that initially were carried by only the tunnel element.

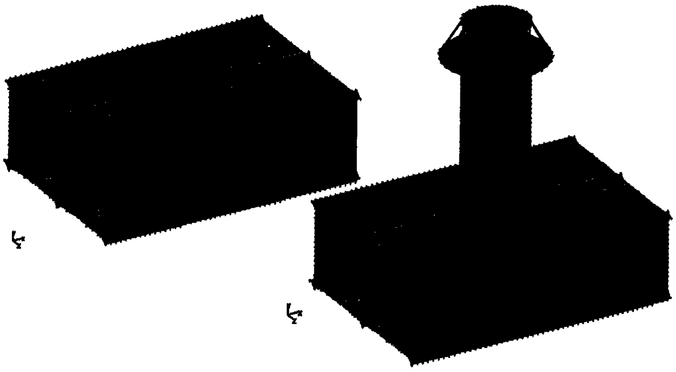
Fig. 6 FEM models

To cope with these loading cases, each cross section had to be checked for the situation during and just after construction and 100 years after finishing the construction period. Two FEM models were made, one for load combinations on the tunnel element without shaft and one for load combinations on the tunnel element together with the airshaft. Each force in the structure in each situation can be found by combining the results of the different FEM models.

As the airshaft and tunnel segment are fixed, they cannot be considered separated from each other. Loads acting on the airshaft effect even the tunnel floor and, as far as present, the pile foundation. For example, horizontal soil pressure against the airshaft cause a bending moment, which will cause the middle walls of the airshaft and the tunnel segment to rotate. The tunnel roof and tunnel floor will prevent this rotation. The result is a bending moment in the structures. High pile reactions can be expected on both ends of the middle wall, because the piles will prevent large displacements of the tunnel floor.

Loads acting on the tunnel segment also influence the airshaft. Most important is the vertical joint load between neighbouring tunnel segments. These are 14 MN large and can act both up- and downward. As at both joints of a tunnel segment, a 14 MN large load will act downward, the segment will be bent such, that there will be longitudinal tension in the tunnel roof. Because the airshaft is fixed to the tunnel roof, there will also be some horizontal tension in the lowest part of the airshaft. This effect, together with the concrete hardening stresses and temperature variations, all very critical near the connection between airshaft and tunnel segment, cause a very complex combination of forces. The challenge to make the whole structure water proof becomes more difficult.

The rebar in the roof is projected in x and y directions and not radial, due to avoiding complex crossing layers of rebar from tunnel wall and roof, shaft ring and shaft wall, temporary closure plate. The connection with the vertical rebar in the shaft required a very detailed design of each

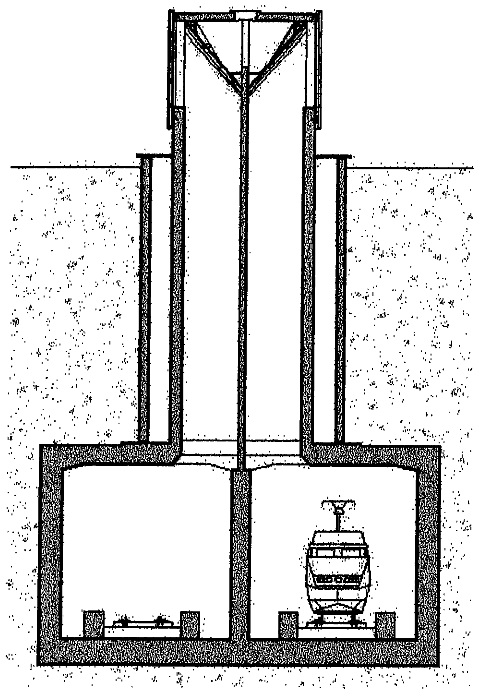

Fig. 4 Air- and soilshaft on immersed tunnel

- The cofferdam structure for the c&c segments will remain. The combiwall, the pile foundation and the under water concrete are fixed to the tunnel segment. This will partly prevent the tunnel segment from moving. Because the soil around the shaft is surrounded by the cofferdam structure and the tunnel, which are fixed to each other by under water concrete, it will partly follow the displacements, which reduces the pressure against the airshaft. This effect does not exist on the immersed tunnel because the combiwall and the tunnel are not fixed by under water concrete and pile foundation.

The airshafts on the immersed tunnels would not be able to withstand these loads without additional measures. To protect these airshafts and underlying immersed tunnel elements, a soilshaft was developed (Figure 4). This is a concrete shaft of 9 m outer diameter with a wall thickness of 350 mm. It is installed on a sliding plate (Figure 5) on top of the tunnel around the airshaft with a distance of 1 m between both shafts. The top is about 250 mm above ground level. In the final stage the space between airshaft and soilshaft is filled with only water, so that the tunnel element with fixed airshaft can move without introducing soil pressures on the airshaft. The soilshaft slides over the tunnel. There will be only radial soil pressure against the soilshaft, which can easily be taken because of the circular shape of the shaft. The wall thickness can be minimized. Table 1 presents a comparison between different ratios of some other civil structures.

Table 1: Comparison of some cylindrical shaped civil structures

Structure	Internal diameter D [mm]	Wall thickness t [mm]	Height H [mm]	D/H [-]	t/H [-]	t/D [-]
Soilshaft	8300	350	14,000	0.59	0.025	0.042
Boston cofferdam	74,000	1800	27,000	2.74	0.067	0.024
Rotterdam windscreen	18,000	250	25,000	0.72	0.01	0.014
Hakucho-Oohashi	34,000	1500	23,000	1.48	0.065	0.044
Chunnel cofferdam	55,000	2500	65,000	0.85	0.038	0.045

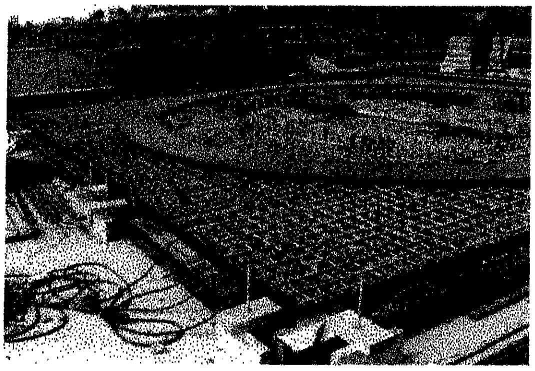

Fig. 5 Sliding plate

An additional load case on the airshaft on an immersed tunnel segment is caused by the joint connection between the segments. The tunnel structure can be loaded by 14 MN on each joint, causing large moments in the tunnel segment. The result is horizontal tension in the tunnel roof and airshaft.

4 Calculations

A cylinder fixed to a box structure and loaded by many