Experimental determination of vibration transmission through soft soil near a tunnel

Experiments pour la determination de transmission des vibrations dans terre faible près d'un tunnel

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ABSTRACT: The Botlek railway tunnel, currently under construction, is part of the cargo line "Betuweroute". This line will run from the port of Rotterdam, The Netherlands, to Germany. The Botlek railway tunnel is a shield driven tunnel and consists of 2 tubes of 1800 m length. The construction project includes some large field tests. The paper deals with the dynamic tests performed at a test site located at the ground surface 500 m from the western entrance. Dynamic measurements are executed by means of 3 seismic penetrometers, 3 instrumented prefab piles, and several surface sensors. The instruments are equipped with 3D accelerometers. Four test sessions are planned. The paper will discuss the test program and the test set-up, as well as some preliminary results.

RÉSUMÉ: Le Botlek tunnel de chemin de fer, qui a en construction jusqu'à le fin de 2002, est un part du chemin de fer "Betuweroute". Le Betuweroute est construit uniquement pour le trafic de marchandises. Le Botlek tunnel est un tunnel segmentée du 1800 m longueur avec 2 tubes. Le project comprends des grandes experiments. Ce publication traite les experiments dynamiques. Un section expérimental est montée en 500 m de l'entrance occidental du tunnel. Le section comprises des segments instrumentées, 3 cônes dans le terre, 3 poteaus prefabriquées et stations en la surface.Trois sessions d'experiments sont prévu. Ce publication traite le programme experimentelle, le composition des experiments et quelques resultats provisoires.

1 INTRODUCTION

The Botlek railway tunnel, currently under construction, is part of the cargo line "Betuweroute" and will enable the underpass of the river Oude Maas. This line will run from Rotterdam, The Netherlands, to Germany. The Botlek railway tunnel is a shield driven tunnel and consists of 2 tubes of 1800 m length. The tunnel diameter is 9.45 m and the lining thickness is 0.40 m. Figure 1 shows a longitudinal cross-section of the Botlek railway tunnel.

The construction project includes some large field tests (F300, 1997). Included in the test program are some dynamic tests. For that purpose, a test site was identified at the ground surface 500 m from the western entrance of the southern tube (Figure 1). The test site consists of an instrumented tunnel ring (nr. 367), 3 cones, 3 prefab piles and surface stations. The test set-up will be discussed in the next section.

The tests are a part of general research program on structural dynamics. Predictions of the tunnel behaviour due to a train passage are made using numerical models. Also, numerical models are used to predict the transmission of vibrations through the (soft) soil to the piles. In the evaluation phase of the research program, predictions and measurements will be compared. It is expected that this study will lead to a better understanding of the dynamic behaviour of tunnels in soft soils. A better insight in tunnel dynamics is required as:

- the dynamic behaviour of a single tunnel lining is crucial to understand the overall structural behaviour;
- the transmission of train-induced vibrations to the surroundings may lead to annoyance in buildings near the tunnel.

Monitoring the dynamic response of a bored tunnel has, in general, already been tried in the past (Petronio et al., 1999; Sattel et al., 1996). However, this project considers aspects which are relatively new in the vast literature of bored tunnels.

Four test sessions are planned, and one of them was already carried out in April 2000. The paper will discuss the test program and the test set-up, as well as some preliminary results.

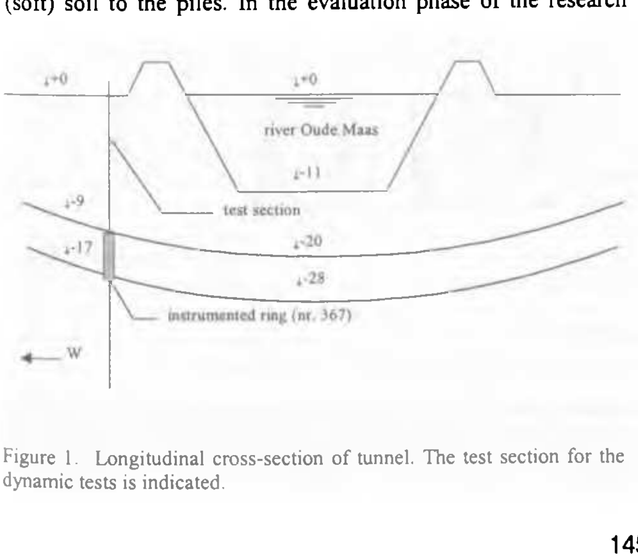

Figure 1. Longitudinal cross-section of tunnel. The test section for the dynamic tests is indicated.

2 TEST SET-UP

A test section was identified at the ground surface 550 m from the western entrance. A vertical cross-section of the test section is given in Figure 2. A plan of the test section is given in Figure 4. Two measuring systems are set up, each having its own data acquisition system. The first system is in the instrumented ring of the tunnel.

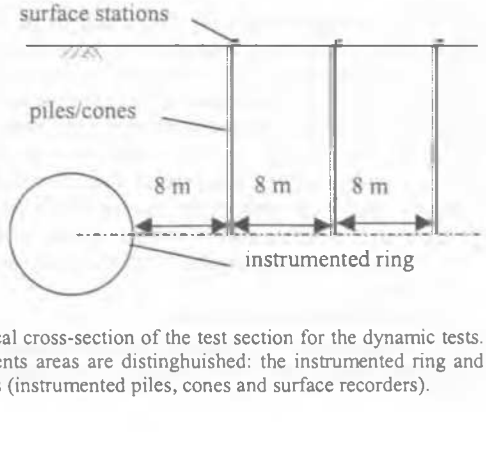

Figure 2. Vertical cross-section of the test section for the dynamic tests. Two measurements areas are distinghuished: the instrumented ring and the surroundings (instrumented piles, cones and surface recorders).

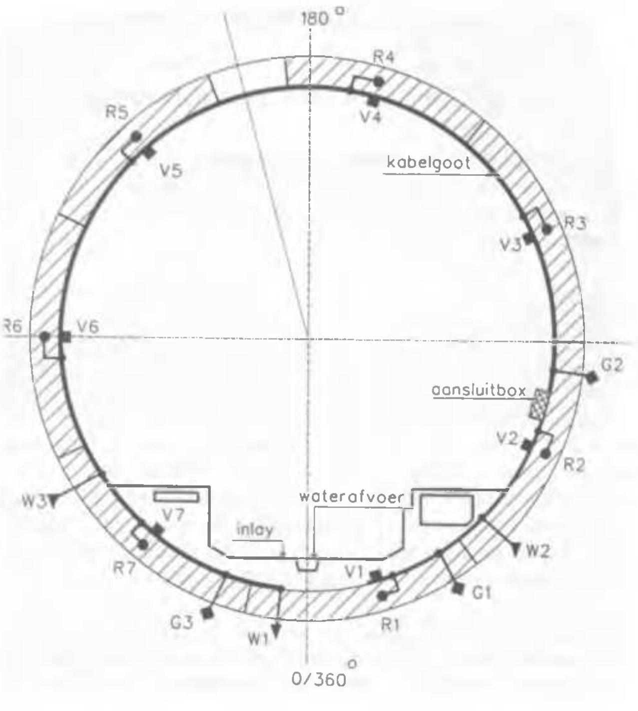

Figure 3. Cross-section of the instrumented ring (nr. 367). Positions of the accelerometers (V), strain gauges (R), water pressure devices (W) and soil pressures devices (G) are indicated.

Table 1 Summary of data channels in the instrumented tunnel ring.

channel nrs	instruments	type	amplification/ conditioning
1	shaker (synchr.)	TNO	Sundstrand
2-22	strain gauges	TNO	KWS
23-43	accelerometers	PCB	Sundstrand/Vishay
44-46	water pressure devices	XTC190M	Ectron
47-49	ground pressure devices	VM-750	Ectron

The instrumented ring is equipped with accelerometers and strain gauges. Ring 367, located 550 m from the western entrance of the southern tube, was chosen to be instrumented, as its surroundings (soil and surface) are rather undisturbed, beneficial for the quality of the vibration transmission measurements.

The Botlek Railway tunnel is made of rings consisting of seven segments and a keystone, as shown in Figure 3. The centre of each segment in the instrumented ring is equipped with 3 accelerometers that measure either radial, tangential or axial accelerations of the concrete surface. The strain gauges are embedded in the concrete and are also located in the centre of the segments.

Six devices have been inserted in the soil through the lining of the instrumented ring. There are three water pressure devices near the ring, as indicated in Figure 3. Also, three soil pressure devices have been inserted through the lining. These devices measure variation in pressure levels due to vibration emission in the tunnel.

Table 1 summarises the 49 data channels in the tunnel. The first channel is used to measure the sine function of the harmonic excitation. This signal is also used to synchronise the two data acquisition systems. The latter is essential for the proper determination of transmission and coherence functions.

The second measuring system is formed by the instruments in the surroundings of the instrumented ring. The following instruments are used to determine the response of the surroundings:

- 3 cones 20 m deep, instrumented with accelerometers (3D);
- 3 prefab piles, instrumented with 9 accelerometers (top and bottom);
- 9 accelerometers at the surface.

Table 2 summarises the channels that are measured in the surroundings during a test. The positions of the instruments relative

Table 2. Summary of data channels in the surroundings of the instrumented tunnel ring.

channel nrs	instruments	type	amplification/ conditioning
1	excitator (synchr.)	TNO	Sundstrand
2-10	accelerometers surface	QA700	HP
11-19	accelerometers pile heads	QA700	HP
20-28	accelerometers pile points	QA650	HP
29-37	accelerometers in cones	QA650	HP

Table 3. Summary of instrument positions in the surroundings of the instrumented tunnel ring. Position numbers refer to Figure 4.

position nr	instruments	channel nrs
1	accelerometers surface/cones	2-4/ 29-31
2	accelerometers pile heads/points	11-13/20-22
3	accelerometers surface/cones	5-7/32-34
4	accelerometers pile heads/points	14-16/23-25
5	accelerometers surface/cones	8-10/35-37
6	accelerometers pile heads/points	17-19/26-28

to ring 367 are indicated in the plan given in Figure 4. Table 3 links the positions in Figure 4 to the instruments in the the surroundings.

The two systems mentioned above contain in total 84 channels, which will be used simultaneously to measuring the response of the tunnel and its surroundings.

3 TEST PROGRAM

Three test sessions are planned. In test sessions 1 and 2, a shaker is located near the instrumented ring and will serve as the source of the vibrations. The position of the shaker will be varied as indicated in Figure 4. The variable position of the shaker enables a study of distance effects in the transmission of vibrations through a segmented lining.

The shaker is made from two eccentric rotating masses that are powered by a frequency-controlled motor. The force applied to the tunnel depends on the angular frequency of the masses. A static pre-load of 5 kN is used to prevent uplift of the shaker.

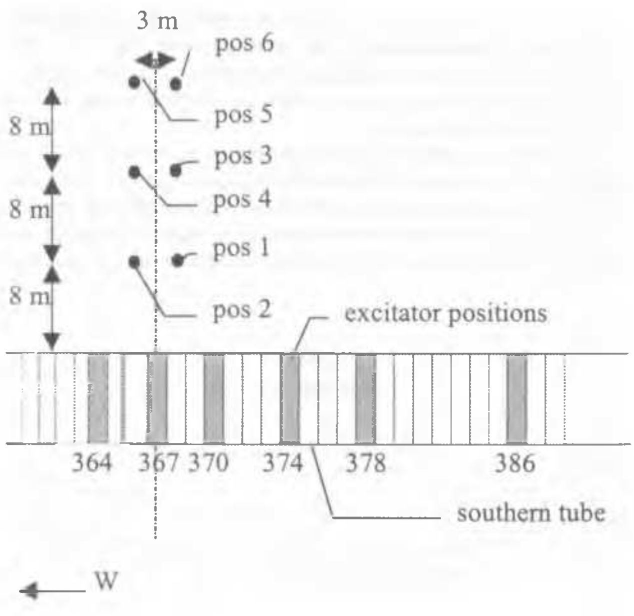

Figure 4. Plan of the test section. Positions of the harmonic force in the test program are indicated by the gray rings. Each ring has a length of 1.5 m. The six positions of the instruments in the surroundings are also given.

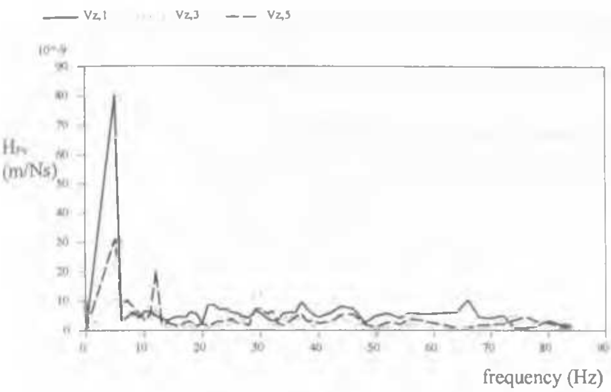

Figure 5. Vertical vibration transmission functions for the three surface stations. Shaker position: ring 367.

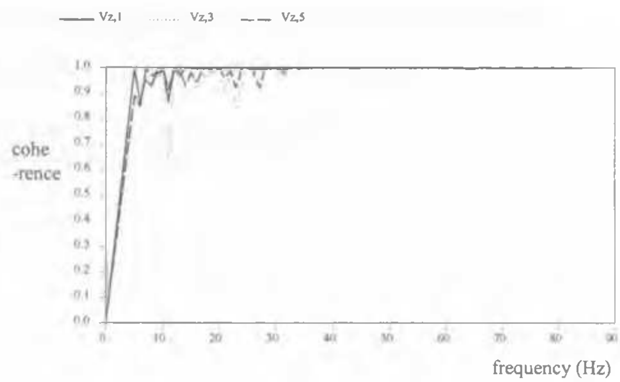

Figure 6. Coherence functions corresponding to the transmission functions in Figure 5.

Bolting is therefore not required, but it limits the force amplitude to 4 kN (single peak).

Test sessions 1 and 2 will be conducted in various stages of the tunnel building process. The first session was performed in April 2000 when the southern tube was finished, but without inlay and before construction of the northern tube. The second session is planned for Spring 2001, when both tubes will be completed. It will consist of two scenarios. In the first, the shaker is placed in the southern tube, including inlay. In the second, the shaker is placed in the northern tube.

In test session 3, the response of tunnel and surroundings to freight trains will be measured. The instrumentation will be the same as in the previous sessions, except for the train detection sensor that will be used to trigger the data acquisition system.

During the tests with the shaker, the frequency of the harmonic force is varied from 5 to 85 Hz. From 5 to 40 Hz, intermediate steps of 1 Hz are taken. Above 40 Hz, steps of 2 Hz are taken. At each frequency step, the response of all channels is measured during 32 seconds at 500 Hz sampling frequency.

By means of Fourier transformation, the frequency-dependent response of each channel may be determined. Since the forcing frequency is known, this is a very accurate testing method for the assessment of vibration transmission using only a small shaker force.

This proves the power of harmonic excitation tests compared to impact tests. The latter type of testing normally shows low to moderate coherence for most of the frequencies and high coherence near the peak in the transmission. An impact test will, therefore, give reliable results that are limited to the peaks in the transmission. For a reliable vibration prediction, however, the coherence should be high for the complete frequency range (approx. 5 to 80 Hz) that is important in the assessment of vibration transmission.

4 PRELIMINARY RESULTS

The first test session was conducted in April 2000. About 2 Gb of data was collected. Although a comprehensive analysis is still to be conducted, some preliminary results can be given.

First, the quality of the measurements is very high. This may be determined from the very high coherence (larger than 0.99 for most of the frequency steps) between force and response signals. See, for example, Figure 6, which shows the coherence functions that correspond to the transmission functions given in Figure 5. The vibration transmission was determined from the shaker located in ring 367 to the vertical component of the vibration velocity in the three surface stations. Above 20 Hz, the coherence is near perfect and even at low frequencies the coherence is above 0.9.

Secondly, it may be stated that there is a general trend toward symmetry in vibration transmission from a source in a segmented lining to soil and surface. In the first test session, the shaker was positioned 3 rings left or right of the instrumented ring (rings 364 and 370 respectively in Figure 1 and 4). The vibration transmission functions that were calculated from the two shaker positions showed, in general, good agreement.

Thirdly, it seems that the force that the shaker applies to the tunnel floor quickly migrates to the soil. This is suggested by the low vibration transmission to the accelerometers and strain gauges in the ceiling of the instrumented ring. It can even be stated that the majority of the vibration transmission runs through the two segments in the bottom. These segments can be recognised in Figure 3 by the position of accelerometers V7 and V1.

The test program of the second test session will be slightly different from the first session, based on the experiences in the first session. The preliminary results suggest that larger frequency steps are allowed, making the testing program more efficient.

5 FUTURE RESEARCH AND CONCLUSION

The tests are a part of general research program on dynamics in The Netherlands, initiated by the Centre for Underground Construction (F300, 1997). Predictions of the tunnel behaviour due to a train passage are made using numerical models. Also, numerical models are used to predict the transmission of vibrations through the (soft) soil to the piles. In the evaluation phase of the research program, predictions and measurements will be compared. It is anticipated that this comparison will lead to a better understanding of the dynamics of tunnels in soft soils.

The use of harmonic excitation yields vibration transmission functions of high quality. Even at low excitation force levels, a reliable vibration transmission function can be determined from a force in a tunnel to points in the surroundings.

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