# Dynamic Response of Bored Tunnel: Modelling and Testing

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**ABSTRACT**

The Botlek railway tunnel 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 tunnel was bored in typical Dutch soft soil. As part of the construction project, an extensive investigation of the dynamic response of the tunnel was carried out. The investigation is focussed on the dynamic effects from the source of the vibrations, the influence of a freight train on the tunnel to the propagation of the vibrations in the soil to the surface and piled foundations. For this research one tunnel ring is instrumented with accelerometers and strain gauges and different transducers have been installed in and on top of the soil and accelerometers have been placed in several foundation piles nearby the tunnel. Several aspects were in the experimental study investigated such as transfer function tunnel-soil and tunnel-foundation, ring-deformation, influence length of the tunnel, and induced stresses in the ground. Prior to the measurements several Finite Element Model calculations have been made to predict the vibrations in the tunnel and the transfer function tunnel-soil. The experimental results are then compared with the numerical modeling results. This paper presents some of the results of the experimental investigation and the comparison with the numerical results.

## INTRODUCTION

In the even larger European economy, production and distribution are taking up a lion's share. Consumers are developing more specific wishes, leading to new world-wide traffic of goods. For the European mainland, the port of Rotterdam is a important gateway for all sorts of goods, such as raw materials, semimanufactures and consumer goods. To be able to handle the growing supply of goods, efficient transit channels are needed in southern and Eastern Europe. Inland shipping and road transport alone are inadequate to deal with the rising demand for transport. To improve the European transportation system, freight trains will have, from 2006, their own double-track railway line spanning 160 km between the port of Rotterdam and the German border without delay.

The Botlek railway tunnel is part of the this new cargo line called "Betuweroute" and enables the crossing of the river Oude Maas close to Rotterdam. The Botlek railway tunnel is a shield driven tunnel and consists of 2 tubes of 1800 m length. The tunnel was bored in typical Dutch soft soil. As part of the construction project, an extensive investigation of the dynamic response of the tunnel and of the soil-structure interaction was carried out. The investigation consisted of two parts, namely the prior modeling of the soil-tunnel dynamic interaction during design of the facility and the experimental testing of the facility after completion of the facility.

This paper presents some results of this research program. In particular, attention is given to the transmission of the energy through the tunnel and from the tunnel to the surrounding.

## SITE AND TUNNEL CONFIGURATION

The Botlek rail tunnel consists of two access ramps – partly open, partly covered – and two bored tunnel tubes (Fig. 1). The tunnel tubes each have a length of 1.835 metres. The Botlek Tunnel was bored by means of Earth Pressure Balance technique, which until then was never used in the Netherlands. The tunnels underpass the river Oude Maas reaching the maximal depth of 28 m under the ground surface. The internal diameter of tunnel is 8.65 m and the distance between the tunnel tubes is approximately 10 m. The minimal horizontal curvature of the tunnels is 2000 m, the minimal vertical curvature is 5000 m, and the maximum angle of inclination is 2.5% . About 600,000 m3 of earth were dug up, about 280,000 $m^3$ were bored, and 85,500 $m^3$ of underwater concrete and 2,400 plies were used for the two tubes. The concrete tunnel ring consists of seven segments and a key-stone. At the site, an upper formation of organic soft soil (mostly Pleistocenic clay and peat) about 12 m thick rests on stiffer Pliocenic sand.

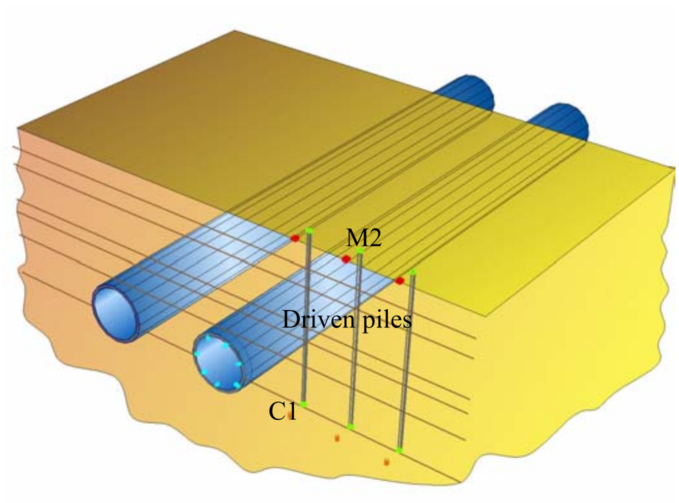


*Fig.1 3D sketch of the Botlek Tunnel*

MODELLING OF THE TUNNEL

A complete 3D FE analyses of a train travelling through a tunnel surrounded with soil layers is not practicable within the current computer power. For that reason a modular model has been developed. First we made assumption that the soil behaves linearly elastic. Furthermore it is assumed that the cross-area of the tunnel and the surrounding soil remains the same along the tunnel axis. This leads to the simplification that the response of a complete train loading can be modelled by convoluting the response of a single pulse. Secondly the analyses have been split into three sub-models, namely:

1 Static deflection model, which computes equivalent parameters for a Timoshenko beam;
2 Track model, which simulates the forces of a riding train on a Timoshenko beam;
3 Transmission model, which calculates the transmission of the vibrations by means of a pulse response.

The flow chart in Fig. 2 shows the relations between the different sub-models. The following paragraphs will describe the sub-models in more detail.

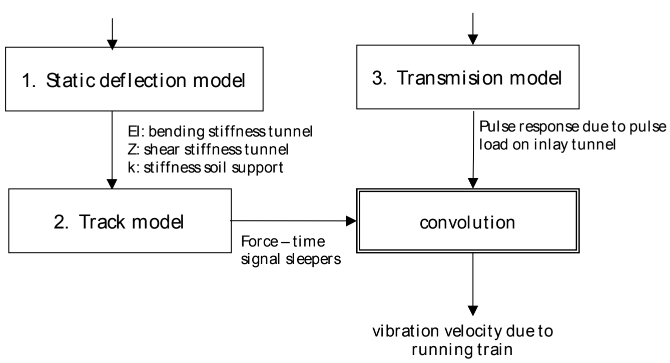


*Fig. 2. Flow chart vibration prediction model.*

Static Deflection Model

This is a 3D static FE model of the tunnel and the surrounding soil layers, which is used to determine the characteristics of the tunnel in terms equivalent of a Timoshenko beam parameters. At the y-z plane and the x-y plane symmetry boundary conditions apply. The model is loaded with a static unit load in the vertical direction at the location of the track.

As a result of that the tunnel will deflect vertically as can be seen in Fig. 3. The vertical deflection along the tunnel axis at the position of the loading axis is used as an input for a curve fit procedure (Fig. 4). From this curve fit procedure follows an equivalent bending stiffness *EI*, the shear stiffness *Z*, and the vertical stiffness *k* of the supporting soil layers. These values are used as input parameters for the next sub model, the track model.

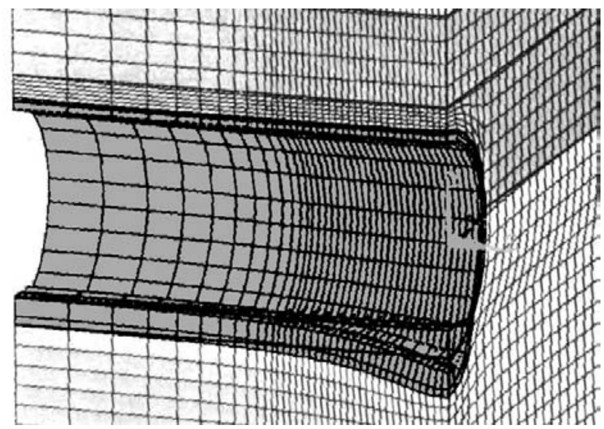

*Fig 3. Static deflection model.*

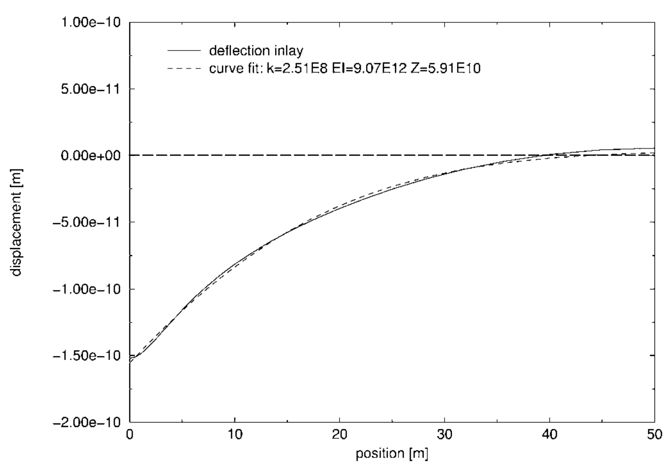


*Fig 4. Curve fit with deflection curve.*

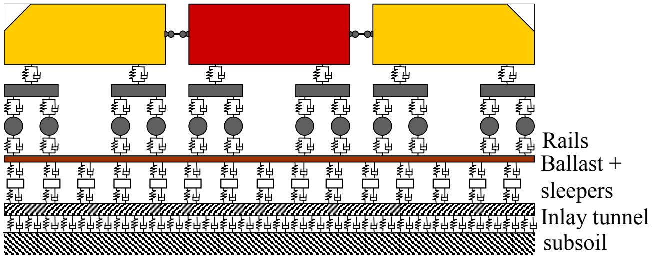


*Fig. 5. Track Model.*

With the equivalent parameters of the tunnel deflection, the characteristic length $L_{eff}$ ($1/\lambda$) can be determined. The characteristic length is defined as the representative deflecting length of an elastic supported beam, which is derived by:

$$\lambda = \sqrt[4]{\frac{k}{4EI}} \tag{1}$$

Where $k$ is the support stiffness per unit length and $EI$ the bending stiffness of the beam. The characteristic length is used by formulating the loading in the 3D geometry to equivalent loading components for the 2D plane strain or 2D axisymmetric transmission calculations.

Track model

The Track Model (Fig. 5) simulates a train travelling in the tunnel. The tunnel and the rails are modelled as a Timoshenko beam, with both bending stiffness $EI$ and shear stiffness $Z$. The ballast and the sleepers are modelled as a single mass –spring system. The rail is modelled also as a Timoshenko beam. The geometry of the rail is modelled with a certain rail irregularity. The train consists of coaches, bogies and wheels, which are all modelled as rigid bodies and are connected by springs and dampers. The wheels can have a certain unevenness. Rails and wheels contact is modelled by means of a moving Hertzian contact spring. The forces are calculated by moving the train across the rail with a certain velocity.

The output of this model is the force of the spring/damper systems between the sleepers and the tunnel inlay (Fig. 6). These forces are applied as a load on the next sub model, the transmission model.

Transmission model

The wave propagation from the tunnel through the soil layers is calculated by a Finite Element Model. It can either be a 2D or a 3D pulse response calculation. At the vertical plane along the tunnel axis, symmetry boundary conditions apply. Infinite boundary conditions apply at the bottom and far sides. These boundary conditions let the seismic energy disappear from the model without reflections, so that the model behaves like an infinite layered half space.

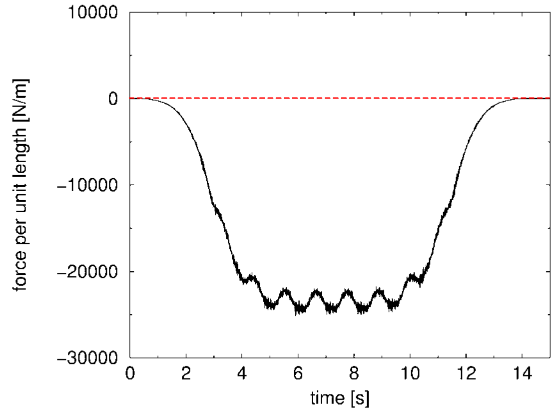


*Fig. 6. Force - time signal from sleepers averaged over characteristic length*

The model is loaded by a unit load for a short time, a pulse, at the position of the track and the response of is calculated in the time domain. Due to this pulse loading waves will propagate through the soil (Fig. 7). The transmission of the vibrations is determined by vibration velocity relative to the unit loading.

By convoluting the force – time signal from the track model with de pulse response, the vibration velocities of an arbitrary point due to a running train can be computed. In order to calculate the correct response due a moving train, a number of excitation points are to be defined along the track from which vibration waves originate. All these vibration waves, starting from different points, contribute to the resulting vibration levels in the response points in accordance with phase shifts and travelling paths.

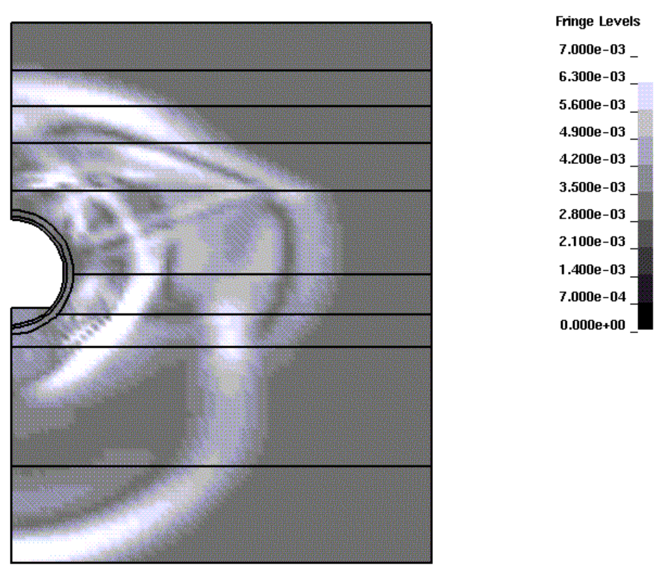


*Fig. 7. Vibration velocities due to pulse response.*

Modelling

The propagation of vibrations from a tunnel through the surrounding soil is a true three-dimensional phenomenon. The propagation of vibrations in the along the tunnel axis is different from the propagation perpendicular to the tunnel. The transfer functions to predict the vibration propagation have been determined numerically for the tunnel and surrounding soil conditions, as mentioned in previous paragraph. To examine the appropriate transfer function 3 different approaches are used:

- Axial-symmetric finite element model,
- Plane strain finite element model,
- 3D finite element using solids.

The axial-symmetric and the plane strain models have the advantage that the finite element models are semi 2-dimensional, and hence reasonably easy to handle. The use of a axial-symmetric finite element model in the situation were a tunnel is at hand, is however doubtful from the beginning, as the tunnel is modelled as a sphere. This approach is probably applicable far from the tunnel, where the 3D influence of the tunnel is limited. In the plane strain approach no deformations perpendicular to the cross-sectional plane are allowed and in fact an endless line load is simulated. This approach is likely to be acceptable for points nearby the location of excitation. The 3-dimensional models are closest to reality because no compromising conditions are imposed. The models are however large, using a lot of memory and computer time, which makes the handling of the calculations rather tedious.

In the graph in Fig. 8 the admittance at surface level for axisymmetric, plane strain is compared to the 3D modelling. The plane strain modelling is very close to 3D modelling until 30 m from the tunnel axis, which is equivalent to the depth of the loading source.

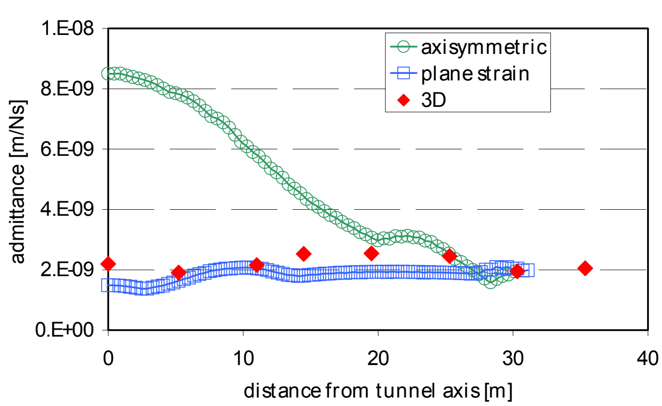


*Fig. 8. Admittance at surface level for axisymmetric, plane strain and 3D modelling.*

For response points far away from the points of excitation however the approach is expected to result in vibration levels too high due to the reduced amount of geometrical damping in the model.

Furthermore the accuracy of the vibration prediction depends on the chosen input parameters. In order to quantify the effect of a certain parameters on the results, several input parameters have been varied. In a study of a Japanese metro tunnel it was found that boundary conditions are rather important (Gardien & Stuit, 2001). The performance of the boundaries can be verified by checking the reflections of the pulse response.

EXPERIMENTAL SETUP

To investigate the dynamic behavior of the tunnel and the soil-structure interaction, the response of the tunnel and of the confining soil was measured. One ring of one tube of the tunnel was instrumented with accelerometers, strain gauges, water pressure cells, and soil pressure cells (Fig. 9).

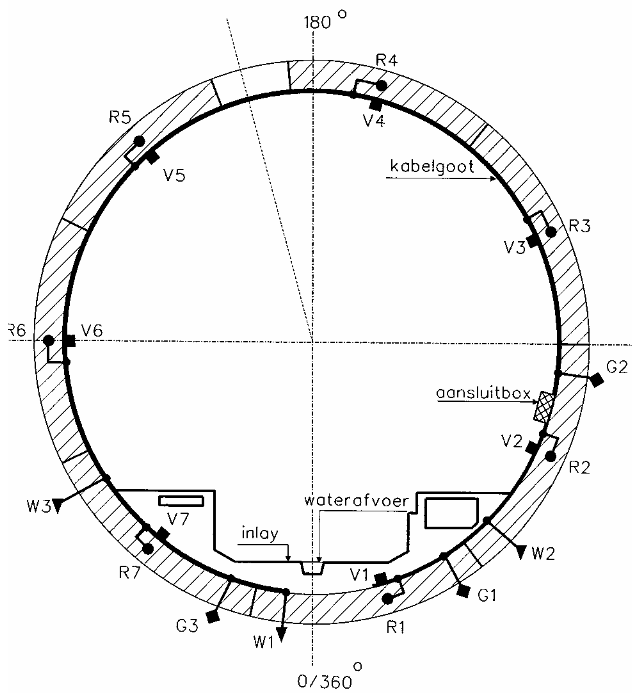


*Fig. 9 Cross-section of the instrumented ring. Positions of the accelerometers (V), strain gauges (R), water pressure devices (W) and soil pressures devices (G) are indicated.*

The center of each segment of the instrumented ring was equipped with 3 accelerometers that measured radial, tangential and axial accelerations of the structural element. The accelerometers were placed onto the internal surface of the tunnel. Strain gauges were embedded in the concrete and were also located at the center of the segments. Water pressure and soil pressure cells were instead placed just outside the overexcavation of the TBM through the lining of the instrumented ring.

Next to the instrumented tunnel, a number of sensors were installed to observe the dynamic response of the soil. Three seismic cones (red dots in Fig. 1) were driven at 20 m below the ground surface. The devices measured accelerations along radial, tangential and axial direction. Three prefab piles were instrumented with nine accelerometers (three at the head and three at the tip) measuring vertical accelerations (green dots in Fig.1). Finally, nine accelerometers were placed onto the ground surface measuring accelerations along radial, tangential and axial direction (red dots in Fig.1).

The dynamic response of the system was measured by exciting the tunnel by means of a shaker. The shaker was placed in the tunnel on the instrumented (reference) ring and them shifted to larger distances. The force exerted to the tunnel depended on the angular frequency of the masses and did not exceed 4 kN (single peak). During the test, the frequency of the harmonic force varied from 5 to 85 Hz. From 5 to 40 Hz, the circular frequency was varied with steps of 1 Hz. Above 40 Hz, steps of 2 Hz were used. Time-histories 32 seconds long were recorded with a sampling frequency of 500 Hz. Each time-history was then Fourier transformed and the frequency-dependent response was determined.

RESULTS

This section presents some of the numerical and experimental results of this study. Other experimental results are in De Boer *et al.* (2001) and Esposito *et al.* (2002).

Transmission in the tunnel

Fig. 10 shows the radial admittance at point V4 (see Fig. 9) when a harmonic source acts on the same ring. The exceptional agreement between modeling and experiment is evident.

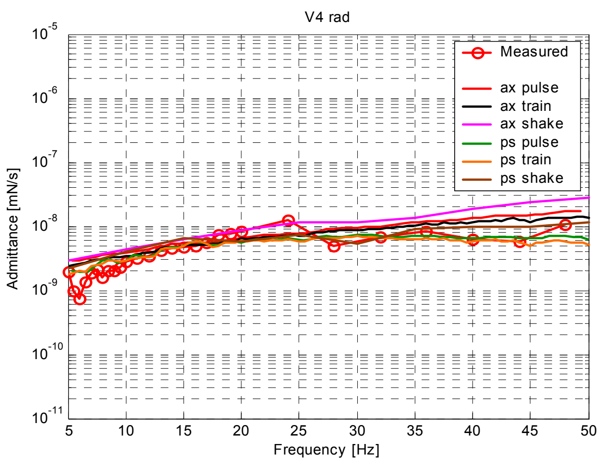


*Fig. 10 Radial admittance at point V4when a dynamic source acts on the same ring*

Fig. 11 shows the measured radial admittance at point V3 (see Fig. 9) whit the dynamic source placed on the same ring and whit the source placed on two rings located 30 m further and 30 m behind. It can be seen that the measured part of the tunnel exhibits a symmetric dynamic behaviour.

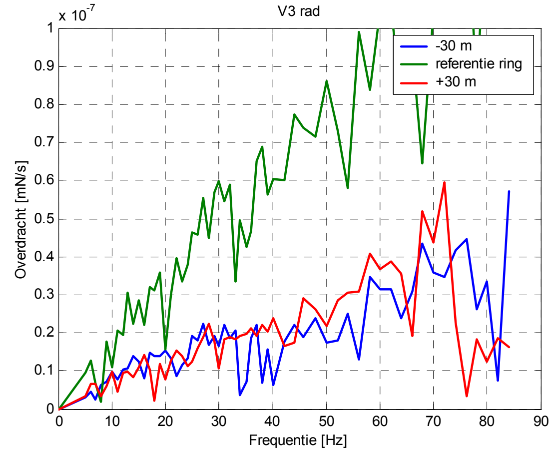


*Fig. 11 Radial admittance at point V3 measured with source at different locations.*

Transmission from the tunnel to the surrounding

Fig. 12 shows the vertical admittance between force in the tunnel and the soil at the shortest distance from the tunnel (point C1 in Fig. 1). It can be seen that the agreement is poor up to 25 Hz for all the modeling strategies. In Fig. 13, the vertical admittance between force in the tunnel and the point M2 (Fig. 1) onto the ground surface is shown.

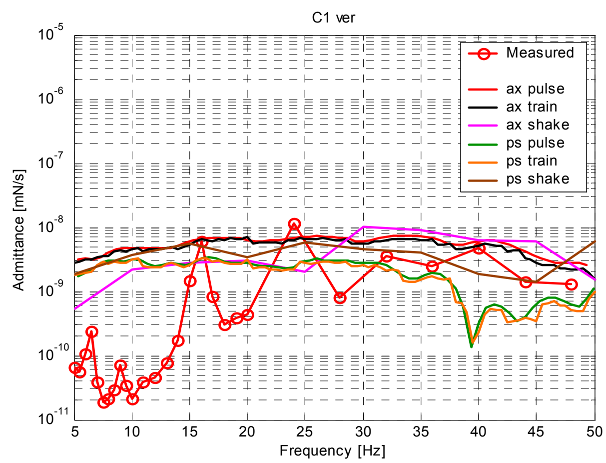


*Fig. 12 Vertical admittance in the soil at depth*

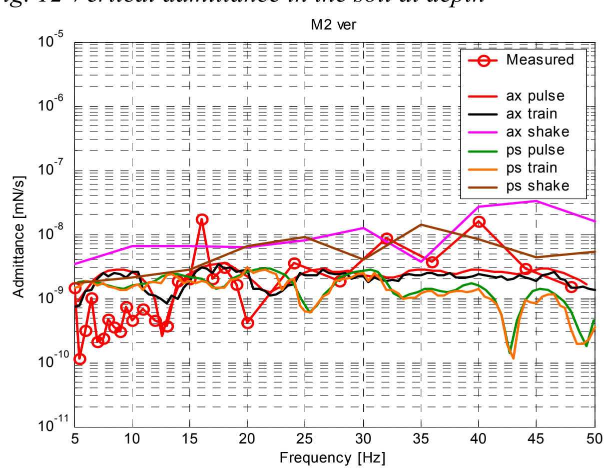


*Fig. 13 Vertical admittance onto the ground surface*

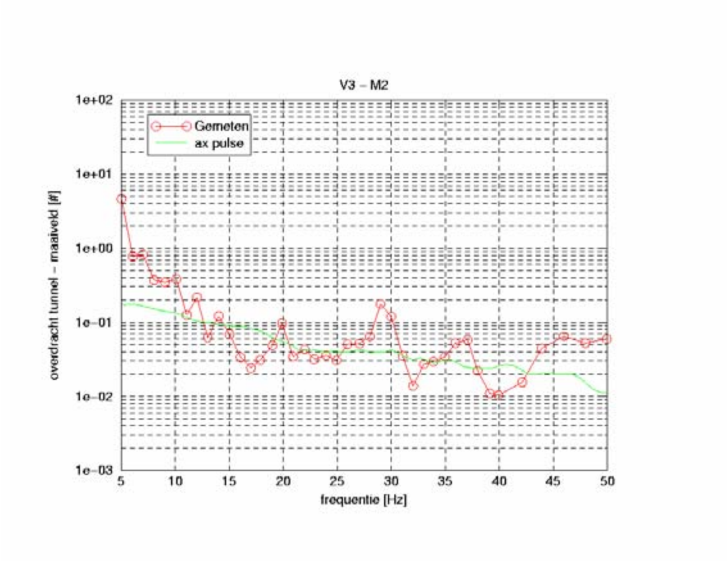


*Fig. 14 Transfer function between tunnel and ground surface*

Figure 14 shows the transfer function between point V3 in the tunnel and point M2 onto the ground surface (see Fig. 1). The measured transfer function is the red line, the calculated one with the axial-symmetric model is the green line. Also in this case, model and experiment show a good agreement.

Ratio Radial/tangential velocity in the tunnel

One of the most interesting questions arising from this experiment was to determine how the rings vibrate when dynamic vertical loads act on the inlay. Fig. 15 shows the ratio between the radial velocity and the tangential velocity at 20 Hz. The lowest point of the tunnel is located at 180 degree. From the figure it appears that the first flexural vibration mode is dominant both in the experiment and in the modeling. In particular, the modeling of the shaker shows the best agreement with the experiment. At other frequencies, higher flexural modes were dominant.

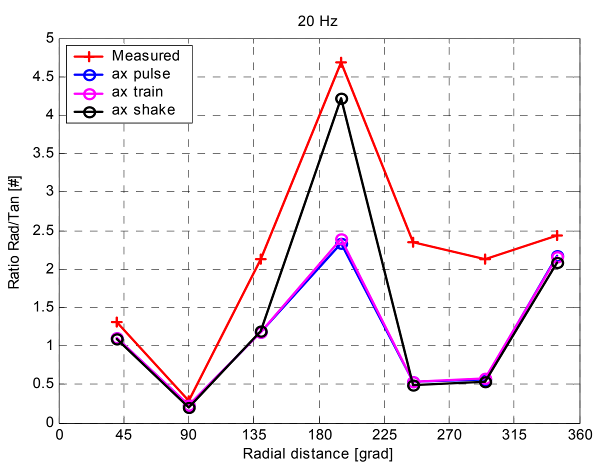


*Fig. 15 Ratio between radial and tangential velocity.*

Ratio Pile head/Pile tip

The last result shown in this paper is the transfer function between pile tip and pile head. In this case, no modeling was carried out. It was interesting for the construction organization to understand how tunnel-induced vibrations propagate through foundations on piles. Therefore, three prefab square piles (0.4 m) were driven into a deep sand layer next to the tunnel (Fig. 1). The piles were, however, were not loaded. Therefore the results shown in Fig. 16 are not representative of the real situation. The assumption is that the energy propagates preferentially from the tunnel through the sand layer.

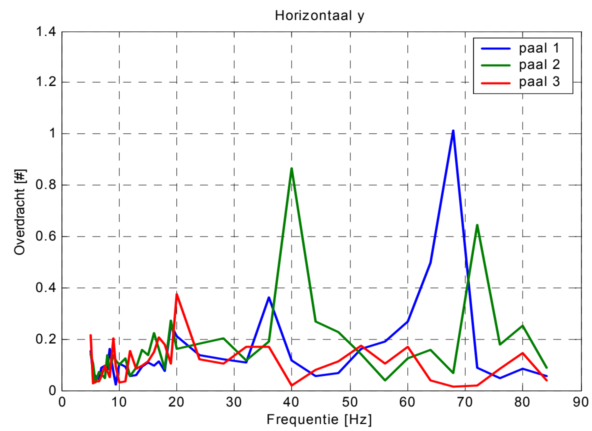


*Fig. 16 Transfer function between pile tip and pile head*

CONCLUSIONS

Some of the results of this extensive study were presented in the previous section. From these and from those given in De Boer *et al.* (2001), Esposito *et al.* (2002), and Gardien and Esposito (2003), the following conclusions can be drawn.

- The transmission of the energy exerted on the tunnel by a dynamic shaker placed on the reference ring was symmetric along the axial (length of the tunnel) direction with respect of the position of the shaker.
- The finite element modelling reproduced with excellent accuracy the mechanism of transmission in the tunnel.
- The accuracy of the finite element modelling in reproducing the transmission from a point inside the tunnel to a point onto the ground surface was acceptable. Less successful was the modelling of the transmission from a point inside the tunnel to a point into the soil.
- Both in the experiment and in the modelling, the first flexural vibration mode of the ring was dominant up to about 30 Hz.
- During the test, the tunnel exhibited large vertical vibration respect to the horizontal vibrations.
- From the transfer function between pile tip and pile head, it can be concluded that the transmission of the energy takes place essentially in the soft layers and that, with similar soil conditions, the contribution of the pile tip to the total energy transmitted to a construction is limited.

ACKNOWLEDGEMENTS

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