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PROGNOSIS OF VIBRATIONS AND LOW FREQUENCY NOISE FOR A BORED TUNNEL IN SOFT SOILS

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ABSTRACT
The city of Amsterdam plans to build a new 9 km long subway between the northern and southern part of Amsterdam. Part of the line will be built just below the old well-known canal houses with the Tunnel Bore Method. The problem to be solved is that little is known about the transmission of vibrations passing a light, segmented and round tunnel in soft soils. The solution to this problem appeared to be an experiment in the recently bored 2nd Heinenoord tunnel near Rotterdam. The measurements and initial calculations show a chance for perceptible levels for vibration and low frequency noise in a wide area around the tunnel if no vibration-reduction measures would be taken.

1 - INTRODUCTION
The tunnel is planned to be constructed 10 to 30 m below surface in layers of clay and sand. The route (of the bored tunnel) is through the old city from Amsterdam Central Station to Rokin, Vijzelgracht, Ceintuurbaan and ends at the RAI convention center. Although the tunnel will follow canals or main roads as much as possible, it still will be quite near to town houses, monuments and company buildings. Therefore, based on experience with classic tunnels, it is expected that the passings of trains result in some vibration and audible low frequency noise.
A bored tunnel for (public) transport systems under the center of a city is new in the Netherlands. This means that practical vibration knowledge for bored tunnels in soft soil hardly exists. The annoying low frequency as induced by the passing train follows a transmission path through the ballasted track, the soil and the foundation of the building. Figure 1 gives the total transmission path with the subdivisions. The tunnel will vibrate due to the vibrations of the passing train. The ballasted track will transmit the vibration of the train. Those two, the train and the railbed, are the parameters which can be influenced: the mass and elasticity of the springs of the train can be slightly adapted, while the ballasted track can be changed more rigorously (special connection of rail, embedded rail, special bed or isolated floor).
Next, the transmission is determined by three nearly unknown parameters: transmission from tunnel to the soil; transmission through the soil: it is hardly possible to determine the dynamic parameters; the transmission from the soil to the piles of the foundation.

2 - VIBRATION EXPERIMENT
The 2nd Heinenoord tunnel is the first bored tunnel in soft soil in the Netherlands. The tunnel is built south of Rotterdam just below the river 'Oude Maas'. The tunnel itself has a diameter of 8 m and is segmented. Each segment has a width of 1.5 m and consists of 7 pieces that form the circle. Basically, the segments are placed freely next to each other with small ridges for exact placement during the building process. On behalf of the North/South Metro Line an experimental field of piles (loaded with seacontainers) was made for determination of ground movements due to the bore process itself (Teunissen and Hutteman, 1998).
The main goal of the vibration experiment is the determination of the transmission from the tunnel to the piles. The source used in the experiment was a concrete weight of approx. 800 kg. In order to prevent

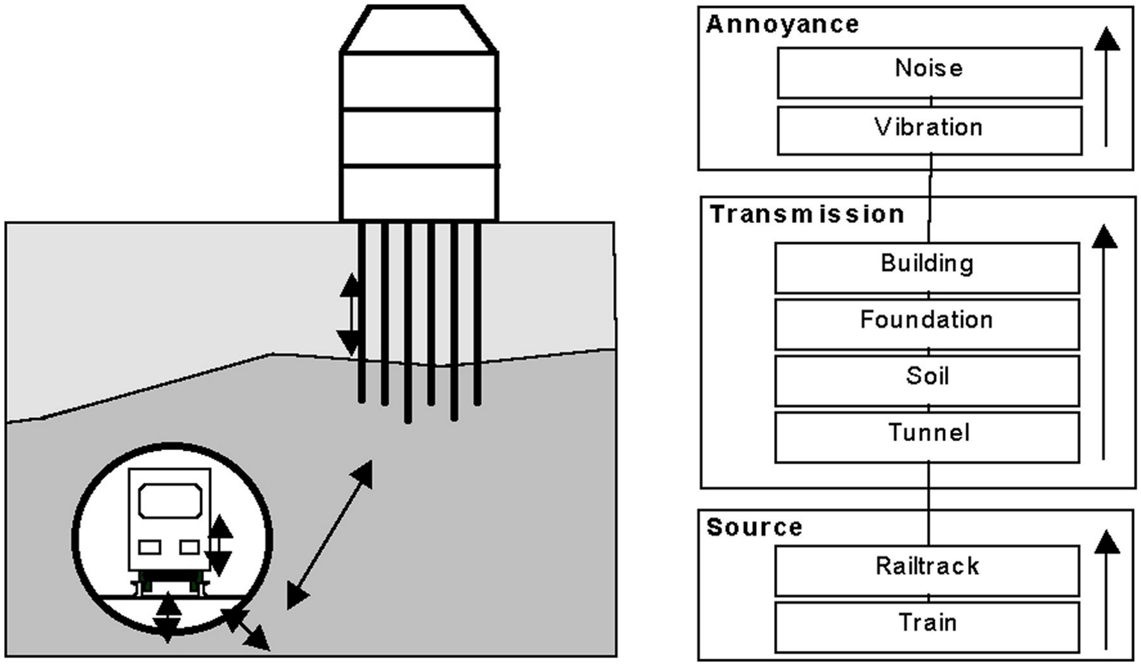

Figure 1: Transmission from vibrations in tunnel to environment.

damage of the concrete lining of the tunnel a steel construction was designed to spread the impulse-force over 3 or 4 segments (size comparable with a pair of wheels of a train). The experiment was designed to measure the dynamic behavior of the tunnel and the several transmission paths through the soil to the surface and the piles (wood, concrete).

3 - VIBRATION MEASUREMENTS

The first check done in the experiment was the displacement of the concrete segments. This was felt most important to avoid damage. The displacement-measurements showed that the actual displacement was not measurable (measurement accuracy was approx. 1 mm) with a striking force of 70 kN.
Figure 2 shows a typical result of the experiment. It gives the result for the transmission from a tunnel segment directly under the metal construction to the surface at a distance of approximately 4 m from the tunnel (left panel). The measurement gives the vertical transfer function based on the acceleration measurements. The transfer function shows a significant transmission between 10 and 150 Hz with a maximum at 70 Hz. The right panel gives the coherence showing reliable data between 10 and 200 Hz.

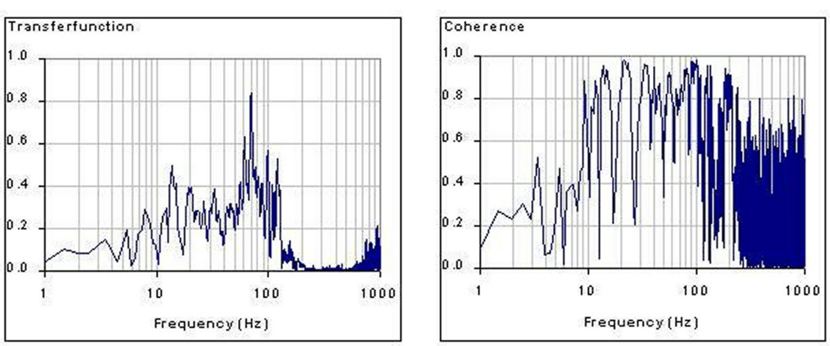

Figure 2: Example measured transmission from tunnel to surface (left) and coherence (right).

The measurements as shown in Figure 2 show a narrowband character of the transfer functions. This finally may result in audible resonance-frequencies in the building. This means that in the final design those frequencies must be taken into account with special attention to the computations in the 1/1 or 1/3 octave frequency bands. From the presented measurements a correction will be needed of about 5 dB. This correction can be avoided when the rail system is chosen to isolate for those resonance-frequencies.

4 - NUMERICAL ANALYSIS

For the numerical analysis two model-types were used: three-dimensional (3D) and axi-symmetrical (AXI) (Geurts, 1999). The left panel of figure 3 gives a sketch of the 3D and AXI model. The 3D-model is theoretically the best model. A point source is handled correct. Disadvantage is the long computation-time and large amount of data. The AXI-model is a semi 2D-model but rotated around its central axis. The advantage of this model is that it can be used for semi-three-dimensional computations with reasonable computation-time. From computations with the models we could conclude that for distances starting from 3.5 m (comparable with the radius of the tunnel) the AXI-model was appropriate due to the local reaction of the segmented tunnel.

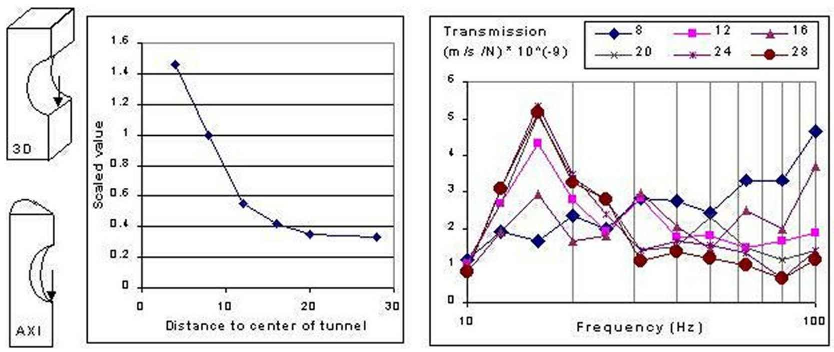

Figure 3: Finite element models (left), scaled value of vibration velocity relative to the center of the tunnel (middle) frequency dependent transmission for different distances to center (right).

5 - RESULTS

The AXI-model was used for computation of the transfer function from the tunnellining to the surface. The middle panel of figure 3 gives the maximum vibration-velocity as a function of the distance. The values are scaled to the maximum value at 8 m from the center. The figure shows hardly any attenuation of the signals for distances larger than 15 m. This can be understood by keeping in mind that the tunnel in this experiment is about 15 m below surface. Although horizontally distances change significant, the relative distance to the tunnel changes hardly.

Next, the right panel gives the transfer functions as a function of the frequency for the distances ranging from 8 to 28 meter. This figure shows that for frequencies around 20 Hz the transmission at larger distances is even larger than for the short distances. This effect originates most likely from reflections between the layers of sand and clay around the tunnel. For frequencies between 30 and 60 Hz we have equal transmission for all distances. From these computations we concluded that it is important to account for vibrations in a wide area around the tunnel.

6 - CONCLUSIONS

The main transmission of the vibrations from the tunnel to the environment is between 10 and 150 Hz. In computations for low-frequency noise based on 1/1 or 1/3 octave frequency bands, a 5 dB correction must be taken into account for resonance-frequencies. This correction can be avoided when the rail system is chosen to isolate for those frequencies. For the situation at the 2nd Heinenoord tunnel we have found hardly any attenuation of vibrations for distances ranging from 12 to 28 meter. This most likely is the combined result of waves being reflected in the layers of sand and clay around the tunnel.

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