# EVALUATION OF VIBRATIONS FROM THE TUNNEL BORING MACHINE IN SOFT SOIL


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## Abstract

A tunnel boring machine can lead to vibration nuisance in nearby residential buildings. The Dutch COB F511 committee has set up a research program that resulted in a vibration assessment protocol for bored tunnels. Vibrations have been measured and predicted during the construction of the “Green Heart Tunnel” in the Netherlands. The measurements and predictions have been evaluated. A simple measurement during several days at the surface provided sufficient information about the vibration behaviour of the tunnel boring machine. Generally, sophisticated 3D FEM models did not give a better prediction than a simple 2D model.


## INTRODUCTION

In densely populated areas of the Netherlands, several bored tunnels have been built in the recent past and are to be built in the near future. At other bored tunnels, it has been found that the Tunnel Boring Machine (TBM) often generates more vibrations than passing trains during the exploitation phase. The COB (Netherlands Centre for Underground Construction) committee F511 has set up a research program for the vibrations during the construction of the “Green Heart Tunnel”. The “Green Heart Tunnel” is part of the high speed train link from Amsterdam to the Belgium border.

Measurements were carried out at 4 locations and several vibration predictions are made. The predictions and measurements have been evaluated.

## MEASUREMENTS

At 4 locations along the tunnel trace, the vibrations are measured [2, 3, 4, 5]. The measurements and measurement locations are shown in Table 1. The results of measurement session 1 are used for vibration predictions at “Patrimoniumpark”. Roughly, the measurements can be divided in 2 groups:

- Travelling measurements: Measurements with one measurement point at the surface above the tunnel axis and one measurement point in the TBM [2]. These measurements start several days before and end several days after the TBM has passed the measurement point at the surface;

- Extensive measurements: Measurements with 9 measurement points at the surface around the TBM and 4 measurement points in the subsoil at the depth of the tunnel axis [4]. During session 3 (Patrimoniumpark), vibrations have also been measured at several points in the TBM and the tunnel and in a nearby residential building.

*Table 1 – Measurement sessions*

| Measurement location | Type of measurement | Location of measurement points | | | |
|---|---|---|---|---|---|
| | | TBM | Subsoil | Surface | Building |
| Session 1 / Achthoven | extensive | | **X** | **X** | |
| | travelling (1) | **X** | | **X** | |
| Session 2 | travelling (2) | **X** | | **X** | |
| Session 3 / Patrimoniumpark | extensive* | **X** | **X** | **X** | **X** |
| | travelling (3) | **X** | | **X** | |
| Session 4 | travelling (4) | **X** | | **X** | |
| | extra measurement | | **X** | **X** | |

After the first measurement session, it became clear that three processes in the tunnel could clearly be distinguished:

- More or less constant vibrations during the boring process of the TBM;
- Short impulse-like vibrations during the placement of the tunnel segments;
- Hardly any vibrations during the daily maintenance period.

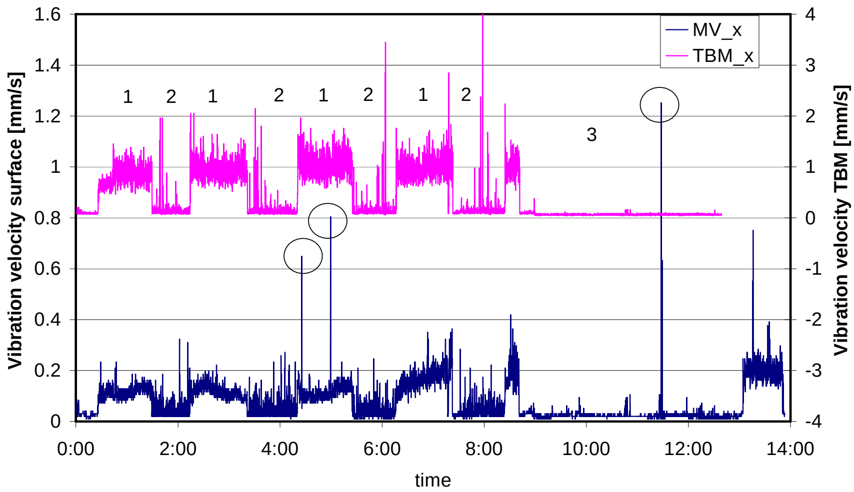


*Figure 1 – Typical vibration levels found in the TBM and at the surface. (1: boring, 2: segments, 3: stand-still). Encircled values are probably not associated with the TBM activities.*

The tunnel axis was about 30m below the surface, and the tunnel has an outer diameter of 15m. The vibration level did not decrease for distances up to 40 m from the cutter wheel of the TBM. Only at the farthest measurement points (approximately 70m) the vibration level was significantly lower than the vibration level near the tunnel.

## PREDICTIONS

Three different parties were commissioned to predict the vibration level at the site “Patrimoniumpark” during the passage of the TBM [6]. All parties were provided by the same information. In Table 2 an overview of the vibration predictions is given. Unfortunately, the measurement points at depth at “Achthoven” did not give reliable results, so that the “shell” around the TBM in which the wave field would be catched was not complete. Therefore, all parties have found alternative ways to predict the vibration level at “Patrimoniumpark”, based on a reduced set of measurements at the surface.

*Table 2 - Overview of vibration predictoins*

| | |
|---|---|
| Party A | Empirical model, with tunnel diameter and global soil properties as input values. No distinction is made among the different processes in the TBM. |
| Party B | - 2D axisymmetrical finite element model that focuses on the vibrations during the placement of the tunnel segments. The excitation function has been derived from the measurements at “Achthoven”<br>- 3D finite element model that focuses on the vibrations during the boring process of the TBM. The excitation function has been derived from the measurements at “Achthoven”. It was assumed that the forces exerted in the direction of the tunnel axis (from the jacks that push forward the TBM) |
| Party C | - Spectral element model that focuses on the boring process of the TBM. The excitation function had been derived from measurements at “Achthoven”<br>- 3D finite element model that focuses on the vibrations during the boring process of the TBM. Vibrations measured at the surface at “Achthoven” are applied at tunnel depth as a prescribed vibraton velocity |

## EVALUATION OF MEASUREMENTS AND PREDICTOINS

### Vibration patterns

During measurement session 3 at “Patrimoniumpark” vibrations are measured both inside and outside the tunnel at several measurement points, so that vibrations from the tunnel could be correlated with vibrations outside the tunnel [7]. The measurement points inside the tunnel were located at the tunnel shield (front side of the TBM), at the wheels that transport the TBM over the tunnel lining and at the tunnel lining approximately 25m from the TBM. During the boring process, both inside and outside the tunnel a pattern of pulses at an interval of about 0.2 seconds was registered. Inside the tunnel, the pulse-like vibrations were best registered at the tunnel shield in the direction of the tunnel axis. This indicates that the source of the vibrations could be the jacks that push the TBM forward in the direction of the tunnel axis.

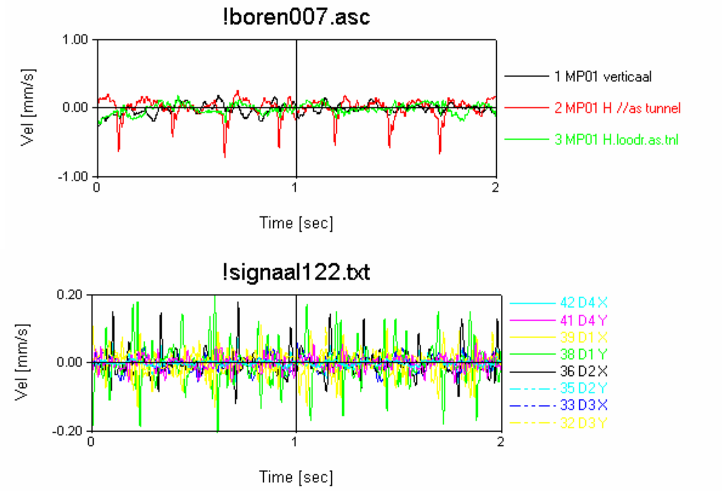


*Figure 2 Pulse-like behaviour at in interval of 0.2s during the boring process inside (above) and outside (below) the tunnel.*

The vibrations during the placement of the tunnel segments have also been registered both inside and outside the tunnel. During the placement of the tunnel segments, individual impulses were registered at irregular intervals. Figure 3 contains the recorded vibrations of a placed segment both inside and outside the tunnel. Inside the tunnel, the largest vibrations were recorded at the tunnel shield, in the direction of the tunnel axis.

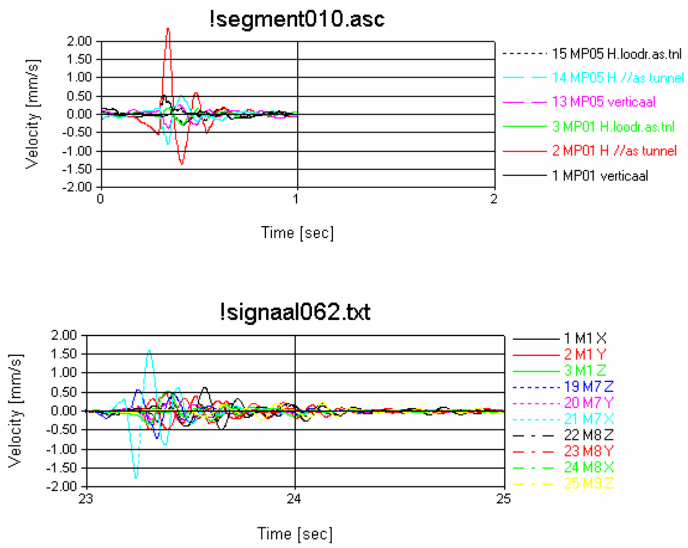


*Figure 3 Vibrations inside (above) and outside (below) the tunnel during the placement of the tunnel segments.*

## Relationships found at measurements

### *Position of TBM with respect to measurement points*

In Figure 4 the Vibration levels measured at "Patrimoniumpark" (extensive measurement, session3) are depicted per direction. The vibration level at a surface point above the tunnel axis during several days is displayed in Figure 5. At all measurement sessions the same observations could be made about the position of the TBM with respect to the measurement points:

- The largest vibrations were found behind the TBM front;
- Generally, vibrations in the horizontal direction are larger than vibrations in the vertical direction;
- Because of the large variation in vibration level in time, the source of the vibrations could not be pinpointed from the time of the maximum vibration level during the TBM passage.

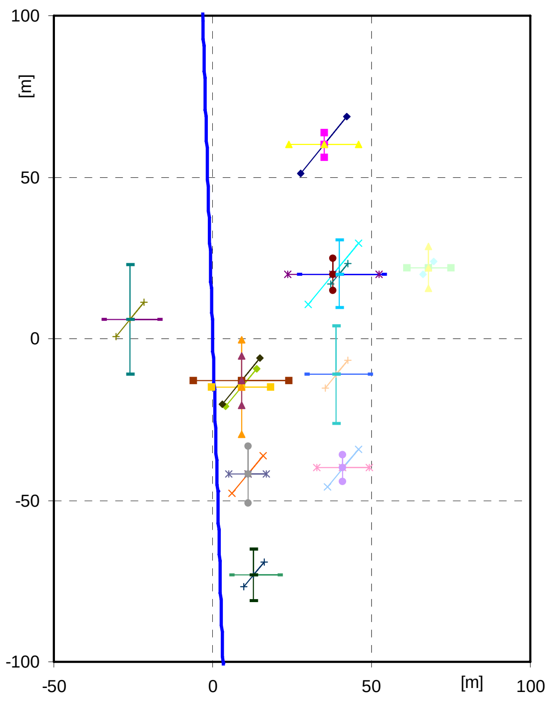


*Figure 4 Vibrations at surface measurement points in 3 directions (session3, Patrimoniumpark). The diagonal bar corresponds to the vertical direction and the bar length is proportional to the vibration level. The TBM front is located at (0,0).*

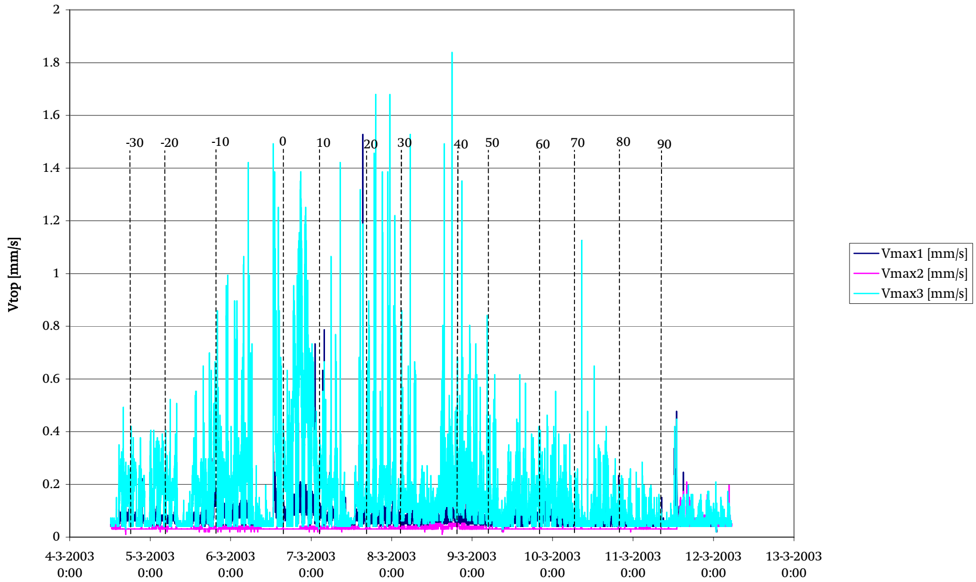


*Figure 5 Vibration level at surface (session 4) during several days (Vmax1: vertical, Vmax2: horizontal parallel to tunnel axis, Vmax3: horizontal perpendicular to tunnel axis).*

### *Relationship between soil properties and vibration level*

At 4 locations identical measurements have been carried out with a 3D geophone that recorded the vibrations during several days at the surface, exactly above the tunnel axis. The measured vibration values and the global soil properties are given in Table 3. The highest peak values (99% values) seem to occur when the TBM is cutting through soil with a low cone resistance. The highest average vibration velocity during the boring process is measured at locations with thin set of top soft soil layers.

*Table 3 - Vibration velocity [mm/s] at 4 measurement locations and global soil properties*

| | 99%, boring | average boring | 99% segments | average segments | average CPT cone resistance at tunnel depth [MPa] | Thickness top soil layers [m] |
|---|---|---|---|---|---|---|
| km 28.150 | 0.88 | 0.28 | 1.01 | 0.12 | 22.5 | 1.6 |
| km 27.760 | 2.77 | 0.20 | 2.83 | 0.17 | 17.5 | 3.3 |
| km 27.510 | 1.62 | 0.14 | 1.22 | 0.12 | 20 | 5.0 |
| km 26.290 | 1.62 | 0.11 | 1.57 | 0.13 | 17.5 | 10.6 |

### *Slurry pressure – vibration level*

At measurement session 4, a remarkable increase in the vibration level was found during the boring process for several hours. It turned out that the tunnel contractor had been experimenting with the slurry pressure at this location. In Figure 6 both the slurry pressure and the vibration level during boring are displayed. The period of increased vibrations corresponded well with the period of increased slurry pressure.

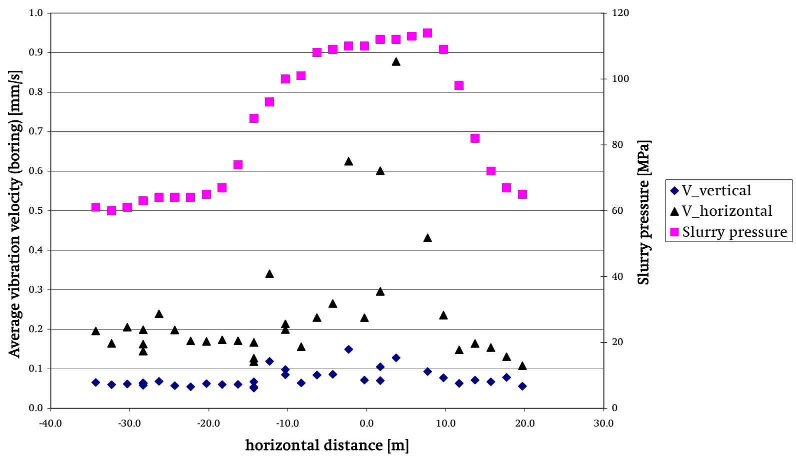


*Figure 6- Vibration level and Slurry pressure as a function of TBM progress.*

## Comparison between predictions and measurements

The vibration predictions focussed on different processes of the TBM. Therefore each prediction should be compared to a measurement values that correspond to the same TBM process as the prediction. As an example, a 2D FEM and 3D FEM prediction are compared with the measurements in Figure 7. The 2D prediction results are generally closer to the measured values than the 3D prediction results. Especially the decrease of 3D FEM vibration level with the distance is much stronger than measured. The impression from all predictions was that a sophisticated 3D FEM model does not give a more accurate prediction than a 2D FEM, 2D spectral element method or a simple empirical model.

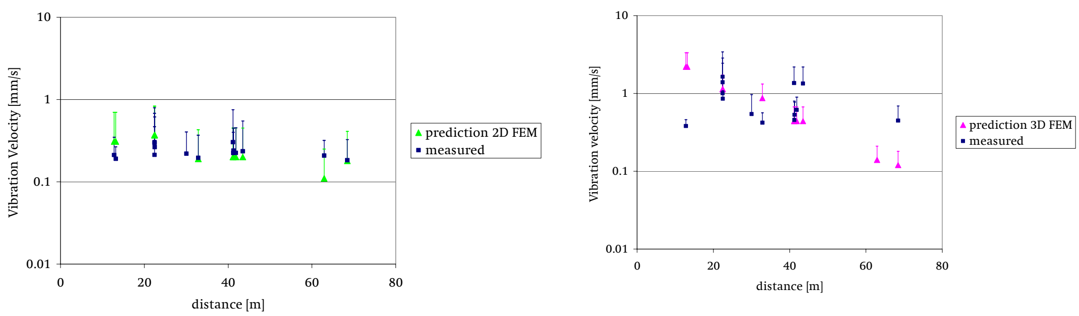


**Figure 7 Comparison between predictions and measurements. Left: representative vibration during segment placement with 2D FEM model. Right: vibration during boring with 3D FEM model.**

## CONCLUSIONS

The research program has resulted in the following conclusions:

- From the measurements follows a distinction among the vibrations during boring, vibrations during the placement of tunnel segments and the vibrations during stand-still of the TBM;
- The typical maximum vibration level at the surface was approximately 1mm/s and the largest vibrations were measured in the direction parallel to the tunnel axis;
- The vibration level exceeds the background level from 50m before to 100m after the cutting wheel has passed a point at the surface;
- Generally, the horizontal vibrations are larger than the vertical vibrations;
- The vibration level behind the TBM front is larger than the vibration level in front of the TBM;
- From the measurements follows a relationship between the slurry pressure and the vibration level;
- A sophisticated 3D FEM model does not give a better prediction than a simple 2D model;
- A limited number of measurement points is sufficient for a vibration prediction;

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