The influence of dynamic soil characteristics on vibration predictions

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Abstract

Reliable prediction of environmental vibrations from railways and metros not only requires reliable models, but also reliable input parameters. Within the frame of the European project CONVURT, an advanced numerical prediction model is developed for subway induced ground-borne vibrations. This model is validated by means of the results of elaborate in situ tests in Paris and London.

On the site in London, a variety of field experiments (CPT, SCPT, SASW) has been performed, as well as advanced laboratory tests on undisturbed samples (bender element test, free torsion pendulum test). Based on rough estimates of the accuracy of the parameters, the influence of the dynamic soil characteristics (shear modulus, bulk modulus, material damping) on the reliability of the numerical predictions is studied. An advice for optimal soil exploration is formulated.

1. Introduction

For new metro lines a reliable prediction of environmental vibrations in adjacent buildings from passing trains is required. Uncertainty in these predictions is always present, but should be reduced as much as possible. This paper will show the importance of the uncertainty of the dynamic soil characteristics on the model predictions and demonstrate how good soil investigation can reduce the level of uncertainty.

This paper describes the results of field tests on a test site in Regent’s Park, London, that have been carried out in order to validate a prediction model developed within the frame of the EU-project CONVURT [3]. Furthermore, the influence on the transfer functions and the free field vibrations is demonstrated by using a simplified two-dimensional finite element model.

2. Problem description

2.1. Modelling vibrations

A model for environmental vibrations generally consists of a chain of sub-models: (1) a source model, giving the dynamic load on the tunnel invert, (2) a transmission model including the tunnel and the soil, giving the velocity in the soil due to a unit load on the tunnel invert, and (3) a model for the response of the building including dynamic soil-structure interaction at the foundation, giving the response of the building due to free field vibrations. The predicted vibrations in the building can be judged against the regulations for vibration hindrance.

All links in this chain contribute to the uncertainty of the answer, but the contribution of each link to the total uncertainty is not clear for the moment. A recent study on the effects of impact and vibratory pile driving and traffic induced vibrations showed that all components have a significant contribution to the total uncertainty [1]. This study did not include train induced vibrations, however, but it is reasonable to expect that the soil has a similarly large contribution to the total uncertainty in this case.

2.2. Generally used soil model

The soil is generally modeled as a horizontally layered half space. This choice is partly supported by the fact that most sediments consist of thin, more or less horizontal layers; also the limitations of the mathematical and numerical models govern this choice. Each layer in a horizontally layer is characterized by 5 parameters: thickness, bulk modulus, shear modulus, volumetric mass and damping.

It must be taken into account that soil deposits are the results of centuries of geological action, sedimentary deposits and erosion. The (dynamic) soil characteristics must be determined by in situ testing. Layers may not be horizontal or homogeneous. These aspects might influence the results, and the real soil layering should be determined for each site.

2.3. London test site

The site at Regent’s Park in London is chosen for validation testing as the Bakerloo line is passing under the park (Figure 1) and free field vibrations can be measured without influence of nearby buildings. The tunnel is indicated by a dashed line at the top of Figure 1; it is a circular bored cast-iron tunnel at a depth of 25 m below the surface. The most nearby buildings are almost parallel with the metro line at a distance of about 70 m from the tunnel. This allows for a simplified two-dimensional model, but was not a prerequisite for the more general three-dimensional model envisaged within the frame of the CONVURT project. A full description of the site, the trains and the building is given in reference [4].

This paper is focussing on the results at six points that are distributed on two measurement lines perpendicular to the tunnel and labeled as FF (Figure 1 and Table 1). On each line, three points are selected at 5.5 m, 23.3 m and 45.5 m from the tunnel.

Table 1 Position of points for simulations and field measurement

code field Figure 1	distance [m]	depth [m]	description position
FF01, FF06	5.50	0.00	surface, nearby
	5.50	15.30	depth, nearby
FF02, FF07	23.30	0.00	surface, middle
FF03, FF08	23.30	15.30	depth, middle
FF04, FF09	45.50	0.00	surface, far
FF05, FF10	45.50	15.30	depth, far

Four of these points (FF02, FF04, FF07 and FF09) determine a rectangle with a length of 26 m (perpendicular to the tunnel) and a width of 33 m (parallel with the tunnel) on which the soil investigation is performed (Section 3.1). The distance between these positions is sufficiently large to have a good idea of the dynamic soil properties in the full area where propagation of waves from the tunnel to the building occurs. At each position, in-situ measurements are performed and undisturbed samples are taken and tested in the laboratory afterwards. In the same field, Spectral Analysis of Surface Waves (SASW) tests are carried out along two perpendicular lines [4].

Vibrations during train passages were measured in these and some additional positions. The measurement points are placed on two lines perpendicular to the track, with positions at the same distance. This choice has been made in order compare these two measurements, which are assumed to be identical, apart from rail roughness and soil properties. Vertical and horizontal (perpendicular to the tunnel) vibrations are measured in all points at the surface, while tri-axial vibration measurements are performed in four points at a depth of 15 m (FF03, FF05, FF08 and FF10).

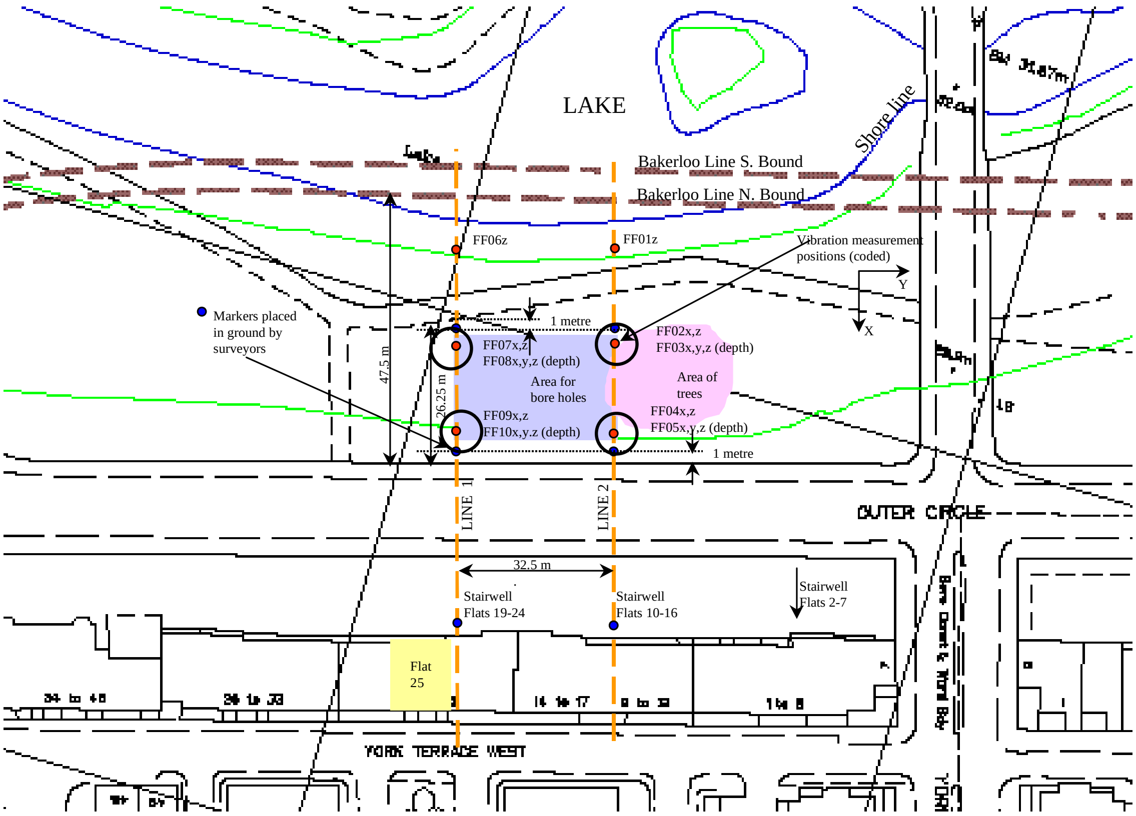


Figure 1 Overview of the test site at Regent's Park London

3. Results of field measurements

3.1. Soil investigation

From geological knowledge and experience at nearby locations it is expected that the soil at this site is quite homogeneous and consists of a top layer of London clay with probably some gravel and a thick deep layer of London clay [2].

At the four positions, a bore hole is drilled and a seismic cone penetration test (SCPT) is carried out in deeper layers. The boring is inspected visually and brought to the laboratory for further tests.

The cone penetration test measures the resistance (of the point and the shaft) of a bar pushed with constant rate into the soil. This test gives information on the strength of the soil, and more importantly, it can be used for soil classification. During installation, the measurement is stopped every meter. An artificial impulsive source at the surface generates a shear wave which propagates downward into the soil. Two transducers in the seismic cone measure the arrival time of the shear wave, allowing the estimation of the shear wave velocity of the soil. Since the wave pattern is very complicated close to the surface, this method is hard to characterize the first few meters of soil.

The SASW method also uses an artificial impulsive source at the surface. The surface waves are measured by a large number of transducers placed at one line from the source. The layering of the soil and the dynamic soil characteristics can be determined by inverse analysis from the dispersion curve of the surface waves. Since the penetration depth of the surface waves is limited, this method can only be used for the determination of properties of shallow layers.

The samples from the boring are tested in the laboratory. After some standard geotechnical classification tests, the following properties are determined in the laboratory: volumetric mass, shear wave velocity and compression wave velocity by acoustic testing and shear stiffness and material damping by a free torsional vibration test. In the free torsional vibration test, a cylindrical sample is first loaded in torsion and brought into free vibration afterwards. The stiffness can be estimated from the resonance frequency and the material damping from the amplitude decay.

3.2. Results of field and laboratory tests

Figure 2 shows the wave speed of vertical SCPT in terms of the mean value over three positions and the two-sided 90% reliability interval for each depth. On average, the shear wave velocity is between +/- 25%, leading to the shear stiffness between +/- 56%.

Figure 3 shows the result of the Cone Penetration Test (CPT). The left graph shows the cone resistance, the middle graph the shaft friction and the right graph the friction ratio (shaft friction/cone resistance). The friction ratio shows a change in material properties at a depth of about 5 m below the surface. From all CPT's, the thickness of the top layer varies between 3.5 and 6 m.

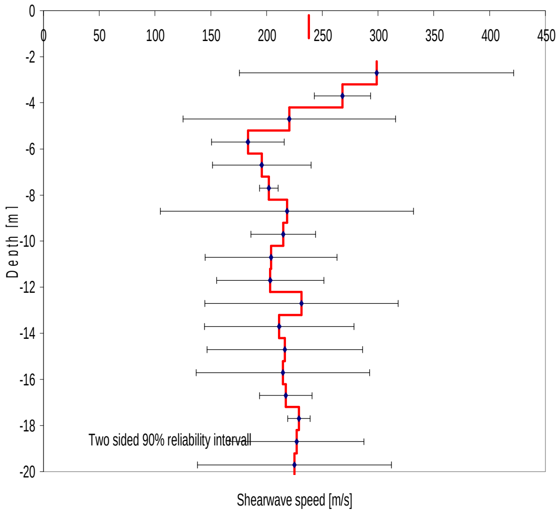


Figure 2 Shear wave velocity profile from SCPT

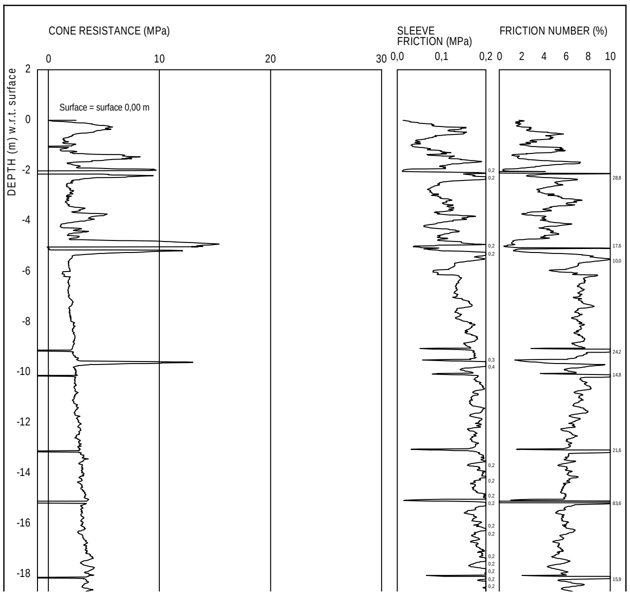


Figure 3 Results of the CPT in point FF04

The results of these measurements can be compared with the results of other measurements. Old measurements by London Underground revealed a shear wave velocity in the same order of 250 m/s and a somewhat lower compression wave velocity than the one determined here. The SASW tests, carried out by K.U.Leuven [4] showed two shallow softer top layers on a half space with a shear wave velocity of 260 m/s. These values might be reasonable for the top layers, since SASW is better for the shallow layers than SCPT. However, the method overestimates the value for the deeper layer, due to the limited penetration depth of surface waves.

The soil is a clay with some silt. The plasticity index is about 55-60. At one position (FF02), the amount of silt was much higher, which leads to a much lower plasticity index. The damping is about 4%, which is a reasonably high value. In the laboratory, the samples are weighted and tested by acoustic methods. Table 2 shows the results of these laboratory tests: volumetric mass, dynamic shear modulus and bulk modulus. It seems that the shallow layer is a bit heavier than the deep layer, but the difference is not significant. Therefore, it was chosen to use one value for the volumetric mass for both layers. The shear modulus could not always be measured and, as a consequence, the bulk modulus and Poisson's ratio can not be calculated. However, the laboratory tests give a quite constant Poisson's ratio in both layers.

Table 2 Soil characteristics from laboratory tests

point	depth [m]	Layer	volumetric mass [kg/m^3]	S-wave velocity [m/s]	P-wave velocity [m/s]	Poisson's ratio [-]
FF02	3.5	shallow	2005	114	1534	0.497
FF02	6.4	deep	1947			
FF04	3.3	shallow	1971			
FF04	6.3	deep	1998	157	1629	0.495
FF08	3.6	shallow	2014	116	1626	0.497
FF08	6.5	deep	1942			
		Mean	1980	129	1596	0.497
		St Dev	31	24	54	0.001

3.3. Final modeling of the soil

Based on all research, there is no evidence that the shallow layer differs strongly from the deep layer. Only a significant difference was revealed for the material damping ratio. In general, the stiffness in the laboratory tests turned out to be lower than the values measured in the field. This is observed in more cases and might be explained by distortion due to sampling and transport. Therefore, the field data are believed to be more reliable. Table 3 shows the finally selected parameters for this case.

Table 3 Final parameter estimation for the layer and the half space (standard deviation between brackets)

layer	bulkmodulus [MPa]	shearmodulus [MPa]	damping [%]	volumetric mass [kg/m^3]
shallow	5095 (245)	96 (43.9)	4.2 (0.06)	1980 (31)
deep	5095 (245)	96 (43.9)	3.9 (0.12)	1980 (31)

3.4. Result of vibration measurements

Vibrations are measured in five points at the surface and four points at depth during the passage of the test train at a speed between 20 and 50 km/h. These measurements are synchronized with the measurements in the train, the tunnel and the nearby building. The KB-value is calculated for all signals and is a measure for annoyance of people in buildings due to vibrations. KB-values lower than 0.1 correspond to vibrations that cannot be felt by inhabitants. Figure 4 and 6 show the KB-values for several train speeds at surface points for vertical and horizontal vibrations, respectively. Figure 5 and 7 show the KB-values for several train speeds in deep points for vertical and horizontal vibrations, respectively. It is noted that the vibration level on the two lines is not always equal, as might be expected from the short distance between the two lines. Furthermore, the vibration level is almost independent of the train speed, which means that a speed limit is not a useful measure to reduce vibration levels in this case.

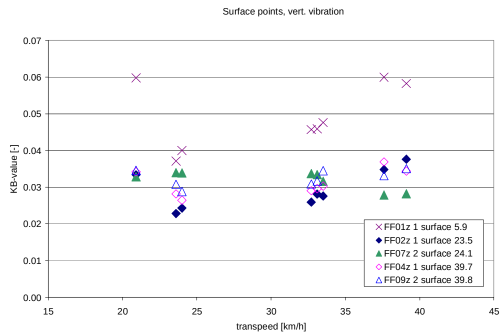


Figure 4 Measured KB-values at surface (vertical)

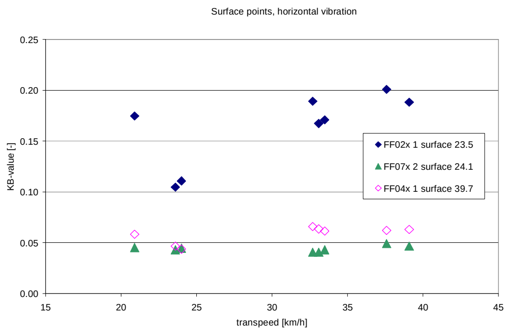
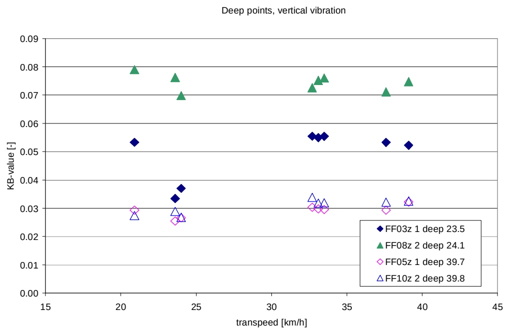


Figure 6 Measured KB-values at surface (horizontal)



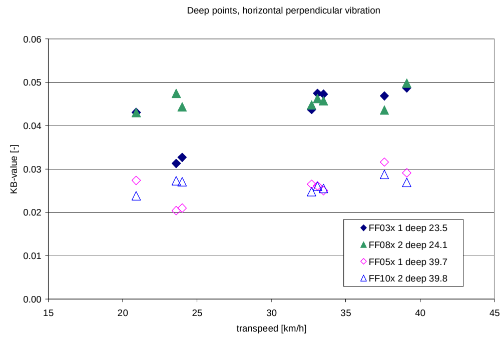


Figure 5 Measured KB-values at depth (vertical)

Figure 7 Measured KB-values at depth (horizontal)

4. Results of simulations

4.1. Model used

The model used in this study is a two-dimensional plane strain finite element model, in which only the cross-section of the tunnel embedded in the soil is modeled. The model is based on a frequency domain approach using non-reflecting boundary techniques to simulate the half space. It allows to make quick predictions in a preliminary study. The use of a two-dimensional finite element model for this problem is subject to a lot of assumptions, which might strongly influence the reliability of the predictions. Before such a model is able to predict vibrations properly, it must be checked (and maybe tuned) by comparison with a full three-dimensional model, as developed within CONVURT, and validated with the results of in situ measurements.

4.2. Choice of parameters

Four cases are selected in order to compare the influence of the soil investigation on the results of numerical predictions of the free field vibrations. Case 1 uses all available data, while cases 2 to 4 are based on limited soil data:

- Case 1: dynamic soil characteristics based on all available data.
- Case 2: dynamic soil characteristics based on one SCPT.
- Case 3: dynamic soil characteristics based on one CPT, using a rule of thumb.
- Case 4: dynamic soil characteristics based on another SCPT.

From a practical point of view, the cases 2-4 correspond to the situation regularly encountered in practice where only limited field data are available. Table 4 shows the resulting soil characteristics.

For case 3, a simplified rule of thumb for the Young's modulus was used: $E = aq_c$, with α an empirical factor and q_c the measured cone resistance (Figure 3). The low resulting value of the shear modulus can be improved by taking into account the plasticity index measured in the laboratory, which gives a more accurate estimate of the empirical factor α. The stiffness increases with a factor 1.8 for the top layer and a factor 1.4 for the deep layer, which is much closer to the dynamically measured values. More advanced empirical relations are available [7], but are outside the scope of this paper. It is seen that the estimated values based on the CPT are outside the 90% confidence interval as mentioned in Section 3.2, which means that more advanced empirical relations are indeed needed.

The other data are chosen according to available data and, apart from the train velocity, kept constant in this study. A full description of the measurement site and the results of the vibration measurement are presented in [5].

Table 4 Selected soil properties

layer number	thickness [m]	bulk modulus [MPa]	shear modulus [MPa]	volumetric mass [kg/m3]	damping [%]	P-wave velocity [m/s]	S-wave velocity [m/s]	Poisson's ratio [-]
case 1	**homogeneous halfspace, based on all available data**							
1	xx	5095	96	1980	4	1624	220	0.491
case 2	**a stiff toplayer, based on one SCPT at point FF04**							
1	4	11031	203	1980	4	2360	320	0.491
2	xx	5086	96	1980	4	1623	220	0.491
case 3	**rule of thumb suggests lower stiffness and damping, based on one CPT**							
1	5	857	16.8	1900	2	672	94	0.49
2	xx	1669	33.6	1900	2	950	133	0.49
case 4	**much more layers, based on one SCPT at point FF09**							
1	5	10070	203	1980	4	2285	320	0.490
2	3	3934	79	1980	4	1428	200	0.490
3	2	10070	203	1980	4	2285	320	0.490
4	xx	4760	96	1980	4	1571	220	0.490

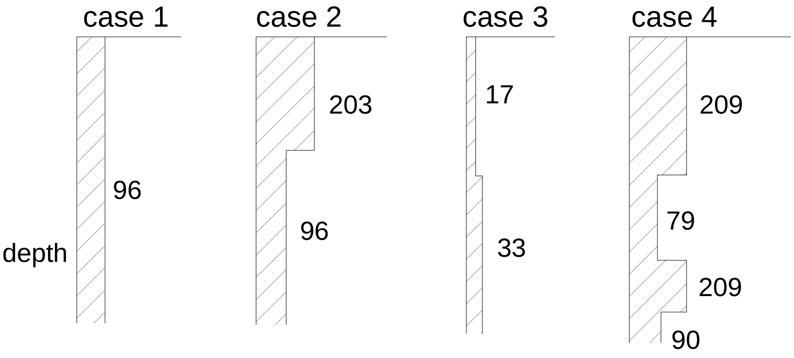


Figure 8 Variation of the shear modulus with depth for the four soil profiles

4.3. Results of the simulations

Figures 9 to 12 show the computed transfer functions for vertical vibrations at two surface and two deep positions at nearby and middle distance from the tunnel. They represent the transfer of vibrations from the tunnel invert to the positions in the free field as a function of frequency. These transfer functions are calculated by two-dimensional plane strain finite element simulations. The figures clearly show that only the results of case 3 (dynamic soil characteristics derived from CPT results using a rule of thumb) differ strongly from the other cases, which result in more or less identical results.

Case 3 gives very different results, which must be expected since the stiffness and damping of the soil is much lower than the values derived from the dynamic measurements. A lower stiffness and lower damping generally give a higher vibration velocity, as long as no (anti-)resonances occur.

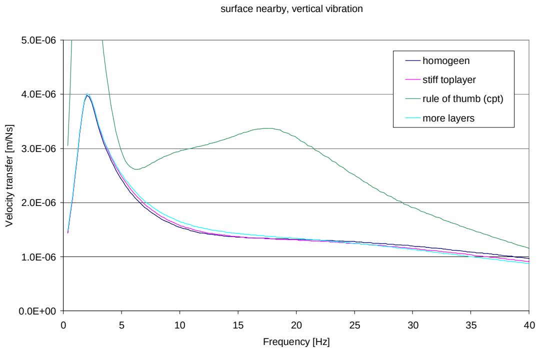


Figure 9 Transfer function for the vertical vibration from the tunnel invert to a surface point nearby

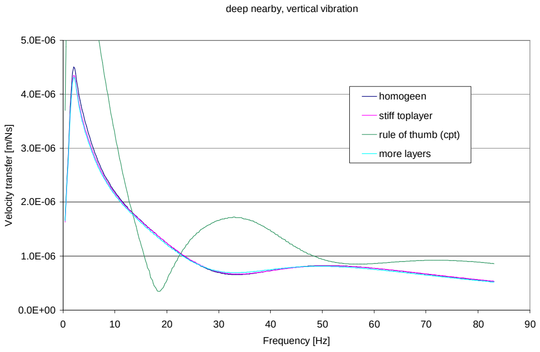


Figure 10 Transfer function for the vertical vibration from the tunnel invert to a deep point nearby

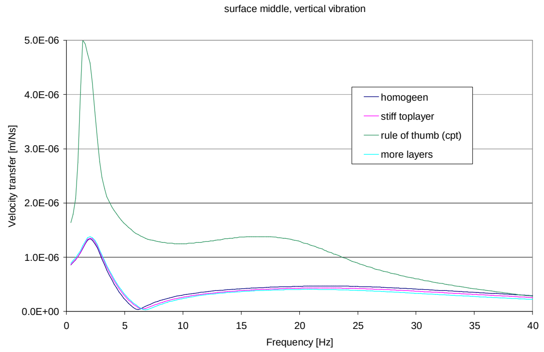


Figure 11 Transfer function for the vertical vibration from the tunnel invert to a surface point middle

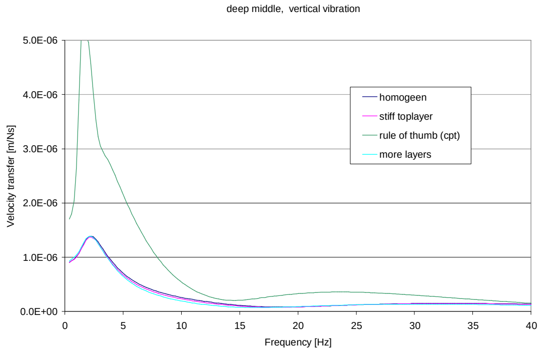


Figure 12 Transfer function for the vertical vibration from the tunnel invert to a deep point middle

The other cases (1, 2 and 4) lead to an almost identical response in the measuring points, although the soil layering differs. This is quite unexpected. It might be explained from the fact that the tunnel is embedded in a layer with almost identical dynamic properties in all three cases. This suggests that it is more important to obtain good values of the dynamic stiffness of the soil around the tunnel, than to pay a lot of attention to the exact layering of the soil at the surface and the longer distances.

Figure 13 and 14 show the transfer function for horizontal vibrations at the surface. The results obtained with the parameters for case 3 (based on the CPT) differ strongly from the other cases, but also the homogeneous case 1 gives a higher (up to 20%) horizontal vibration. For the horizontal vibrations, the layering is more important than for the vertical vibrations. In deeper points, the differences are smaller (not shown here).

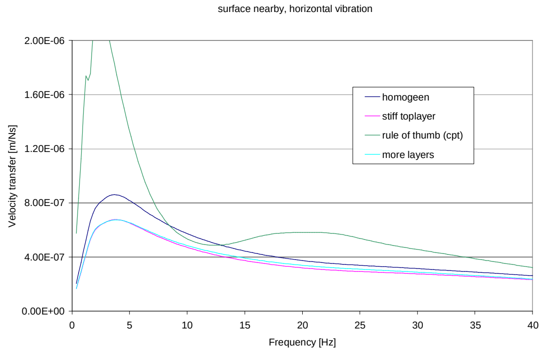


Figure 13 Transfer function for the horizontal vibration from the tunnel invert to a surface point nearby

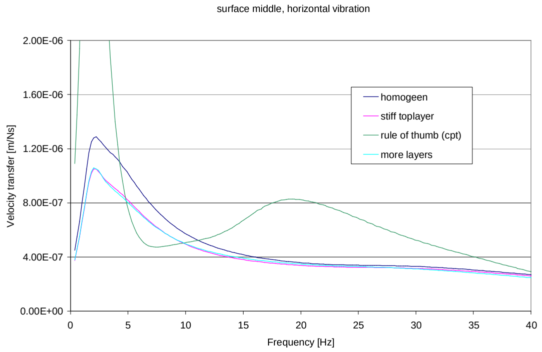


Figure 14 Transfer function for the horizontal vibration from the tunnel invert to a surface point middle

5. Discussion and conclusion

This paper gives a short overview of the field measurements carried out within the CONVURT project at the site in Regent's Park, London. In order to obtain a reliable set of dynamic soil characteristics, several types of field and laboratory tests were carried out. Based on all measurements, it is concluded that the site can be well represented by a homogeneous half space.

Results of vibration measurements in several points along two lines perpendicular to the tunnel show that the vibration level at two points at the same perpendicular distance from the tunnel, but at different lateral positions, may be clearly different, although the site is quite homogeneous.

The possible consequences of a limited soil investigation are presented. It is assumed, for example, that only results of a single SCPT or CPT are available. Vibration predictions using a soil profile that is based on the results of a single CPT turn out to be poor; they can be improved by using better empirical relations that relate the cone resistance to the Young's modulus, requiring more information. The difference between the other cases was small, which might be explained form the fact that the soil's stiffness around the tunnel is equal in these cases. This suggests that the stiffness of the soil in the immediate vicinity of the tunnel has a major influence on the predicted vibration levels. Here, the layering of the shallow layers has a minor influence on the horizontal vibrations and almost no influence on the vertical vibrations.

The application of more advanced numerical models should be accompanied by a comparable increase of the reliability of the input parameters. Generally, the input parameters of man-made structures can be read from design drawings. Rail roughness and soil properties must be measured at the location of interest. The most reliable method is a direct measurement of the wave speeds in the field at the location. This measurement must extend to a deeper level than the tunnel, since the stiffness of the soil surrounding the tunnel is important. Since the layering seems to be less important, this does not need to be measured separately. Laboratory experiments for volumetric mass and Poisson's ratio are useful. The measurement of material damping can be done in the laboratory by using a free vibration torsion test, as its determination in the field is difficult. In order to obtain a reliable model of the subsoil, one cannot rely on one simple test.

Acknowledgements

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