Modelling the railway induced ground vibrations in soft soil areas of Western Finland

A Pelho¹ and J Mansikkamäki¹

¹ AFRY Finland Oy, Hatanpäänkatu 1, 33900 Tampere, Finland

antti.pelho@afry.com

Abstract. The vibrations induced by railway are a major problem in Western Finland’s soft soil areas, where the residential areas are located near railway. FTIA started to investigate the problem and together with VR-Transpoint, they organized extensive test drives in the Kokemäki-Pori railway. The rolling stock was brought to test drives from Russia. The test drives were monitored and the measured data is used in this study for the 2D modelling of the vibration phenomena. The main goal of this study was to investigate the resulting vibrations at various train speeds at particular site in 2D FE model. The study focuses on the frequency of the input load and the output vibration. The track-embankment-ground system has a frequency response to the input load, which can be assumed to be the natural frequency of the subsoil. The natural frequencies can be calculated with response analyses. With good assumption of the natural frequencies of the ground, the model can be used to discover which frequencies of the input load causes harmful vibration in the railroad environment. The train speed affects to the frequencies of the input load. The model can also be used to find the certain speed of a certain rolling stock, which will cause the certain frequency that will propagate and cause harmful vibrations in a certain soft soil areas.

1. Introduction
The vibrations induced by railway are a major problem in soft soil areas, where the residential areas are located near railway. The vibrations can be harmful for the structures of the buildings, but commonly they are affecting the areas comfort of living.

In last couple of years in western Finland the vibrations induced by railway started to disturb the residents of the area. The residents started to complain to the Finnish Transportation Infrastructure Agency (FTIA) about the situation. FTIA started to investigate the problem and together with VR-Transpoint, they organized massive test drives in the Kokemäki-Pori railway. The rolling stock was brought to test drives from Russia, because the disturbing vibration started at the same time as heavy coal transportation from Russia to the port of Pori.

The problem was located to soft soil areas. Two sites were chosen to be instrumented with monitoring equipment. The ground vibrations in different distances from the railroad were measured by Suomen louhintakonsultit Oy. The deflection of railroad and the vertical and horizontal forces affecting the rail by trains were measured by Tampere University.

Test drives happened in two weekends of August 2019. The test trains were driven in four different speeds from 40 km/h to 70 km/h as fully-loaded and in five different speeds from 40km/h to 80 km/h as empty. Fully loaded carts had an axle-load of approximately 22.5 tons.
The goal of this study was to investigate the resulting vibrations at various train speeds at particular site in 2D FE model. How and why the vibration propagates and dampens as measured and how the train’s speed affects the vibrations.

2. Theory
Vibration happens when a driving force affects a system. In railroad environment the driving force which induce the vibration is the trainload and the system is a combination of the track, the embankment and the ground. Trainload causes the track to deflect which causes a low frequency vibration to the railroad environment. The train also causes higher frequency vibrations from the rolling stock and the wheel-rail contact.

The vibration in railroad environment can be viewed as an input-output relation, where the trainload/the force is the input and the output is the vibration. Representing the input and output in the frequency domain allows the relation represent in figure 1. The track-embankment-ground -system has the frequency response which is the measure of phase and magnitude of the output as a function of frequency. When the input force has a same frequency as the systems frequency response the output vibration grows, and when the input force has a different frequency as the frequency response the output vibration dampens. [2]

![Figure 1. The input force and the frequency response together causes the output vibration. Modified after [2]](image)

In this case the natural frequency of the subsoil can be thought as the frequency response of the system. The biggest measured vibrations from the test sites has the same frequency as the subsoils natural frequency. Because of that one can assume that other frequencies will dampen in the system and the vibration which has a same frequency as the natural frequency of subsoil and its multiplies will increase or at least propagate in the subsoil.

In this study the modelling focuses on the frequency of the input force and the natural frequency of the subsoil. The frequency of the input force changes with the speed of the train and the dimension of the rolling stock.

3. Test sites and Measurements
Test sites were located in Kokemäki-Pori railway in a soft soil area, where FTIA have had complains about train induced vibration. The test sites are referred as Ulvila and Nakkila. This study focuses on Ulvila test site.

The Ulvila test site is near the city of Ulvila. The soil from surface to bedrock in Ulvila test site is 0.5 m of dry crust, 2.5-3.5 m of clay, 2.0-5.0 m of silt, 3.0 m of sand and 2.0-5.0 of stiff till. The following picture shows the 2D FE-model and the soil layers of Ulvila test site. The track embankment height is 3.0 m. The track had a motorway of 4 lanes right beside it which can be seen in figure 2.
The Ulvila test site was instrumented with geophones which measured the vibration of ground. The geophones were installed in 10 m, 30 m, 50 m and 70 meters from the railway. The track was instrumented with displacement sensors which measured the deflection of the sleepers. The deflection was also measured with acceleration sensors which were installed on the surface of the sleeper. The rail was instrumented with strain gauges to measure the axle-load of the rolling stock.

The vibration measurements made by Suomen louhintakonsultit gave the information of the vibration in the ground. In Ulvila site the vibrations were relatively high when the test train drove 70 km/h and 60 km/h, but were almost two times smaller when the test train drove 50 km/h and 40 km/h. The peak values of the vibration (mm/s) from all the test drives measured in Ulvila test site is shown in figure 3 and the frequencies of measured vibration are presented in figure 4.
Figure 4. The dominating frequency of vertical vibration in one-third octaves in Ulvila test site from vibration measurements.

The measured vibration values are used as a reference which the modelled values can be compared to. The main points which the model tries to accomplish are to model the big drop of the peak value in 50 km/h train speed compared to 60 km/h train speed and the frequencies of said vibrations.

The measured deflection of the sleeper and the axle-loads are used as an input force in model. One example of measured deflection of the sleeper in Ulvila test site is presented in figure 5.

Figure 5. The deflection of a sleeper in Ulvila test site.

The deflection the sleeper was measured with the displacement sensor. Figure 5 shows the deflection of a sleeper when test train drives past the test site in a speed of 70 km/h.

4. Modelling
The modelling was made with PLAXIS 2D. Because the approach is two-dimensional, it is not possible to achieve precise results. The model can not take account of the interference between waves or the three-dimensional dynamic amplification of displacements.

The PLAXIS 2D model uses numerical implementation of dynamics. The formulation of the time integration constitutes an important factor for the stability and accuracy of the calculation process. The used method was the implicit time integration scheme of Newmark with standard settings of PLAXIS.
The critical time step was calculated with maximum frequency and the coarseness of the finite element mesh. The time step was chosen to ensure that the wave during single step does not move larger distance than the minimum dimension of an element.

The boundaries of model in x-direction were viscous. In the viscous boundaries, a damper is used. The damper ensures that an increase in stress on the boundary is absorbed without rebounding. [4] In y-direction the upper boundary was free and the boundary in bedrock was fully fixed. If the bottom y boundary would be viscous the whole model would move and the results of the calculations would be hard to read.

The superstructure of the railroad was modelled in the model. The rail was modelled as a plate-element and the sleepers and the ballast with linear elastic material model. The embankment was also modelled with linear elastic model. The parameters for superstructure, ballast and embankment were obtained from Kalliainen [1].

The subsoil layers were modelled with Mohr-Coulomb material model. For reason not yet discovered the linear elastic material model didn’t work in the model when the input load was axle-load to the rail. The sleeper moved in the dynamic loading and after the loading it was moved considerably. The Mohr-Coulomb model which works as a linear elastic model with failure criterion didn’t have the same effect. Therefore the Mohr-Coulomb material model was used in the subsoil layers.

Parameters for the subsoil layers were derived from old soil investigations. The soil investigations included CPT- and laboratory tests which were made 10 years prior this study. The used parameters were shear modulus, volume weight and poisson’s ratio. The shear velocity was calculated from the shear modulus by the PLAXIS. The shear modulus was defined by $G_{\text{max}}$ using correlations proposed by Langö [5] and Larsson and Mulahdic [6]. The poisson’s ratio of 0,2 was used in all soil layers.

In the next phase of the study the shear modulus of the soil will be investigated in-situ with dynamic CPTu tests and in laboratory with Bender Element test method. After the tests one can compare how accurately the vibration phenomena can be modelled with only pre-existing soil investigations compared to the more accurate soil investigations.

4.1. Trainload and the deflection of the sleeper as input force
The input- or the driving force of the dynamic system creates the vibration which will then propagate through subsoil. In the model two different driving forces were used. The axle-load affecting the rails and the deflection of the sleeper.

At first the aim was to use axle-load as an input force. As the model iterated, one noticed that the stiffness of the subsoil were notably more dependent of the load time than it was measured to be. As the train drove slower the load time increases for the subsoil. As a result the modelled deflection of the sleeper induced by axle-load to the rail was larger when the train drove slower. In the model difference in the deflection of the sleeper between slower and faster loading time was significant. The vibration results were not comparable to one another. Also the measured axle-load is in reality affecting to several sleepers. In example the FTIA report [3] uses assumption that the axle-load affects to three sleepers. The measured axle-load from the rail is not a good input force to the 2D -model as the 2D -model can only take account of a plane strain section of the track.

The measured deflection of the sleeper was the other used input force for the models. In reality the deflection is not an input force but is a response for the real input force, the train load. In the model the deflection of the sleeper can still be used as a input force for the system. The deflection of the sleeper has the same frequencies as the axle-load which was confirmed with the measurements from the rail and the sleeper. The measured deflection is also a real phenomenon which causes the low frequency vibration to the railroad environment.

4.2. Response analysis of the frequencies of subsoil
The natural frequency of the subsoil can be calculated with equations (1) and (2). Unfortunately the subsoil is not a homogenous and the soil layers are not horizontally straight, so the calculations are
hard to make by hand. The model can be used to calculate the natural frequencies of the soil in different places. The natural frequencies were calculated with response analysis.

The response analyses were made by using 1 kN force to the rail. The force affected as a sine wave which had an amplitude of 1 and the frequencies change from 1 Hz to 20 Hz. The forces affected the system 10 seconds in every frequency. The results of the response analyses are presented in section 5.1.

5. Results
The results are from Ulvila model. The used input force was the measured deflection of the sleeper except for the response analyses which used 1 kN force. The natural frequency of the subsoil was calculated with response analyses. The results from response analyses and the modelling with real measured data are presented in following paragraphs.

5.1. The natural frequency of soil
The natural frequency of the soil depends on the parameters and thicknesses of the soil layers. The natural frequency can be thought as the frequency response of the system. The results of the natural frequency response analyses are presented in figure 6. The peak value of the ground surface’s vertical displacement is presented in y-axis and the frequency of the input force is presented in x-axis.

![Figure 6. The results of a response analyses from different distances from the track.](image)

As the figure 6 shows the natural frequency of the soil changes when it is calculated in different distance of the railroad. The figure shows that the certain input frequency causes a much bigger output vibration than other frequencies. In that way we can see the frequency response of the system. The frequencies between 2-7 Hz propagates better through the subsoil than the other frequencies. The natural frequencies of the soil are between 2-7 Hz.

5.2. The effect of speed of the train to the vibration
The effect of the train speed to the vibration was modelled with different measured deflection of the sleeper as a input force. The deflections were from a four different test drives where the train drove 70 km/h, 60 km/h, 50 km/h and 40 km/h. The used input deflection for the 70 km/h test drive was presented in figure 5. The amplitude of a sleeper stayed almost the same even though the speed
changed. The deflection of a sleeper in millimeters was about 1.8 when the train drove 70 km/h and 1.9 mm when the train drove 40 km/h. The difference is explained with the load time dependence of the subsoil’s stiffness.

In the figure 7 the peak value of modelled vertical vibration is shown in different distance from the railroad in a different train speed. The absolute values of vertical displacement of the ground are not the same as the measured values, because the model can’t depict three dimensional phenomenon correctly.

![Figure 7](image)

**Figure 7.** The result of a modelled ground vibrations with different input forces in Ulvila test site.

The figure 7 shows that the 70 km/h and 60 km/h train speed causes noticeably larger vibration than the 50 km/h and 40 km/h train speeds. In the figure there can be seen a larger amplitude in 70 meters than 50 meters away from the railroad, which was also noticeable in real vibration measurements in figure 3. The phenomena of trains speed effect to the vibration was modelled successfully.

6. **Conclusions**

The main goal of this study was to clarify and understand the phenomena that occurs in the railroad environment vibration. The study focuses on the frequency of the input load and the output vibration. The track-embankment-ground system has a frequency response to the input load, which can be assume to be the natural frequency of the subsoil. The subsoil and every soil layer of the subsoil has a natural frequency. The natural frequencies can be calculated with response analyses, where a same size input load affects the system in different frequencies. The frequencies which doesn’t dampen in the system can be assume to be the natural frequencies of the subsoil. The 2D FE-model is a great way to calculate the natural frequencies as it can take into account all the changes of the boundaries between soil layers and the changes in parameters with soil layer depth.

With good assumption of the natural frequencies of the ground, the model can be used to discover which frequencies of the input load causes vibration in the railroad environment. The train speed and the dimension of the rolling stock affects to the frequencies of the input load. Slower trains causes smaller frequency input loads to the track-embankment-ground -system. If the trains speed goes up, so goes the frequencies of the input load.

The 2D FE-model can be used to figure out which frequencies are harmful in the railroad environment. The model can be used to find out what frequencies of the vibration will cause problems
in different distances from the railroad. The model can also be used to find the certain speed of a certain rolling stock, which will cause the certain frequency, that will propagate and cause harmful vibrations.

7. Suggestions for a Further Research
In the future there will be comprehensive soil investigations for the test sites. The soil investigations should be made with CPTu-tests. The dynamic CPTu test can measure the shear velocity of soil layers. With better soil investigations the natural frequencies of the subsoil would be more accurate.

The input force of the model must be more accurate and easier to obtain. The deflection of the sleeper is accurate, but it is more laborious to measure. The axle-loads and dimension of the rolling stock are easier to obtain. Shall be studied if the axle-load should be used straight to the subsoil or the embankment without superstructure. The 2D FE-model could be used to calculate the stresses which are induced to the embankment from the train load. The stress to the embankment should be more accurate depiction of the input force than the axle-load to the rail.

References
[1] Kalliainen A, Kolisoja P & Nurmikolu A 2014 Radan 3D-rakennemalli ja ratarakenteenkuormituskestävyys Liikenneviraston tutkimuksia ja selvityksiä 55/2014.
[2] Talja A & Törnqvist J 2014 Liikennetärinä: Alueiden tärinäkartoitus ja rakenteiden vaurioitumisalttius VTT Tutkimusraportti VTT-R-04703-14.
[3] Liikennevirasto 2018 Ratatekniset ohjeet (RATO) osa 3 Radan rakenne p 29
[4] PLAXIS 2D Scientific manual 2019
[5] Lango H V 1991 Cyclic shear modulus of natural intact clays Doctoral dissertation Geotechnical Division Norwegian Institute of Technology
[6] Larsson R & Mulabdic M 1991 Shear moduli in scandinavian clays Swedish Geotechnical Institute Report No. 40.