Vibration Prediction Model for Building Developments Adjacent to Railways

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ABSTRACT

This paper presents the experimental and computational evaluation of ground-borne noise and vibration impacts at sensitive receivers in the vicinity of existing track sections. Vibration problems occur as an effect of train passings adjacent to buildings and structures, thus needing to satisfy stringent vibration and ground-borne noise criteria. Therefore, it is necessary to quantify comprehensively the vibration impact in the design of new developments and the compliance with the provided criteria. Test measurements of vibration propagation through the structure are often possible only under certain circumstances since, based on the construction work progress, many relevant parts of the analyzed structure have not yet been completed. In such cases, measurement data is combined with computation data applying the Finite-Element-Method (FEM). The structure is modelled as a basis for dynamic analyses and the subsequent tuning of damping systems. The paper presents a semi-empirical prediction model on the basis of measurements and computational models that was applied to international projects. One of the projects is in close vicinity of one of the metro stations in Doha, including a six-level underground parking structure with various facilities and a large development with numerous towers of different use on top. Another project that will be presented in the paper is a luxury hotel located adjacent to another station along one of the Doha metro lines. Outcomes summarize the state of the art aforementioned topic.

Keywords: Vibration tests; Measurement data; FEM; Railways; Damping systems

1 INTRODUCTION

Inner-city railway sections are highly frequented, and they happen to be cross densely populated urban areas. Besides all benefits of modern mass transport systems, the generation of annoyance due to noise and vibration that impacts people living close by is an aspect that needs to be studied and possibly solved.

In general, human beings in buildings are relatively sensitive to structural vibrations. Particularly in places where people sleep, it is essential to prevent the interference of vibration.

Compared to car traffic, railways and trains are generating a much higher level of vibrations due to wheel-rail interface. Those vibrations are transferred via the track structure, the tunnel structure and subsoil to the adjacent buildings. Within those buildings, vibrations are often amplified and transferred directly to sensible locations.

The ground-borne noise and vibration problem occurs as an effect of train passings adjacent or below future developments, thus needing to satisfy stringent vibration and ground-borne noise criteria. Therefore, it is necessary to quantify comprehensively the ground-borne noise and vibration impact in the future developments and to verify the compliance with the provided criteria.

Such aspects need to be considered in an early design stage of both railway sections or developments, that are planned to be built close to existing tracks. In this case, semi-empirical spectral prediction models as presented in the FTA-manual are applied [FTA, 2018]. These models are based on the principle that vibration impact is a product of the source input (train emission), the vibration transfer through the ground, the coupling at the foundation (transfer soil-structure) and the amplification inside the building (transfer structure – receiver). All these spectra can be determined independently. Figure 1 shows the general prediction model of vibration and ground-borne noise.

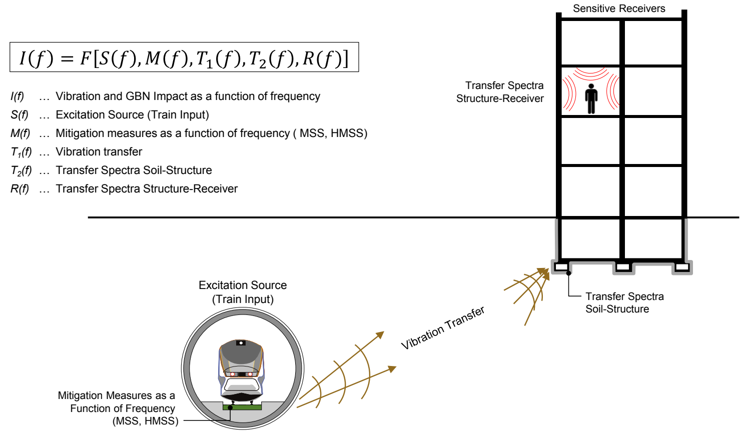


Figure 1: General prediction model of vibration and ground-borne noise

2 PREDICTION BASED ON MEASUREMENTS

Vibration propagation tests through the structure are one of the most valid tools for predicting future consequences. However, measurements are often not possible as the future structure does not exist yet. In such cases, measurements are limited to specific parts of the prediction chain, for instance:

- Measurement of the vibration emission with transducers placed on the rail, on the sleeper or on ballast less track, on the tunnel foundation or on the tunnel wall. The requirement is that similar trains running on similar track sections and speeds are accessible to measurements.
- Measurement of the ground transfer with transducers placed inside the tunnel and close to the future foundation. The requirement is that tunnel and excavation pit are already existing and accessible at the exact site, other measurement results can hardly be applied due to different soil conditions.

- Measurement of soil-structure interaction with sensors placed on bottom / on top of foundation.
- Measurement of building transfer with sensors placed at the foundation and at various locations inside the building.

Based on the construction work progress, many relevant parts of the analyzed structure have not yet been completed. In such cases, measurement data is combined with computation data applying the FEM.

3 PREDICTION BASED ON FEM

Vibrations due to train operations excite the structure at the base in the vertical direction. For this reason, the structure needs to be modelled and analyzed without any mitigation measures to quantify for the requirement to damp out vibrations caused by traffic. Each substructure needs to be modelled in detail regarding geometric and structural properties, i.e., properties of major structural elements, such as thickness and span of slabs, or material parameters, i.e., strength and stiffness properties that are associated with structural members. For the calculation of the vibration transmission through the building, a steady-state analysis is used. The numerical model is created using commercial software, such as Sofistik or SAP2000, and it consists of:

- Soil-structure interaction
- Foundation
- Basement
- Superstructures

Often it is not required to model the entire structural model. The finite element size strongly depends on the structural properties, but also on the settings of the dynamic analysis. The need for a fine FE mesh results in a very high number of nodes and model complexity. To avoid very long computational time, the model is subdivided into more sub-models based on the locations of expansion joints.

For the calculation of the transfer function the model is excited at the foundation with a uniform acceleration in the vertical direction. The response amplitude at specific points is compared to the uniform loading amplitude, thus not requiring train emission data as input.

Generally, a train can be approximated as a line source that generates vibrations at the wheel-rail interface. It is therefore useful to apply several concentrated impacts based on the train's wheelset location to consider a line source as input to the model. Please see Figure 2 for details.

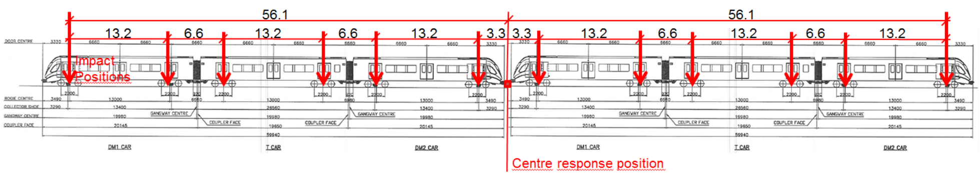


Figure 2: View of a typical load pattern for a passenger train

By defining as input nodes the ones at the locations of the running train or at the foundation and as output nodes the ones at the locations of the future sensitive receptors (inside the apartments), the transfer function between these nodes can be determined. Transfer functions are the ratio of output and input and are unitless. They can be determined for each of the parameters displayed in Figure 1.

4 IMPLEMENTATION EXAMPLES IN DOHA

VCE has completed the ground-borne noise and vibration assessments for numerous major construction projects. Two related developments will be presented in Chapter 4. Measurements of transfer functions have been carried out by third party in order to ensure transparency and super partes results.

4.1 Metro station development

This area is characterized by the crossing of two lines, and several future developments, including a six-level underground parking structure with various facilities and a large development with numerous towers of different use on top. All future developments aforementioned need to satisfy very stringent vibration and ground-borne noise criteria. Thus, it was necessary to comprehensively quantify the vibration impact in the future developments and to verify compliance with the provided criteria.

Test measurements of vibration propagation through the structure of this station were not possible in the planning stage because, based on the construction work progress, many relevant parts of the structure were not yet completed. Figure 3 shows overviews during the construction condition. For this reason, a numerical approach using a spatial FEM to describe the vibration propagation in the structure was applied.

Figure 3: Overviews of construction condition during the planning stage

A comprehensive numerical model representing this area has been defined using commercial structural-analysis software Sofistik [VCE, 2018]. Buildings, basements, and the foundation system have been modeled in detail to identify dynamic characteristics of noise and vibration in structural members. Figure 4 shows the complete FEM model of the structure. Comprehensive parameter studies have been applied to verify settings, such as finite element size, time step size and the damping model assigned to the structure. Dynamic analysis has been conducted by means of direct integration methods for different load patterns, which represent metro trains passing at various locations on different tracks. Subsequently, transfer functions have been determined to transform predefined spectra of trains from the tunnel-level to specific floor levels. The ramping function as illustrated in Figure 3 is used to define the time dependent excitation for

Response History Analysis (RHA). Therefore, a Dirac impulse will be approximated by a rectangle ramping path. At time instances t>0.004 the ramping function remains zero, implying the structural response represents a free damped vibration.

Safety factors depending on location of the metro have been used to take into account possible uncertainties. At representative floor positions, floor velocity spectra have been compared to predefined velocity spectra of performance targets.

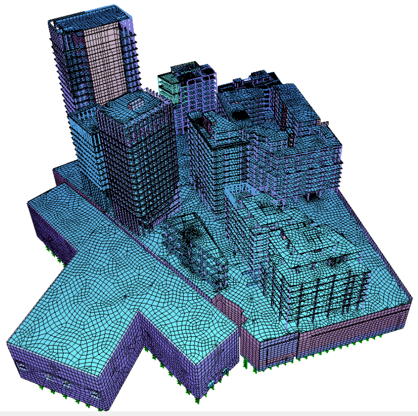


Figure 4: Finite element model of station development

The assessment resulted into the installation of mitigating track systems (mass-spring systems) in the track underneath the development. This very efficient method of mitigating track-borne impacts was made possible because the metro tunnels and the development on top were both at planning stage and so the issue of noise and vibration came to attention at the very right time. Figure 5 summarizes the results for ground-borne noise with and without mitigation measures.

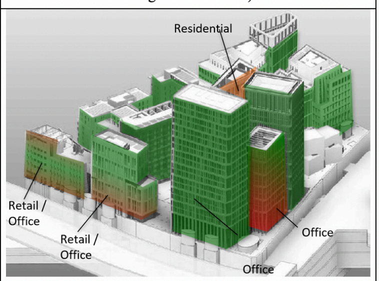
<table>
<tr><th colspan="5">Ground-Borne Noise Levels</th><th>Overview of the locations with exceeded limits (without mitigation measures)</th></tr>
<tr><th rowspan="2">Building output node & location</th><th rowspan="2">Use</th><th rowspan="2">Worst case floor</th><th colspan="2">$L_{A.max.s}$ [dB ref. 5 x 10^{-8}]</th><td rowspan="7">
</td></tr>
<tr><th>without measures</th><th>measures included</th></tr>
<tr><td>LC01-20011</td><td>office</td><td>4</td><td>65</td><td>35</td></tr>
<tr><td>LC02-18131</td><td>residential</td><td>6</td><td>66</td><td>32</td></tr>
<tr><td>LC03-18011</td><td>residential</td><td>6</td><td>63</td><td>30</td></tr>
<tr><td>LC04-14001</td><td>commercial</td><td>4</td><td>47</td><td>32</td></tr>
<tr><td>LC05-19091</td><td>office</td><td>12</td><td>59</td><td>34</td></tr>
<tr><td>LC06-13071</td><td>office</td><td>3</td><td>69</td><td>29</td><td rowspan="6"></td></tr>
<tr><td>LC07-13071</td><td>office</td><td>3</td><td>69</td><td>27</td></tr>
<tr><td>LC08-12101</td><td>office</td><td>2</td><td>64</td><td>23</td></tr>
<tr><td>LC09-14001</td><td>commercial</td><td>4</td><td>53</td><td>41</td></tr>
<tr><td>LC10-14001</td><td>commercial</td><td>-1</td><td>48</td><td>37</td></tr>
<tr><td>LC11-13992</td><td>prayer room</td><td>-3</td><td>67</td><td>42</td></tr>
</table>

Figure 5: Summary of results and graphical overview

4.2 Hotel development

The Hotel development is 5 a stars hotel located adjacent to one of the metro stations. The site area is 11.184 m². The project is composed of three basement levels, ground floor, mezzanine, and seven stories with 257 guest rooms and amenities.

For this assessment, extensive measurement data could be used for the prediction [VCE, 2013]. The train emission was determined by a set of tests and the transfer through the soil was determined in the area adjacent to the project. The missing link was the coupling of the foundation and the vibration propagation through the building. For this calculation, a 3D model was generated in the commercial structural-analysis software SAP2000. Figure 6 shows the whole FEM model.

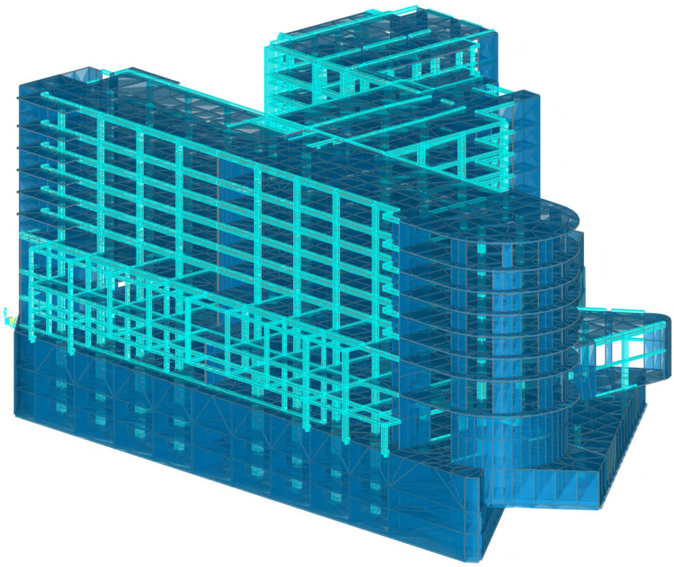


Figure 6: Finite element model of the hotel structure.

The prediction included the determination of the impact levels of vibration and ground-borne noise. For the calculation of the transfer function, the model is excited at the foundation with a uniform acceleration in the vertical direction. The response amplitudes at certain points are compared to the uniform loading amplitude. The result of this computation is the transfer function which denotes the amplification of the input amplitudes at an output node.

To verify the impact criteria, the levels were predicted in absence of any mitigation measures at specific points in the structure. The fact that the adjacent metro section included a mass-spring system as mitigation measure helped to have already ground-borne noise and vibration limits fulfilled. For this reason, additional mitigation measures were not required under the development foundations.

5 VALIDATION

In order to validate the outcomes of numerical models, validation measurements are often applied. Such measurements can include:

- Determination of track insertion loss: an in-situ determination of the insertion loss within the framework of a measurement campaign according to DIN SPEC 45673-3 to be conducted by a competent measurement engineer.
- Validation of building transfer (after completion) with artificial force impacts: the vibration amplitude caused by mechanical impacts generated by a falling mass (input) can generally be measured at all output locations at mid-span in vertical direction and compared to the transfer functions determined with the model. It is essential to select an input force with enough energy input, such as a standard soil sampling hammer, as shown in Figure 7.

Figure 7: Falling weight machine

- Validation measurements of ground-borne noise and vibration limits at sensitive receptors: usually vibration or acceleration transducers are placed on the floor of the sensitive receptor. Ground-borne noise is determined on the basis of vibrations according to international standards and is then compared to national limit values.

6 CONCLUSION

This paper presents a study relative to the evaluation of ground-borne noise and vibration impacts at sensitive receivers in the vicinity of existing track sections. Integration between experimental and computational information are presented here. Where test measurements were not possible, computation data applying the FEM were considered and developed. Structures were modelled as a basis for dynamic analyses and the subsequent tuning of damping systems.

The results stem from a semi-empirical prediction model on the basis of measurements and computational models that have been applied to international projects. The first project is relative to one of the metro stations in Doha, including a six-level underground parking structure with various facilities and a large development with numerous towers of different use on top. The analysis evidenced the necessity of the installation of additional mitigation measures. The second project was a luxury hotel located adjacent to another station along one of the Doha metro lines. The analysis did not evidence the necessity of the installation of additional mitigation measures.

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