A case study on railway-induced ground-borne noise numerical modeling

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Abstract
A hybrid railway-induced ground-borne noise evaluation method based on numerical modeling and on-site measurements was developed by the department of acoustical engineering of AINS Group. Numerical modeling and railway-induced vibration measurements were carried out in a five-story apartment building with typical precast concrete element construction. The ground properties were measured on-site using impact source with the spectral analysis of surface waves method. The 3D numerical model consisted of the upper ground layers and the loadbearing structures of the building. The harmonic response of the building was calculated using the finite element method. The proposed evaluation method utilizes on-site measured railway-induced ground vibration levels and vibration transfer functions from the numerical model. The results of the study show that the proposed evaluation method enabled more accurate and detailed assessment of ground-borne noise in the investigated building than the widely used Finnish ground-borne assessment guidelines. The proposed evaluation method was also shown to be viable for use in construction projects.

Keywords: railway**,** ground-borne noise, modelling, finite element method.

1 Introduction

Railway-induced ground-borne noise and vibration has become an important issue in the recent years. Due to urbanization and new railway and light rail projects, railway-induced vibration and ground-borne noise must be taken into account more often in the acoustical design of new buildings. However, the tools available for acoustic and vibration consultants are often simple and based on empirical findings. Such tools may not be suitable or accurate for evaluation of vibration and ground-borne noise e.g. in a large modern building complex or a building with unusual building materials. Thus, a need for more detailed and accurate evaluation methods for railway-induced vibrations and ground-borne noise has been identified.

The ground-borne noise assessment guidelines as well as evaluation methods used in Finland [1] are based on the FTA vibration assessment guidelines and evaluation methods [2]. In construction projects near an existing railway, the ground-borne assessment in the building is usually based on ground vibration measurements at the site. The ground-borne noise levels in the building are predicted using the adjustments for coupling to building foundation, floor-to-floor attenuation, amplification due to resonances and the conversion from vibration to ground-borne noise as presented in the FTA guidelines. In some construction projects, the ground-borne levels are assessed using purely the empirical formulae with vibration level base curves and single-number adjustment factors.

A hybrid railway-induced ground-borne noise evaluation method was developed and investigated in a research project carried out by the department of acoustical engineering of AINS Group. The goal was to develop a ground-borne noise evaluation method for use in acoustical design of buildings that would offer more detailed prediction as well as more accuracy than the commonly used empirical formulae. The evaluation method would be used by acoustical engineers in building construction projects. More detailed documentation of the research project in Finnish can be found in the master's thesis of the first author [3].

2 Case study

The vibration measurements and numerical modelling were carried out in a five-story apartment building which was located 100 m from a railway line. The apartment building is constructed with precast concrete elements. The building has load bearing reinforced concrete walls and hollow-core slabs. The external walls of the building are reinforced concrete sandwich elements. The building represents a typical Finnish apartment building. The basic floor plan of the building is shown in figure 1. The floor plan is identical in each floor except for the 1st (ground) floor. The railway is located 100 m from the façade shown on the right-hand side of the floor plan.

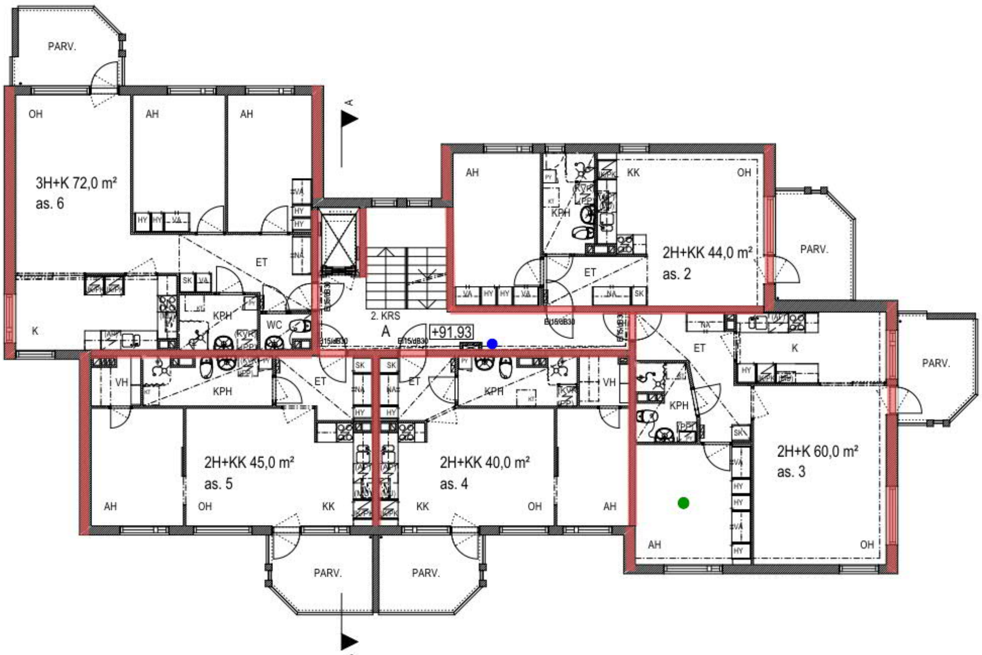

Figure 1 – The floor plan of the investigated building. The walls marked with red are load bearing. Also shown are the measurement points in the load bearing structures (blue dot), midpoint of the floor (green dot) and ground (red dot).

2.1 Vibration measurements

Railway-induced vibration was measured at the test site from the ground and in the building. The measurement point on the ground was located few meters in front of the building. The vibrations of the building were measured on each floor at near load bearing structure in the middle of the building. In addition, the vibration of the midpoint of a floor in a room was measured. The measurement points are shown in the floor plan of figure 1 with a blue dot depicting the measurement point in the load bearing structure, a green dot the measurement point at midpoint of the floor and a red dot the measurement point on the ground. The measurements were made with triaxial velocity sensors with frequency range of 1 - 350 Hz and by following the basic guidelines set by the ISO 14837-1:2005 standard [4].

All measured train passages were identified at the site in order to rule out any sources of external vibration. However, the building had residents during the time of the measurements. Therefore, some measurement results had to discarded due to vibration from external sources. Ground-borne noise measurements with a sound level meter had to be discarded as well due to high level of background noise.

Total of 11 train passages were analyzed, 5 of which were freight trains and the rest were passenger trains. The 95 % percentile of A-weighted vibration levels with slow time constant was calculated for each measurement point. The calculated vibration levels were used for comparisons between the proposed and empirical assessment methods and vibration measurements.

2.2 Numerical model

The numerical modelling of vibrations with finite element method (FEM) in frequency domain was carried out using Ansys 20R1 physics simulation software. Frequency domain finite element method was chosen from several possible numerical methods [5] since it can be implemented relatively easily with commercial software. The numerical model of the building and the ground at the test site was created based on the available structural and architectural drawings of the building and the site investigation report. The numerical model of the building is shown in figure 2.

The 3D model of the building consists of the load bearing walls, self-supporting external walls and floors. The walls and floors of the building were modelled as surface elements with door and window openings based on the technical drawings. Other building elements such as interior walls and roof structures as well as furniture etc. was taken into account in the model by setting a uniform surface mass on the floors.

The building is founded on reinforced concrete piles which rest on the dense ground layer or bedrock. The effect of the piles on the building response was taken into account by setting a vertical elastic supports at the positions of the piles in the building foundation. Only the vertical support of the piles based on the assumption that the vertical vibration is the most significant vibration direction for ground-borne noise. The stiffness of the supports was determined by calculating the vertical stiffness of the reinforced concrete piles.

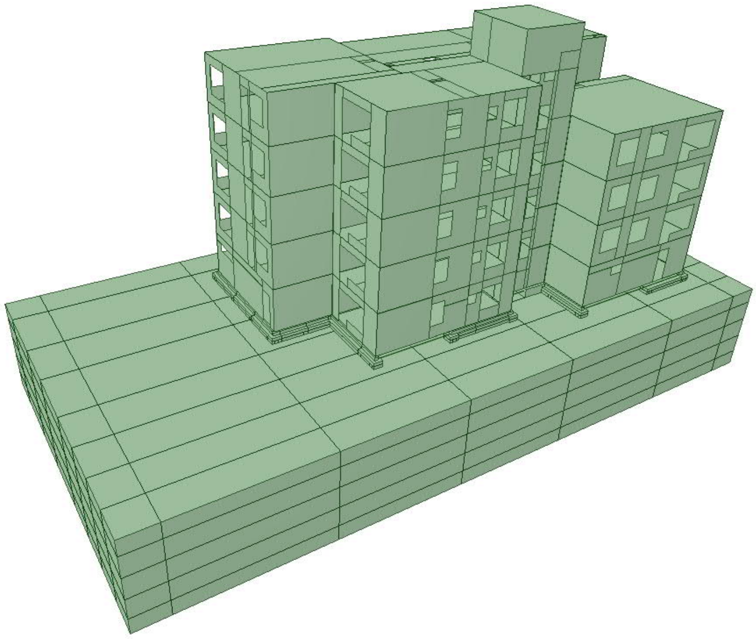

Figure 2 – Numerical model of the building.

The ground at the test site was composed of approximately 5 m layer of silt, 8 m layer of dense silt or sand and 2 m layer of moraine. The shear wave velocity of the top layer was measured with spectral analysis of surface waves method [6] and was determined to be around 150 m/s. In the numerical model, the uppermost layer of the ground was modelled as a 3D linear elastic material. The other ground layers were ignored because the ground was assumed to be homogenous. Perfectly matched layers were utilized as absorbing boundary conditions on the edges of the calculation domain to prevent reflections. In order to minimize the computational load of the calculation, the size of the calculation domain was kept as small as possible.

The numerical model included only the receiving building with assumption of a weak coupling between the source and receiver in railway-induced vibrations [7]. The modelling was carried out in the frequency domain by calculating the harmonic response of the building. The vibration caused by a passing train was modelled with a line source instead [8]. The harmonic source of the vibration in the model was set to a vertical end surface of the modelled ground with vertical and horizontal force components. This was done in order to mimic the far-field vibration where vibration field consist mainly of Rayleigh waves with much smaller calculation domain. The resulting approximation of the far-field vibration that excites the building was deemed sufficient.

3 Proposed evaluation method

A ground-borne noise evaluation method based on on-site vibration measurements and numerical model of the building was developed. The proposed evaluation method was created for use in construction projects where more accurate and detailed assessment of ground-borne noise levels in different parts of the building needs to be made. The proposed method also offers the possibility to evaluate the effect of different construction methods or details of the building on the ground-borne noise levels. Therefore, the method can also be used as a design tool.

The evaluation method requires railway-induced vibration measurements at the construction site. The vibration is measured on the surface of the ground at the area of the planned building according to standard procedures for railway-induced vibration measurements. The measurement results are calculated according to the guidelines and limits for ground-borne noise levels.

The numerical model of the building and the ground at the site is made based on the structural and architectural drawings of the project. Models for structural calculations may be available in some cases and can be utilized as well. In the case study, mainly the load bearing structures of the building were modelled, however, different building types may need different approaches for creating the model.

The numerical model is used to calculate vibration transfer functions from the ground to the rooms where ground-borne noise assessment is to be made. In the case study, vertical vibration of the midpoint of the floor was used as an evaluation point. Actual re-radiated ground-borne noise can be evaluated from the vertical vibration of the midpoint of the floor using e.g. single quantity correction factor from the FTA guidelines. Estimating the ground-borne noise levels in a room from the vertical vibration of the floor is commonly used method and many options exist for determining the relationship between floor vibration and ground-borne noise, e.g. [9]. The ground-borne noise could also be calculated directly in the numerical model [10], but it was left out of the scope of this study.

The ground-borne noise assessment is composed of the vibration measurement results on the ground, the transfer functions from the numerical model and correction factor from floor vibration to re-radiated noise. All calculations are in 1/3-octave frequency bands which allows for evaluation of the ground-borne noise spectra. The single number quantity relative to the ground-borne noise guideline values can be further calculated from the 1/3-octave results. Figure 3 shows the block diagram of the proposed method.

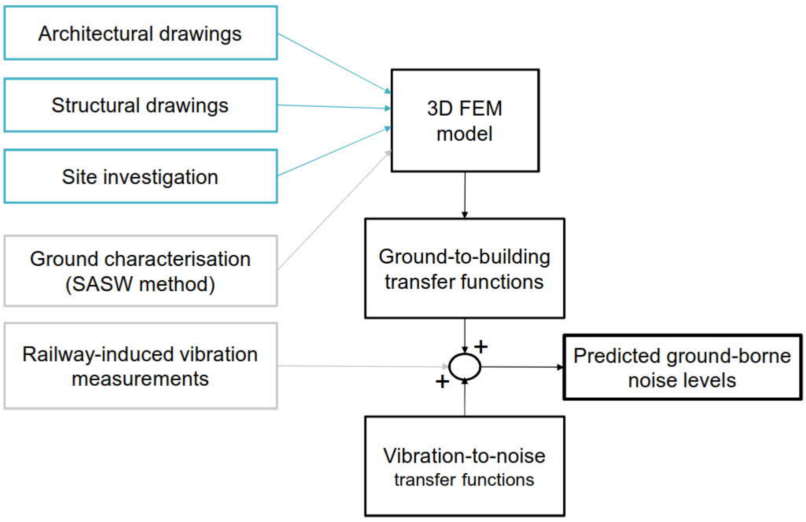

Figure 3 – Block diagram of the proposed evaluation method.

4 Results

The results of the vibration measurements in the building were compared to the empirical evaluation method with single-number quantity correction factors and to the proposed hybrid method which utilizes numerical modeling to calculate ground-to-building transfer functions. Figure 4 shows an example of the numerical model with visualization of vibration. Results of the comparison are presented for vertical vibration for each measurement point in the building, i.e. load-bearing structure in each floor and a midpoint of floor of a room. The evaluation points in the numerical model of the proposed method are matched to the actual measurement points in the building. In the empirical method [1], the appropriate adjustment factors for each measurement location are used.

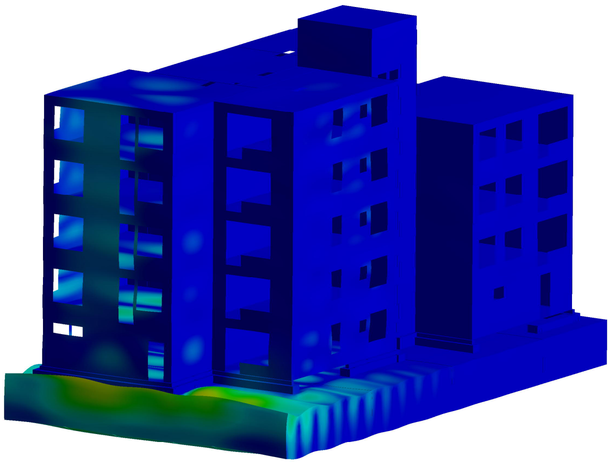

Figure 4 – Visualization of vibration in the numerical model. PML regions and parts of the modelled ground are not shown.

Figure 5 shows the measured and evaluated results for the 95th percentile values of vibration velocity levels at the measurement points in the building. Regarding ground-borne noise evaluation, the measurement point at the midpoint of the floor is analogous to ground-borne noise levels and thus the comparison between the evaluation methods and measurement should be focused on that measurement point.

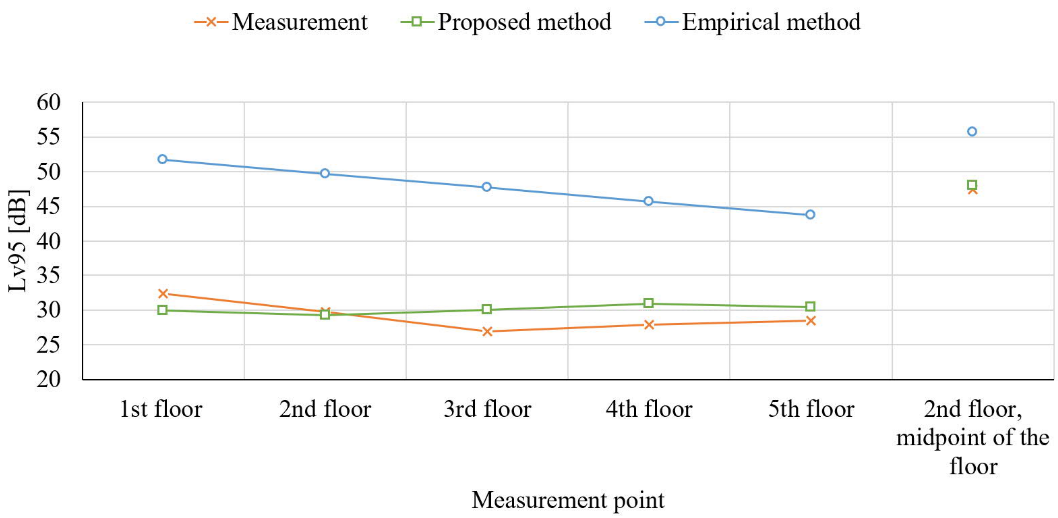

Figure 5 – Comparison of evaluation methods and measurements in the building.

Based on the results presented in figure 5, the proposed method utilizing a numerical model of the building was able to predict the vibration levels in the building with good accuracy. The empirical method using single-number quantity correction factors, however, is an overestimate. The measurement points were in the middle of the building and the empirical method does not take into account the decrease of the vibration in the building foundation when moving further away from the railway in horizontal direction. Therefore, the results presented here show such high overestimate especially in the 1st to 5th floor measurement points. Had these measurement points been at the building façade nearest to the railway, the results from the empirical method would have been closer to the measurement results.

5 Discussion

The results of this study have proven that it is possible to use numerical models as a tool for acoustical engineers in construction projects. In the case study, the results of the proposed ground-borne noise evaluation method were close to the measurement results. However, many sources of uncertainty can be identified in the numerical model of the building most of which have to do with the simplifications to the geometry or the material parameters. Therefore, a sufficient safety margin should be used in the assessment as well as sensitivity analysis for material parameters which have the greatest effect on the results. Validation and verification of the modelling methods should be conducted as described in the ISO 14837-1 standard [4] if possible. However, in the case study such validation procedures were not possible and instead sources of uncertainty were identified using the checklist presented in the standard.

Even though the assessment might be more accurate with the proposed method, it is by no means the definite answer for all construction projects subjected to the risk of railway-induced ground-ground-borne noise. In extreme cases where the on-site measurements show either very low or very high levels of vibration on the building site ground, the empirical method may be enough to assess the situation and decide on possible vibration insulation procedures. However, in complex buildings, such as hybrid buildings with variety of uses, more accurate and detailed analysis of ground-borne noise in different parts of the building can be beneficial and worth the resources needed for creating the numerical model.

6 Conclusions

The proposed hybrid ground-borne noise evaluation method consisting of on-site vibration measurements and numerical model of the building was shown to be able to predict vibration levels in the building with good accuracy. The research goal of developing a ground-borne noise evaluation method using numerical methods which would yield more accurate results than the currently empirical method was achieved.

The case study also showed that numerical methods can be used in acoustical design of buildings in construction projects relatively easily utilizing commercial simulation software. The proposed method also enables comparison of different construction designs and their effect on the predicted ground-borne noise levels in the building.

Acknowledgements

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