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Effect of structural design on traffic-induced building vibrations

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Abstract

Population growth and urbanization results in densified cities, where new buildings are being built closer to existing vibration sources such as road-, tram- and rail traffic. In addition, new transportation systems are constructed closer to existing buildings. Potential disturbing vibrations are one issue to consider in planning urban environment and densification of cities. Vibrations can be disturbing for humans but also for sensitive equipment in, for example, hospitals. In determining the risk for disturbing vibrations, the distance between the source and the receiver, the ground properties, and type and size of the building are governing factors. In the paper, a study is presented aiming at investigating the influence of various parameters of the building's structural design on vibration levels in the structure caused by ground surface loads, e.g. traffic. Parameters studied are related to the type of construction material (if it would be a light or heavy structure), and to the slab thickness. The finite element method is employed for discretizing the building structure that is coupled to a semi-analytical model considering a layered ground.

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Keywords: Traffic-induced vibrations; vibration mitigation; structural design

1. Introduction

The densification that occurs today in the urban development of cities increases the risk of having disturbing vibrations in buildings. An example of an increasingly disturbing source is faster trains, and an example of a more sensitive receiver is the more advanced equipment housed in hospitals and research facilities. The distance between source and receiver is shortened in today's densification of cities, e.g. having railways closer to buildings. Moreover,

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due to economic and environmental arguments, the building industry tends to build with lighter structural elements and thus use less material, for example, using wooden structures and long-span hollow-core concrete slabs. The building industry is, therefore, exposed to challenges related to disturbing vibrations.

Analysis of traffic-induced ground vibration is complicated since the problem involves a vast amount of unknown factors. The vibration propagation problem can be divided into different regions as illustrated in Fig. 1a. The different regions are: the source; the region of propagation; and the receiver, usually a building. The parameters and properties of each region affect the vibration levels occurring in a building. In case of predicting or measuring too high vibration levels in a building, vibration-reduction measures can be applied. Several measures have been developed to reduce disturbing vibrations. Reduction in vibration levels can be carried out by modifying the source, medium, or receiver. To reduce disturbing traffic-induced vibrations, for instance soil stabilization can be applied under a railway track, or wave barriers [1,2] can be installed in the ground medium, or the ground surface can be shaped in a wave-like pattern [3]. Soil stabilization can, moreover, be employed at the receiver, for example, beneath a slab-on-grade [4]. Designing and constructing a vibration-reduction measure can be connected to appreciable costs in a construction project.

The aim of the paper is to investigate, by a preliminary study, to which extent the building structure itself can be used as a vibration-reduction measure. The objective is to investigate the influence of the floor slab thickness and the material choice in the main structure on the vibrational response. It is done by comparing a heavy-weight structure made of concrete with a light-weight structure in wood. The buildings in the study are subjected to ground vibration stemming from a vertical harmonic unit load applied on a circular surface area with a radius of 1 m. The load is applied 20 m from the building. The frequency range used in the paper is 5-15 Hz, applied in steps of 0.5 Hz. Both road and rail traffic can have major frequency content in this range [2,5]. Moreover, see Fig. 1b for measurement data of ground response caused by a passing freight train, evaluated 35 and 60 m, respectively, from the track. The fundamental frequency of slabs in the types of buildings considered here often lies within the frequency range of 5-15 Hz. The study is hence limited to study effects of varying structural parameters for a frequency range where the ground has its first resonance frequency, which coincides with the common range of fundamental frequencies of slabs.

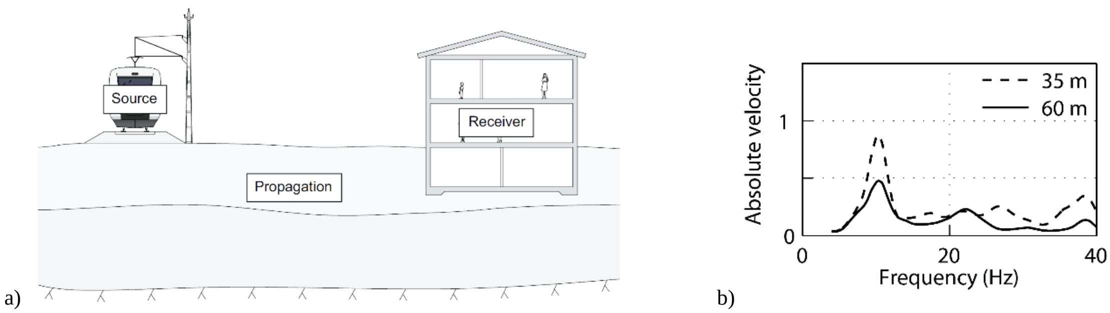

Fig. 1. a) Illustration of the vibration propagation problem. b) Example of measured ground velocity response caused by passing freight train, evaluated 35 and 60 m from the track, respectively [5].

2. Computational model

Using the finite element (FE) method to simulate propagation of ground waves often lead to very large numerical models, which can require substantial computational power resulting in very long simulation times. Therefore, a semi-analytical approach was used to model the ground involving soil and bedrock. The semi-analytical model is an extension of the work by Andersen and Clausen [6] and described in detail in [7]. The building structures were modelled using Euler-Bernoulli beam finite elements with two nodes and cubic Hermitian displacement interpolation and Mindlin-Reissner shell finite elements with nine nodes and biquadratic Lagrangian interpolation of the mid-plane displacements and rotations. The FE model was coupled to the semi-analytical model at connection points—so-called soil-structure-interaction (SSI) nodes. The model for the ground was formulated in horizontal wavenumber–frequency domain, i.e. in terms of (k_x, k_y, ω), thus reducing the problem to an ordinary differential equation in the depth direction, i.e. the z direction. For any combination of (k_x, k_y, ω), this allowed an analytical expression of the Green's function expressing the displacement at depth z_1 due to an axisymmetric distributed load applied on a horizontal plane at depth

z_2. The limitation of the model was that only horizontally stratified soils with homogeneous, linear viscoelastic material in each layer could be treated. The Green's function in space–frequency domain was obtained by discrete inverse Fourier transformation and evaluated for all combinations of points where external forces were applied or internal forces occurred due to interaction with the foundations of the structure. This produced a compliance matrix. A stiffness matrix for the ground was then established for the degrees of freedom associated with the SSI nodes. In this process, it was taken into consideration that some SSI nodes corresponded to single points in or on the ground, whereas other SSI nodes served as reference points for the motion of foundation structures modelled as rigid bodies.

In Fig. 2 the model of the building and the ground surface is shown, where the ground surface is in grey colour, the columns in red and the slabs in grey. The footprint of the building is 7×10 m^2. The building has two stories, each 3 m in height. There are columns with cross-section of 0.2×0.2 m^2 standing on square rigid footings (coloured in green) at each corner of the building, as well as in the middle of the longer sides. The longest distance between columns is 7 m and is regarded as the span-length of the slabs. Two different types of buildings were analysed. The first type of building had a solid wooden load-bearing structure consisting of wood columns and slabs of cross-laminated timber (CLT) elements. CLT elements are constituted of solid wood parts that are layered in a cross-wise pattern, see Fig. 3. The wood is assumed to be of quality C24, which has an elastic modulus of 11 GPa. Note that in buildings a thin concrete topping can be casted on the CLT elements to decrease the step sound. This is however not accounted for in the paper. The elastic modulus of the CLT element is reduced to 75% of the elastic modulus of C24 to account for low stiffness of the timber parts that are placed in the perpendicular direction in relation to the span-length. The other type of building was made of concrete, using solid concrete columns and solid concrete slabs. These two type of structures are common in Scandinavia for use in residential multi-story buildings. In the studied building, the base thickness of the slabs was 0.30 m for concrete and 0.24 m for CLT, in order to fulfil the static design criteria. A layered ground model was used, involving a 10 m deep soil layer on top of a half-space of bedrock, see Tab. 1 for the material properties. The bedrock is involved in the model since the wave propagation in it can be essential to account for [2].

All materials were modelled as linear viscoelastic isotropic homogeneous materials. Assuming isotropy is apparently a simplification, especially for the CLT slab. However, the vibration mode of interest here is the first bending mode of the slab, and this mode is not markedly affected by the shear properties of the slab. Moreover, determining absolute vibration levels are not within the scope of this study since this is a comparative investigation that focuses on relative vibration levels. The damping is accounted for by introducing the rate-independent loss factor through a complex stiffness matrix, values are shown in Tab. 1.

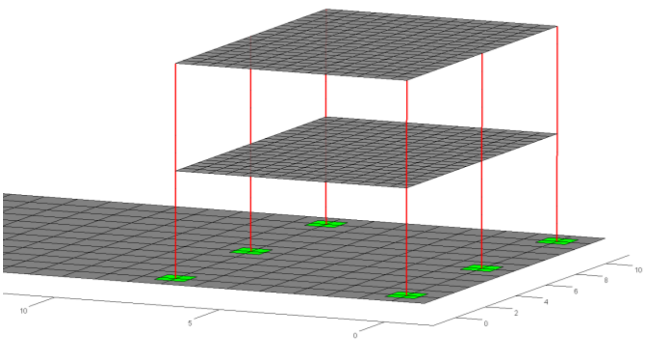

Fig. 2. The model of the example case.

Table 1. Material properties. Note that three different values for the soil layer was used, depending on the analysis. The elastic modulus within brackets are used for the CLT elements.

Material	Elastic modulus (MPa)	Poisson's ratio	Mass density (kg/m3)	Loss factor
Soil	[100 150 200]	0.48	2000	0.06
Bedrock	10,000	0.40	2500	0.04
Wood	11,000 [8250]	0.35	500	0.06
Concrete	32,000	0.20	2500	0.04

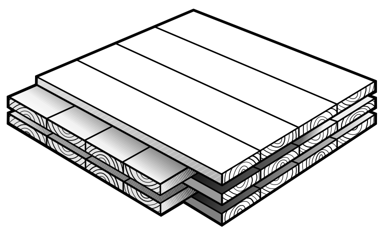

Fig. 3. Illustration of a CLT element.

The building was modelled by structural finite elements with linear interpolation. Beam elements were used to model the columns, and shell elements were used to model the slabs. All parts in the model are assumed to have high friction in-between and are hence fully tied to each other.

3. Parametric study

Steady-state analyses were performed for evaluating the frequency response of the ground and building structure between 5 and 15 Hz. Focus was put on studying effects of varying the thickness of the slabs, effects of the differences between a heavy-weight concrete and a light-weight wooden building structure, and effects of varying the soil properties. The magnitude of the complex velocity amplitude is used as a measure of the vibration level. The system is excited by a rigid footing placed on the ground surface 20 m from the building. A vertical unit load is applied on this surface footing. The ground response was evaluated at a node 20 m from the load, between two columns, at the boundary of the building's footprint. The response on the second floor was evaluated at a node located in the mid-span and 2.5 m from the slab edge. Since a unit load was applied, the frequency-response function can easily be obtained and be used together with load spectra to determine the vibration response. The elastic modulus of the soil was varied by selecting three values: E = 100, 150 and 200 MPa, corresponding to 150 MPa ± 33.3% which is a common margin error level of geophysical measurements. The thicknesses of the concrete slab was 0.25, 0.30, 0.35, 0.40, 0.45, and 0.50 m, and the CLT slab was modelled with the thicknesses 0.20, 0.24, 0.28, 0.35, and 0.50 m.

3.1. Results for concrete buildings with different soil properties and slab thicknesses

In Fig. 4a, the absolute velocity is shown for a node on the ground surface, just in front of a concrete building, from varying the stiffness of the soil. As expected, it is seen in the figure that the vibration response is lower for a stiffer soil, and the resonance frequency of the soil shifts upwards from 7.0 Hz to 10.0 Hz. In Fig. 4b, the absolute velocity is shown for the upper slab for the concrete structure on soils with varying stiffness.

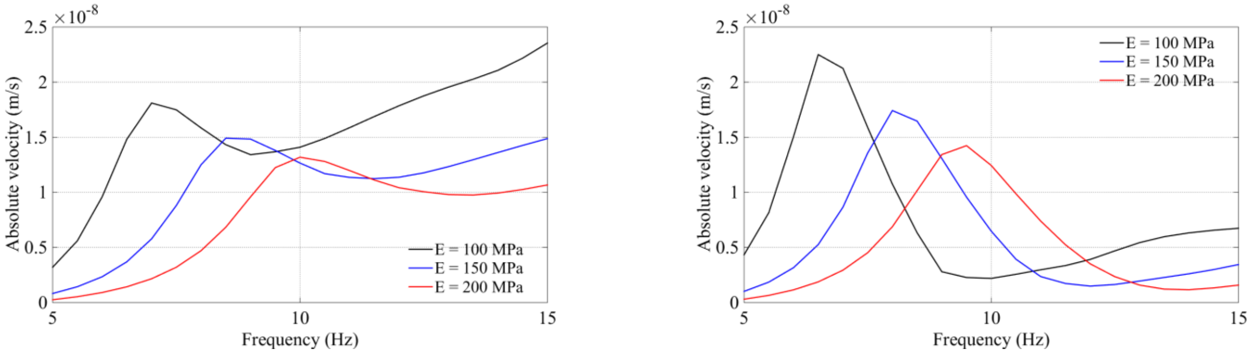

Fig. 4. Vibrations evaluated for the concrete building with slab thickness of 0.30 m on soils with different stiffness: 100 MPa; 150 MPa; 200 MPa. a) on the ground surface just in front of the building; b) on the top floor.

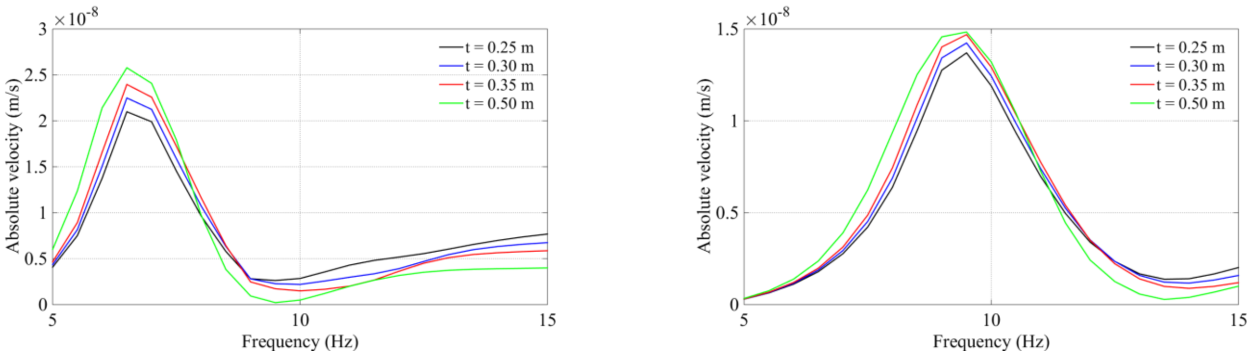

Fig. 5. Vibrations evaluated on the top floor of the concrete building for two types of soils: a) E = 100 MPa and b) E = 200 MPa. The thickness of the slabs were varied from 0.25 to 0.50 m.

As expected, the vibration response on the slab is lower for a stiffer soil. The peak response of the slab for the case with the stiffer soil is 63% of the peak response of the softer one. Hence, adequate soil parameters are essential in predicting absolute vibration levels in buildings. It should also be noted that the frequency associated with the peak response changes, from 6.5 Hz to 9.5 Hz. The response peaks in Figs. 4a and 4b occur at almost identical frequencies, indicating that the slab is controlled by the response frequency of the soil. In comparing Fig. 4a with Fig. 4b, one can notice that amplification of the vibration levels occur in the building, i.e. the velocities of the slab are larger than those on the ground surface.

In the plots shown in Fig. 5, the vibrations are evaluated on the top floor of the concrete structure for two types of soils: one with an elastic modulus of 100 MPa and one with an elastic modulus of 200 MPa and with varying the thickness of the slabs. As seen in the figure, the peak response increases when the slab becomes thicker, at least up to 0.50 m. It is clear, however, that changing the thickness of the slab has a minor effect on the slab vibration levels. It should be pointed out here that a slab thickness of 1 m results in a peak response which is only about one half of the peak response of a 0.50 m thick slab. However, it is simply not realistic to increase the thickness of the slabs with approximately 300% in order to reduce vibration levels.

3.2. Results for wooden buildings with different soil properties and slab thicknesses

In Figs. 6 and 7 the resulting vibration levels of a wooden building are shown for different soil properties and slab thicknesses. By comparing the results in Fig. 4a with Fig. 6a, it is seen that a lower response in the ground is found for the presence of a concrete building as compared to the wooden building. This can be explained by the concrete building being more than five times heavier than the wooden building. Further, a comparison of Figs. 6a and Fig. 6b reveals that the vibration levels in the building are much smaller than the ground vibration levels. The situation was the opposite for the concrete structure. This may, at least partly, be explained by the higher damping assigned to the wooden building as compared to the concrete building (cf. Tab. 1) and the higher mass of the concrete building.

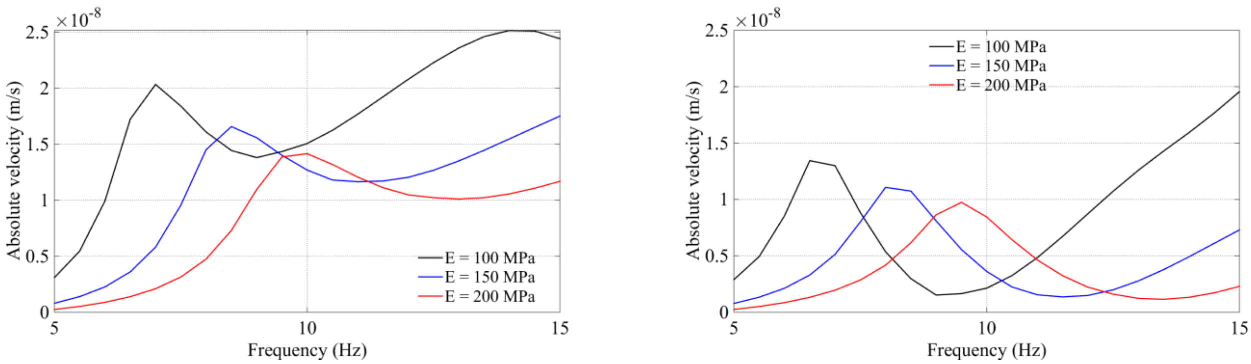

Fig. 6. Vibrations evaluated for the wooden structure with slab thickness of 0.24 m on soils with different stiffness: 100 MPa; 150 MPa; 200 MPa. a) on the ground surface just in front of the building, b) on the top floor.

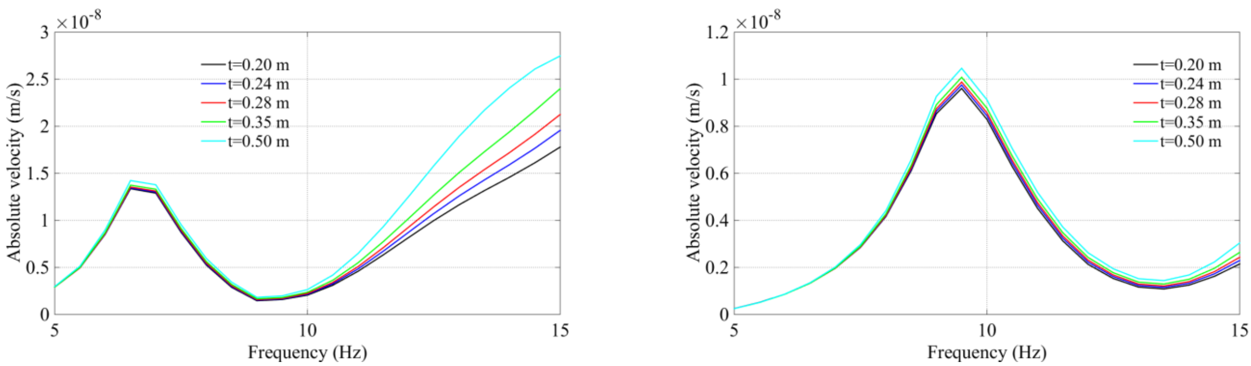

Fig. 7. Vibrations evaluated on the top floor of the wooden structure for two types of soils, a) E=100 MPa and b) E=200 MPa, respectively. The thickness of the slabs were varied between 0.20 to 0.50 m

In Fig. 7 the same tendencies are seen as in Fig. 5, namely that the thickness of the slab has a minor, almost negligible, influence on the vibration levels on the slabs. Moreover, as for the concrete building, a minor increase of the slab thickness actually increases the vibration levels. A possible explanation for this may be a relative shift between the resonance frequencies associated with the first floor mode and the first modes of the soil–structure system. In any case, it is again found that a large increase of the slab thickness will decrease the floor response.

4. Concluding remarks

A computational model consisting of an FE model for the building structure and a semi-analytical model for the soil was applied for studying effects of structural modifications of a building subjected to ground vibration. The analysis was focused on frequencies where train and trucks can have major energy content. Moreover, the same frequency range involved the fundamental frequency of slabs normally used in multi-family residential buildings. The ground response at the building is affected by the type of building (heavy or lightweight). This is also noted in [8] where Andersen points out the response depends on if the building has a cellar or not. The major contribution of this paper is the clear results regarding the difficulties of controlling the vibrational response of slabs at frequencies at the first resonance frequency of the ground, which occurs in the same range as the fundamental frequencies of the slabs.

It is seen in the paper, only concerning the first resonance frequency, that a thicker slab, and hence a higher fundamental frequency, will increase the vibration response on the slab. It should be noted, however, that a slab with a higher first resonance frequency resists footfall-induced vibration to a larger extent, since the footfall has its largest energy content at very low frequencies. One should keep in mind that we are only studying the effects at frequencies close to the first response frequency of the ground and of the slabs. For a wider frequency range of interest, the results found here may not be as clear, or more distinguished, or even different. In future studies, the effects of changing the span lengths as well as size of footprint should be investigated, since such changes may have a larger effect on the vibrational response of the slabs. I would also be interesting to quantify how different structural modifications can affect the response of slabs in a residential building subjected to disturbance of ground-borne waves. These can also be related to vibration reduction measures applied to the ground, such as barriers and shaped landscapes.

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