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Numerical study on reducing building vibrations by foundation improvement

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ABSTRACT

Vibration disturbances in buildings may stem from ambient sources, such as motorway traffic, or from internal sources such as people walking inside the building. Vibrations can exceed requirements for sensitive equipment or cause annoyance to humans and therefore the vibrations may need to be reduced. Vibrations from both external and internal sources can be reduced by modifying the properties of concrete slabs and of the soil underneath. Soil can be improved by being mixed with a binder material in order to increase its stiffness. In this study, parametric finite element analyses were conducted on the achieved vibration reduction on a slab on soil from improving the properties of a concrete slab on soil or of the soil underneath. The size, elastic modulus, and depth of the stabilised soil were found to markedly affect the level of reduction obtained. The soil stabilisation at a vibration-sensitive facility was used as an example case, where the developed finite element model was calibrated to green-field measurements carried out on-site. Frequency spectra of both road traffic loads and internal pedestrian loads were considered in the model. The calibrated finite element model predicted reductions of almost 60% for the road traffic and 80% for the pedestrian load.

1. Introduction

A vibration-reduction problem can be divided into three parts: the *source* generating vibrations, the *medium* in which vibrations are propagated, and the *receiver* that is to be protected. Each of these three parts need to be considered in today's urban planning developments. The desification that occurs increases the risk of vibration disturbances. An example of a source is faster trains, and an example of a receiver is more advanced and therefore more sensitive medical equipment. The medium is affected by the densification of cities, i.e. having buildings closer to existing vibration sources such as motorways or railways. Owing to economic and environmental reasons, there is a trend in the building industry to build with lighter elements and thus use less material, such as wooden structural parts and hollow-core concrete slabs. Thus, the building industry is facing increasing challenges regarding vibrations. In such cases, effective measures to reduce vibrations are desirable.

Since Woods' pioneering field-tests of trenches in 1968 [1], there have been extensive studies on several measures aimed at reducing incident ground vibrations stemming from external sources. Since then, several research groups have investigated the vibration reduction effects of various types of wave obstacles, such as trenches (open, back-filled and water-infiltrated) [2,3] and shaped landscapes [4]. The idea of placing a wave obstacle is to introduce a disturbance in the incident wavefront by reflection and refraction of the waves.

Other techniques aim at reducing vibrations at the externally located source. Yang and Hung [5] developed a finite element (FE) model to investigate the reduction in train-induced vibrations by various measures, such as an elastic foundation below the train track. They concluded that a soft foundation performs better than a stiff one. However, they did not account for static loads. They also showed that the elastic foundation performs poorly at low frequencies (i.e. long wavelengths); hence, a large foundation in relation to the wavelengths may be beneficial. Andersen and Nielsen [2] used a coupled FE–boundary element (FE-BE) model to study the effects of improving the soil underneath a train track on ground vibrations. The soil was improved by increasing the elastic modulus by a factor of ten from 200 to 2000 MPa. They found that soil improvement was especially efficient at reducing ground vibrations at and close to the track compared to trenches. For some frequencies and loading situations, a larger vibration reduction was achieved by soil improvement then by a trench. In general, however, trenches resulted in larger reductions than soil improvement

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for the increase in elastic modulus that they considered. Hung et al. [6] used a coupled FE-BE model to investigate the vibration reduction effect on train-induced ground vibrations of different measures, such as trenches and wave-impeding blocks (WIBs). They found that WIBs may be used as an efficient vibration reduction measure. However, the width of the WIB is much smaller than the occurring wavelengths at low frequencies. Then, the waves will not be trapped, which can result in a poor vibration reduction performance. In general, the WIBs did not perform as well as open trenches but better than in-filled ones.

Methods for reducing vibrations at the building to be protected usually involve thickening the whole slab, slitting the slab into isolated islands, or supporting the slab with piles. Sanayei et al. [7] studied using a thickened lower floor in a multi-story building as a vibration reduction measure for train-induced ground vibrations. They tested a full-scale building to verify an analytical prediction model created with a methodology which they previously developed [8,9]. They investigated the vibration reduction efficiency of the thickened floor for various thicknesses and concluded that it can be used as a reduction measure for external vibration sources. Xiong et al. [10] studied the effect of various cases on reducing train-induced building vibration levels. They concluded that, for example, a stiffened foundation–slab system may an effective vibration reduction measure. They found that an island of a thicker slab-on-grade reduced the vertical vibrations compared to the surrounding conventional slab-on-grade but increased the horizontal vibrations at some frequencies. It should be noted that the reduction in vertical vibrations was strongly dependent on the occurring wavelengths; thus, the conclusions may differ under other site conditions. Amick et al. [11] performed vibration measurements in order to evaluate how the stiffness of a slab-on-grade or of a building affected the vibrations at a construction site. They concluded that isolating part of the slab where vibration-sensitive equipment is to be placed is only effective for vertical vibrations with frequencies higher than a certain limit (20 Hz in this specific case). Thus, for low frequencies (i.e. long wavelengths), there is no positive effect from using isolated islands, and horizontal vibrations may even be amplified. They noted that the obtained vibration reduction depends on the ratio of the present wavelength and dimensions of the slab-on-grade. Amick et al. [12] conducted an experimental study on three types of concrete slabs to determine their vibration reduction ability: (i) a 300 mm solid slab, (ii) 300 mm slab with a separated island of 900 mm and (iii) the same as the latter but the island was placed on concrete piles instead of soil. The vibrations were evaluated with both external and internal excitation sources. For the externally excited vertical vibrations, the slab with piles performed the best and the continuous slab performed the worst. For the internally excited vertical vibrations, the slab type resulting in the largest vibration reduction depended on the frequency of interest. In general, they concluded that the performances of the different slab types depend on the frequency range of interest and on the excitation type. Note that the island they considered was three times thicker than the continuous slab. Thus, their study was not complete in terms of investigating the benefits of a slit/gap in a slab.

The authors [13,14] previously found that improvement of the soil parameters have a greater effect on the vibration levels in a building than structural modifications have when internal loads are applied. The soil parameters were also found to have a major effect when external loads are applied [15].

1.1. Soil stabilisation as a vibration reduction measure

One approach to improve the soil parameters is to stabilise the soil by mixing it with a binder in order to increase its stiffness. It is frequently used to improve soft soils for road and railway construction and for building foundations to decrease settlements. There are several types of binders that can be used for this purpose, either singly or in conjunction with one another, such as cement, lime, blast furnace slag, and fly ash. The first two are employed most frequently nowdays. Soil stabilisation with cement as a binder commenced in the U.S. in the early 1900s [16]. The fundamental aim is to increase the elastic modulus of the soil by adding an adequate amount of binder, the procedure is as follows: (i) the soil down to the desired depth is dug up, (ii) spreading out a layer of original soil, (iii) spreading out a layer of binder (cf. Fig. 1a), (iv) mixing the original soil with the binder (cf. Fig. 1b), (v) the mixed soil is packed and (vi) the procedure is repeated from step ii until the required thickness of the stabilised soil is achieved. Fig. 1 shows two photographs of the stabilisation process.

By improving the soil underneath the building to be protected, both externally and internally induced vibrations may be reduced. However, soil stabilisation underneath a slab-on-grade as a vibration reduction measure is not well-examined in the literature. The vibration reduction effect of stiffening the soil underneath a slab-on-grade is twofold. First, the bending stiffness of the foundation is increased from solely incorporating the slab-on-grade to also include the stabilised soil. This is advantageous for vibrations stemming from both external and internal sources. If different material properties of the stabilised soil and ambient soil are used, differences in the wave speed and mass density occur between the stabilised soil and ambient soil. Since the mechanical impedance is defined as the wave speed multiplied by the mass density ($Z = c\rho$), an impedance mismatch occurs between the two materials. Thus, when an incident wave front hits the boundary of the stabilised soil, energy is reflected since the impedance mismatch governs the amount of energy reflected [27]. The impedance mismatch also results in refraction of the incident wave front. Thus, improving the soil by stabilisation may reduce vibrations from both internal and external vibration sources in an efficient manner.

1.2. Present study

The present study has its origin in the conceptual design of the research facility MAX IV Laboratory. See Section 6 for more information about the facility (hereafter referred to as 'Max IV'). In the design of the facility, numerical conceptual studies were carried out to investigate the effects of modifications to the soil and structure on vibration levels within the facility to satisfy the strict vibration requirements applied there.

In the paper, parametric FE analyses were conducted to investigate the vibration reduction on a slab on soil from improvements to the slab and the soil underneath and to develop general guidelines to be used in the design stage of vibration-sensitive buildings. A FE model calibrated to measurements was used to predict the obtained vibration reduction on a slab on soil by soil stabilisation at a real-life example case.

The study was divided into two major parts. As discussed in Section 3, the first part involved creating an FE model including a concrete slab located on a homogeneous soil. Various parameters of the slab were varied, and the related vibration phenomena were examined. As discussed in Section 4, the influence of soil stabilisation was included in the parametric studies; different parameters of the soil and stabilisation were varied. The influence of bedrock underneath the soil on the vibration reduction was investigated. Section 5 summarises the findings from the parametric studies as general design guidelines. In the second major part, soil stabilisation at the vibration-sensitive Max IV was used as an example case. This is discussed in Section 6. Frequency spectra of occurring road traffic loads and internal pedestrian loads were considered in the model.