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ORIGINAL PAPER

Effect of foundation shape and properties of the adjacent buildings on the railway-induced vibrations

Jabbarali Zakeri[1] · Morteza Esmaeili[1] · Mehrad Mousavi-Rahimi[1]

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Abstract
Controlling the ground-borne vibrations affecting structures by changing the geometry and weight of foundation as an inexpensive and efficient method has rarely been considered by researchers. In this article, the effect of foundation geometry and weight built on different soil types on the induced vibration level in a building at the proximity of the railway track is investigated. To this end, a three-dimensional finite/infinite element model including soil, building and track is developed by considering the elastodynamic aspects. The accuracy of numerical modeling is demonstrated using the field tests. A comprehensive parametric analysis on three soil types (soft, medium and stiff) and specifications of building foundation is conducted. The obtained results unveiled that, contrary to the existing belief, foundation integration or increasing its weight does not necessarily end in the reduction in vibration level in building floors. Also, the transferred level of vibration to the building floors depends on the soil type, foundation properties and roof natural frequency. The findings highlight an orthogonal strip foundation in soft soil and single footing in medium and stiff soils transfer smaller vibration amplitude to floors. Additionally, the strip footing with greater weight on soft soil results in the highest vibration reduction in floors, while the single footing with lower weight on stiff soil has the same effect.

Keywords Train-induced vibration · Finite/infinite simulation · Foundation properties and geometry · Slab natural frequency

Introduction

With increasing urban population, the development of railway transportation systems is a mandatory step for addressing the traffic. It is, therefore, inevitable to construct railways in the proximity of residential areas, hospitals and other buildings that are sensitive to vibration. To tackle the ensuing issues in such structures including noise and vibration, numerous researchers have studied control methods of vibrations generated by railway vehicles. Different means of controlling railway vibrations are categorized as vibration control: (1) at source, (2) along the transmission path and (3) at receiving building. A number of researchers have considered the vibration attenuation at source. Balendra et al. (1989) and Hui and Ng (2009) probed the effect of floating slab track on the train-induced vibrations. Krylov (1995) and Heckl et al. (1996) considered the train velocity and sleeper effect on the vibrations. Other studied subjects include the impact of resilient mat underneath the track as well as its dynamic and static properties, application of energy absorbers (Dere 2016; Kraśkiewicz et al. 2016) and utilization of steel springs beneath the rail (Lei and Jiang 2016; Zhu et al. 2017). Some researchers investigated the reduction in ground-borne vibrations along the transmission path. Among such studies, one can mention the application of wave barriers including open and infilled trenches (Adam and Von Estorff 2005; Thompson et al. 2016; Yang et al. 2018), pile wave barriers (Kattis et al. 1999) and wave impeding blocks (Adam and Chouw 2001).

Vibration attenuation with the aid of modifications in soil and building foundation has been a riveting subject for researchers. Using a numerical approach, Talbot and Hunt (2003) modeled the impact of pile foundation on the vibrations reaching the building. Ju (2007) employed a three-dimensional (3D) finite element method (FEM) to inspect the effect of isolations using different foundations such as retaining walls, soil enhancements and pile foundation on

✉ Morteza Esmaeili
m_esmaeili@iust.ac.ir

[1] Iran University of Science and Technology, Tehran, Tehran, Iran

the train-induced vibrations in buildings. Persson et al. (2016) conducted an FEM analysis to investigate the effect of different parameters of concrete slabs and stabilized soil underneath the slab on the vibration reduction of concrete slab. Their results showed that the slab width and elastic modulus and depth of stabilized soil were effective in mitigating the vibrations of concrete slab. Aided by a computer program, François et al. (2007) studied the effect of foundation type on the traffic-induced vibrations on a two-story building by considering the soil–structure interaction. The results showed acceptable accuracy in the case of a rigid structure located on a soft soil. Sanayei et al. (2011a, b) documented that increasing the thickness of first floor in a multistory building was a means of reducing the ground-borne vibration due to the passage of trains. They examined a scale-down building so as to test a previously developed analytic prediction model (Sanayei et al. 2011a, b, 2012). They investigated the vibration reduction due a thick slab with respect to its thickness and concluded that it can be utilized as an attenuator of external vibration source. Their study, however, did not consider the soil–structure interaction. Auersch (2008) analytically computed the vertical transfer functions of soil–structure system due to its resonance and compared the findings with field results. Also, the building was considered to be a lumped mass on foundation and the impact of soil type and foundation geometry on the vibration in different floors was neglected. In a more comprehensive study, Kuo et al. (2019) benefited from a hybrid (empirical–numerical) model in order to evaluate the effect of structure and soil parameters on the amount of vibration. Their results indicated that the existence of building decreased the vibrations in the free field around the structure. Additionally, the soil type had a much more noticeable effect on the vibrations compared with the building geometry, while the foundation type had a small effect on the vibrations in different floors. Nevertheless, they did not consider the foundation weight on the vibration of floors. Also, they did not propose a well-organized procedure for predicting the effect of foundation geometry built on different soil types on the vibration of floors.

The influence of various parameters and loadings such as Winkler–Pasternak constants, material properties, wave number, thermomechanical loading, … on the wave propagation and static/dynamic behavior of functionally graded (FG) sandwich/anisotropic plates and FG beams rested on elastic foundation using the theory known as refined plate theory (RPT) without shear correction factor is investigated and detailed in some previous research (Karami et al. 2019; Mahmoudi et al. 2019; Boukhlif et al. 2019; Addou et al. 2019; Kaddari et al. 2020; Chaabane et al. 2019). Using the new shear strain shape function, the main privilege of the proposed theory is that it involves fewer unknowns as well as the stretching effect.

In addition, the influence of several material parameters and geometric ratio on the buckling response of the single-layered graphene sheet (SLGS) embedded in Visco-Pasternak's medium is evaluated using nonlocal four-unknown integral model, which includes the effect of transverse shear deformation without using shear correction factors by Bellal et al. (2020). Alimirzaei et al. (2019) studied nonlinear maximum deflections, critical buckling load and natural frequency of viscoelastic micro-composite beam reinforced by uniform, FG-V and FG-X distributions of boron nitride nanotube (BNNT) with initial geometrical imperfection on elastic foundation using FEM.

The effect of masonry infills on floor response spectra in reinforced concrete (RC) buildings subjected to earthquake was evaluated in (Surana et al. 2018; Perrone et al. 2020). They selected some random variables (dynamic characteristics, loads and material properties) to construct the building population and presented results taking into account the effect of masonry infills in the floor dynamic response.

The literature review shows a lack of comprehensive studies on the concurrent effect of foundation characteristics (geometry and weight) and soil type on the amount of induced vibrations in the building floors in the vicinity of railway track. Accordingly, the present paper seeks to address some main variables in the field of train-induced ground-borne vibration in the structure and illuminate this uncharted area. To this end, a 3D FEM of the soil, structure and railway track was developed. In this model, the free-field boundary was modeled using the infinite elements. The dynamic analysis was carried out using the implicit operator. The numerical model was then validated against the results obtained from the field test of soil under impact loading. The effect of foundation properties and soil type on the generated vibrations in a conventional building (four-story, concrete frame) in the proximity of railway was evaluated. To this aim, three common foundations including single, single-linked and orthogonal strip footings with different weights on three soil types (stiff, medium and soft) were considered. The loading due the passage of a wagon was applied as a step point load on the model, and the dynamic response of building in the mentioned cases was obtained. The key contribution of this work is in the first attempt it provides some helpful information for civil engineers to choose proper foundation for the building near the railway track considering soil type and slab natural frequencies.

Numerical modeling

Model description

To investigate the effect of (geometry and properties of) foundation on the vibrations arriving at the building location, a 3D numerical model using finite element analysis software ABAQUS (Dassault Systèmes 2014) was developed according to Fig. 1. In this regard, a conventional four-story one-span concrete building was considered in the proximity of railway track. The central lines of columns were 6 m apart in two directions. The lateral dimension of the concrete slab of roofs was 6.5 m, and its thickness was 0.2 m. The dimensions of columns cross section were 0.5 × 0.5 m, and their net height was 3 m. The total height of structure from the foundation was 12.8 m. The distance between the center of structure and embankment (D) was taken as 22 m. The geometric characteristics of foundation are described in Sect. 3. The embankment width and height were, respectively, 8 m and 1.5 m. According to previous studies, by properly modeling the boundary of finite domain, the model dimensions will have no effect on the results (Kouroussis et al. 2014). Hence, the optimal dimensions of the finite domain of soil, i.e., B and H, were taken as 40 m and 10 m, respectively, as such that enough space is provided for the finite element simulation.

For the purpose of meeting the finite element compatibility, all utilized elements for the soil, embankment and structure were eight-node solid elements of C3D8 (an eight-node linear brick) type. To simulate the infinite soil medium and avoid wave reflection from the boundary of finite space, infinite elements (CIN3D8) were employed (Dassault Systèmes 2014). According to Fig. 2, when utilizing infinite elements, the distance from each node on the boundary (between infinite and finite medium) to the node located at infinity should be equal to the distance from the same node to a known node (pole) inside the finite space (Zienkiewicz et al. 1983). It should be noted that to mesh the infinite space, an auxiliary algorithm was utilized. This code receives the model geometry and identifies the boundary nodes, and then places the infinite element in the right direction. To guarantee the acceptability of modeling accuracy, a dynamic analysis in the time domain using an implicit solution was used. Model validation (Sect. 2.3) showed that a time increment of 0.001 s was suitable for the analysis.

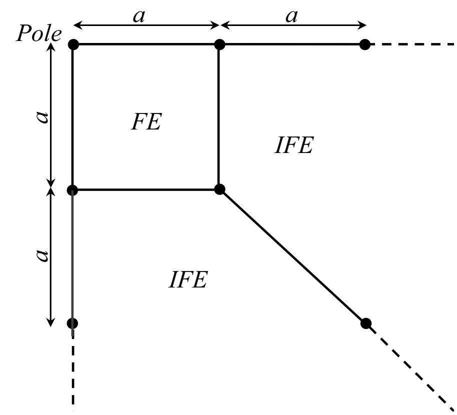


Fig. 2 Connection geometry of the finite and infinite elements along with the pole position

Since the wave propagation caused by railway yields small shear strain (smaller than 10^{-5}), the soil was considered as an isotropic medium with linear elastic characteristics (Kouroussis et al. 2009, 2014). Accordingly, the material behavior in the current study was assumed to be linearly elastic.

With regard to the numerical modeling of soil damping, a Rayleigh model was adopted, which is particularly efficient in the time domain analysis. The Rayleigh damping was obtained from Eq. (1) as in (Chopra 1995)

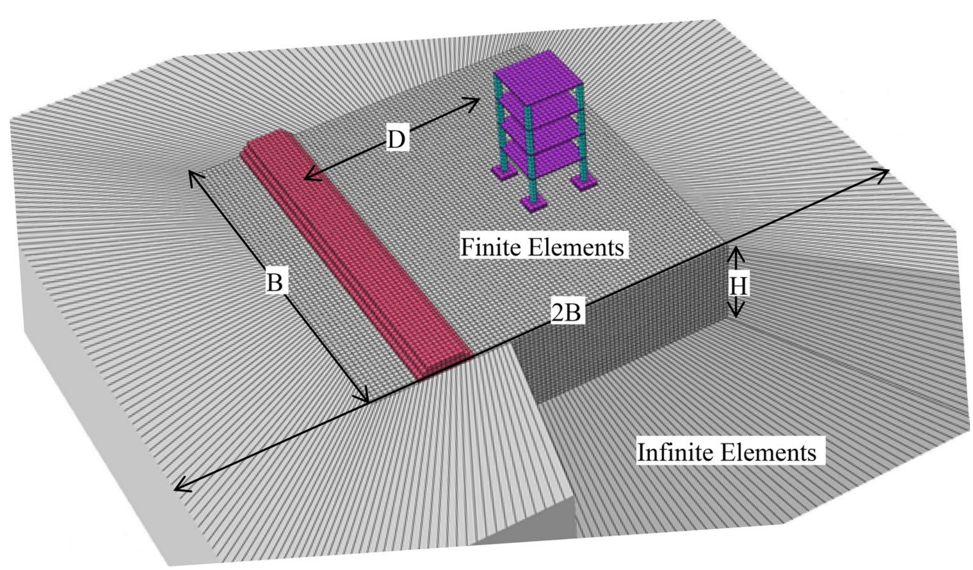


Fig. 1 Meshed finite/infinite element model of soil, structure and embankment

$$\mathrm{C} = \alpha \mathrm{M} + \beta \mathrm{K} \tag{1}$$

where [M] is the mass matrix, [K] is the stiffness matrix and α and β are, respectively, the mass and stiffness coefficients obtained from the damping ratio (ξ) for two different vibration modes in the form of Eq. (2),

$$\alpha = \frac{2\xi\omega_i\omega_j}{\omega_i + \omega_j}, \quad \beta = \frac{2\xi}{\omega_i + \omega_j} \tag{2}$$

where ω is the angular frequency ($\omega = 2\pi f$) and the subscripts i and j represent the frequency ranges of analysis (Kouroussis et al. 2013). Since Rayleigh damping formulation is frequency dependent, α and β were chosen in order to obtain a relatively constant damping in the range of frequencies of interest or main expected frequencies. This value was selected up to 50 Hz. The soil damping ratio was around 3% for the small strains (Kouroussis et al. 2009, 2013). In this article, for a constant damping ratio of 3%, the value of α was 0, while β was 0.0003 s. The properties and materials used in the modeling of soil and building are listed in Tables 2 and 3, respectively.

Loading

The considered loading on the model should be selected so as to simulate the loading effects caused by the train passage. According to previous studies, train-induced vibrations are generally along the vertical direction with a frequency up to 80 Hz (Heckl et al. 1996). However, for heavy haul trains yielding the largest vibration amplitudes in surrounding buildings, the frequency has been reported to go up to 35 Hz (Adam and Von Estorff 2005). To cover the frequency range in this study, a locomotive with an axle load of 100 kN, velocity of 25 m/s and center-to-center distance of 1.5 m was adopted as exhibited in Fig. 3a.

This loading scenario simulated as the moving-point loads was applied on the nodes in the embankment elements. To avoid a transient response in the numerical model, the loads were considered as triangular pulses (Hall 2003; Fernández Ruiz et al. 2017). Thus, as displayed in Fig. 3b, the time increment of each loading step was obtained as 0.02 s by considering the element size of 0.5 m. The time period of train passage on the track was 2.5 s, and the total analysis time was 4 s.

Mesh size study and model validation

In order to validate the numerical model, it was used to compute the vibration response of the ground surface due to a falling object as the excitation on the soil surface. The field test has already been performed by Kouroussis et al. (2009). The weight had a mass of 50 kg and fell from a height of 1 m. The dynamic characteristics of the soil are listed in Table 1. Vibration measurements were carried out at a distance of 16 meters from the center of loading at seven points. In addition, mesh size dependency is critical to validate the convergence of numerical analyses. Therefore, the

Table 1 Soil properties

Part	Depth (m)	Elastic modulus, E (MPa)	Poisson's ratio, ν (–)	Mass density, ρ (kg/m^3)	Damping, β (s)
Finite soil layer	3	120	0.3	1600	0.0003
Half-space	–	704	0.3	3500	0.0003

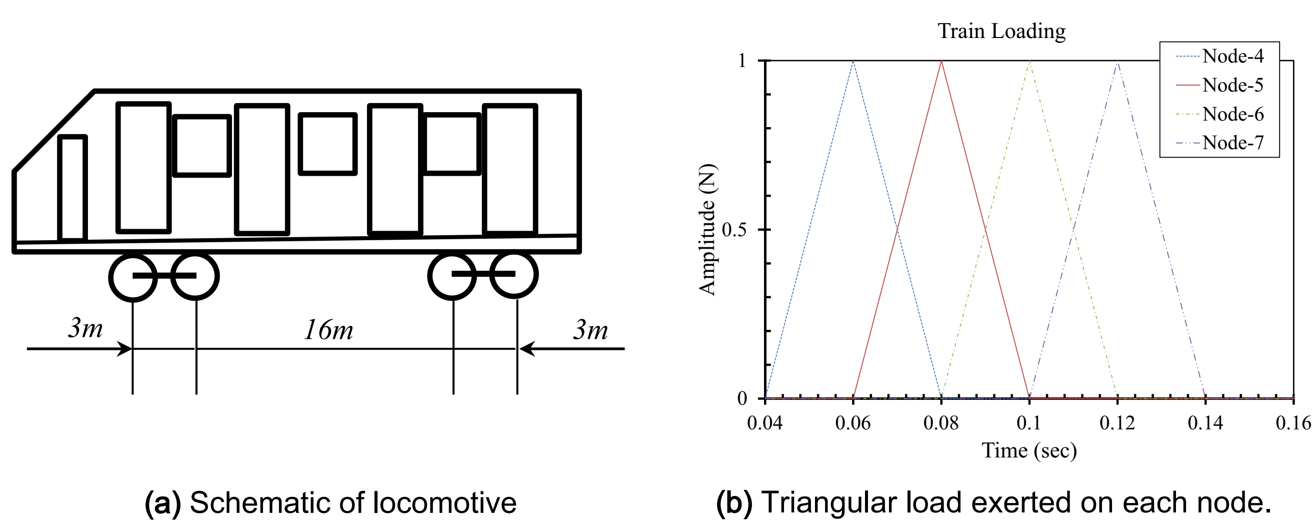


Fig. 3 Schematic of locomotive and triangular moving load exerted on the track

numerical model was employed with different mesh sizes of 2, 1 and, 0.5 m. The results obtained from the field were then compared with those of the model when all the properties of the field were taken into the model. Figure 4 compares the experimental and numerical values of peak particle velocity at various distances from the source.

Many studies suggest that the maximum element size in FEM should be less than one-eighth of the shortest Rayleigh wavelength. Although some references have stated that the maximum element size should be less than one-fifth of the generated Rayleigh wavelength in the model (Celebi and Göktepe 2012; Bo et al. 2014), it was used to mesh the primary numerical model. It was observed that the results of model with the mesh size of 0.5 m are in a good agreement with the field measurements, whereas the results of numerical model with the mesh size of 2 m are not satisfactory. Hence, the mesh size of 0.5 m (in the range of one-fifth to one-third of Rayleigh wavelength) was selected for the modeling purposes. When the model loading incorporates a wide range of frequencies (up to 100 Hz), the maximum element size has been proposed to be less than one-third of the smallest Rayleigh wavelength (Xu et al. 2015). The obtained results in this section also corroborate this notion.

Results and discussion

According to the objective of this study, the developed model (Sect. 2) was used to scrutinize the effect of foundation geometry and weight as well as the soil type on the train-induced vibrations in the building close to railway track (Fig. 1). To this end, considering the classification of seismic regulations (Engineers 2010), three different soil types (i.e., soft, medium and stiff) were considered. The dynamic properties of soil are mentioned in Table 2. Moreover, to

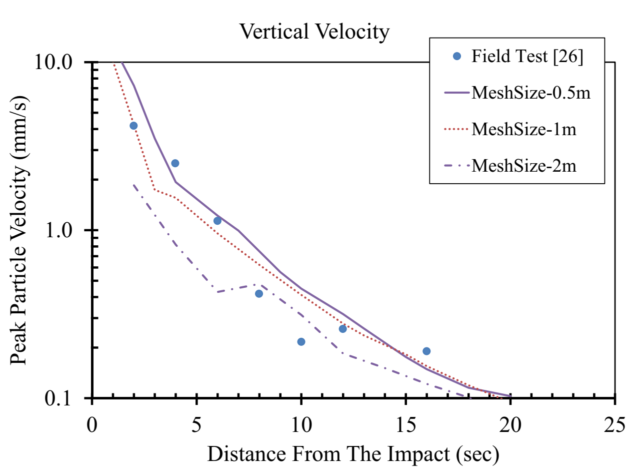


Fig. 4 Peak particle velocity versus the distance from the load application point

Table 2 Soil properties

Soil type	Shear wave velocity, m/s	Poisson's ratio, ν (–)	Mass density, $\rho\,(\mathrm{kg/m^3})$	Damping ratio, ξ (%)
1	400	0.3	1800	3
2	200			
3	100			
Embankment	250			

evaluate the geometry effect on the received vibration at the location of the building adjacent to the track, three common foundations, i.e., single, single-linked and orthogonal-strip footings, were considered (see Fig. 1). The properties of materials and elements of the structure are expressed in Table 3. It should be noted that in all analyses in this study, uncracked concrete is evaluated.

Frequency content evaluation is mainly performed in the standard spectrum of one-third octave band. Additionally, as the human body responds to the average amplitude of a signal, the root-mean-square (RMS) of signal (signal power quantity) is used in inspection of vibration level in different floors. To this end, the present research used the one-third octave band and RMS according to FTA regulation (Hanson et al. 2006) for the velocity term so as to study the vertical vibrations.

Effect of foundation geometry

In order to study the effect of foundation geometry on the vibrations received at the base of column and the amount of transferred vibrations to the floors, three different foundations, namely single, single-linked and orthogonal-strip footings (common foundation types in the residential and industrial buildings), were considered as shown in Fig. 5. In what follows in this section, the effect of foundation type on the frequency content of the structural response and vibration level of floors is demonstrated.

Table 3 Properties of structural elements

Structural members	Elastic modulus, E (GPa)	Poisson's ratio, ν (–)	Mass density, $\rho\,(\mathrm{kg/m^3})$	Damping ratio, ξ (%)
Single foundation	25	0.2	2500	3
Strip foundation				
Link elements				
Column				
Slab				

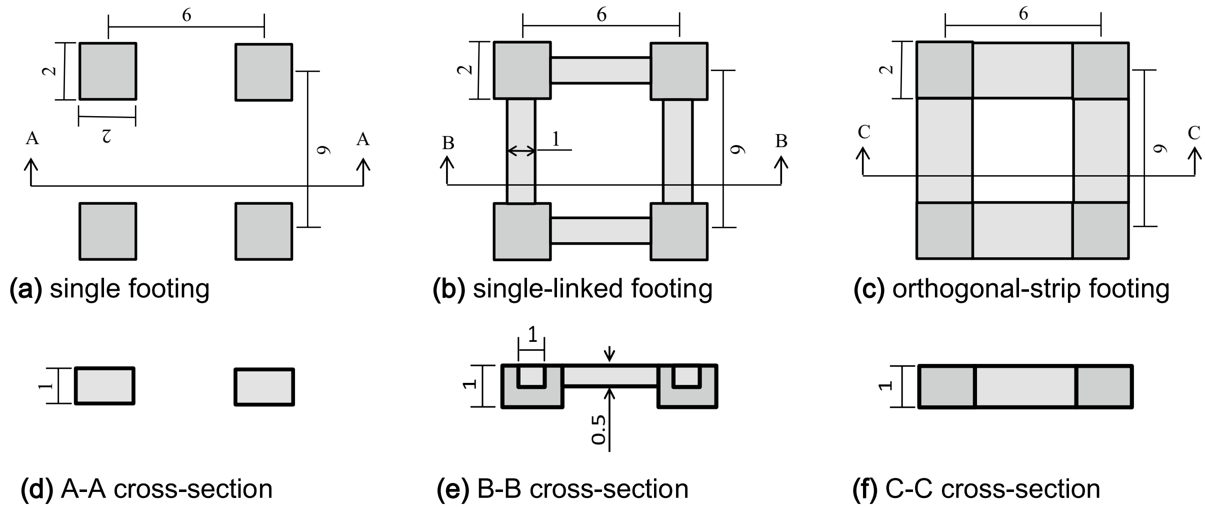


Fig. 5 Schematic representation of the three studied footings

The effect of foundation geometry on frequency content

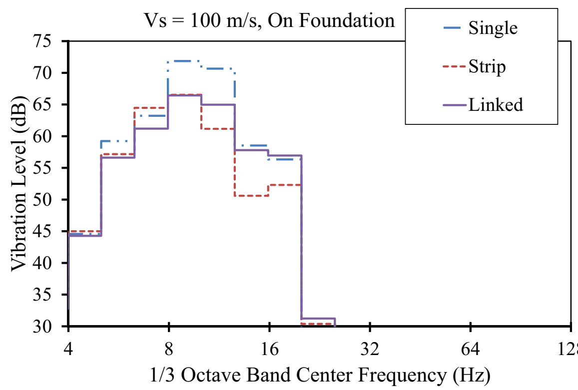
Figure 6 shows the vertical vibrations of the structure for three soil types 1–3 in one-third octave band. The left column in Fig. 6 depicts the vibration level at the column base. As observed, with increasing soil stiffness from type 3 (Fig. 6a) to type 1 (Fig. 6e), the peak of frequency response on the horizontal axis shifts to higher frequencies. This peak belongs to the frequency of rigid body motion on the soil in the vertical direction. In this study, this frequency is named as the eigenfrequency of the rigid body motion or simply EFRBM. The values of EFRBM for soil types 1–3 reside in the ranges of 24–31 Hz, 16–20 Hz and 8–10 Hz, respectively. Although the soil type has a profound impact on the EFRBM, the foundation geometry does not considerably affect that. The left column of Fig. 6 also shows that with increasing soil stiffness, the vibration level at the base of column decreases significantly. The maximum vibration level at the column base for the three footings has reduced from 70 dB in soil type 3 to 57 dB in soil type 2 and 45 dB in soil type 1.

In the right column of Fig. 6, the vertical velocity level at the middle point of the fourth floor's slab can be seen. In Fig. 6b, f, two peaks in the frequency response spectrum can be seen. One peak belongs to the EFRBM and the other peak the roof natural frequency, which is independent of the soil type and footing (Kuo et al. 2019). According to Fig. 7, the value of this frequency for the studied structure is obtained using the modal analysis in the range of 14–16 Hz. Hence, in the frequency response spectrum pertained to soil type 3 (Fig. 6b), the second peak indicates the slab natural frequency, whereas in soil type 1 (Fig. 6f), the first peak belongs to the slab. In other words, in soil type 3, the EFRBM is lower than the slab natural frequency, while being larger than that in soil type 1. It needs to note the natural frequency of the slab changes with the variation in material properties and dimensions of the slab and columns. According to Fig. 6d, in the frequency response diagram of the structure on soil type 2, only one peak can be observed unlike soil types 1 and 3. This is due to the proximity of EFRBM and slab natural frequency. This has augmented the vibration level in the fourth floor's slab; hence, vibration level is higher than soil type 3 contrary to expectation.

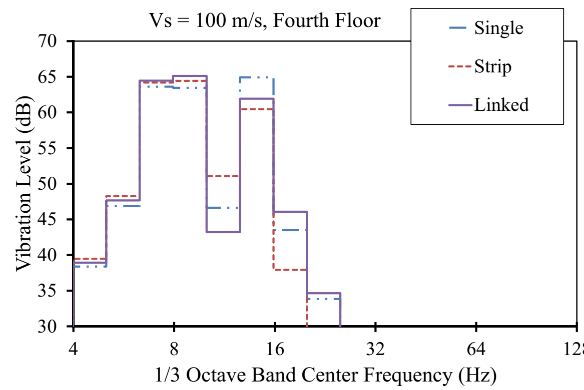
Figure 6 also depicts that the averages of the maximum vibration levels at the base of column and in the fourth slab (for the three footings) on soil types 3, 2 and 1 are, respectively, 70 dB and 65 dB, 57 dB and 67 dB, and 45 dB and 55 dB. For the structure on the soft soil, comparing Fig. 6a, b shows that the structural vibration level in the fourth slab is less than the vibrations on the footing. Since the EFRBM is lower than the roof natural frequency in this case, the soil has acted as a damper for the structure. With increasing soil stiffness, the EFRBM has increased and exceeded the roof natural frequency. Thus, the soil has failed to display its damping functionality. As a result, the vibration level of the floor on soil types 1 and 2 has increased relative to the vibration on the footing.

The effect of foundation geometry on vibration level

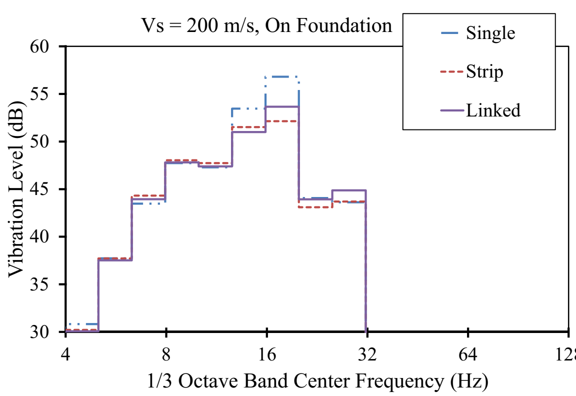
The vibration RMS of floors for the three considered footings on the three soil types is demonstrated in Fig. 8. The lowest vibration level in floors has occurred on the soft soil (Fig. 8a) in a structure with strip footing, while the maximum vibration amplitude on soil types 1 and 2 (Fig. 8b, c) has happened in a structure with strip footing compared with the other two footings. In other words, the strip footing on soil type 3 has caused the lowest vibration level in the



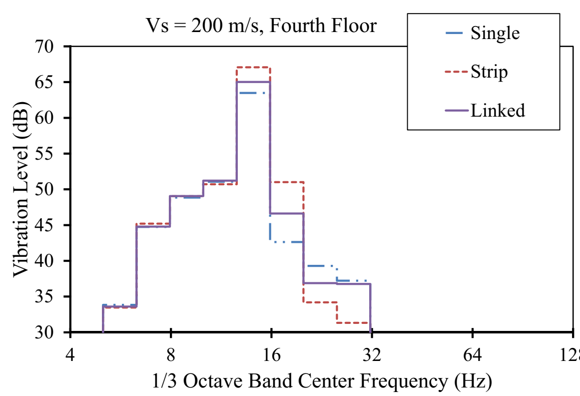
(a) Vertical velocity level (Lv) on the footing



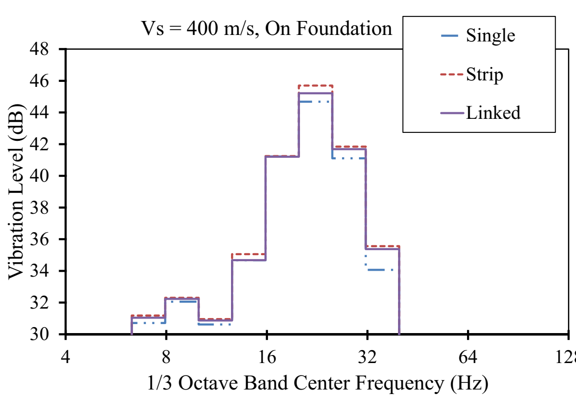
(b) Vertical velocity level (Lv) in the slab of 4th floor



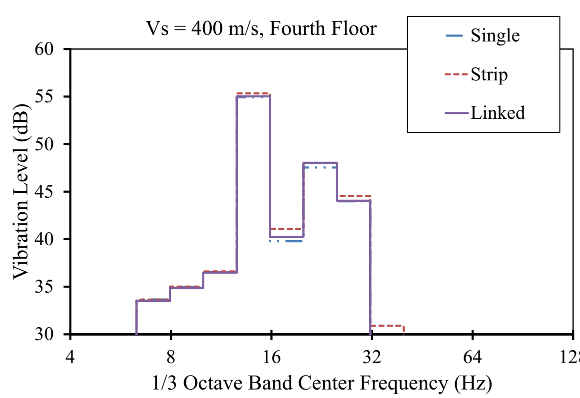
(c) Vertical velocity level (Lv) on the footing



(d) Vertical velocity level (Lv) in the slab of 4th floor



(e) Vertical velocity level (Lv) on the footing

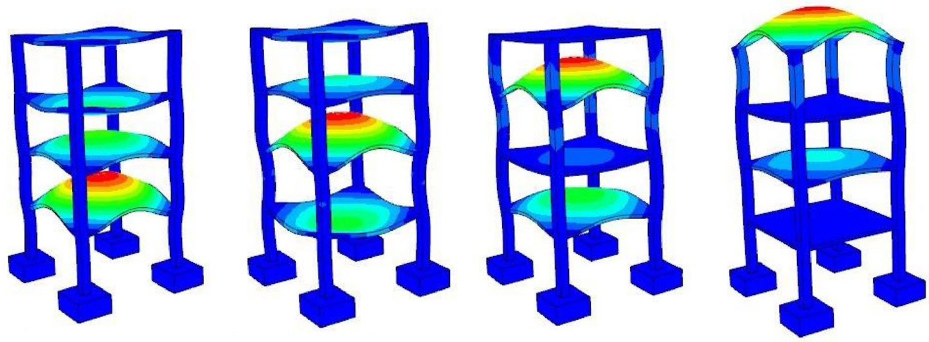


(f) Vertical velocity level (Lv) in the slab of 4th floor

Fig. 6 Vibration velocity level (L_V, $V_{ref} = 2.54 \times 10^{-8}$ m/s) on the foundation and in the fourth slab of structure on three soil types

floors and the highest vibration level on soil types 1 and 2 vis-à-vis the other two footings. This is possibly ascribed to the integrity of strip footing in contrast to the other two foundations. Actually, when the EFRBM is lower than the natural frequency of floors' slab, the performance of strip footing is better than the other two footings in terms of vibration reduction. However, when the EFRBM is higher than the natural frequency of slabs, the single footing is a

Fig. 7 Mode shapes and fundamental frequencies of floors' slab

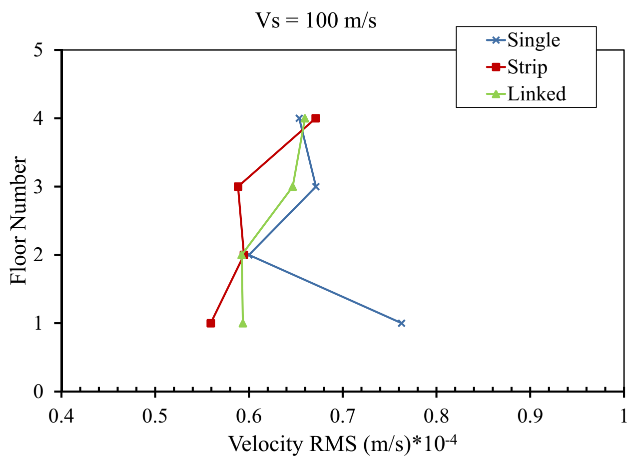


(a) Natural frequency of the vertical mode of first slab, 16.1 Hz.

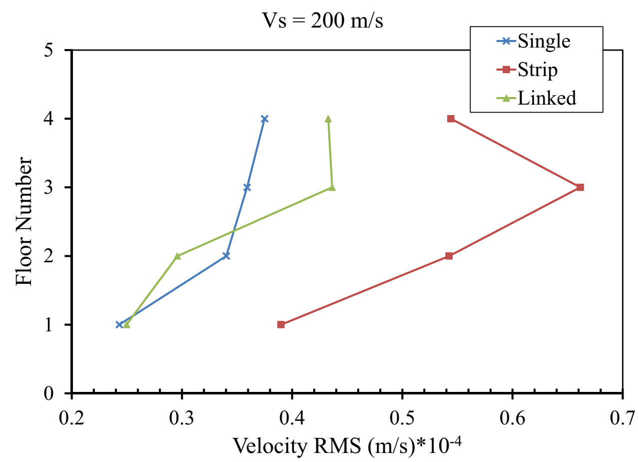
(b) Natural frequency of the vertical mode of second slab, 15.6 Hz.

(c) Natural frequency of the vertical mode of third slab, 15.2 Hz.

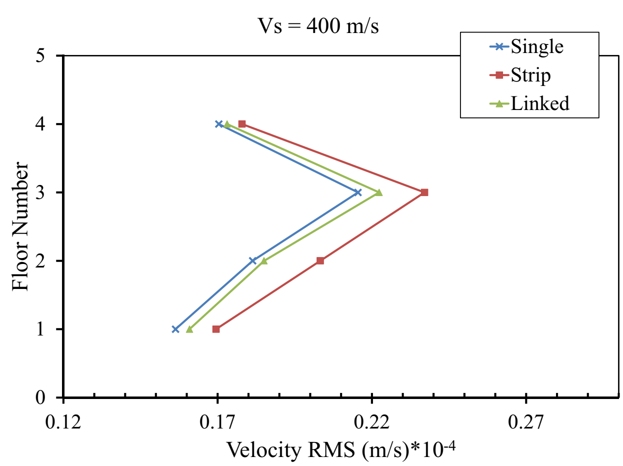
(d) Natural frequency of the vertical mode of fourth slab, 14 Hz.



(a) Vibration RMS of floors in the structure on soft soil.



(b) Vibration RMS of floors in the structure on moderate soil.



(c) Vibration RMS of floors in the structure on stiff soil.

Fig. 8 RMS of vertical velocity in the middle of floor's slab for a structure with three different footings on three different soil types better choice. Hence, the strip footing on the soft soil and the single footing in the moderate and stiff soils are better at reducing the transferred vibration to the floors.

In view of the literature regarding this subject, the general consensus is that the vibration level of floors has an irregular increasing trend with rising floor number (Xia et al. 2009). However, the findings of this study show that the trend of variations in the vibration level of floors is entirely dependent on the soil type, foundation geometry and dynamic characteristics of the structure (i.e., roof natural frequency) and can be either increasing or decreasing.

To quantitatively compare the performance of different foundations on the three soil types against the received vibrations, the ratio of the vibration RMS of floors with strip and single-linked footing to that with single footing is presented. Values smaller than 1 in this table indicate the better performance of described footing compared with the single footing, while values greater than 1 indicate the worse performance of considered foundation compared with the single foundation. Table 4 displays that on soil type 3, single-linked and strip footings evince a better performance in comparison with single footing. In the structure with strip and single-linked footings, the average of vibration RMS in floors has been 9% and 7% lower than in a structure with single footing. Accordingly, as mentioned previously, a more integrated footing on the soft soil presents a superior performance in reducing vertical vibrations. Table 4 also indicates that the single footing on soil types 1 and 2 (unlike soil type 3) has shown a better performance compared with the other two footings. The average of vibration RMS in floors on soil type 2 demonstrates that the strip and single-linked footings transfer 62% and 7% more vibration to the floors compared with the single footing. These values are equal to 9% and 2% on soil type 1. Hence, when the EFRBM is greater than the roof natural frequency, a more integrated footing results in a higher vibration RMS value in floors. These results show that unlike certain studies (Adam and Von Estorff 2005), integration of footing does not necessarily result in the vibration level reduction of the floors.

The effect of foundation weight

According to the concepts of soil–structure interaction, one expects that the foundation weight increase (structure weight increase) decreases EFRBM; hence, vibration level of the building in the proximity of railway track changes. In this regard, some studies have claimed that the increase in foundation weight reduces the vibration level in floors (Sanayei et al. 2011a, b). This notion was probed by increasing the weight of single and strip footings (introduced in Sect. 3.1) by considering three different values of $W_1 = W$, $W_2 = 2W$ and $W_3 = 4W$. As mentioned above, the concrete is considered without cracking.

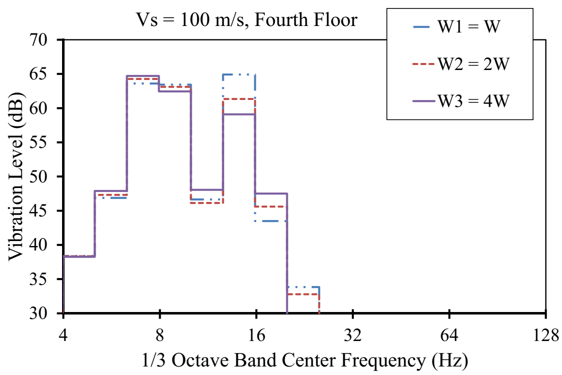
Effect of foundation weight on frequency response content

The response of fourth floor's slab for single footing (left column of Fig. 9) and strip footing (right column of Fig. 9) with varying foundation weight on the three soil types was gleaned in one-third octave band. As noted, although the foundation weight increase has not significantly changed the EFRBM, it has altered the vibration level in the natural frequency range of slab (14–16 Hz). Regarding soil type 3 (Fig. 9a, b) and soil type 1 (Fig. 9e, f), a heavier foundation has, respectively, caused a decrease and an increase in the vibration amplitude around the resonance frequency of the fourth slab. However, changing the foundation weight on soil type 2 has yielded a different trend in the variations in the response of structure's fourth slab with single and strip footings (Fig. 9c, d).

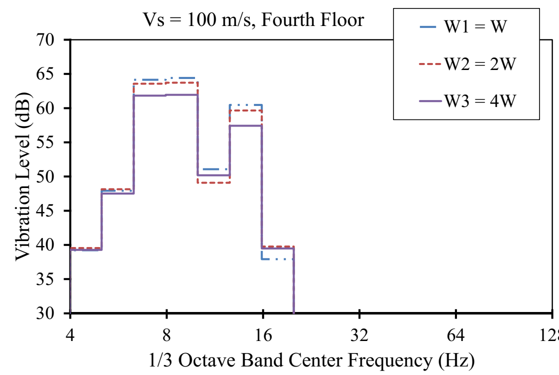
In other words, the increase in the weight of single footing has caused a small rise in the vibration level around the resonance frequency range of slab, whereas the increase in the weight of strip footing has decreased the vibration amplitude in the same range. As described earlier, the natural frequency of slab and EFRBM are quite close in soil type 2. Since the increase in the strip footing weight generates a greater reduction in EFRBM compared with the single footing, the EFRBM in soil type 2 for the strip footing has become lower than the roof natural frequency and has decreased the vibrations in the fourth floor.

Table 4 Ratio of vibration RMS in floors on three soil types

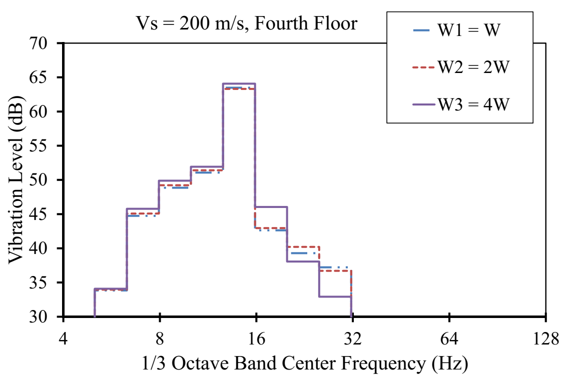
Soil type	RMS ratio	Floor number				Average
		1	2	3	4	
3	(Strip/single) foundation	0.73	0.99	0.88	1.03	0.91
	(Linked/single)	0.78	0.99	0.96	1.01	0.93
2	(Strip/single)	1.60	1.59	1.84	1.45	1.62
	(Linked/single)	1.03	0.87	1.21	1.15	1.07
1	(Strip/single)	1.08	1.12	1.10	1.04	1.09
	(Linked/single)	1.03	1.02	1.03	1.02	1.02



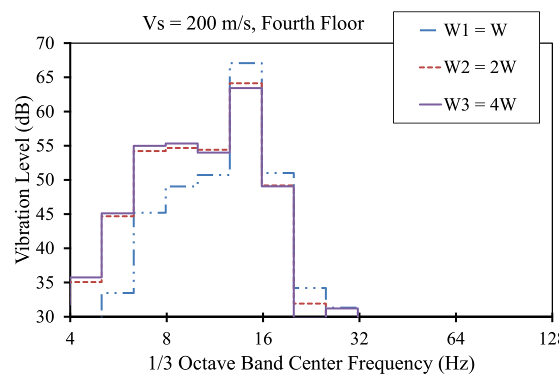
(a) Vertical velocity level (*Lv*) in the fourth floor of building with Single footing on the soil type 3.



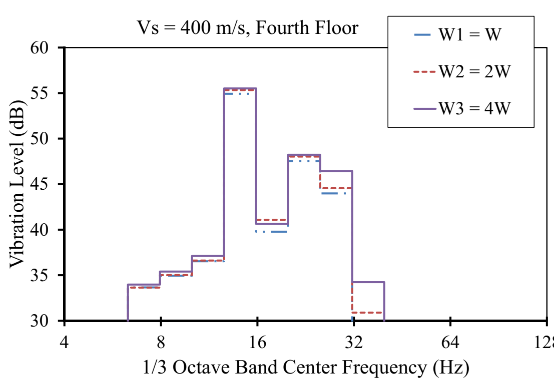
(b) Vertical velocity level (*Lv*) in the fourth floor of building with Strip footing on the soil type 3.



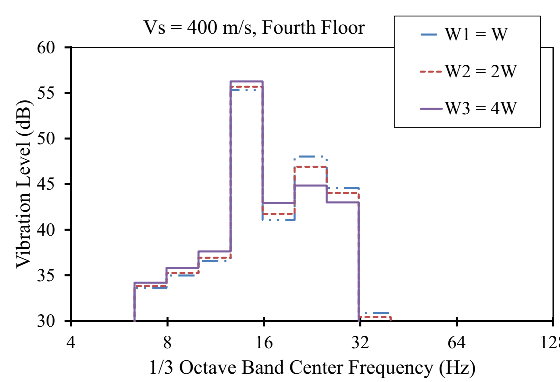
(c) Vertical velocity level (*Lv*) in the fourth floor of building with Single footing on the soil type 2.



(d) Vertical velocity level (*Lv*) in the fourth floor of building with Strip footing on the soil type 2.



(e) Vertical velocity level (*Lv*) in the fourth floor of building with Single footing on the soil type 1.



(f) Vertical velocity level (*Lv*) in the fourth floor of building with Strip footing on the soil type 1.

Fig. 9 Vertical velocity level (L_V, $V_{ref} = 2.54 \times 10^{-8}$ m/s) in the fourth slab of structure with single and strip footing on the three soil types

The effect of foundation weight on the vibration level

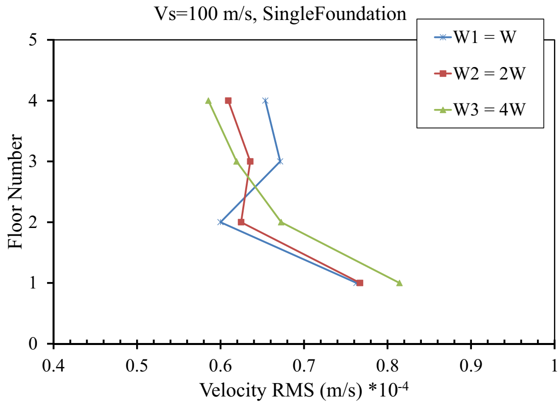
The vibration RMS of floors on the three soil types with varying foundation weight is drawn in Fig. 10 for a structure with single footing (left column of Fig. 10) and strip footing (right column of Fig. 10). Figure 10a shows that despite the reduction in the vibration RMS of third and fourth floors with increasing weight of single footing, an unexpected increase in vibration RMS can be seen in the first and second floors. This is caused by the nonintegrity of single footing against vertical vibrations. In contrast, the vibration RMS in all floors has displayed a decreasing trend with increasing strip footing weight on soil type 3 (Fig. 10b). In soil type 1 (Fig. 10e, f), with increasing weight of both foundations, the vibration RMS has increased in all floors. In fact, the high stiffness of soil type 1 (unlike soil type 3) results in an integrated performance from the single footing (similar to the strip footing) and makes its behavior predictable against vertical vibrations. In soil type 2 according to Fig. 10c, the increase in the single footing weight has ended in an increase in the vibration RMS of floors with an irregular trend. Increasing strip weight, however, causes the vibration RMS to decrease in a regular pattern (Fig. 10d). As explained in the previous section, this is attributed to the increase in the weight of strip footing that results in a greater reduction in EFRBM compared with the single footing.

The findings of this article show that unlike some studies (Sanayei et al. 2011a, b), the increase in foundation weight does not always end in reduced vibration levels of floors. In other words, the alteration in the vibration level of floors as a result of altering the foundation weight is completely dependent on the foundation geometry, soil type and natural frequency of floors' slab.

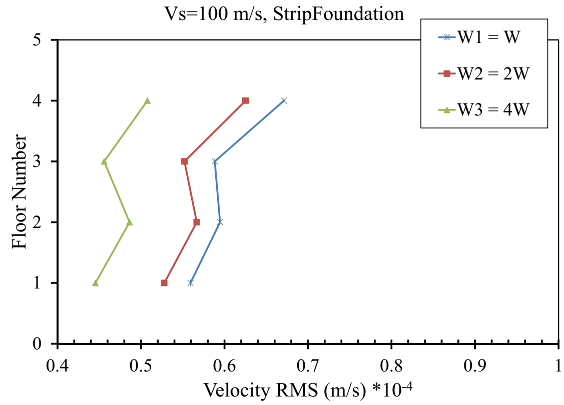
Conclusion

This paper investigated the effect of (geometry and weight of) foundation placed on different soils on the amount of induced vibrations in a building close to a railway track. To this end, a 3D finite/infinite element model including the soil, structure and track was developed. The accuracy of the numerical model was demonstrated using field test (response of infinite soil medium to impact loading). Next, to achieve the study goals, a four-story one-span concrete frame on three common foundations including single, single-linked and strip footings with different weights was considered on three soil types 1, 2 and 3 (stiff, moderate and soft). The moving load due to the passage of wagon with a velocity of 25 m/s on the railway embankment was also applied. The structural response was obtained at the base of column and in the middle of floors' slab. In the following, a summary of analyses on the results is proffered:

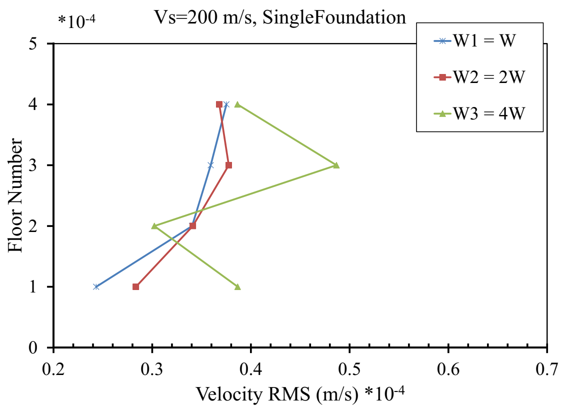
1. A peak can be observed in the frequency response spectrum of column base. This peak was named the eigenfrequency of rigid body motion, abbreviated as EFRBM. With increasing soil stiffness from type 3 to 1, the value of EFRBM shifts toward higher frequencies. In addition, regardless of footing type, the vibration level at the base of column decreases with increasing soil stiffness.
2. The natural frequency of floors' slab is independent of the type of footing and soil; however, it depends on material properties and dimensions of the structure; it is located in the range of 14–16 Hz. The value of EFRBM in soil type 3 is lower than the slab natural frequency, while being larger than that in soil type 1. Hence, for the structure placed on the soft soil, the soil acts as a damper and the vibration level in the building, regardless of the footing type, is lower than that on the foundation. Unlike the soft soil, the roof vibration level in the moderate and stiff soils has increased vis-à-vis the vibration level on the foundation. In soil type 2, as the EFRBM is close to the slab natural frequency, the slab vibration level has intensified and reached the highest value among the three soil types.
3. A heavier footing (irrespective of the footing type) on soil type 3 and soil type 1 has resulted in, respectively, the decrease and increase in vibration amplitude in the structure. This finding indicates that unlike the existing belief, the increase in the footing weight does not always end in a reduced vibration level of floors. In fact, the change in the vibration level of floors with increasing footing weight is completely dependent on the footing geometry, soil type and natural frequency of floors' slab. In general, the farther the EFRBM from the resonance frequency of floors' slab, the lower the vibration amplitude in the floors.
4. When the EFRBM is lower than the natural frequency of floors' slab (soft soil), the performance of strip footing is better than the other two footings due the decrease in the vibration level of floors. Also, when the EFRBM is higher than the natural frequency of the floors' slab (medium or stiff soil), the performance of single footing seems more appropriate. This is due to the integration of strip footing compared with the other two foundations.
5. Due to the nonintegrity of the single footing, as its weight on soil type 3 increases, the variation in vibration RMS has been irregular in floors (increasing or decreasing). However, with increasing weight of the strip footing on soil type 3, vibration RMS has decreased



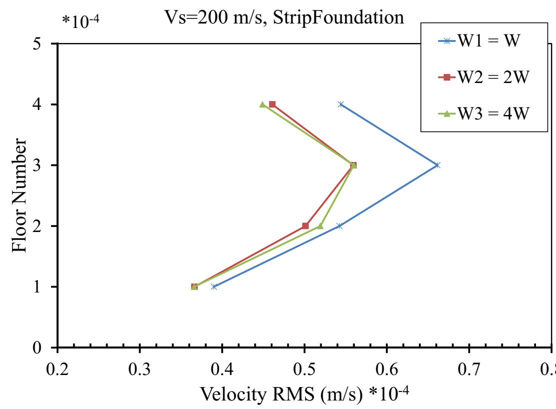
(a) Vibration RMS of floors in the building with single footing on the soil type 3.



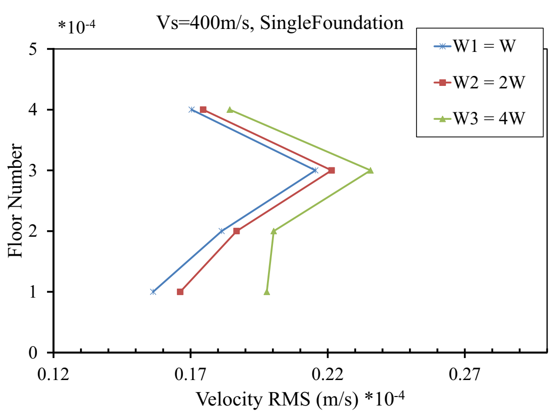
(b) Vibration RMS of floors in the building with strip footing on the soil type 3.



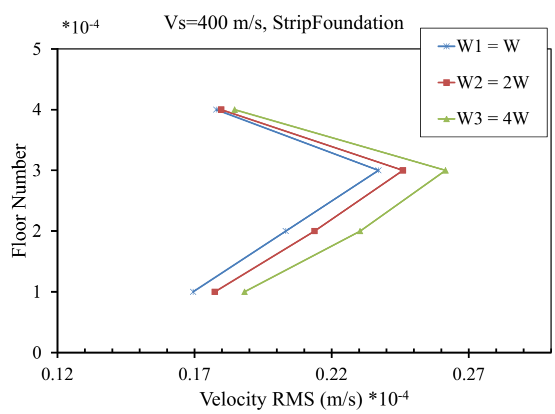
(c) Vibration RMS of floors in the building with single footing on the soil type 2.



(d) Vibration RMS of floors in the building with strip footing on the soil type 2.



(e) Vibration RMS of floors in the building with single footing on the soil type 1.



(f) Vibration RMS of floors in the building with strip footing on the soil type 1.

Fig. 10 Vibration RMS of floors in the structure with single and strip footing on the three soil types in all floors as anticipated. With regard to soil type 1, an increase in the weight of both foundations (single and strip) has ended in the increase in vibration RMS in all floors.

6. Unlike some prior studies, the change in the vibration level of floors (as the floor number rises) is thoroughly dependent on the soil type, foundation geometry and dynamic characteristics of the structure (i.e., roof natural frequency), having an increasing or decreasing trend.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Adam, M., & Chouw, N. (2001). Reduction of footing response to man-made excitations by using a wave impeding barrier. *Journal of Applied Mechanics, 4,* 423–431.

Adam, M., & Von Estorff, O. (2005). Reduction of train-induced building vibrations by using open and filled trenches. *Computers & Structures, 83*(1), 11–24.

Addou, F. Y., Meradjah, M., Bousahla, A. A., Benachour, A., Bourada, F., Tounsi, A., et al. (2019). Influences of porosity on dynamic response of FG plates resting on Winkler/Pasternak/Kerr foundation using quasi 3D HSDT. *Computers and Concrete, 24,* 347–367.

Alimirzaei, S., Mohammadimehr, M., & Tounsi, A. (2019). Nonlinear analysis of viscoelastic micro-composite beam with geometrical imperfection using FEM: MSGT electro-magneto-elastic bending, buckling and vibration solutions. *Structural Engineering and Mechanics, 71,* 485–502.

Auersch, L. (2008). Dynamic stiffness of foundations on inhomogeneous soils for a realistic prediction of vertical building resonance. *Journal of Geotechnical and Geoenvironmental Engineering, 134*(3), 328–340.

Balendra, T., Chua, K. H., Lo, K. W., & Lee, S. L. (1989). Steady-state vibration of subway-soil-building system. *Journal of Engineering Mechanics, 115*(1), 145–162.

Bellal, M., Hebali, H., Heireche, H., Bousahla, A. A., Tounsi, A., Bourada, F., et al. (2020). Buckling behavior of a single-layered graphene sheet resting on viscoelastic medium via nonlocal four-unknown integral model. *Steel and Composite Structures, 34,* 643–655.

Bo, Q., Ali, L., & Irini, D. M. (2014). Numerical study of wave barrier and its optimization design. *Finite Elements in Analysis and Design, 84,* 1–13.

Boukhlif, Z., Bouremana, M., Bourada, F., Bousahla, A. A., Bourada, M., Tounsi, A., et al. (2019). A simple quasi-3D HSDT for the dynamics analysis of FG thick plate on elastic foundation. *Steel and Composite Structures, 31,* 503–516.

Celebi, E., & Göktepe, F. (2012). Non-linear 2-D FE analysis for the assessment of isolation performance of wave impeding barrier in reduction of railway-induced surface waves. *Construction and Building Materials, 36,* 1–13.

Chaabane, L. A., Bourada, F., Sekkal, M., Zerouati, S., Zaoui, F. Z., Tounsi, A., et al. (2019). Analytical study of bending and free vibration responses of functionally graded beams resting on elastic foundation. *Structural Engineering and Mechanics, 71,* 185–196.

Chopra, A. K. (1995). *Dynamics of structures: Theory and applications to earthquake engineering*. Prentice: Prentice-Hall Inc.

Dassault Systèmes, SIMULIA. (2014). *ABAQUS 6.14. Theory and User's Manuals.*

Dere, Y. (2016). Effectiveness of the floating slab track system constructed at Konya Light Rail. *Measurement, 89,* 48–54.

Engineers, ASOC. (2010). Minimum design loads for buildings and other structures. *ASCE, 7,* 10.

Fernández Ruiz, J., Alves Costa, P., Calçada, R., Medina Rodríguez, L. E., & Colaço, A. (2017). Study of ground vibrations induced by railway traffic in a 3D FEM model formulated in the time domain. *Experimental Validation. Structure and Infrastructure Engineering, 13*(5), 652–664.

François, S., Pyl, L., Masoumi, H. R., & Degrande, G. (2007). The influence of dynamic soil-structure interaction on traffic induced vibrations in buildings. *Soil Dynamics and Earthquake Engineering, 7,* 655–674.

Hall, L. (2003). Simulations and analyses of train-induced ground vibrations in finite element models. *Soil Dynamics and Earthquake Engineering, 23*(5), 403–413.

Hanson, C. E., Towers, D. A., & Meister, L. D. (2006). *Transit noise and vibration impact assessment*, No. FTA-VA-90-1003-06.

Heckl, M., Hauck, G., & Wettschureck, R. (1996). Structure-borne sound and vibration from rail traffic. *Journal of Sound and Vibration, 193*(1), 175–184.

Hui, C. K., & Ng, C. F. (2009). The effects of floating slab bending resonances on the vibration isolation of rail viaduct. *Applied Acoustics, 70*(6), 830–844.

Ju, S. H. (2007). Finite element analysis of structure-borne vibration from high-speed train. *Soil Dynamics and Earthquake Engineering, 27*(3), 259–273.

Kaddari, M., Kaci, A., Bousahla, A. A., Tounsi, A., Bourada, F., Tounsi, A., et al. (2020). A study on the structural behaviour of functionally graded porous plates on elastic foundation using a new quasi-3D model: bending and free vibration analysis. *Computers and Concrete, 25,* 37–57.

Karami, B., Janghorban, M., & Tounsi, A. (2019). Wave propagation of functionally graded anisotropic nanoplates resting on Winkler–Pasternak foundation. *Structural Engineering and Mechanics, 70,* 55–66.

Kattis, S. E., Polyzos, D., & Beskos, D. E. (1999). Vibration isolation by a row of piles using a 3-D frequency domain BEM. *International Journal for Numerical Methods in Engineering, 46*(5), 713–728.

Kouroussis, G., Conti, C., & Verlinden, O. (2013). Investigating the influence of soil properties on railway traffic vibration using a numerical model. *Vehicle System Dynamics, 51*(3), 421–442.

Kouroussis, G., Van Parys, L., Conti, C., & Verlinden, O. (2014). Using three-dimensional finite element analysis in time domain to model railway-induced ground vibrations. *Advances in Engineering Software, 70,* 63–76.

Kouroussis, G., Verlinden, O., & Conti, C. (2009). Ground propagation of vibrations from railway vehicles using a finite/infinite-element model of the soil. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 223*(4), 405–413.

Kraśkiewicz, C., Lipko, C., Płudowska, M., Oleksiewicz, W., & Zbiciak, A. (2016). Static and dynamic characteristics of resilient mats for vibration isolation of railway tracks. *Procedia Engineering, 153,* 317–324.

Krylov, V. V. (1995). Generation of ground vibrations by superfast trains. *Applied Acoustic, 44*(2), 149–164.

Kuo, K. A., Papadopoulos, M., Lombaert, G., & Degrande, G. (2019). The coupling loss of a building subject to railway induced vibrations: numerical modelling and experimental measurements. *Journal of Sound and Vibration, 442,* 459–481.

Lei, X., & Jiang, C. (2016). Analysis of vibration reduction effect of steel spring floating slab track with finite elements. *Journal of Vibration and Control, 22*(6), 1462–1471.

Mahmoudi, A., Benyoucef, S., Tounsi, A., Benachour, A., Bedia, E. A. A., & Mahmoud, S. R. (2019). A refined quasi-3D shear deformation theory for thermo-mechanical behavior of functionally graded sandwich plates on elastic foundations. *Journal of Sandwich Structures and Materials, 21,* 1906–1929.

Perrone, D., Brunesi, E., Filiatrault, A., & Nascimbene, R. (2020). Probabilistic estimation of floor response spectra in masonry infilled reinforced concrete building portfolio. *Engineering Structures, 202,* 109842.

Persson, P., Kent, P., & Sandberg, G. (2016). Numerical study on reducing building vibrations by foundation improvement. *Engineering Structures, 124,* 361–375.

Sanayei, M., Maurya, P., Zhao, N., & Moore, J. A. (2012). Impedance modeling: An efficient modeling method for prediction of building floor vibrations. In *Structures Congress* (pp. 886–897).

Sanayei, M., Zhao, N., Maurya, P., Moore, J. A., Zapfe, J. A., & Hines, E. M. (2011a). Impedance modeling for prediction of train induced floor vibrations. In *Structures Congress* (pp. 371–382).

Sanayei, M., Zhao, N., Maurya, P., Moore, J. A., Zapfe, J. A., & Hines, E. M. (2011b). Prediction and mitigation of building floor vibrations using a blocking floor. *Journal of Structural Engineering, 138*(10), 1181–1192.

Surana, M., Pisode, M., Singh, Y., & Lang, D. H. (2018). Effect of URM infills on inelastic floor response of RC frame buildings. *Engineering Structures, 175,* 861–878.

Talbot, J. P., & Hunt, H. E. M. (2003). A computationally efficient piled-foundation model for studying the effects of ground-borne vibration on buildings. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 217*(9), 975–989.

Thompson, D. J., Jiang, J., Toward, M. G. R., Hussein, M. F. M., Ntotsios, E., Dijckmans, A., et al. (2016). Reducing railway-induced ground-borne vibration by using open trenches and soft-filled barriers. *Soil Dynamics and Earthquake Engineering, 88,* 45–59.

Xia, H., Chen, J., Wei, P., Xia, C., De Roeck, G., & Degrande, G. (2009). Experimental investigation of railway train-induced vibrations of surrounding ground and a nearby multi-story building. *Earthquake Engineering and Engineering Vibration, 8*(1), 137–148.

Xu, Q., Xiao, Z., Liu, T., Lou, P., & Song, X. (2015). Comparison of 2D and 3D prediction models for environmental vibration induced by underground railway with two types of tracks. *Computers and Geotechnics, 68,* 169–183.

Yang, Y. B., Ge, P., Li, Q., Liang, X., & Wu, Y. (2018). 2.5 D vibration of railway-side buildings mitigated by open or infilled trenches considering rail irregularity. *Soil Dynamics and Earthquake Engineering, 106,* 204–214.

Zhu, S., Yang, J., Cai, C., Pan, Z., & Zhai, W. (2017). Application of dynamic vibration absorbers in designing a vibration isolation track at low-frequency domain. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 231*(5), 546–557.

Zienkiewicz, O. C., Emson, C., & Bettess, P. (1983). A novel boundary infinite element. *International Journal for Numerical Methods in Engineering, 19*(3), 393–404.