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THE SIGNIFICANCE OF SOIL-STRUCTURE INTERACTION FOR THE BASE-ISOLATION OF BUILDINGS AGAINST GROUND-BORNE VIBRATION

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Abstract: Base isolation is well known within the seismic community as a means of protecting buildings from earthquake damage. A related technique, also known as base isolation, is known to the noise and vibration community as a means of limiting the disturbance in buildings caused by ground-borne vibration, such as that caused by busy roads or railways. Despite extensive use of the technique, there remains a lack of understanding over certain aspects of base-isolation performance.

This paper considers current practice in base-isolation design against ground-borne vibration, and presents some initial work that highlights the significance of soil-structure interaction when assessing isolation performance.

Introduction

Ground-borne vibrations in civil structures are increasingly significant for three reasons in particular:

- in general, modern structures are increasingly susceptible to vibration as designs become more efficient – whilst strength is assured via standard design procedures, adequate mass, stiffness and damping may not be (see Table 1);

- the expansion of urban railway networks – particularly tram networks and underground railways – has led to a steady growth in the number of locations affected by ground-borne vibration; and

- noise and vibration limits are now commonplace as part of the wider serviceability requirements for a typical project.

Table 1. Traditional vs modern building design with regard to vibration sensitivity

Traditional	Modern
Massive and stiff (masonry, bulk concrete)	Light-weight and flexible (pre-stressed concrete, steel frames, strength optimised design)
Short (high frequency) spans (by necessity)	Long (low frequency) spans (by design, e.g. open-plan offices)
Heavily damped (many joints / frictional interfaces)	Lightly damped (fewer joints, glazed facades, open-plan 'minimalist' interiors)

As suggested above, it is roads and railways that are the most significant sources of ground-borne vibration, with the potential to cause disturbance to large numbers of people many times a day. Typical vibration levels lie in the range from 0.1 to 1.0 mm/s. Such levels are significantly below those at which even light damage, such as the cracking of plaster, may be expected. Nevertheless, the daily disturbance caused to building occupants and the disruption caused in specialist buildings, such as hospitals and research facilities, can have significant social and economic consequences.

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Disturbance may be caused in two ways: by unacceptable levels of structural vibration; and/or by re-radiated noise, which radiates in the audible frequency range from vibrating elements of the building. In the case of ground-borne vibration due to railways, both structural vibration and re-radiated noise tend to be most noticeable in the frequency range from approximately 25 to 250 Hz, with the latter manifesting as a low-frequency ‘rumble’.

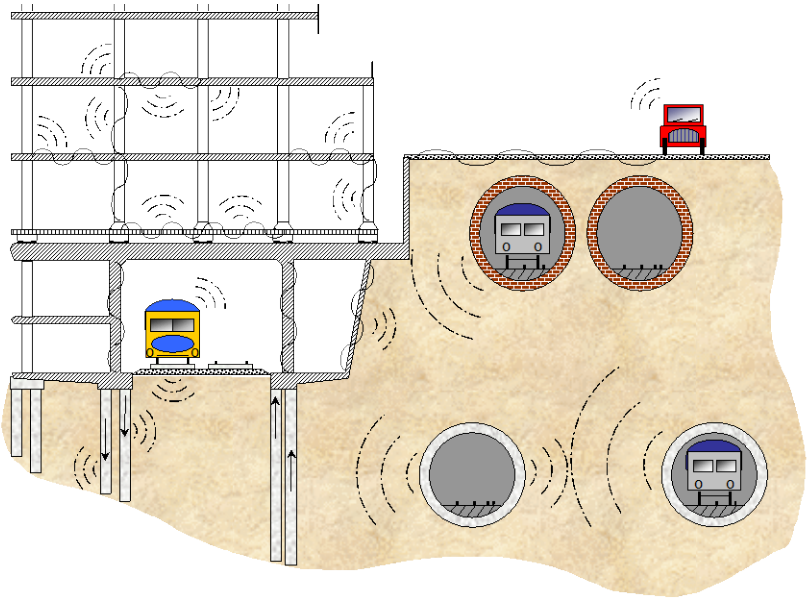

Figure 1. The problem of ground-borne vibration

Base Isolation against Ground-borne Vibration

Base isolation is well established in the noise and vibration community as one of the most effective techniques for limiting the disturbance in buildings caused by ground-borne vibration. Since the first examples were built in the 1960s [1], base-isolated buildings have become commonplace in our major cities, in particular, where high-specification buildings are built in close proximity to railways. Examples exist across a wide range of buildings, from residential to commercial, and include specialist buildings such as cinemas [2], hospitals [3] and broadcasting studios [4].

In all cases, the objective is to reduce vibration transmission into the building by incorporating vibration isolation bearings within the primary structure. For modern buildings, this usually involves inserting either elastomeric bearings or steel helical springs between the base of the primary structure and the foundation. This is a similar technique to that used to protect buildings from earthquakes [5], although both the governing theory and the practical implementation differ in detail due to the nature of the ground motion (see Table 2).

Table 2. Some differences between the seismic and ground-borne vibration response of buildings

Seismic	Ground-borne Vibration
Often dominated by a single, low-frequency global vibration mode	Comprises a combination of many, higher vibration modes
Large-amplitude, non-linear transient response	Low-amplitude, steady-state response
Predominantly horizontal input motion, acting uniformly across the foundation	Multi-axial input motion, varying in amplitude and phase across the foundation

For both earthquakes and ground-borne vibration, the principles of base-isolation are often introduced by reference to the single-degree-of-freedom (SDOF) model (see Figure 2). The building is represented as a rigid mass supported on some form of spring-damper element to represent the isolation bearing; ground motion is represented by an imposed displacement amplitude X at the base; and the resulting motion of the building is described by the displacement amplitude of the mass Y. The precise expression describing the variation in the ratio Y/X with frequency depends on the nature of the damping element but the essential features are the same in all cases: (1) the bearings act to amplify any low-frequency vibration, and this is greatest at the isolation frequency; (2) the bearings are only effective for frequencies greater than $\sqrt{2}$ times the isolation frequency, above which the isolation improves with frequency; and (3) damping acts to limit the resonance amplitude but reduces the isolation performance.

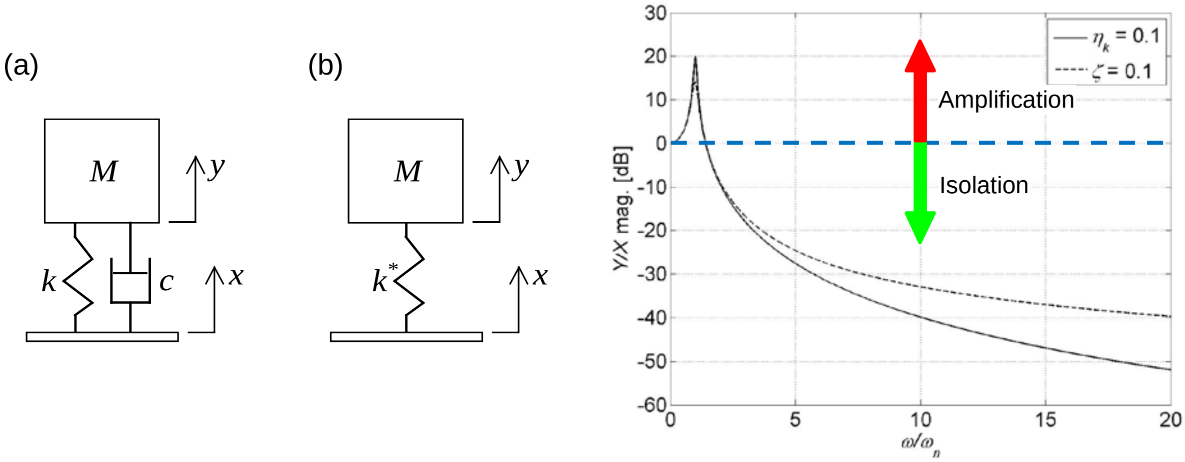

Figure 2. The SDOF model of a base-isolated building, where the rigid mass *M* represents the building and the linear spring *k* represents the isolation bearing. Damping may be accounted for by (a) a viscous dashpot or (b) a complex (hysteretic) spring stiffness

These features of the SDOF model may suggest some guiding design principles but the model is far too simplistic for making any useful predictions of isolation performance. For the latter, more comprehensive models are required.

Analysis of Base-Isolated Buildings

No standards currently exist specifically governing the design of base-isolated buildings. In practice, designs are usually based on past experience and some form of analytical model. For practicing engineers, a common approach is to use a commercial finite-element code to model the building, since these are readily available and often already employed in the structural (static) design. Although convenient, great care is required to extend such models, and this is particularly so in the area of soil-structure interaction (SSI).

SSI has been known for some time as being significant in the seismic response of buildings but its significance with regard to ground-borne vibration has only begun to be recognised relatively recently with the development of more comprehensive models [6–10]. Furthermore, it is far from clear how the effects of SSI should be accounted for efficiently in the design of base-isolated buildings. The ultimate aim of the work presented here is to develop a fundamental understanding of SSI by returning to simplified models, such that appropriate design methods may be developed.

There are several possible measures of performance when considering the benefits of base isolation in a design context [6, 7]. A common approach for new buildings is to assess the absolute performance of the proposed isolation using ‘green-field’ site predictions. In such cases, advantage is taken of the opportunity to measure the existing vibration levels at the proposed site, prior to any construction work, before applying these levels to the base of a building model in an attempt to predict the final vibration levels in the completed building. This is often done without any reference to the ground or building foundation – a fundamentally flawed approach because it fails to account for some important effects of SSI. There are two primary effects: (1) the soil provides significant radiation damping to the building structure; and (2) the coupling of a structure to the soil acts to modify the free-field vibration. The latter, which has been termed the 'added-mass' effect, is the primary subject of this paper. Importantly, both effects are such that ignoring them tends to over-predict vibration levels in the completed building, perhaps even to the extent that isolation may not be required in practice.

The Added-Mass Effect

Consider the model shown in Figure 3, which combines a SDOF mass-spring representation of the isolated building, with a foundation model based on a single surface footing.

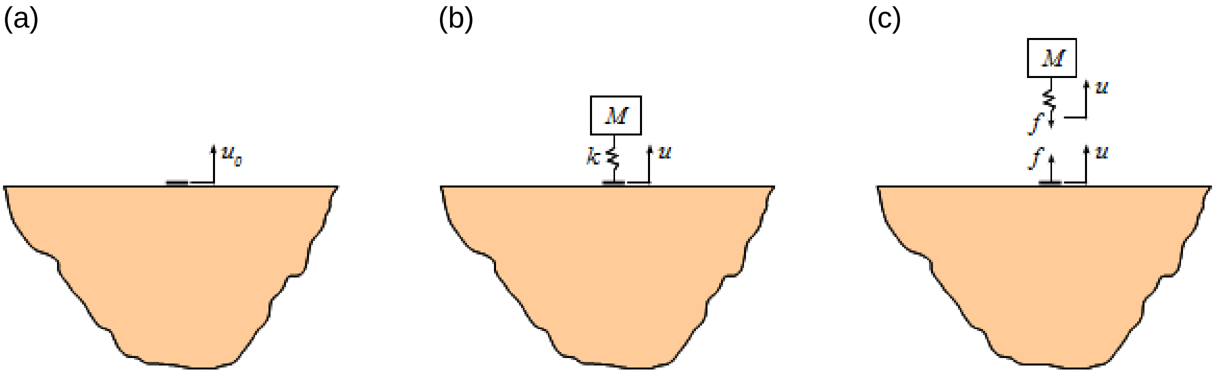

Figure 3. A SDOF building model of a base-isolated building. A SDOF system is founded on a rigid, massless, footing bonded to the surface of an elastic half-space. Prior to construction of the building (a) the footing moves with amplitude u_0 ; following construction (b) this becomes u

Assume that, prior to the construction of the building, a ground vibration field exists which causes the footing to move vertically with a harmonic displacement amplitude u_0. Following the construction of the building, the footing amplitude becomes u, which may be expressed as the superposition of the original amplitude and that due to the force f applied by the SDOF system:

$$u = H_f f + u_0 \tag{1}$$

where H_f is the driving-point displacement frequency-response function (FRF) of the footing. The fundamental assumption here is that, whilst the coupling (SSI) between the building and the ground may be strong, that between the building and the vibration source is weak. A recent numerical investigation [9] supports this, provided the distance between the source (a railway tunnel) and the building is larger than the dilatational wavelength in the soil.

Equilibrium of forces ensures that an equal but opposite force acts on the base of the SDOF system, and compatibility of displacements ensures that this also moves with amplitude u (see Figure 3(c)). Therefore, for the building:

$$u = -H_b f \tag{2}$$

where H_b is the displacement FRF of the building. The latter takes the familiar form:

$$H_b = \frac{1-(\omega_n/\omega)^2}{k} \tag{3}$$

where $\omega_n = \sqrt{k/M}$ is equivalent to the isolation frequency of the building in rad/s and ω is the frequency of excitation.

Eliminating the force f from Equations 1 and 2 enables the final footing amplitude to be calculated:

$$u = \left(\frac{H_b}{H_b + H_f} \right) u_0 \tag{4}$$

Equation 4 suggests why ignoring SSI may be problematic: in general $u \neq u_0$. The ratio u/u_0 only approaches unity, that is, the construction of the building has negligible effect on the response of the footing, if $H_b >> H_f$. This is equivalent to saying that the dynamic stiffness of the isolated building – which is the inverse of the displacement FRF – must be much less than that of the foundation. In such cases, green-field site measurements may indeed be applied directly to the base of a building model but this is not a valid approach in general.

A Mass-Spring Model

Figure 4 illustrates this effect by plotting u/u_0 against frequency for the cases of a 5 Hz and 15 Hz isolation frequency (representing the typical range of practical isolation frequencies) and an 'infinitely stiff' bearing corresponding to an unisolated building. Here, the foundation is modelled as a rigid massless footing bonded to the surface of a linear-elastic homogeneous half-space. The calculation of the footing FRF H_f is achieved with the aid of the boundary-element method, using a similar approach to Wong and Luco [11] but based on Green's functions calculated using the ElastoDynamics Toolbox [12]. The nominal parameter values used are: mass of building = 10^5 kg; shear modulus of soil = 200 MPa, with a shear wave speed of 316 m/s; footing radius = 0.5 m; and damping loss factors of 0.05 assigned to both the isolation bearing and the half-space.

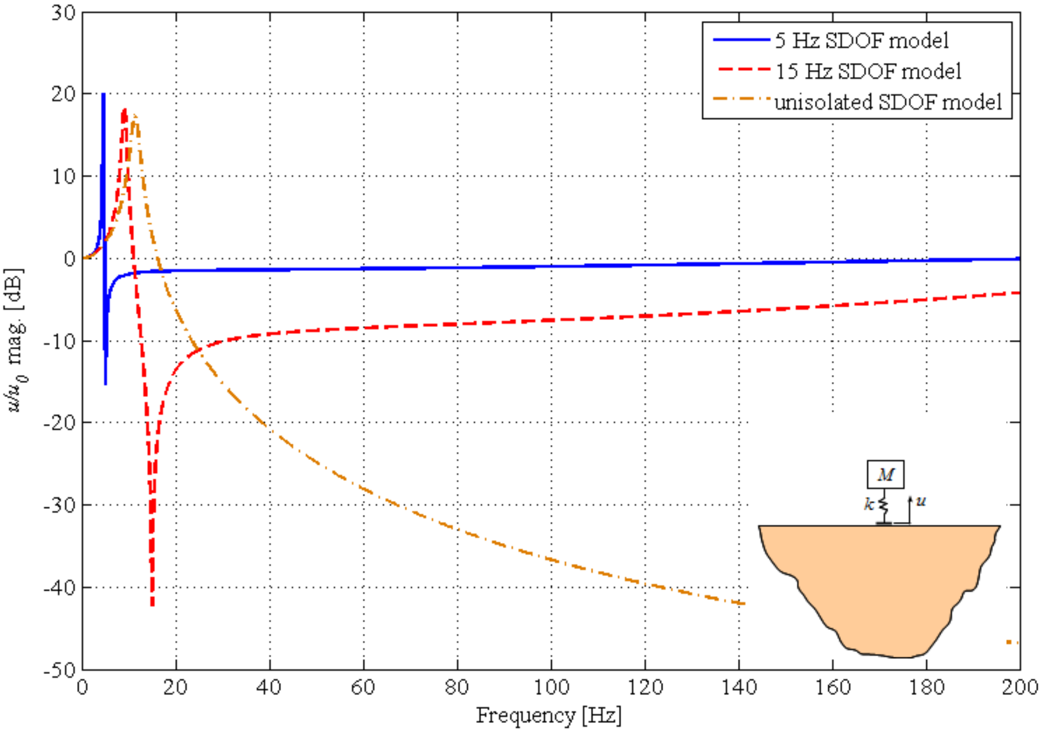

Figure 4. Soil-structure interaction of a base-isolated building as predicted by a SDOF building model founded on a surface footing. The ratio of the final footing amplitude u to that prior to the construction of the building u_0 is shown for different isolation frequencies

At low frequencies, two resonances dominate the behaviour of the model. The resonance of the SDOF system on its foundation occurs first, leading to amplified 'post-construction' vibration levels, followed by the resonance of the mass on the spring, at which the high dynamic stiffness of the SDOF system constrains the foundation, resulting in the anti-resonances in the curves. At higher frequencies, the dynamic stiffness of the SDOF system tends towards the static stiffness of the spring and, since this is much lower than the dynamic stiffness of the footing, the effect of the SDOF system becomes smaller. It is clear from these results that $u \neq u_0$.

A Column Model

It is instructive to replace the rigid-mass representation of the building with an elastic column of height *L*, cross-sectional area *A*, Young's modulus *E* and density ρ. In this case, Equation 3 becomes [13]:

$$H_b = \frac{1}{k} + \frac{1}{EA\lambda}\left(\frac{e^{\lambda L} + e^{-\lambda L}}{e^{\lambda L} - e^{-\lambda L}}\right) \tag{5}$$

where $\lambda = i\omega\sqrt{\rho/E}$.

With this new form of FRF describing the building, Equation 4 yields the results plotted in Figure 5. The parameter values for the spring, footing and half-space remain the same as before while those of the column are as follows: $L = 30$ m; $E = 10$ GPa, with a nominal damping loss factor of 0.01; $\rho = 2400$ kg/m^3, representative of concrete; and $A = 1.39$ m^2, such that the overall mass of the column is the same as that of the SDOF model.

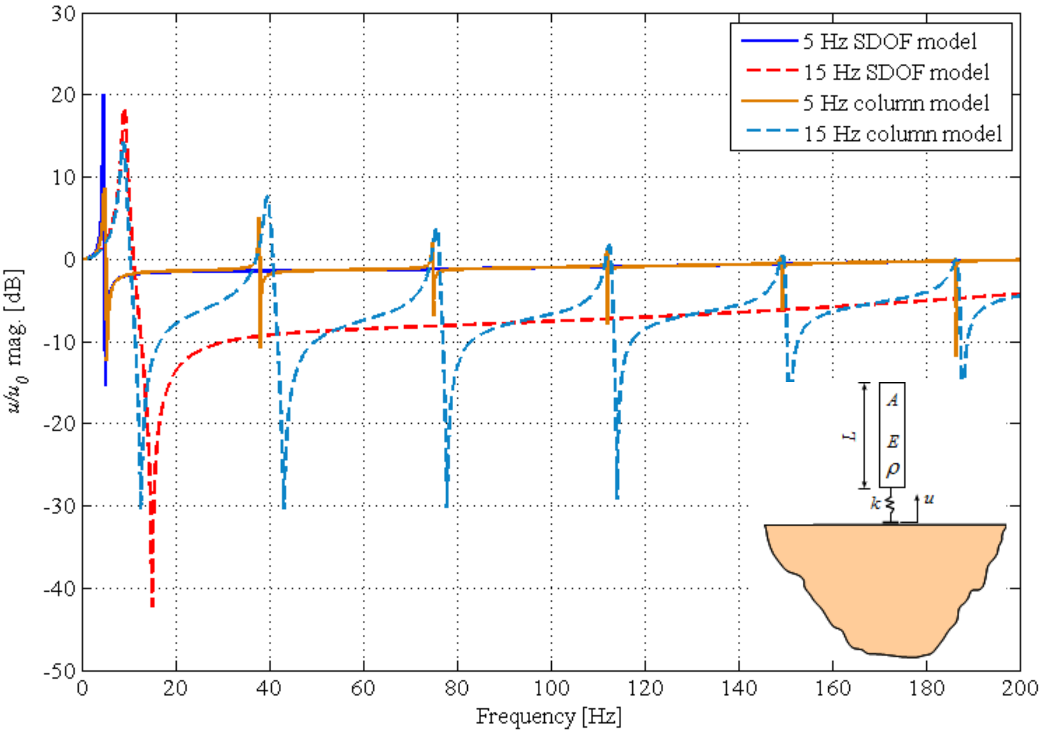

Figure 5. Soil-structure interaction of a base-isolated building as predicted by a building model comprising an elastic column on a spring, founded on a surface footing. The ratio of the final footing amplitude u to that prior to the construction of the building u_0 is shown for different isolation frequencies, along with the results of Figure 4 for comparison

The primary effect of the building's flexibility, as modelled by the elastic column, is to superpose a series of resonance and anti-resonance peaks on the response. The first point to note is that these resonances act to reduce the isolation efficiency. Clearly, any building model that treats the building as rigid will over-predict isolation performance – a conclusion that is supported by more comprehensive building models [6]. The second point is that the mean response remains the same as if the building was rigid, indicating that the constraining effect of a building is primarily an added-mass effect due to its inertia, rather than its stiffness.

These results replicate similar behaviour that has been observed in practice. Newland and Hunt [14] present measured data that support the idea of an added-mass effect. Their data show decreasing vibration levels at the pile-cap level of a foundation as the construction of the building progresses. The results also replicate behaviour observed experimentally by Sharif [15], in that the improved decoupling of a building from its foundation achieved with a lower isolation frequency limits this added-mass effect, resulting in higher post-construction vibration levels of the foundation than if the building was unisolated. Note that this latter effect highlights the inadequacy of describing isolation performance in terms of vibration levels above and below the bearings: the performance of a soft isolation is exaggerated by greater vibration amplitudes beneath it.

Multi-input Models

In addition to having distributed mass and stiffness, a real building has multiple connections to the ground, which raises questions over the significance of differences in vibration amplitude and phase at these inputs. The analysis presented above may be generalised to account for this, leading to the matrix form of Equation 4 [7]:

$$\mathbf{u}_{bf} = \left[\mathbf{I} + \mathbf{H}_f^{11}\left[\mathbf{H}_b^{11}\right]^{-1}\right]^{-1}\mathbf{u}_{bf0} \tag{6}$$

where $\mathbf{H}_f^{11}$ and $\mathbf{H}_b^{11}$ are the FRF matrices of the foundation and building that relate displacements and forces on the building-foundation interface, $\mathbf{I}$ being the identity matrix. Equation 6 allows all displacements at locations on the building-foundation interface in the presence of the building $\mathbf{u}_{bf}$ to be calculated from those in its absence $\mathbf{u}_{bf0}$.

As a simple example of a multi-input model, the SDOF model of Figure 3 may be extended to a 2-DOF model, now with mass and moment of inertia, and founded on two footings. This is the simplest possible model that enables wave interaction effects to be studied. The pre-construction vibration field must now be defined in detail to account for amplitude and phase differences between the two footings. One physically based representation of $\mathbf{u}_{bf0}$ is the steady-state excitation due to passing Rayleigh waves. Assuming that the building is far enough away from the source of the Rayleigh waves, such that the wavefronts are parallel lines, the motions of the two footings are related by:

$$u_0^2 = u_0^1 e^{-i\omega S / c_R} \tag{7}$$

where u_0^1 and u_0^2 are the vertical displacement amplitudes of the two footings in the absence of the building, with a phase difference between them that is dependent on their spacing *S* and Rayleigh wave speed c_R.

Figure 6 plots the ratio u^1 / u_0^1 for Footing 1, for the cases of a 5 Hz and 15 Hz isolation frequency (the results for Footing 2 are similar). The building is now modelled as a uniform mass of 10^5 kg, as for the SDOF model, with a width equal to the footing spacing, $S = 8$ m, and a height $L = 30$ m; the parameter values for the footings and the half-space remain the same as in the two previous models.

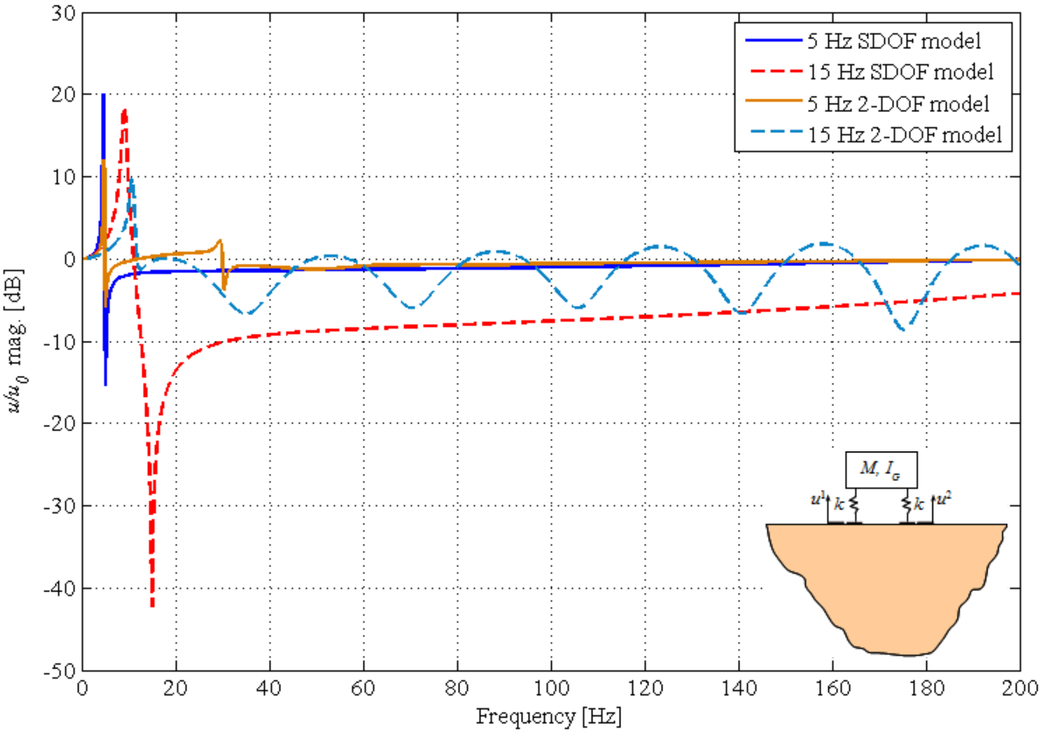

Figure 6. Soil-structure interaction of a base-isolated building as predicted by a 2-DOF building model founded on two surface footings. The ratio of the final footing amplitude u to that prior to the construction of the building u_0 is shown for different isolation frequencies, along with results of Figure 4 for comparison

As with the SDOF model the vertical foundation and building resonances are evident but now there also exist equivalent rocking modes at higher frequencies. Above these initial resonances, wave interactions occur between the two footings. When the footings move in phase (at 35 and 70 Hz), the building model behaves as a SDOF model and acts to constrain the ground; when they move in anti-phase (at 55 Hz), the effect of the building on the ground becomes negligible. Again, a lower isolation frequency affects the foundation to a lesser extent.

Conclusions

Although the significance of soil-structure interaction has been known for some time in the seismic response of buildings, its significance with regard to ground-borne vibration has only begun to be recognised relatively recently. This paper has examined some simplified models that aim to investigate how SSI influences the design of base-isolated buildings. They suggest that, whilst a building's flexibility introduces resonances that act to reduce the isolation efficiency, it is the 'added-mass' of a building that predominantly acts to constrain its foundation and reduce the free-field vibration levels. This is an important effect since, together with radiation damping into the ground, it leads to an overall reduction in vibration levels in the completed building. Ignoring this SSI may therefore lead to base-isolation systems being over-designed.

Whether this effect is similarly evident in more comprehensive models, and whether it may be accounted for efficiently in improved design methods, remains the subject of current research.

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