A generic model for evaluating the performance of base-isolated buildings

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Ground-borne vibration has existed ever since the development of urban road and rail networks. Vibration generated by the moving traffic propagates through the ground and into buildings, resulting in unacceptable levels of internal noise and vibration. A common solution to this increasingly significant problem is the base-isolation of buildings by incorporating vibration isolation bearings between the buildings and their foundations. This technique has been employed for over forty years but the exact performance of base isolation remains uncertain. This paper describes a generic computational model; generic in that it accounts for the essential dynamic behaviour of a typical base-isolated building in order to make predictions of isolation performance. The model is a linear one, formulated in the frequency domain, and consists of a two-dimensional portal- frame model of a building coupled to a three-dimensional boundary-element model of a piled-foundation. Both components of the model achieve computational efficiency by assuming they are infinitely long and using periodic structure theory. Following an overview of the model, a virtual case study is presented to illustrate its practical application. Along with some initial observations, the case of a point-load surface excitation of the foundation is used to investigate the isolation performance of typical isolation bearings.

1. Introduction

There is an increasing need to tackle the problem of ground-borne vibration. Increasing public sensitivity to noise and vibration has led to more demanding legislation dictating acceptable levels within our homes and places of work. In addition, there is pressure to expand road and rail networks, and develop existing urban sites. Such sites that remain are often the undesirable ones close to railways or busy roads.

Since the 1960s base isolation has enabled the construction of buildings on sites otherwise deemed unacceptable due to high levels of ground-borne vibration. Despite many such projects, the performance of base isolation remains uncertain. The objective is to reduce vibration transmission by at least 10 dB for frequencies above approximately 10 Hz but this is difficult to verify and is not thought likely to be achieved in practice. There remain unanswered questions concerning the specification and design of the bearings, such as what is the most appropriate stiffness of the bearings for a given application and how important is the level of internal damping? The answers to these questions are important because they have significant implications for the design and cost of a base-isolated building. There is therefore a clear need for a means of determining the effectiveness of base isolation and objectively evaluating the alternative types of bearing.

The primary aim of this research is to develop a computational model in order to make predictions of isolation performance. It is a generic model in that it accounts for the essential dynamic behaviour of a typical base-isolated building rather than a specific example. The model has three main uses:

- to determine the effectiveness of base isolation against ground-borne vibration;
- to evaluate objectively the various types of isolation bearing;
- to help establish the best design practice.

The aim is to ensure that the model is computationally efficient and suitable for use on a standard personal computer so that, in principle, manufacturers, consultants, and designers can readily evaluate various base-isolation designs.

2. Overview of the Building Model

The building model is based on that developed by Cryer for studying vibration transmission in buildings [1, 2].

This is an infinitely long two-dimensional portal-frame model produced by combining the dynamic-stiffness method (DSM) with periodic structure theory. The primary reason for choosing this approach is the computational efficiency with which a multi-story building may be modelled. Experiments have also shown that predictions of vibration transmissibility agree well with measurements made in a real building [1].

2.1 The Dynamic Stiffness Method

There are several methods of modelling a building. The finite-element [3] and finite-difference [4] methods require considerable computing power to achieve reasonable results, even with relatively simple models. Statistical energy analysis [5] is also considered inappropriate given that modal behaviour is important in the frequency range associated with ground-borne vibration.

The DSM has the primary advantage of improved accuracy at higher frequencies without the need for large multi-element models. The solutions are exact within the limitations of the underlying theory, which describes the dynamic behaviour of each element of the portal frame by the analytical solutions for an elastic bar and Euler beam (Figure 1).

For a model with N nodes subject to harmonic excitation, the complex amplitudes of the generalised nodal forces and displacements are related through the global dynamic-stiffness matrix $\mathbf{K}$:

$$\mathbf{f} = \mathbf{K}\mathbf{u} \qquad (1)$$

where ('T' denoting the vector transpose)

$$\mathbf{u} = \left[u^1\ v^1\ \theta^1\ u^2\ v^2\ \theta^2 \cdots u^N\ v^N\ \theta^N\right]^{\mathrm{T}}$$
$$\mathbf{f} = \left[f^1\ s^1\ q^1\ f^2\ s^2\ q^2 \cdots f^N\ s^N\ q^N\right]^{\mathrm{T}}$$

Given a vector of applied nodal forces, the resulting nodal displacements are obtained by inversion of $\mathbf{K}$. The displaced shape and internal forces of the portal frame may then be calculated using the equations describing each element.

The analysis of large models at many frequencies involves long computation times and it is for this reason that the DSM is combined with periodic structure theory.

2.2 Periodic Structure Theory

A periodic structure consists of a number of identical structural elements, or repeating units, which are coupled together end-to-end and/or side-by-side to form the whole structure. The governing theory was initially developed by Newton but its application to engineering structures came later [6]. The theory used here describes one-dimensional and quasi-one-dimensional structures, that is, those in which wave propagation occurs in one dimension only.

The application of periodic structure theory to building models is illustrated in Figure 2. The portal frame is assumed to be infinitely long and based on a repeating unit comprising a column and several floors.

Full details are given by Hunt and Talbot [2, 7] but the essence of the method may be appreciated by considering wave propagation along the right-hand semi-infinite structure of Figure 2. The dynamic behaviour of the repeating unit is described by its *transfer-matrix* $\mathbf{T}$:

$$\mathbf{s}^{j+1} = \mathbf{T}\mathbf{s}^{j} \qquad (2)$$

where $\mathbf{s}^j = [[\mathbf{u}_1]^{\mathrm{T}}\ [\mathbf{f}_1]^{\mathrm{T}}]^{\mathrm{T}}$ describes the state of the jth unit in terms of the complex amplitudes of the generalised displacements $\mathbf{u}_1$ and forces $\mathbf{f}_1$ on the left-hand side of the unit.

Given that the repeating units are identical, all states are identical in form and propagate along the structure with only a change in amplitude and phase:

$$\mathbf{s}^{j+1} = \lambda\mathbf{s}^{j} \qquad (3)$$

where λ is a complex amplitude-modifying factor.

Equations 2 and 3 constitute an eigenvalue problem in $\mathbf{T}$. The eigenvectors corresponding to eigenvalues with magnitudes less than one represent the states that are able to propagate along the structure at a given frequency. They are mutually orthogonal and any general state may therefore be represented by a linear combination of these eigenvectors. This includes the state of the first unit in the right-hand semi-infinite structure:

$$\mathbf{s}^1 = \bar{\mathbf{S}}\mathbf{a} \qquad (4)$$

where $\bar{\mathbf{S}}$ is a matrix of the eigenvectors and $\mathbf{a}$ is a matrix of unknown coefficients.

The coefficients are eliminated from

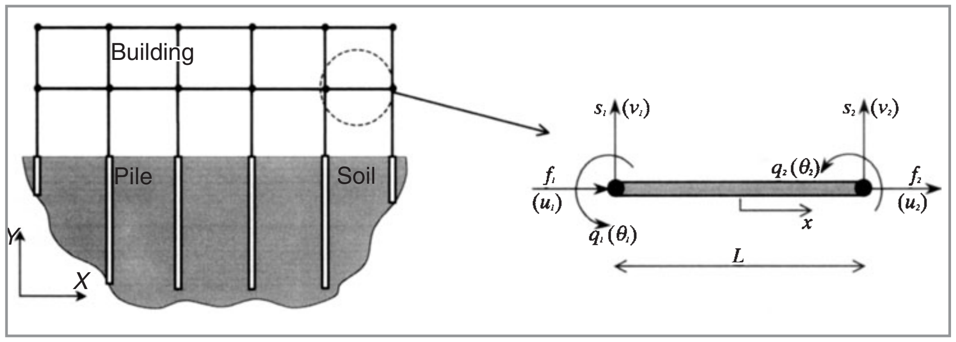


Figure 1 *A typical DSM element from a two-dimensional portal frame. The generalised forces* f, s *and* q, *and the corresponding generalised displacements* (u, v *and* θ) *are related through the element's dynamic-stiffness matrix. Junctions between elements are known as nodes (•).*

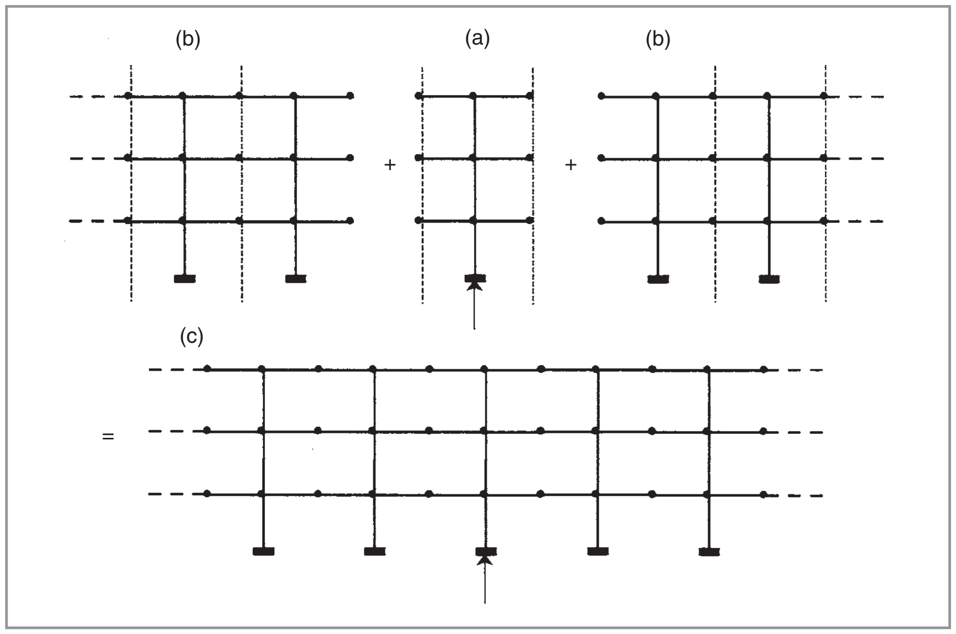


Figure 2 *An infinitely long two-dimensional portal-frame model of a building, based on the dynamic-stiffness method and periodic structure theory. The central loaded unit (a) is coupled to two semi-infinite structures (b) to form the complete model (c). The repeating units are defined by dashed vertical lines.*

Equation 4 by partitioning $\overline{\mathbf{S}}$ to separate the rows associated with the displacement and force components of $\mathbf{s}^1$:

$$\mathbf{s}^1 = \begin{bmatrix} \mathbf{u}^1 \\ \mathbf{f}^1 \end{bmatrix} = \begin{bmatrix} \overline{\mathbf{U}} \\ \overline{\mathbf{F}} \end{bmatrix} \mathbf{a} \qquad (5)$$
$$\mathbf{u}^1 = \overline{\mathbf{U}}\mathbf{a} \quad \text{and} \quad \mathbf{p}^1 = \overline{\mathbf{P}}\mathbf{a}$$

This enables the displacements to be written purely in terms of the forces:

$$\begin{aligned} \mathbf{u}^1 &= \overline{\mathbf{U}}\left[\overline{\mathbf{F}}\right]^{-1}\mathbf{f}^1 \\ &= \mathbf{H}_\mathbf{r}\mathbf{f}^1 \end{aligned} \qquad (6)$$

where $\mathbf{H}_\mathbf{r}$ is the frequency-response function (FRF) matrix of the right-hand semi-infinite structure. The equivalent matrix for the left-hand row $\mathbf{H}_1$ is obtained by symmetry.

It is now evident why the application of periodic structure theory leads to a computationally efficient model. The full dynamic behaviour of the semi-infinite structures is described by just two matrices, $\mathbf{H}_\mathbf{r}$ and $\mathbf{H}_1$. To complete the model the semi-infinite structures are coupled to the central unit. This is achieved in a conventional way from considerations of compatibility and equilibrium.

2.3 The Isolation Bearings

Assuming linear elasticity, and ignoring torsion about the vertical axis, an isolation bearing may be described by three massless springs, as illustrated for a rubber bearing in Figure 3.

The isolation frequency f_{isol} for a particular base-isolated building is defined (in Hz) as the frequency of vertical oscillation of the building assuming it behaves as a rigid mass on a spring. As far as modelling is concerned, therefore, the isolation frequency defines the vertical stiffness of each bearing as:

$$k_v = 4\pi^2 f_{isol}^2 M \tag{7}$$

where M is the mass supported per bearing.

In practice, the horizontal and rotational stiffnesses depend heavily on the design details of the particular application. No general relationship exists between them and the value of k_v, although the horizontal and rotational stiffnesses are generally less than the vertical stiffness. Here $k_h = 0.5k_v$ and $k_q = a^2k_v$, where a is a length scale of the bearing.

3. Overview of the Foundation Model

Two-dimensional representations of a foundation are also often preferred for their simplicity and the need to restrict computation times. However, with a foundation, the assumption of invariance in the anti-plane direction significantly limits the ability to correctly model wave propagation. For example: vibration that in practice may propagate on spherical wavefronts is constrained to cylindrical wavefronts, and therefore attenuates less rapidly with distance; foundations such as piles are represented as infinitely long barriers around which waves can no longer diffract; and point excitation becomes a coherent line-source. It is therefore considered essential that the three-dimensional nature of the foundation is accounted for.

A new three-dimensional piled-foundation model is used here based on the boundary element method (BEM) [8] and the periodic structure theory outlined in Section 2.2. The model is comprehensive in that it accounts for the longitudinal and transverse motion of the piles due to both external pile-head loads and interaction between neighbouring piles through wave propagation in the surrounding soil. As with the building model, by assuming the foundation comprises an infinite number of identical units, significant gains in computational efficiency are achieved. The model is summarised in Figure 4.

The piles are modelled using the solutions for an elastic bar and Euler beam, while the soil is represented by a uniform elastic half-space. The repeating unit consists of a central pile coupled to a BEM model representing the surrounding soil. The unit is effectively a vertical slice of the pile row and, as such, the BEM mesh should extend to minus infinity in the x_3-direction and plus and minus infinity in the x_2-direction. In practice the mesh may be curtailed at a finite distance from the pile, determined by observing the convergence of the required solution.

Full details of the model are given by Talbot [7].

4. Coupling the Building and Foundation Models

The approach chosen here is to solve the infinite building and pile-row models separately and then couple the two together at a *finite* number of pile heads. The necessary number of coupling points is determined by observing the

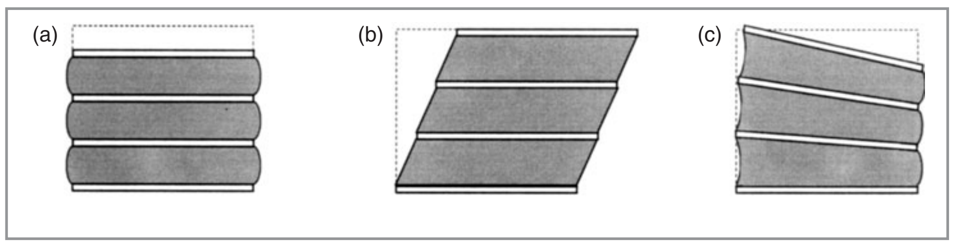


Figure 3 The three modes of deformation associated with an isolation bearing are described by three stiffnesses: (a) k_v, vertical compression; (b) k_u, horizontal shear; and (c) k_θ, rotation.

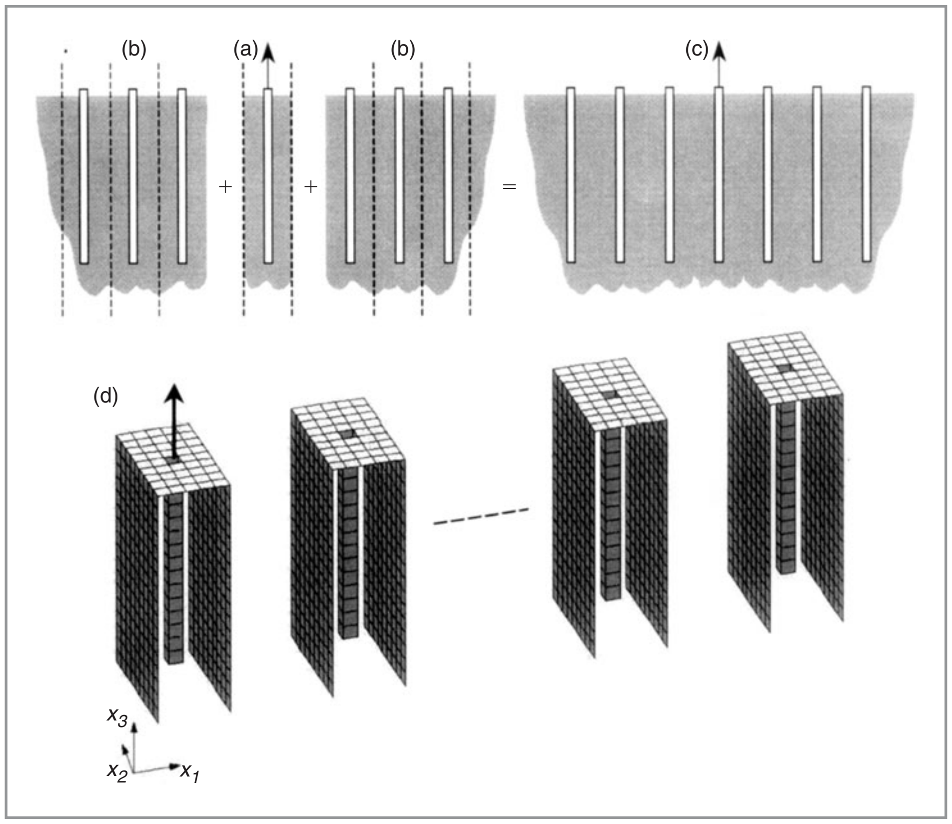


Figure 4 *An infinitely long three-dimensional model of a piled foundation, based on the boundary-element method and periodic structure theory. The central loaded unit (a) is coupled to two semi-infinite models (b) to form the complete model (c). The BEM mesh for the soil component of one half of the model is also shown (d).*

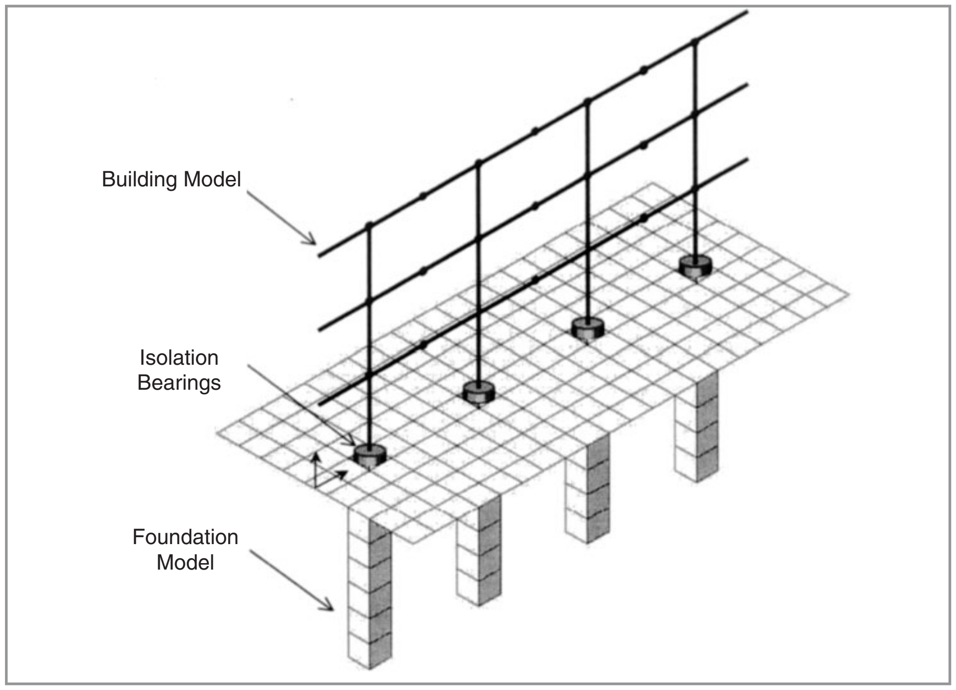


Figure 5 *Schematic isometric projection of the generic model. The infinitely long two-dimensional portal-frame model of a building is coupled to the infinitely long three-dimensional model of a piled foundation.*

convergence of the required solution as more piles are included. The advantage of this approach is that parameter changes may be made to the building model without the need to re-solve the foundation model, which is by far the more computationally intensive component. A schematic diagram of the complete model is shown in Figure 5.

The details of the coupling procedure are as follows. The generalised forces and displacements of the N_{ph} pile heads that are to be coupled to the building are related through the $3N_{ph} \times 3N_{ph}$, FRF matrix $\mathbf{H_f}$ describing the foundation:

$$\begin{bmatrix} \mathbf{u}_{\mathbf{ph}}^{1} \\ \mathbf{u}_{\mathbf{ph}}^{2} \\ \vdots \\ \mathbf{u}_{\mathbf{ph}}^{N_{ph}} \end{bmatrix} = \begin{bmatrix} \mathbf{H}_{\mathbf{f}}^{11} & \mathbf{H}_{\mathbf{f}}^{12} & \cdots & \mathbf{H}_{\mathbf{f}}^{1N_{ph}} \\ \mathbf{H}_{\mathbf{f}}^{21} & \mathbf{H}_{\mathbf{f}}^{22} & & \\ \vdots & & \ddots & \\ \mathbf{H}_{\mathbf{f}}^{N_{ph}1} & & & \mathbf{H}_{\mathbf{f}}^{N_{ph}N_{ph}} \end{bmatrix} \begin{bmatrix} \mathbf{f}_{\mathbf{ph}}^{1} \\ \mathbf{f}_{\mathbf{ph}}^{2} \\ \vdots \\ \mathbf{f}_{\mathbf{ph}}^{N_{ph}} \end{bmatrix} + \begin{bmatrix} \mathbf{u}_{\mathbf{ph0}}^{1} \\ \mathbf{u}_{\mathbf{ph0}}^{2} \\ \vdots \\ \mathbf{u}_{\mathbf{ph0}}^{N_{ph}} \end{bmatrix} \tag{8a}$$

or

$$\mathbf{u}_{\mathbf{ph}} = \mathbf{H}_{\mathbf{f}}\mathbf{f}_{\mathbf{ph}} + \mathbf{u}_{\mathbf{ph0}} \tag{8b}$$

The three $3N_{ph} \times 1$ vectors $\mathbf{f}_{\mathbf{ph}}$, $\mathbf{u}_{\mathbf{ph0}}$ and $\mathbf{u}_{\mathbf{ph}}$, are assembled, respectively, from the 3×1 vectors containing the generalised forces, and the generalised displacements before and after construction of the building, of each pile-head.

The force and displacement amplitudes of the pile heads, after construction of the building, are also related through the FRF matrix describing the building, which is obtained from the inverse of its dynamic-stiffness matrix:

$$\begin{bmatrix} \mathbf{u}_{\mathbf{ph}}^{1} \\ \mathbf{u}_{\mathbf{ph}}^{2} \\ \vdots \\ \mathbf{u}_{\mathbf{ph}}^{N_{ph}} \end{bmatrix} = -\begin{bmatrix} \mathbf{H}_{\mathbf{b}}^{11} & \mathbf{H}_{\mathbf{b}}^{12} & \cdots & \mathbf{H}_{\mathbf{b}}^{1N_{ph}} \\ \mathbf{H}_{\mathbf{b}}^{21} & \mathbf{H}_{\mathbf{b}}^{22} & & \\ \vdots & & \ddots & \\ \mathbf{H}_{\mathbf{b}}^{N_{ph}1} & & & \mathbf{H}_{\mathbf{b}}^{N_{ph}N_{ph}} \end{bmatrix} \begin{bmatrix} \mathbf{f}_{\mathbf{ph}}^{1} \\ \mathbf{f}_{\mathbf{ph}}^{2} \\ \vdots \\ \mathbf{f}_{\mathbf{ph}}^{N_{ph}} \end{bmatrix} \tag{9a}$$

or

$$\mathbf{u}_{\mathbf{ph}} = -\mathbf{H}_{\mathbf{b}}\mathbf{f}_{\mathbf{ph}} \tag{9b}$$

Eliminating the forces from Equations 8 and 9 gives the final displacements of the pile heads in terms of those prior to the construction of the building:

$$\mathbf{u}_{\mathbf{ph}} = \left[\mathbf{I} + \mathbf{H}_{\mathbf{f}}\left[\mathbf{H}_{\mathbf{b}}\right]^{-1}\right]^{-1}\mathbf{u}_{\mathbf{ph0}} \tag{10}$$

where $\mathbf{I}$ is a $3N_{ph} \times 3N_{Ph}$ identity matrix.

For any chosen pre-construction displacements of the pile-heads, the displacements given by Equation 10 may be used to find the corresponding forces by inversion of Equation 9. These forces are then applied, in the opposite sense, to the building model to determine the full response.

5. A Virtual Case Study

The generic model is flexible, computationally efficient and there are many possible studies that may now be undertaken. This section discusses some initial observations concerning the behaviour of a base-isolated building along with the results of one study into isolation performance. The results are presented in the form of a virtual case study in order to illustrate the practical application of the model.

noise notes

Court backs Council

A café owner has been ordered to pay nearly £6,000 after twice breaching a noise abatement order. Gaby Kolajo, who owns a café in Leyton, was fined £5,000, and ordered to pay costs of £463.34 by magistrates. Mr Kolajo, previously appeared before magistrates in October 2003. He was found guilty of breaching the same noise abatement notice in January 2003. Mr Kolajo was fined £700 and ordered to pay costs of £344 after the first offence. A council spokeswoman said magistrates decided that a higher fine was appropriate in this recent case because, despite his awareness of the nuisance caused, Mr Kolajo's behaviour continued. The notice was originally served on Mr Kolajo after a series of complaints from people to the council's environmental health team about excessive noise coming from the property on Thursdays, often after midnight.

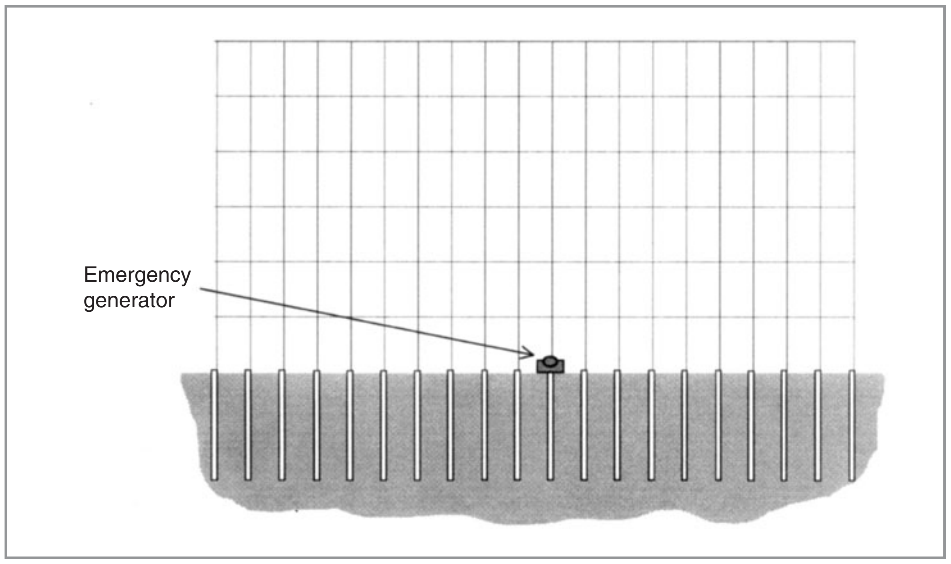


Figure 6 Schematic elevation of a new hospital. An emergency generator located at ground-floor level may lead to excessive levels of internal vibration and base isolation of the building is a potential solution

Figure 6 shows a schematic elevation of a design for a new hospital.

The design is based on a typical concrete-framed structure founded on piles and includes an emergency generator at ground-floor level located close to one of the central piles. It is recognised that the generator may lead to excessive vibration levels in the hospital. Consequently, following construction of the foundation, a consultant is asked to simulate operation of the generator by using a harmonic shaker mounted on the pile head nearest to the location of the generator. Based on measurements of the resulting motion of the pile heads, the consultant concludes that vibration would indeed be a problem in the completed hospital and that base isolation of the structure should be investigated.

The results presented here are all based on a model of a concrete-framed building founded on concrete piles; the parameter values are given in the appendix. The excitation from the harmonic shaker is modelled as a vertical unit-amplitude force applied to the central pile-head. This results in the pre-construction pile-head vibration amplitudes $\mathbf{u}_{ph0}$, which are calculated using the pile-row model alone. An upper frequency limit of 80 Hz is chosen, which includes the range of frequencies in which ground-borne vibration levels typically peak.

5.1 Initial Observations

Figure 7 illustrates the predicted response of the hospital in the event that it is left unisolated and the columns of the buildings are directly coupled to the piles. In this case it is clear that the building and foundation experience comparable vibration amplitudes and behave as one system. It is also clear that the piles undergo horizontal, as well as vertical, motion.

Figure 8 illustrates the equivalent results when the building is base-isolated with an isolation frequency of 5 Hz; the damping loss factor of the bearings is 0.01. The same displacement magnification factor is used in Figures 7 and 8, and it is clear that the isolation significantly reduces the vibration amplitudes of the building. This is achieved by the isolation bearings allowing relative motion between the pile heads and the bases of the building columns.

These initial observations indicate qualitatively that base-isolation would be beneficial for the hospital, at least at 50 Hz. A quantitative measure of this, for different isolation bearings and over a range of frequencies, is considered in Section 5.2.

5.2 Predictions of Isolation Performance

In this section, power-flow insertion gain (PFIG) is used as an overall measure of the base-isolation performance of the hospital. The principle behind PFIG is

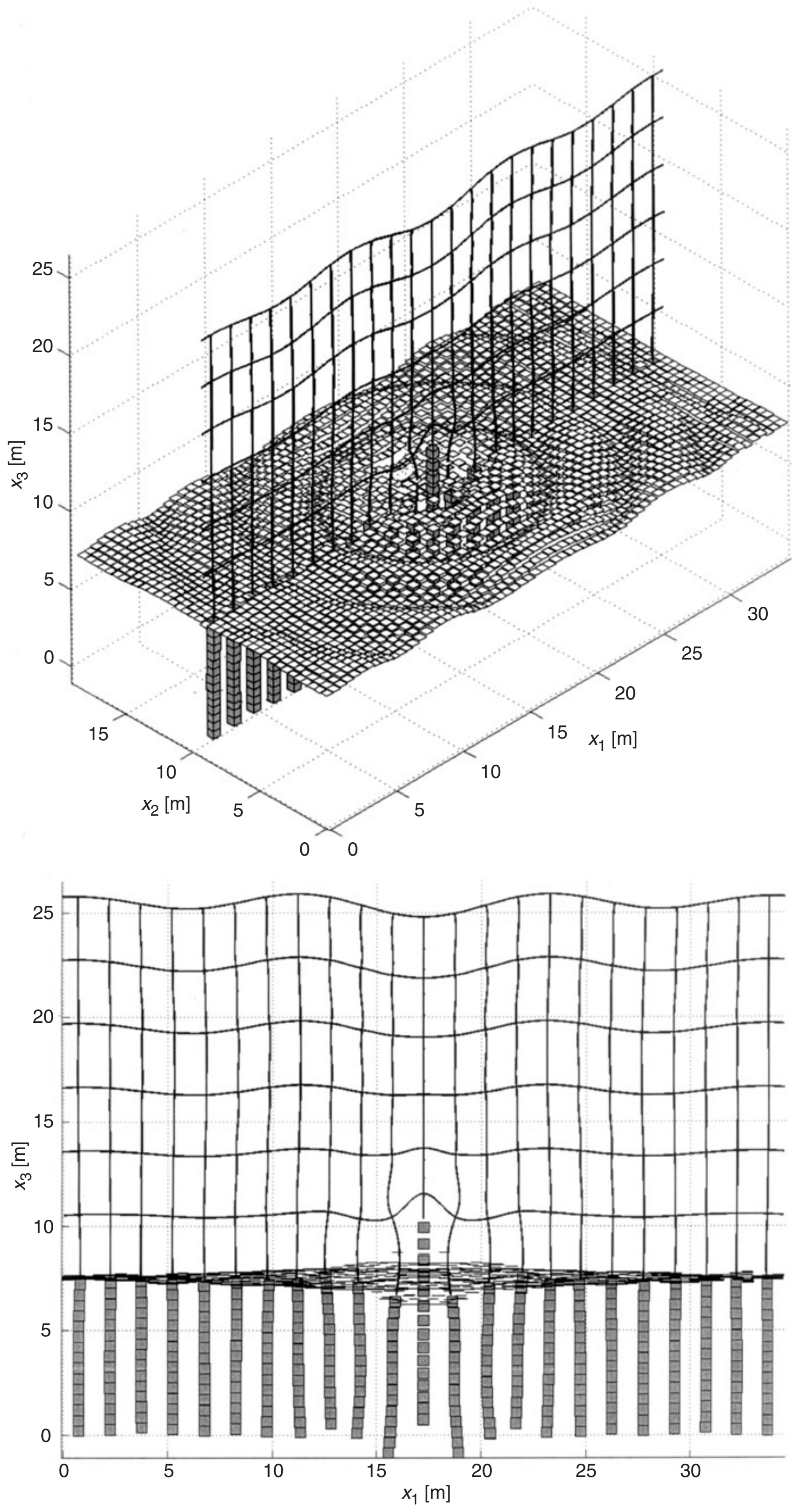
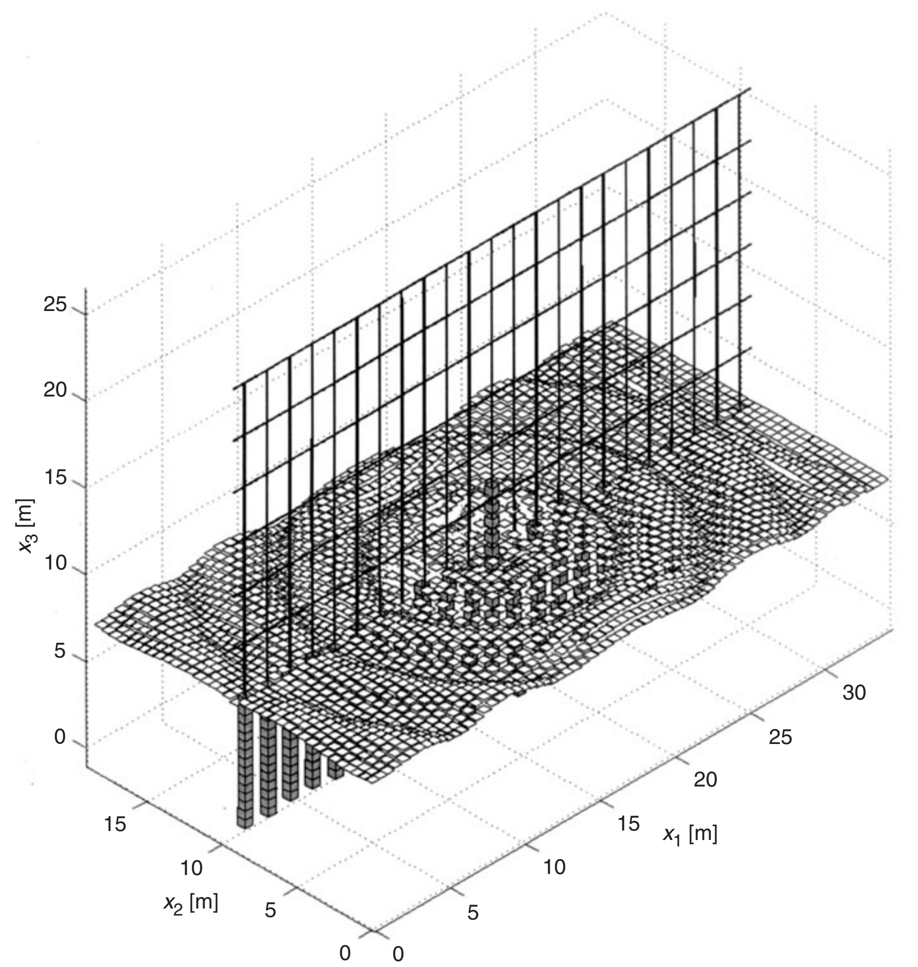


Figure 7 *Vibration of an unisolated hospital as predicted by the generic model. The 50 Hz excitation corresponds to a vertical unit-amplitude force applied to the central pile-head prior to the construction of the building. All displacements are magnified by 1×10^{10}.*



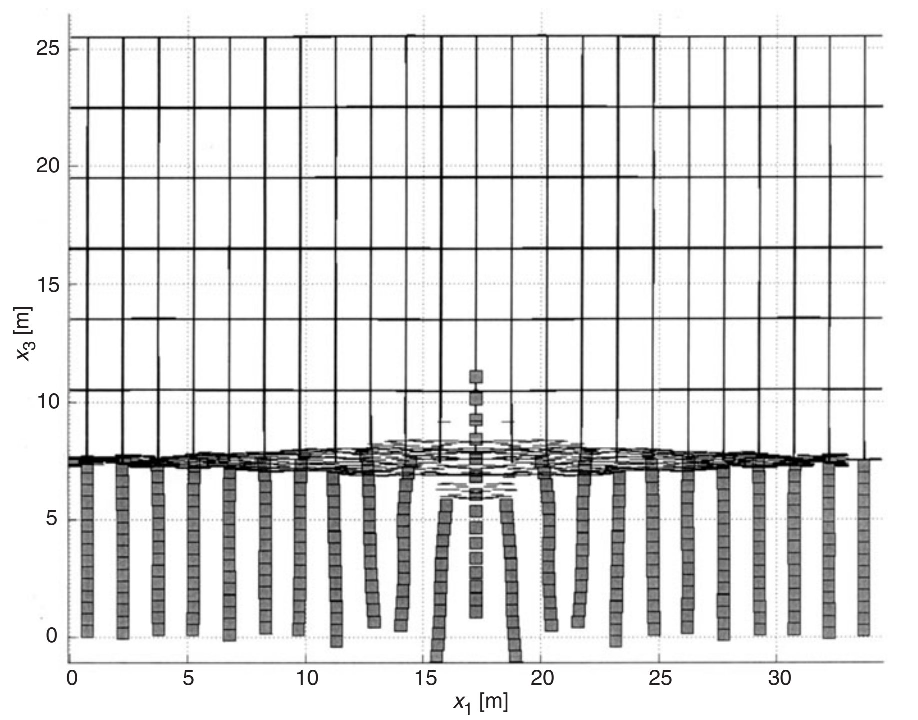


Figure 8 *Vibration of a '5 Hz' base-isolated hospital as predicted by the generic model. The 50 Hz excitation corresponds to a vertical unit-amplitude force applied to the central pile-head prior to the construction of the building. All displacements are magnified by 1 × 10*^{10}*.*

that the mean vibrational energy entering a building drives all internal structural vibration and reradiated noise, assuming there are no internal sources of either [9, 10].A reduction in PFIG is therefore guaranteed to reduce the average noise and vibration levels in a building.

$$\text{PFIG} = 10 \log_{10}\left(\frac{\bar{P}_{isol}}{\bar{P}_{unisol}}\right) \quad (11)$$

where $\bar{P}_{isol}$ and $\bar{P}_{unisol}$ are the total mean power flows entering the building in the isolated and unisolated cases respectively.

PFIG has clear advantages over performance measures based on vibration amplitudes because it accounts for multidirectional vibration at multiple inputs and is insensitive to the spatial distribution of vibration levels within a building. It is also useful in design because the variation in isolation performance with frequency, for a particular set of design parameters, may be represented by a single curve.

Figure 9 shows the variation with frequency in the PFIG when the hospital is base-isolated on bearings giving isolation frequencies of 5, 10 and 15 Hz, with internal damping loss factors of 0.1 and 0.01. This range of parameters is typically found in practice: a 15 Hz isolation with a loss factor of 0.1 is representative of high-hysteresis rubber bearings while a 5 Hz isolation with a loss factor of 0.01 is representative of undamped steel springs.

The first thing to note about Figure 9 is the smoothness of the curves: there are no strongly defined resonant peaks. This is due to the infinite nature of the model, which radiates energy away from the excitation and prevents resonances from being established. This behaviour was originally noted by Cryer [1] when developing the infinite building model and was found to be more representative of real buildings, which do not exhibit the strong resonant behaviour of finite models.

The peaks that are evident in Figure 9 are due to peaks in the total mean

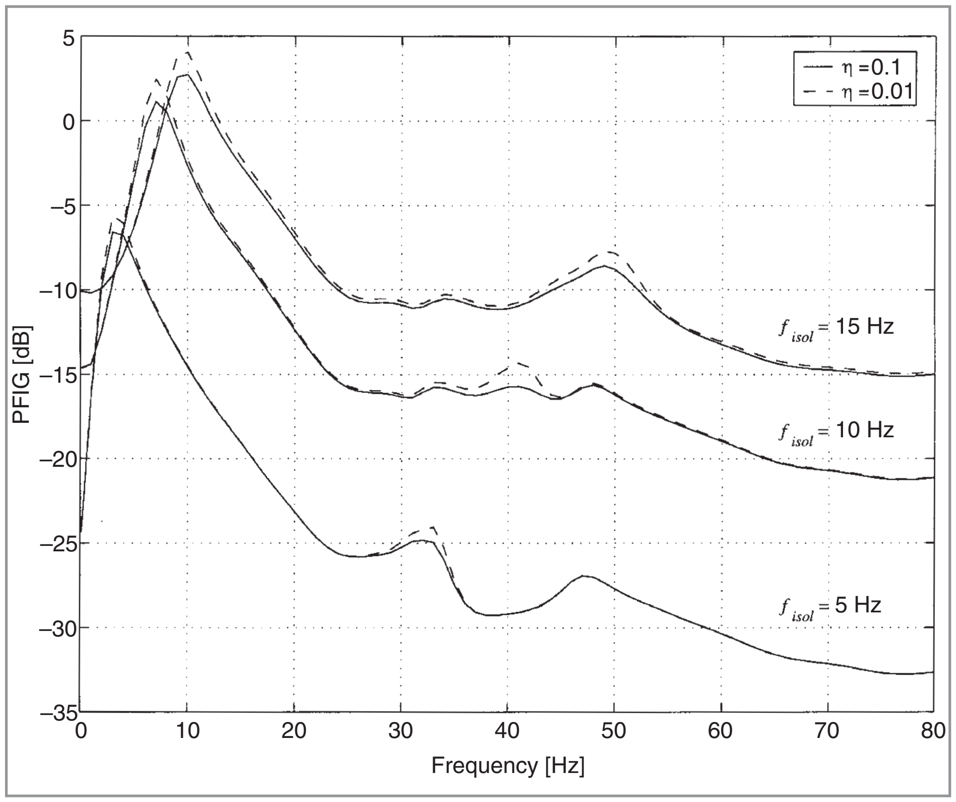


Figure 9 *Variation with frequency in the power-flow insertion gain of a base-isolated hospital, as predicted by the generic model. Isolation frequencies of 5, 10 and 15 Hz are considered, provided by bearings with internal damping loss factors of 0.1 and 0.01. The excitation corresponds to a vertical unit-amplitude force applied to the central pile-head prior to the construction of the building.*

vibrational power flow into the isolated building. The first of these occurs near the isolation frequency and corresponds, in essence, to the global 'bounce' mode of the building on the isolation bearings, although the response is localised around the excitation. The smaller peaks – in the region of 30, 40 and 50 Hz – appear to occur at frequencies when vibration can propagate freely along the structure in the region of the building-foundation interface.

Of interest to the consultant is the fact that the choice of isolation frequency makes a large difference to the efficiency of the isolation. The differences are not as great as predicted by simpler models [7] but they are nevertheless significant and would certainly influence a design decision. In general, the level of internal damping in the bearings has a negligible effect on performance. However, it does have an effect at frequencies when relative motion between the pile heads and the bases of the building columns is significant, that is, when the isolation bearings undergo significant deformation.

It must be stressed that the predictions presented here are for a surface point-force excitation and that a different conclusion may be drawn for less localised excitation, such as that from an underground railway. This is the subject of continuing research.

6. Conclusions

This paper has presented a generic model of a base-isolated building as a means of determining the effectiveness of base isolation and objectively evaluating the alternative types of bearing. The model consists of a two-dimensional building model coupled to a three-dimensional model of a piled foundation. Computational efficiency is achieved by assuming both are infinitely long.

A virtual case study has been presented, based on the specific case of a point-load surface excitation of the foundation. The primary conclusions are as follows.

1. The building and foundation act as one system: changes to the building affect the foundation and vice versa. This means that it is impossible to make good predictions of building behaviour by modelling the building alone.
2. The choice of isolation frequency can make up to a 15 dB difference to the efficiency of the isolation for typical bearing designs. This is significant for the design of a particular building but the difference is likely to depend on the nature of the excitation.
3. In general, the level of internal damping in the isolation bearings has a negligible effect on the performance. However, it does

Heathrow

BAA Heathrow has issued a call to the aviation industry, to work together to make improvements to the noise climate around Heathrow, at a recent seminar. Organised by airport operator, BAA, the event brought together a range of interested parties, including anti-noise group, HACAN, local authorities, airlines and aircraft manufacturers. Eryl Smith, BAA Heathrow's Business Strategy Director, commented: 'We understand that noise is the issue that impacts most on people living around the airport. 'BAA Heathrow accepts that there are many challenges ahead on the subject of noise, but we also understand that improvements can only be made when working alongside others. BAA Heathrow is directly able to control only ground noise. Examples include the extensive use of Fixed Electrical Ground Power and the progressive introduction of Pre-Conditioned Air, which reduces noise while aircraft are parked on the stands, and restricting engine tests. Airlines are being encouraged to modernise their fleets with newer aircraft, through discounts on landing charges for quieter planes, and, in addition to the Department for Transport's restrictions on night flights, BAA Heathrow and airlines have a voluntary agreement which further limits types of aircraft used. Aircraft manufacturers, Boeing and Airbus, which presented at the seminar, illustrated the operational advancements and developments in technology that they will bring online in the coming years. The manufacturers also stressed that the issue of noise was now an integral part of the design process.

increase internal power dissipation at frequencies when the isolation bearings undergo significant deformation. It is therefore important for controlling local resonant behaviour of the base of the building structure, which would otherwise lead to an increase in the vibrational power entering the building.

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Appendix

The parameter values used in the example of Section 5 are given below.

Given that no precise structural damping model currently exists, the hysteretic model is adopted throughout, primarily for its mathematical simplicity in the frequency domain [11].

Building property	Value	Foundation property	Value
Number of storeys	6	Length of piles [m]	7.5
Height of columns [m]	3	Radius of piles [m]	0.354
Length of floors [m]	1.5	Spacing of piles [m]	1.5
Bending stiffness of elements [GPam^4]	0.4	Bending stiffness of piles [GPam^4]	0.34
Axial stiffness of elements [GPam^4]	5.0	Axial stiffness of piles [GPam^4]	11.0
Young's modulus of elements [GPa]	10	Young's modulus of elements [GPa]	28
Density of elements [kg/m^3]	2400	Density of piles [kg/m^3]	2667
Damping loss factor of elements	0.1	Young's modulus of soil [GPa]	0.28
		Density of soil [kg/m^3]	2000
		Poisson's ratio of soil	0.4
		Damping loss factor of soil	0.02