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BASE ISOLATON OF BUILDINGS: A REVIEW

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ABSTRACT

Base isolation of buildings serves two main purposes: noise and vibration attenuation; earthquake protection. This paper will address the main issues confronting both of these areas and will concentrate on some of the difficulties which arise when evaluating the performance of systems for noise and vibration reduction.

Base-isolation systems for urban noise and vibration attenuation are aimed at controlling vibration at frequencies above 10Hz. Vertical ground motion is the primary source and vibration amplitudes are small (<<1mm). The purpose of such systems is to reduce annoyance; structural damage is of no concern. By contrast, earthquake systems are designed to deal with large-amplitude motion of the ground at very low frequencies (below 1Hz). Horizontal ground movement is of primary importance. Such vibration has potential to cause structural damage to the building as well as to the building services. There may be internal damage if furniture and fittings collapse and architectural damage (such as cracking of plaster) is regularly observed in buildings subject to earthquake. Simple models are required for the correct evaluation of base-isolation systems and a review of existing methods will be presented. There are some very promising ways forward and these will be discussed

1. INTRODUCTION

Base-isolated buildings are found wherever there are high levels of ground vibration, for instance in urban areas (usually near railways) and in areas prone to earthquakes. For these two applications the task of vibration isolation differs significantly:

<u>Vibration in urban areas</u> [1,2]	<u>Earthquake vibration</u> [3,4]
vibration control is required continuously	vibration control required only during occasional extreme events
vibration causes sleep disturbance and annoyance but no damage to buildings	vibration causes major structural damage
transmitted vibration is predominately vertical	transmitted vibration is predominately horizontal
vibration amplitudes are small <<1mm	vibration amplitudes are large (>>1mm)
frequency content principally above 10Hz	frequency content principally below 10Hz
the source of vibration is man made	the source of vibration is natural

In consequence the methods used for vibration isolation are very different. For isolation of buildings against earthquake motion systems can be used that are rigid except in the presence of extreme earth movements when rigid links break and the isolation system is free to function. This isolation permits horizontal motion while remaining effectively rigid to vertical vibration. This is because buildings are effictively rigid in the vertical direction at low frequencies and are able to tolerate vertical motions. The lateral flexural frequencies of tall buildings are low and these are more easily excited by horizontal ground motions. But perhaps the major difference between systems to control urban and earthquake vibration is that the former is man made. In principle it is possible to identify the source of vibration and to ask that something be done about it. It might also be possible to ask for compensation of some sort. There is significant pressure on railway operators to control noise and vibration at source. The rest of this paper will deal specifically with the methods used to control urban vibration.

2. BASE ISOLATION FOR URBAN VIBRATION

For the most part base-isolation systems for urban environments are used to control railway vibration. The specification of structural bearings for buildings is usually derived from empirical design rules and little science [5]. This is not to say that base isolation is ineffective as a method of controlling vibration transmission into buildings and there is a long history of successful application of the method, particularly in London [1,6]. The concern of the author is rather that the ultimate "performance" of an isolationsystem cannot be predicted or assessed with any accuracy. The problems lie in three areas:

1. a building is not a rigid body;
2. motion in the ground is not uniform;
3. there is no agreed measure of "performance".

These seem obvious, perhaps, but the only analytical model in widespread use is the mass-on-a-spring model depicted in Fig. This model does not account for building flexibility neither does it account for non-uniform ground motion. It also gives no opportunity to observe that vibration levels differ widely when measured at different positions within the building. For these reasons it is almost impossibile to 'validate' such a model against site measurements.

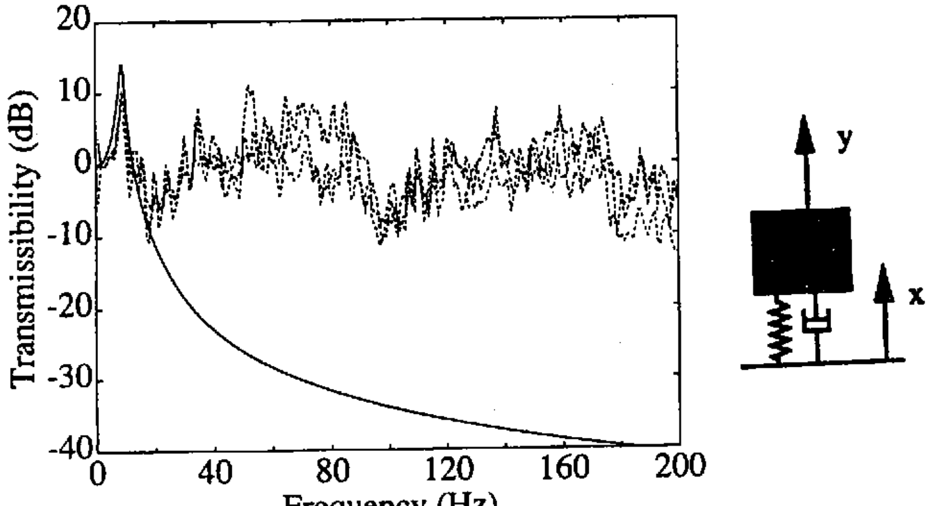

Fig. 1. Vibration transmissibility measured in a 13-storey base-isolated building above an underground railway in London shown as dotted lines. The solid line is a prediction of the transmissibility for a 9 Hz isolation frequency using a lumped-mass model.

These difficulties are well illustrated in Fig.1. This shows measurements made in a 13-storey building in London base-isolated using rubber bearings at basement level. The total required stiffness of rubber was calculated on the assumption that the building moves as a rigid body to give a natural frequency of vertical vibration of 9 Hz. The solid line in Fig.1 shows transmissibility ('vibration amplitude in building' over 'vibration level in ground') calculated from the mass-on-a-spring model. There is a resonance at 9Hz and the curve shows effective isolation performance at frequencies above 9v2 Hz as expected. After completion of the building vibration transmissibility was measured across the isolation as shown by the dotted lines. The resonance at 9Hz is clearly

visible and this indicates that the rubber has produced the desired natural frequency – but otherwise the model and the measurements bear no resemblance to one another. Clearly the model is not working, but it was found that the isolation achieved was in fact very effective and the client was happy.
What is going on in Fig. 1? How can the isolation be said to be effective? Was it worth paying the extra for base isolation? There are six issues here.

1. The building is flexible. Columns and floors have their own natural frequencies and there is internal damping as a result. A study of the effect of the column-like nature of buildings carried out by Newland et al. [7] demonstrates not only that internal resonances are extremely significant but also that the method used to model damping can influence the results enormously. This can be seen in Fig.2 where a substantial reduction in isolation performance is observed as a result of column resonances. This effect has also been observed by Swallow [8].

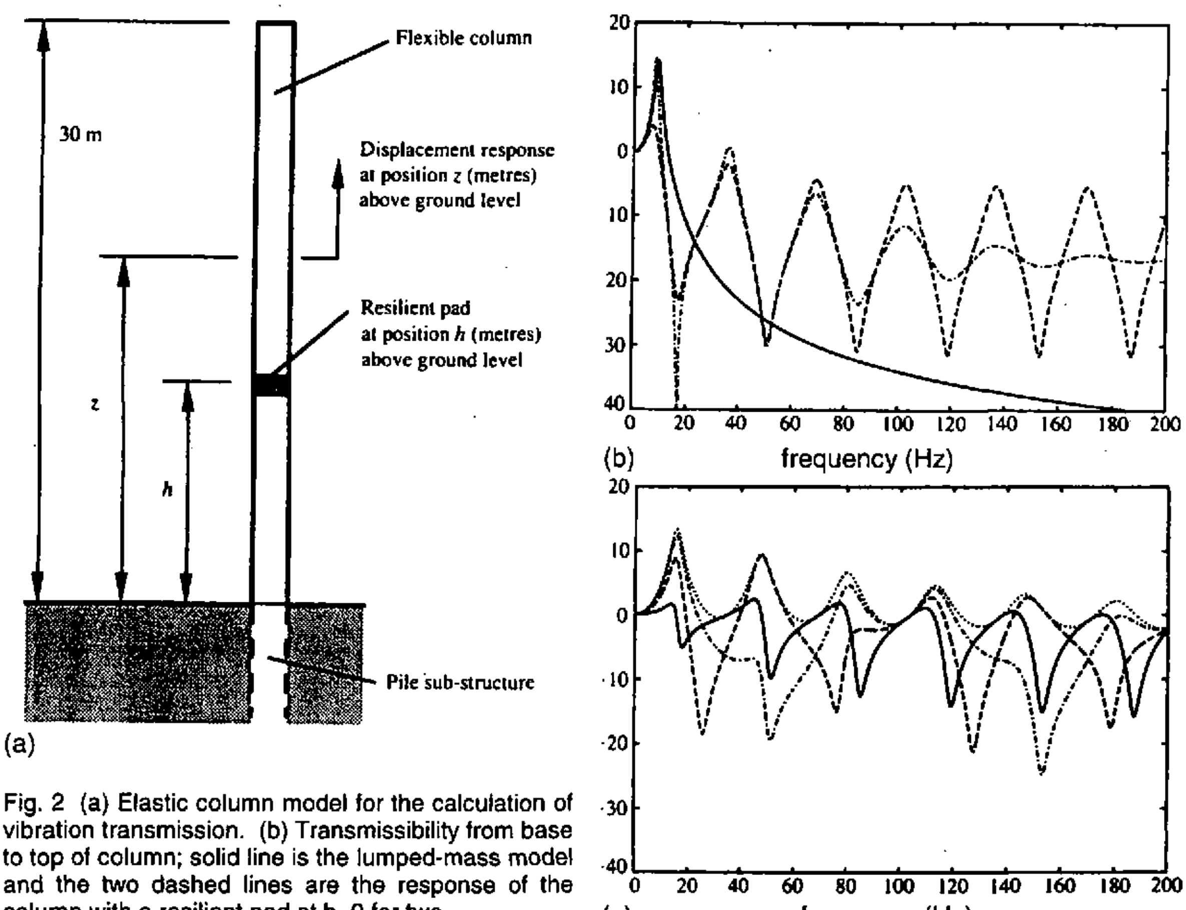

Fig. 2 (a) Elastic column model for the calculation of vibration transmission. (b) Transmissibility from base to top of column; solid line is the lumped-mass model and the two dashed lines are the response of the column with a resilient pad at h=0 for two different damping models. (c) A column rigidly fixed to a vibrating pile. Transmissibility is calculated at various points up the column but now by comparison with the pile cap vibration *in the absence of the column* to show that vibration levels are reduced owing to effect of added mass. For details see [7].

Broadly speaking, the mass-on-a-spring model begins to fail when the first internal resonance frequencies are encountered. A useful method for dealing with building flexibility generically (since all buildings are different) is to consider models of infinite length [9,10]. The computational effort required to produce a model of infinitely-long building is, surprisingly, much less than that required to model a finite building. The results are also easier to interpret. A diagrammatic representation of such a model is given in Fig. 3.

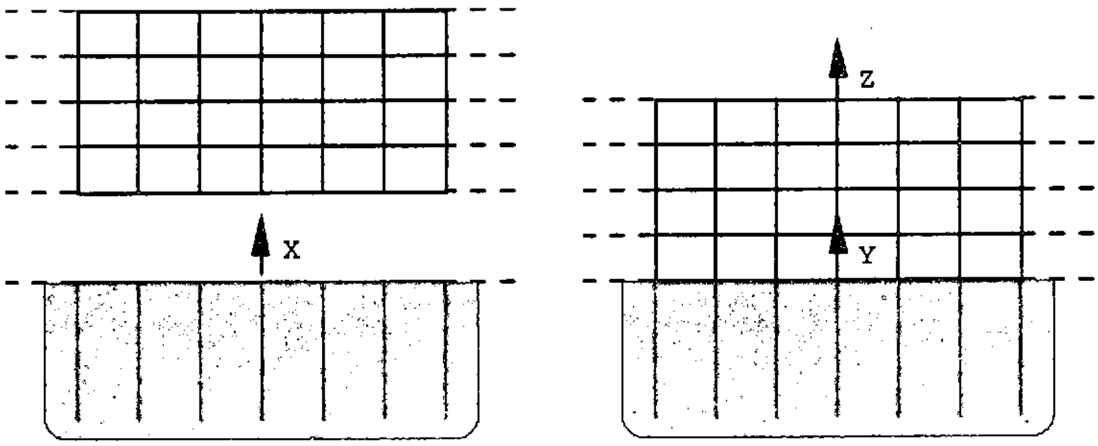

Fig.3. A building model and a piled foundation showing the vibration input displacement X of the pile cap before 'attaching' the building and two possible output displacements Y and Z

2. The building mass modifies vibration levels in the ground. Without isolation a rigid body placed on flexible moving ground would have the effect of locally reducing vibration levels. The inertia of the building holds the ground still, as it were. This effect can be seen for a single column in Fig. 2(c). The effect is reduced if there is flexibility in the building and decoupling the building from the ground through base isolation actually increases vibration levels in the ground. It is often argued that this effect alone might nullify any benefit of base isolation and this is the subject of ongoing research [11, 2]. In order to quantify this effect models must be made which take into account the coupling of the building with the ground. transmissibility might then be measured between Z and X in Fig. 3 rather than between Z and Y as is conventional.

3. The building is supported on the vibrating ground at more than one point. With such a multi-input system the vibration response measured at a single point is the resultant sum of vibration transmitted via many different routes. For the purpose of measuring transmissibility it is therefore sensible to attempt to isolate the single nearest input and this can be done rather crudely using spectral analysis. This gives rise to the concepts of 'direct transmissibility' and 'indirect transmissibility' described by Newland et al [7,9] but these are of limited practical use. The primary difficulty is that we do not know what the inputs actually are without measuring force transmission into the building at every point of contact with the ground.

4. Measured vibrations depend on the location of the measurement point. If, for instance, measurements are made close to a nodal point for a given mode of vibration then low vibration levels will be observed, especially if the mode is especially well excited by the vibration source. This effect can be seen in the column model shown in Fig.1(b). Correct choice of measurement point is not easy. It is believed that a more objective measure of vibration isolation performance can be achieved by considering power flow [11] and this is the subject of ongoing research.

5. Vibration in the buildng is re-radiated into the ground. This effect is not unrelated to the added mass effect described above. There is a two-way coupling between the building and the ground and a correct model must consider vibration transmission in both directions. The procedure for producing accurate models of this kind is difficult since models of semi-infinite elastic continua require careful thought. The boundary-element method is possibly the only method of getting reasonable results.

6. Bridging and entrapped air. The effectiveness of any isolation system will be compromised if the resilient element bis short circuited by a relatively rigid material such as plaster, water pipes, electric cables, ventilation ducts etc [2]. This is known as 'bridging' and the utmost care must be taken to avoid it. It is the plasterers' job to fill in any gaps and the site engineer must prevent them from doing so! The effect of entrapped air is also significant [12]. If there are two parallel surfaces adjacent to each other vibration can be transmitted effectively between them even though they are isolated by resilient elements. Care must be taken at the design stage to avoid this possibility.

The motivation behind continuing work into base-isolation of buildings is not only to gain a thorough understanding of the reasons for the large discrepancy between measured and 'predicted' transmissibility in Fig. 1, but also as a result to devise simple computational models that can be used by foundation designers to make more realistic predictions very quickly.

3 RUBBER VS STEEL

A question that is often asked is whether steel springs provide better base isolation that rubber blocks. The issue is discussed directly by Muhr [13]. There are two principle issues here.
1. Natural frequency.
The mass-on-a-spring model depicted in Fig. 1(a) tells you that the lower the natural frequency of your isolation the better its performance. The measurements in Fig. 1(b) might make you think again. There is a clear rigid-body resonance at 9Hz but other resonances and effect at higher frequencies cloud the picture. Does natural frequency matter? The drive for lower natural frequencies to achieve better isolation may not turn out to be justified but the trend continues. Steel springs can provide a lower natural frequency than rubber for a given static deflection (see below) but there is no reason why rubber bearings cannot also be deisgned to give low a natural frequencies [13].
2. Damping. The mass-on-a-spring model tells you that better isolation performance is achieved with a resilient element with low inherent damping. Using more elaborate models [9,10] it has been fairly conclusively shown that damping in the isolation element really has no effect at frequencies below 200Hz. This can be seen in Fig. 4 where the response of a building to vibration in the ground is calculated using an infinite model similar to that shown in Fig. 3. Above 200Hz it is perhaps beneficial to have low damping but at high frequencies the accuracy of modelling is questionable. Steel springs have low damping and this might be considered to be a slight advantage but there are internal lightly-damped resonances n steel springs which can lead to unwanted high-frequency transmission. This effect is easily dealt with by various means.
The most important practical issue is static deflection, ie the amount by which isolation springs compress under the static weight of a building. For the purposes of arranging services (plumbing, electricity, sewerage etc) it is best to minimize static deflection. One way of acheiving this is to encase your resilient element in a preloaded steel box. The building does not bear on the resilient element until it is nearly complete and small static deflections can be achieved. The additional advantage of this method is that faulty bearings can, in principle, be removed from service. Also adjustments can be made to account for differential foundation settlement. Free access to the bearings is required for this kind of work to be done but in principle the method is applicable to steel or rubber springs.

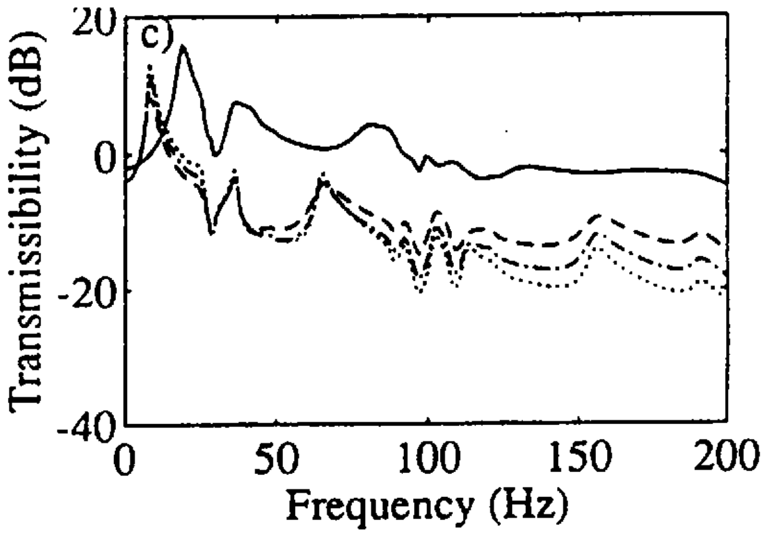

Fig.4 Transmissibility for a building model of infinite extent. The solid line shows the response of the building rigidly attached to iyts piled foundation and the dashed lines show the response of the building on isolation bearings. The three curves (dotted, chained, dahed) show increasing degrees of damping in the bearing. Transmissibility is calculated with reference to the pile caps in the absence of the building. The added-mass effect can be observed in the solid line which falls below zero over a wide range of frequencies.

Steel springs are almost always supplied prestressed. This is a practical solution to the problem of handling and positioning individual springs on site. Several springs are assembled into a box and prestressed. Again the same could be done with rubber bearings but they are easily handled on site without packaging or prestressing and so it is normal for them to be supplied au naturel. It might be sensible for the manufacturers of rubber bearings to supply prestressed packages more routinely. This will also enable the initial creep of the rubber to take place in the factory rather than on site.
Issues such as corrosion, longevity, UV degradation, oil absorption etc are all addressed by the manufacturers of isolation systems and are not usually problematic. Stephenson [14] has found that natural rubber bearings in buildings last more than 100 years.

4 CONCLUSIONS

There is a great deal of work yet to be done in order fully to understand the mechanisms of vibration transmission into buildings. The same can be said of the mechanisms of vibration generation by railway trains and road vehicles. The difficulties arise in the interaction between finite structures and the ground which cannot be modelled as a finite structure. Simple models simply do not explain what is going on and complicated models are unwieldy. It is hoped that some significant breakthrough in understanding will take place in the near future and that base isolation will be taken onto a new plane of effectiveness.

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