INFLUENCE OF BUILDING FOUNDATION DESIGN ON TRANSMISSION OF GROUND VIBRATIONS

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SUMMARY

A small rigid building was analysed for horizontal ground vibration frequencies ranging from 0.5 hertz to 20 hertz. The building response was examined for several shallow foundations ranging from a raft to small footings. Generally it was found that the foundations amplified the ground motion on hard ground but the higher frequency vibrations were attenuated when the building was located on soft ground. If isolating springs are incorporated in the foundation it is possible to increase the range of frequency of the ground vibration over which amplitude attenuation takes place.

INTRODUCTION

In analysing the response of building to earthquake vibrations, it is often assumed that the building is firmly attached to the ground, so that the base of the building is subjected to the same vibrations as the ground beneath. The vibration amplitudes experienced by the building (considered as a rigid mass in this discussion) may be reduced or amplified for some frequencies by using a particular type of foundation and allowing for flexibility of the ground in the analysis, or by placing an isolating spring between the building and the ground. Parmelee et al (Ref. 1), for example, have shown that the response of a single storey structure (idealised as a damped mass-spring system) may be varied as the rigidity of the foundation soil varied.

The idea of isolating buildings from ground vibration is not new, although there seems to be very few cases where it has been applied in practice. Brett (Ref. 2) describes the isolation of buildings from railway vibrations using lead - asbestos as the isolating spring material. Mann (Ref. 3) mentions the isolation of a London building from railway vibrations for which neoprene - asbestos was the spring material. Natural rubber was the spring material used in the case of isolation from railway vibrations of a five floor building as described by Waller (Refs. 4,5). A brief mention of the isolation of a building in the Soviet Union was made in Pravda (Ref. 6). This building was isolated from earthquake vibrations using helical steel springs but no other details are available.

The theoretical literature on vibration isolation and energy absorbing systems for earthquake motions is extensive. Jagadish et al (Ref. 7) review some of these contributions and described a system in which the top floor of a two floor building could be designed to act as a vibration absorber. Lee and Medland (Ref. 8) have studied the effectiveness of a number of bilinear hysteretic isolation systems and demonstrated that building response to earthquakes may be significantly reduced by their use.

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In this paper a study is made of the effects of building foundations and base isolation systems using linear springs, on the building response to ground vibrations. The problem has been idealised as a two degree of freedom system with the lower spring relating to the ground itself. Some implications relating to foundation design and damping of the ground have been examined.

INFLUENCE OF FOUNDATION DETAILS ON BUILDING RESPONSE

The influence of foundation details such as footing size, bearing pressure and rigidity of the ground is most simply demonstrated by examination of a specific example. Analyses of response of a rigid building of 30 m by 30 m plan dimensions and total mass of 4000 Mg have been carried out. Two values of shear modulus, 10 MPa and 200 MPa, were chosen for calculation purposes to represent soft and hard ground respectively. From these values of the shear moduli the respective spring constants were calculated by means of equation (1) (Ref. 9). The damping characteristics for horizontal vibrations are controlled by the foundation details in accordance with equation (2) (Ref. 10).

$$\text{spring constant, } k_x = \frac{32(1-\nu)\ Gr}{(7-8\nu)} \qquad (1)$$

$$\text{damping ratio, } D_x = 0.288\left[\frac{32(1-\nu)}{(7-8\nu)} \cdot \frac{\rho r^3}{m}\right]^{\frac{1}{2}} \qquad (2)$$

where G and ν are the shear modulus and Poisson's ratio for the ground
r is the radius of the circular building foundation or
the radius of an equivalent area of foundations of other shapes.

m is the total mass being supported by a footing of radius r.

Five types of foundation were considered :

(a) a raft foundation covering the whole plan area of the building.
(b) 20 footings each of 20 m^2 area.
(c) 20 footings each of 10 m^2 area.
(d) 10 footings each of 20 m^2 area.
(e) 40 footings each of 5 m^2 area.

The building response for horizontal vibrations, analysed as a single degree of freedom system is shown in Figs. 1 and 2 for some of the foundations mentioned above. For the soft ground, Fig. 1 and the results for foundation types (d) and (c) show that amplification of the vibration amplitude occurs for the low frequency end of the range and attenuation occurs for the higher frequencies. If the dominant ground vibration is within the frequency range of 1 hertz to 6 hertz, this figure indicates that the raft foundation would be the best foundation choice to minimise the displacement amplitudes experienced by the building.

When the frequencies of the dominant ground vibrations exceed about 6 hertz the raft foundation is not the best choice of foundation. Fig. 1 shows that for foundation alternatives containing the same number of footings, those with the higher foundation stress will produce greater attenuation of the high frequency vibrations. Further, if the foundation stress is kept constant, greatest vibration attenuation is obtained with footings designed to have the greatest individual areas.

For the hard ground, Fig. 2 shows that the footing foundations produce a significant amplification of the high frequency ground vibrations . For the raft foundation there is a relatively minor difference between the vibration amplitudes in the building and those in the ground.

In order to minimise the vibration amplitudes experienced by the building, a study of Figs. 1 and 2 indicates that building foundations on soft ground should be designed to incorporate the following features:

(a) the natural frequency of the foundation - ground system should be kept to a minimum and should be well below the dominant frequencies of ground vibration,

(b) the damping ratio should be kept as low as possible.

These features may be achieved by designing the building foundations with the highest possible foundation stress consistent with static design considerations. If it is not possible to achieve a natural frequency below the dominant ground frequencies, as may occur with hard ground, the building vibration amplitudes will be greater than those in the ground. It appears therefore that some control over the magnitude of building vibrations may be exercised by varying the size of the foundations. More control may be exercised however by the inclusion of isolating springs in the foundation.

USE OF ISOLATING SPRINGS

If isolating springs are placed in the foundation (between the building and a foundation block, the problem may be analysed as a two degree of freedom system. It may be shown for the undamped case that the displacement transmissibilities for the foundation block (T_{D1}) and the building (T_{D2}) are as follows :

$$T_{D1} = A_1/X_o = \frac{k_1[(k_2/m_1m_2) - \omega^2/m_1]}{\omega^4-\omega^2\ [(k_1 + k_2)/m_1 + k_2/m_2] + (k_1k_2/m_1m_2)} \qquad (3)$$

$$T_{D2} = A_2/X_o = \frac{(k_1k_2/m_1m_2)}{\omega^4-\omega^2\ [(k_1 + k_2)/m_1 + k_2/m_2] + (k_1k_2/m_1m_2)} \qquad (4)$$

where m_1 is mass of the foundation block

m_2 is mass of the building

k_1 is spring constant for the ground

k_2 is spring constant for the isolating springs

X_o is displacement amplitude of ground motion

A_1, A_2 are displacement amplitudes of the foundation block and building respectively

ω is the ground motion frequency.

The displacement transmissibility for the building (T_{D2}) is plotted in terms of a frequency ratio (ω/ω_n) in Fig. 3 for a particular value of (m_2/m_1). The natural frequency (ω_n) that has been used in the abscissa in the figure is defined as the natural frequency of the foundation - ground system for the case where no isolating springs (k_2) have been installed. The natural frequency is given by

$$\omega_n^2 = k_1/(m_1 + m_2) \tag{5}$$

With the exception of the curve for a (k_2/k_1) value of infinity, the undamped response curves in Fig. 3 exhibit the usual double peak with infinite amplitudes occurring at two principal frequencies.

One conservative way of approaching foundation design to minimise building vibrations, is to consider the falling limb of each response curve at the high frequency end (labelled B in Fig 3) as a lower bound for the desired frequency ratio. This means for example that, for (k_2/k_1) = 1.0, it would be necessary for the value of (ω/ω_n) to exceed 15 if it was desired to keep the displacement transmissibility below a value of 0.1. Such analyses show that in order to achieve low vibration amplitudes in the building, the natural frequency (ω_n) must be quite low in relation to the frequency (ω) of the ground motion. This requirement is necessary to an increasing degree as the mass ratio (m_2/m_1) increases and as the ratio of spring constants (k_2/k_1) increases. In applying this design approach it would be quite difficult to produce any effective reduction in building vibration amplitudes particularly for low frequencies. Further analyses show that for a particular foundation design, the vibration amplitude for the foundation block will exceed those for the building. This means that effective control of vibrations in the foundation block is even more difficult than control of vibrations in the building.

ADVANTAGES IN USING SOFT ISOLATING SPRINGS

In contrast to the design approach mentioned above, which is anticipated to be relatively ineffective in controlling building vibration amplitudes, the use of soft isolating springs (low values of k_2/k_1) is known to be effective for certain ground frequencies. An examination of the undamped response curves in Fig. 3 shows that the size of the trough between the resonant peaks gets deeper as the ratio of spring constants (k_2/k_1) decreases. The width of the trough, as indicated by the separation between the two principal frequencies, enlarges as the mass ratio (m_2/m_1) increases. The depth of the trough, as indicated by the minimum value of the displacement transmissibility (T_{D2}), is found to vary inversely with the mass ratio (m_2/m_1). These findings confirm that significant reductions in the amplitudes of building vibrations (compared with the ground vibrations) may be brought about by the use of soft isolating springs. However, before this conclusion is examined quantitatively the effect of damping needs to be considered.

Although some damping may be present in the isolating springs (k_2), the most important source of damping is in the ground. That is, damping should be associated with the spring k_1. The two degree of freedom system was examined with the addition of viscous damping acting in parallel with the spring k_1. For this case the displacement transmissibility for mass m_2 was found to be

$$T_{D2} = \left[\frac{k_1^2 k_2^2 \; + \; c^2 k_2^2 \omega^2}{\{(k_2 - m_2\omega^2)(k_1 - m_1\omega^2) - k_2 m_2 \omega^2\}^2 \; + \; c^2\omega^2(k_2 - m_2\omega^2)^2} \right]^{\frac{1}{2}} \qquad (6)$$

where c is the viscous damping coefficient for the ground.

The effect of this damping is shown in Fig. 3 where lines for a damping ratio (D) of 1.0 have been plotted. The damping ratio here is defined as

$$D = c/(2\omega_n \, (m_1 + m_2)) \qquad (7)$$

Fig. 3 shows that damping produces higher values of the displacement transmissibility (T_{D2}) in the trough described above but this effect is significant only for large values of k_2/k_1 (greater than about unity). One very important effect of damping is that the resonant peak at the higher principal frequency is largely removed.

The application of the two degree of freedom analysis to some of the building foundations discussed initially, in order to determine the building response to ground vibrations is illustrated for soft ground, in Fig. 4 for a particular value of the ratio of spring constants (k_2/k_1) and the mass ratio (m_2/m_1). Similar analyses show that only the higher frequency vibrations are attenuated when the building is erected on hard ground. For soft ground however, attenuation is observed for vibrations with frequencies greater than 1 to 2 hertz. For both soft and hard ground, the raft foundation is found to be more effective than the footing foundations in reducing building vibration amplitudes. In some circumstances similar information is obtainable from one degree of freedom analyses, and this simpler approach gives acceptable conclusions when the ratio of spring constants (k_2/k_1) is less than about 0.1.

CONCLUSIONS

In order to minimise the vibration amplitudes experienced by a rigid building without isolating springs, foundations on soft ground should be designed if possible to incorporate the following features

(a) the natural frequency of the foundation - ground system should be kept to a minimum and should be well below the dominant frequencies of ground vibration,

(b) the damping ratio for the ground should be kept as low as possible.

If isolating springs are incorporated in the foundation it is possible to increase the range of frequency of the ground vibration over which amplitude attenuation takes place. In evaluating building response in these cases, a two degree of freedom analysis should be used unless the ratio of stiffnesses of the isolating spring and the ground is less than about 0.1, in which case the single degree of freedom analyses is acceptable.

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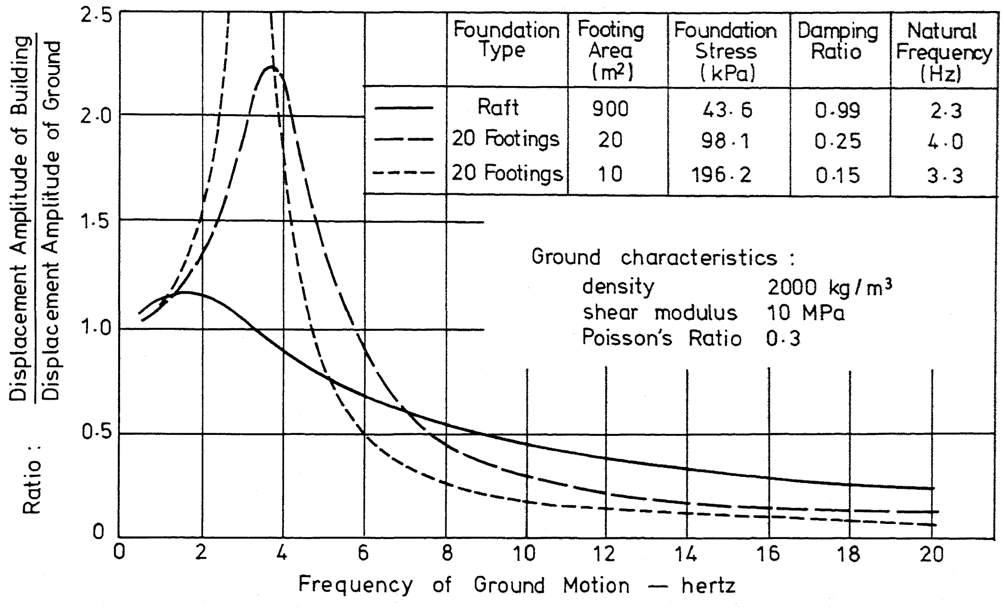
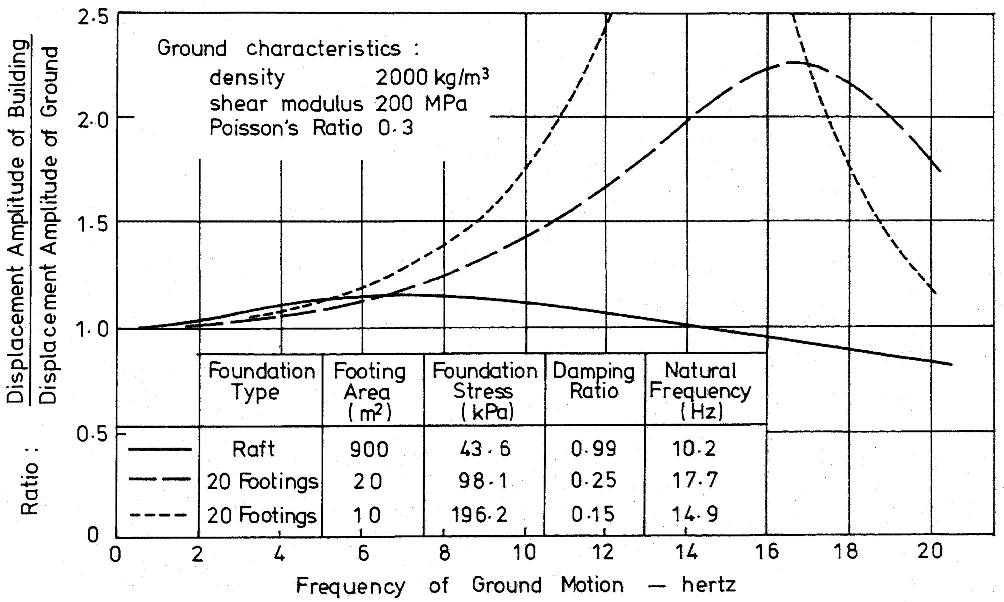


	Foundation Type	Footing Area (m²)	Foundation Stress (kPa)	Damping Ratio	Natural Frequency (Hz)
——	Raft	900	43·6	0·99	2·3
— —	20 Footings	20	98·1	0·25	4·0
- - - -	20 Footings	10	196·2	0·15	3·3

Ground characteristics :
density 2000 kg/m³
shear modulus 10 MPa
Poisson's Ratio 0·3

FIG. 1 BUILDING RESPONSE – SOFT GROUND
SINGLE DEGREE OF FREEDOM ANALYSIS



Ground characteristics :
density 2000 kg/m³
shear modulus 200 MPa
Poisson's Ratio 0·3

	Foundation Type	Footing Area (m²)	Foundation Stress (kPa)	Damping Ratio	Natural Frequency (Hz)
——	Raft	900	43·6	0·99	10·2
— —	20 Footings	20	98·1	0·25	17·7
- - - -	20 Footings	10	196·2	0·15	14·9

FIG. 2 BUILDING RESPONSE – HARD GROUND
SINGLE DEGREE OF FREEDOM ANALYSIS

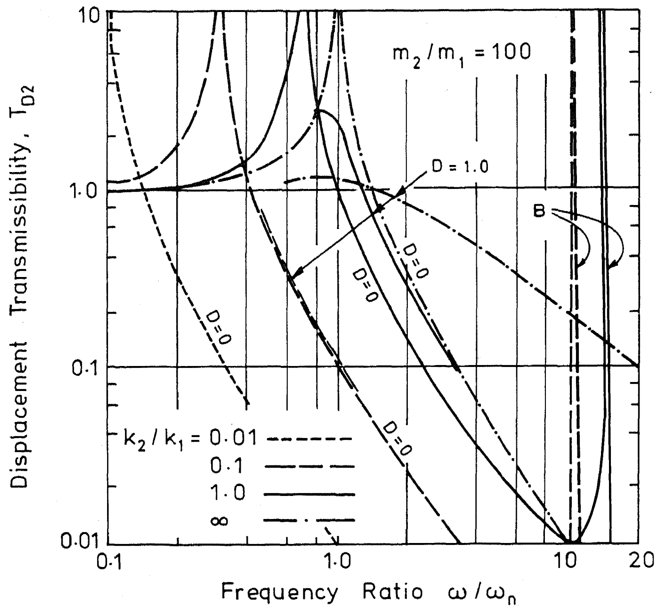
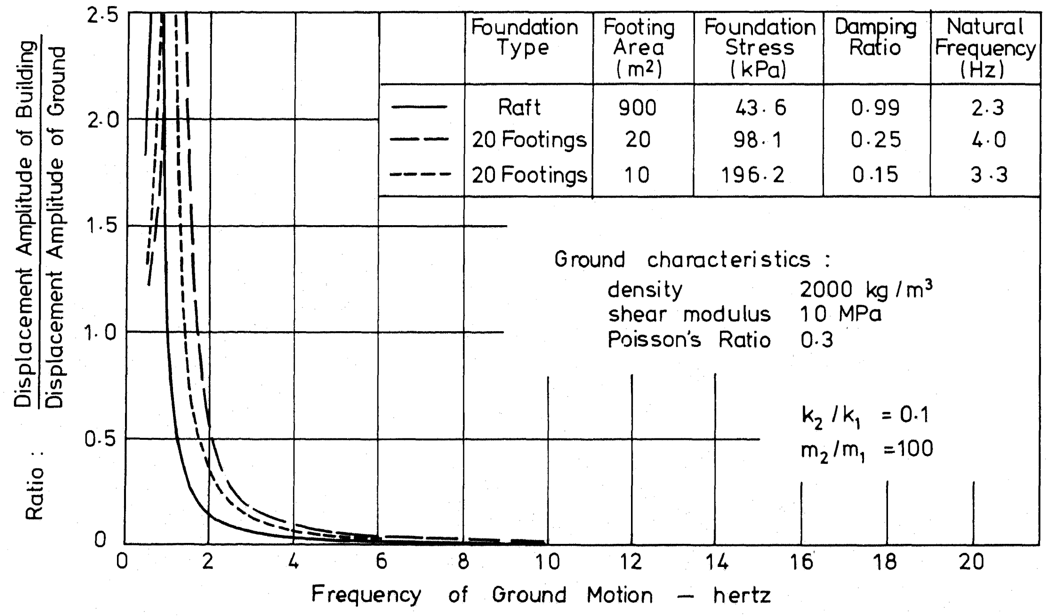


FIG. 3 DISPLACEMENT TRANSMISSIBILITY FOR BUILDING



	Foundation Type	Footing Area (m^2)	Foundation Stress (kPa)	Damping Ratio	Natural Frequency (Hz)
———	Raft	900	43·6	0·99	2·3
— — —	20 Footings	20	98·1	0·25	4·0
- - - -	20 Footings	10	196·2	0·15	3·3

Ground characteristics :
density 2000 kg/m^3
shear modulus 10 MPa
Poisson's Ratio 0·3

$k_2 / k_1 = 0{\cdot}1$
$m_2 / m_1 = 100$

FIG. 4 BUILDING RESPONSE — SOFT GROUND
TWO DEGREE OF FREEDOM ANALYSIS