
Mechanical and Electrical Equipment

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1. INTRODUCTION

Past earthquakes around the world have demonstrated the need for the aseismic design of mechanical and electrical equipment to mitigate property losses and protect life during a severe earthquake event. Equipment located in the buildings is subjected to modified and often amplified earthquake motions (Fig. 1). In particular equipment that has been isolated to minimise the transmission of vibrations to the building and its occupants under normal operation can experience significant amplifications if the natural frequencies of the isolated equipment and building are closely spaced and resonance develops.

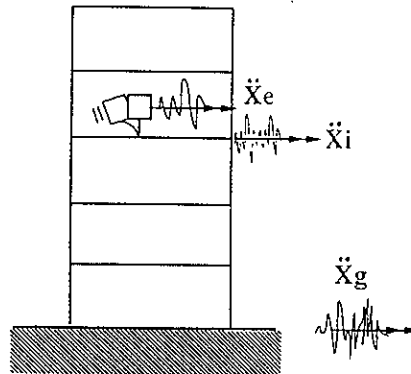


Figure 1 - Transmission of ground vibrations within a building

Section 5 of the new Australian Earthquake Loading Standard, AS1170.4 (Ref 1) provides guidance for the design of mechanical and electrical equipment to resist earthquake loading.

These provisions are critically reviewed in this paper and compared with the results from an analytical study carried out using a two degree of freedom model subjected to earthquake ground motions.

An alternative design method to Section 5 of AS1170.4 for calculating earthquake forces on equipment is presented based on the results from the analytical investigation.

2. AS1170.4 SECTION 5

AS1170.4 provides the following equation for the calculation of earthquake forces in mechanical and electrical equipment:

$$F_p = aI S A_x A_c C_c W \quad (1)$$

where:

a	=	acceleration co-efficient
I	=	importance factor
S	=	soil factor
A_x	=	height amplification factor (1.0 - 2.0)
A_c	=	attachment amplification factor (1.0 - 2.0)
C_c	=	component earthquake co-efficient (0.6 - 2.0)

The physical interpretation of this equation is shown in Fig. 2. The product (aIS) can be considered the earthquake acceleration at ground level which is transmitted up the structure and modified by the factor A_x at higher levels. The product $aISA_x$ can be considered the floor acceleration which excites the equipment expressed as a proportion of gravity at the level under consideration.

The response of the equipment is modified from the floor response by the factor, A_c , to account for resonance effects between the building and the equipment, and the factor, C_c , to account for the ductility and importance of the equipment.

The product ($aI SA_x A_c C_c$) is the effective acceleration of the equipment expressed as a proportion of gravity.

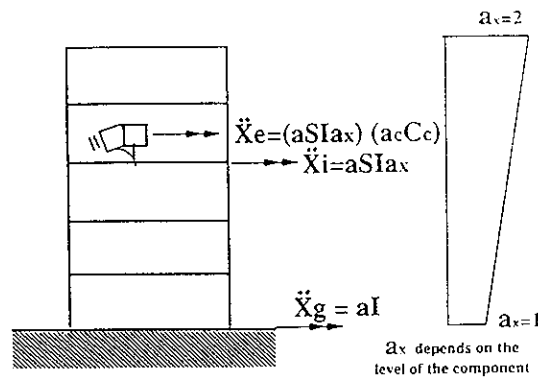


Figure 2 - Effective acceleration levels, Section 5, AS1170.4

The expression for F_p has been formulated so that design professionals responsible for the functional design of such items can use this section of AS1170.4 independently of both the structural framing system and the dynamic characteristics of the building. The appropriateness of the method is investigated using an analytical model described in the following section.

3. ANALYTICAL STUDY

A two degree of freedom model was used to simulate the response of spring mounted equipment to earthquake ground motions (Fig. 3). The first degree of freedom represented the dynamic characteristics of the first mode shape of the building whilst the second lumped mass dashpot and spring system modelled the spring mounted equipment. This model could be reduced to a single degree of freedom if the equipment was rigidly attached to the building floor.

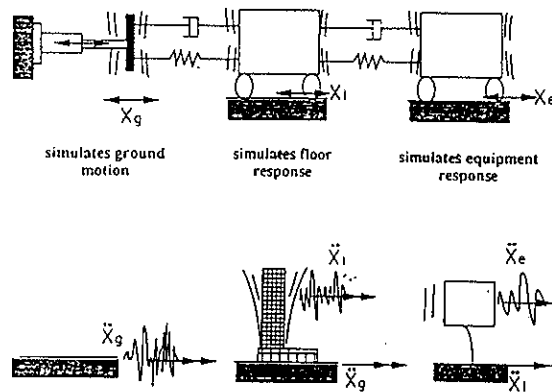


Figure 3 - Analytical two DOF model

A spring with a nonlinear capability was introduced to model the stiffness of the building. Two cases were considered, one where the building remained elastic under the extreme earthquake event ($R = 1$) and the other where the building responded inelastically with a structural response factor, R , equal to 4. Three different building heights were considered reflecting a 5, 10 and 20 storey regular building. The damping assumed in the building was 5%.

A wide range of equipment mounting systems were modelled with natural periods ranging from 0.1 seconds to 2.0 seconds and with a critical damping ratio of 0.5%.

The well documented El Centro earthquake of 1940 (Ref. 2) and two synthetic earthquakes with different durations but compatible with the $S = 1$ response spectrum presented in AS1170.4 were used in the analyses. (Fig. 4).

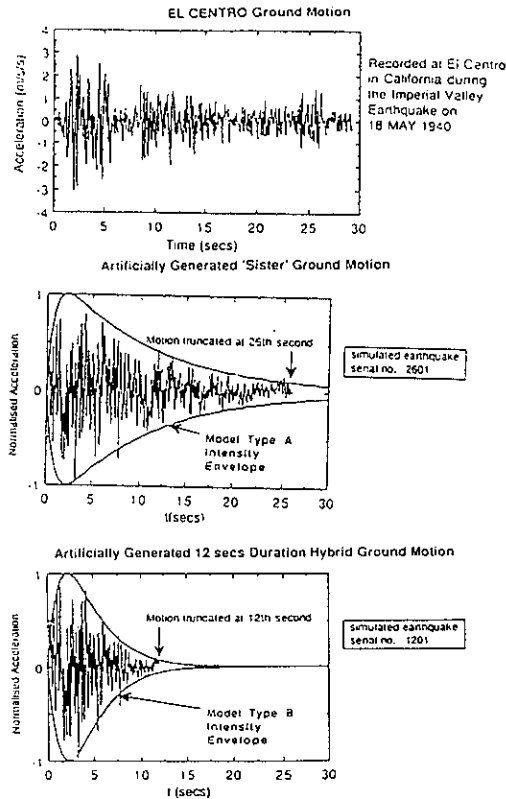


Figure 4 - Earthquake ground motions

The nonlinear computer program, DRAIN 2D, (Ref. 4) was used to perform the analyses.

The earthquake ground motions were scaled such that the effective peak ground acceleration was 0.10g. The scaled ground motions were then multiplied by the participation factor of the respective buildings so that the earthquake accelerations calculated would be representative of the motion at the top of the building.

The maximum accelerations of the equipment located at the top of the building under earthquake excitation were then calculated for the 5, 10 and 20 storey buildings behaving elastically ($R = 1$) and inelastically ($R = 4$). The results are plotted in Fig. 5 (reproduced from Ref. 5) for the El Centro ground motion. The equivalent equipment acceleration levels calculated using Section 5.3 of AS1170.4, with $A_x = 2$ and $C_c = 2$ have also been presented in Fig. 5 for comparative purposes.

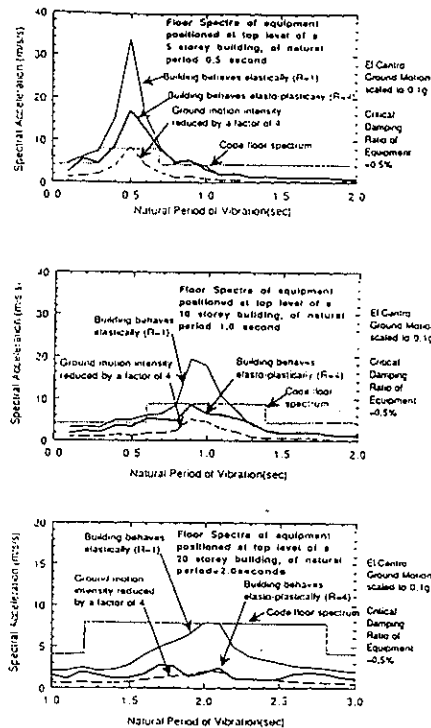


Figure 5 - Floor spectra for equipment located at the top level of building (after Ref. 5)

The analytical study clearly demonstrates that the earthquake response of the equipment is very dependent on both the dynamic characteristics and the extent of inelastic behaviour of the building.

The equipment design accelerations calculated using AS1170.4 were generally conservative provided that the equipment and building material frequencies were not closely spaced. For rigidly mounted equipment the study demonstrated that the code approach was quite conservative.

Further, the analytical study demonstrated that the equipment design accelerations significantly reduced as both the building height and inelastic demand increased. In contrast, the accelerations calculated using Section 5 of AS1170.4 remained effectively constant. (It should be noted that this study considered only the first mode response of the building. Preliminary studies have shown that the higher modes will increase the equipment response in the order of 20% for the 10 storey and 35% for the 20 storey buildings.)

The AS1170.4 approach was unconservative for the situation where the building and equipment natural frequencies were nearly equal, resulting in some resonance. In such situations the equipment accelerations could be significantly greater than the code predictions for short buildings, particularly if the building response remained in the elastic range.

The following section discusses an alternative and what is considered a more rational procedure for calculating the earthquake forces developed in equipment by including the effects of the building response.

4. ALTERNATIVE DESIGN METHOD

An alternative design method to Section 5 of AS1170.4 involves the calculation of the earthquake acceleration of the floor under consideration (using either Section 6 or 7 of AS1170.4) and then to apply a dynamic amplification factor to account for the interaction between the building and equipment.

The design earthquake floor acceleration can be considered equal to the design storey induced earthquake force divided by the storey mass (these storey forces can be calculated using the static method of Section 6, AS1170.4 or the response spectrum method of Section 7, AS1170.4). The resulting floor acceleration directly accounts for the dynamic characteristics and inelastic behaviour of the building. It is recommended that the storey acceleration at any level be interpolated from the design storey acceleration at the top of the building and the acceleration at ground level given by a1 (Fig. 6).

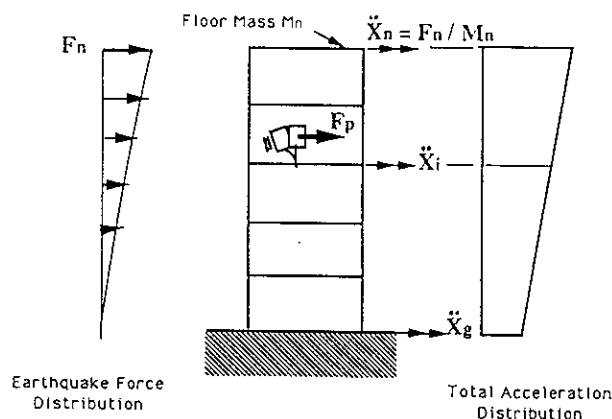


Figure 6 - Effective acceleration levels, Section 6, AS1170.4

A modification needs to be made to the top storey acceleration for buildings in which the actions caused by wind loads are greater than those caused by the earthquake loads. In such cases, the building has some overstrength capacity and the top storey acceleration should be scaled by the ratio of the wind to earthquake overall building base bending moment at the ultimate limit state. This modified top storey acceleration need not exceed the acceleration value corresponding to elastic behaviour ($R = 1$).

The dynamic amplification factor for equipment mounted at elevation in buildings is dependent on the ratio of equipment to building frequency. Fig. 7 shows a suggested amplification factor based on an ensemble of floor motions representing a variety of earthquake ground motions, building heights and degrees of inelastic building behaviour. The shape of the curve is similar to the response of a single degree of freedom model subjected to pure harmonic excitation.

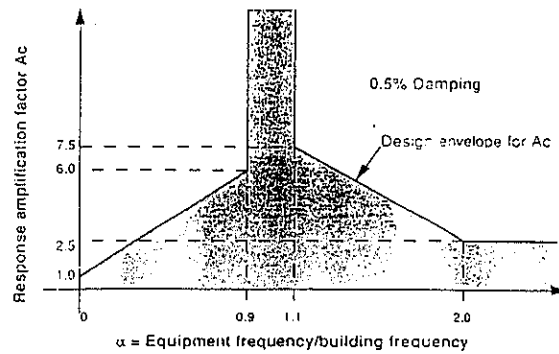


Figure 7 - Normalised floor spectrum

It is acknowledged that the method presented could underestimate the equipment response when the building and equipment modes are closely spaced (Ref. 5). However, it is strongly recommended that the equipment frequency be modified if it is in the range of 0.75 to 1.3 times the building frequency to avoid the significant amplification associated with resonance and cross coupling of modes.

The resulting earthquake force on a piece of equipment, F_p , can be expressed as follows:

$$F_p = \ddot{X}_i a_c' M_c \quad (2)$$

where:

\ddot{X}_i	=	floor acceleration
a_c'	=	dynamic amplification factor
M_c	=	equipment mass

A comparison between the two methods for calculating earthquake induced forces in equipment is illustrated with the following example.

5. CASE STUDY

A 20 metre tall, 5 storey, reinforced concrete frame building located on stiff soil in Melbourne has some spring mounted rotary equipment located on the fourth floor. The natural frequency of the spring mounted equipment is 4 HZ. The design earthquake forces on the equipment using the two methods can be calculated as follows:

i. AS1170.4 Section 5

$$F_p = (a I S A_x) (A_c C_c) W_c$$

a	=	0.08 (Melbourne)
s	=	1.0 (Stiff soil)
I	=	1.0 (non-essential facility)
A_x	=	$1 + 4/5 = 1.8$ (fourth floor)
A_c	=	2.0 (since $T_c/T = \frac{0.25}{0.43} = 0.6$)

$$\begin{aligned}
C_c &= 2.0 \text{ (rotating equipment)} \\
F_p &= (0.08 \times 1.0 \times 1.0 \times 1.8) (2.0 \times 2.0) W_c \\
&= 0.14 \times 4 W_c \\
&= 0.56 W_c \\
F_p &= 0.50 W_c \text{ (} F_p \geq 0.5 W_c \text{)}
\end{aligned}$$

ii. Alternative Design Method

$$\begin{aligned}
F_p &= \ddot{X}_i a_c \cdot M_c \\
\ddot{X}_i &= 0.08g \text{ (using AS1170.4 Section 6, } R = 4.0, T = 0.43 \text{ seconds)} \\
a_c &= 3.9 \left(T/T_c = \frac{0.43}{0.25} = 1.7 \right) \\
F_p &= 0.08 \times 3.9 \times W_c \\
F_p &= 0.31 W_c
\end{aligned}$$

In this example, the method presented in AS1170.4 Section 5 produces design earthquake forces in the order of 60% larger than the alternative method developed from the analytical studies.

6. CONCLUSIONS

Two methods have been presented for the calculation of earthquake induced forces in mechanical and electrical equipment mounted at elevation in buildings. AS1170.4 Section 5 is a convenient design method for mechanical and electrical engineers for the calculation of earthquake induced forces on equipment, since no reference to the building properties is required. Analytical studies have demonstrated that the method specified in AS1170.4 Section 5 is generally conservative provided that the natural frequencies of the equipment and building are not closely spaced.

An alternative method based on the analytical study which considers the dynamic characteristics and energy absorption capabilities of the supporting building has been presented. It is considered that the alternative method provides more realistic design forces for mechanical and electrical equipment compared to the method presented in Section 5 of AS1170.4.

7. ACKNOWLEDGEMENT

The advice and financial support provided by G.P. Embelton and Co. Pty Ltd is gratefully acknowledged.

8. REFERENCES

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