Vibration Isolators as a Tool to Prevent Earthquake Damage

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SUMMARY

The objective of earthquake resistant design for a nuclear power plant is to be able to shut down safely during a major shock, and also to be able to restart afterwards, in such a way that no undue damage occurs to the structure and equipment. If a conventional method of design is followed, the additional cost of achieving earthquake resistance may be excessively high because, in the conventional philosophy of design, the entire structure and installations are subject to the full shaking of ground motion, causing large deformations and stresses throughout. The structure itself is expected to absorb the full earthquake energy by developing plastic hinges and cracks at critical points. Although the structure is not expected to collapse, stresses are allowed to go into the plastic range, and secondary elements like pipes, installations, etc., may undergo severe damage, endangering public safety and requiring excessive cost of repair.

When vibration isolation is used, however, all of these undesirable effects are avoided, and the earthquake safety of the nuclear power plant is ensured at a much less cost and with more reliable accuracy, because the ground motion energy is not transferred into the superstructure and is absorbed at the foundation level by means of appropriate shock absorbers. Neoprene pads and spring-dashpot systems are ideally suitable for this purpose.

The basic idea behind vibration isolation is to modify the natural period of vibration of the structure, to be markedly different from the predominant period of the ground motion and thus to reduce significantly the earthquake response of the structure. In fact, when vibration isolators are used, the entire building behaves almost like a rigid body, causing no internal stresses and displacements.

Helical springs and dashpots are proven to be an excellent arrangement for vibration isolation for all three directions of vibration. Neoprene pads, however, provide vibration isolation only in the horizontal direction. The pads are very stiff in the vertical direction and therefore the structure is exposed to severe internal stresses under vertical and rocking motions. It is shown explicitly, by means of a simple numerical example, that the underlying soil, however soft it may be, does not at all assist the neoprene pads in the vertical direction. The additional cost of earthquake resistance of a nuclear power plant may be in the order of 40% to 60% of the overall cost when conventional principles are used. This drops down to 3% to 6%, however, when vibration isolators are used.

1. INTRODUCTION

1.1 Conventional Design

The conventional principle of earthquake resistant design for reinforced concrete structures is to allow the primary structural elements to undergo large plastic deformations during a strong ground motion. The stresses are expected to go beyond the elastic range and plastic hinges and minor cracks are expected to develop at critical points such that the main load carrying system does not collapse. All nonstructural elements, such as plasters, partitions, piping system, etc., however, may be damaged, requiring extensive repair.

It is evident that the conventional principle of earthquake resistant design not only calls for additional cost due to the requirements of ductility of the load carrying elements, but also endangers the immediate and safe use of the building after a major earthquake, because of the possible extensive damages which occur in the nonstructural elements. There are other disadvantages of the conventional design principle:

a) Construction of highly deformable structural and nonstructural elements is more difficult and expensive.

b) If secondary elements, like the piping system in a nuclear power plant, fail to function properly, not only does the cost of repair become prohibitively excessive but also the safety of the public may be exposed to great danger.

c) Inelastic design, when compared with elastic design, involves greater complexity and approximations in material stresses, structural behaviour, and mathematical procedures.

1.2 Vibration Isolation

When vibration isolators are used under the foundation, however, almost all of the disadvantages of the conventional design principle are avoided. The energy of the ground motion is absorbed basically by the vibration isolators at the foundation level and the structure behaves almost like a rigid body with little or no relative storey displacements. The basic idea in vibration isolation is that the natural period of vibration of the structure is increased to a level much greater than the predominant periods of the earthquake ground motion. The dampers reduce the amplitudes of displacements. Consequently, all material stresses remain always within the elastic range.

2. TYPES OF VIBRATION ISOLATION

A variety of shock absorbing devices may be used as vibration isolators, such as mechanical (Refs. 1 and 6), neoprene pads (Refs. 7 to 10) and spring-dashpot systems (Refs. 11 to 14). The basic idea behind the vibration isolation is to modify the natural period of vibration of the structure and thus to reduce drastically the transfer of ground motion into the superstructure. The concept of vibration isolation is widely used all over the world in connection with machine foundations. Its application, however, to structures and nuclear power plants is relatively new.

The advantages of the use of helical springs and dashpots over the other systems as vibration isolators are discussed in great detail in refs. (13) and (14). Helical springs and dashpots are ideally suitable for the vibration isolation of nuclear power plants, since the isolation is efficiently achieved in all three directions of vibration. The neoprene pads provide vibration isolation only in the horizontal direction and they are ineffective in the vertical direction.

3. ISOLATION OF THE WHOLE NUCLEAR ISLAND

A nuclear power plant consists of various important structures like the reactor building, the fuel building, safequard building, and the turbine building, etc. on the "nuclear island". These buildings adjacent to each other are interconnected by a network of electrical and mechanical installations and also by heating and other piping systems. If only one of these buildings is vibration isolated, there may be undesirable relative displacements between the adjacent buildings resulting in a possible damage of the installations. If the complete foundation raft of the whole nuclear island is vibration isolated, however, as shown in fig. 1, the whole island behaves like a rigid body during a strong ground motion and practically no relative displacements occur among the individual structures, thus the installations remain undamaged. In any case, the critical installations and piping elements, especially those extending from an isolated to a non-isolated building, should be supported and detailed by means of special energy-absorbing restrainers as described in reference (15).

4. MATHEMATICAL FORMULATION

For the purpose of determining the best suitable arrangement of helical springs and dashpots, the superstructure and the underlying soil are idealised into a planar or spatial mathematical model. It is normally sufficient to reduce the structure into as simple a mathematical model as possible, consisting of a sufficient number of lumped masses interconnected with one or two dimensional structural elements, since no complex behaviour occurs in the superstructure. Typical mathematical models are given in reference (12).

The subsoil medium may be represented by means of either an assemblage of finite elements or a series of lineal elastic springs. In this presentation, for reasons of simplicity in determining the effects of local soil conditions, the subsoil is represented by means of equivalent elastic springs. After the mathematical model is decided, the time history response to any selected ground motion may be determined by means of a numerical integration technique.

A typical one-mass mathematical model and its response to the horizontal components of the 1940 EL Centro ground motion are illustrated in figures 2 and 3. Similarly, the mathematical model of a seven-story building and its acceleration response are shown in figures 4 and 5 (ref. 12). It is seen that the response is significantly reduced when an appropriate arrangement of helical springs and dashpots is used. A more sophisticated mathematical model of a reactor building is illustrated in figures 6 and 7.

5. INFLUENCE OF SOIL CONDITIONS

5.1 Idealisation Scheme

In order to demonstrate the influence of local soil conditions on the vibration isolation, a simple numerical example is studied. The mathematical model of a typical nuclear reactor building given in reference (16) is idealised into a two-mass assembly of structure and soil as shown in figure 8. A single spring is sufficient to represent the vertical action of the soil, because only the tendency of the influence of the soil condition is investigated. Similarly, the superstructure is reduced to a single mass, because the whole structure moves like a rigid body causing almost no stresses or strains in the superstructure. Further, the purpose of this particular analysis is only to investigate the changes of natural periods of vibration due to different soil conditions.

5.2 Numerical Example

The total weight of the reactor building is given as W_2 = 45 000 ton in reference (16). The total weight of the lower foundation, combined with the phase in mass of the soil, is assumed as W_1 = 10 000 ton. The total horizontal stiffness of the reinforced elastomer bearing pads is calculated from equation (1) of the reference as $K = 1.12 \times 10^5$ ton/m. Assuming the vertical stiffnesses to be 800 times greater than the horizontal stiffnesses, the total vertical stiffness becomes $k_2 = 9 \times 10^7$ ton/m. Two different soil conditions will be considered:

a) "Soft soil" representing fine dense sand with an allowable bearing stress of 25 ton/m^2 requiring a mat foundation area of about 1800 m^2. Assuming the modulus of subgrade as k = 5 kg/cm^3 the total vertical stiffness becomes $k_1 = 0.9 \times 10^7$ ton/m.

b) "Hard Soil" representing dense gravel or rock-like soil with an allowable bearing stress of 35 ton/m^2 requiring a mat foundation area of about 1300 m^2. Assuming the modulus of subgrade as k = 22 kg/cm^3, the total vertical stiffness becomes $k_1 = 2.84 \times 10^7$ ton/m.

5.3 Changes in the Natural Period of Vibration

The natural period of vibration of a two-spring model is

$$T = 2\omega/\pi \quad \text{and} \quad \omega = \left(\frac{B \mp \sqrt{B^2 - 4A}}{2}\right)^{\frac{1}{2}} \tag{1}$$

where

$$A = \frac{k_1 k_2}{m_1 m_2} \tag{2}$$

$$B = \frac{k_1 + k_2}{m_1} + \frac{k_2}{m_2} \tag{3}$$

Incorporating the above mentioned numerical values in these expressions, the periods of vibration are obtained for "soft" and "hard" soil conditions as, T = 0.162 sec, and T = 0.098 sec, respectively. For infinitely rigid subsoil condition, the natural period of vibration in the vertical direction is T = 0.045 sec. It is seen that the influence of soft soil condition on the change of natural period of vibration is very insignificant.

5.4 Discussion

The soil under most nuclear power plants is hard soil. Even in the case of soft soil, its contribution to the vibration isolation is practically nil. In the case of neoprene pads, no vibration isolation is supplied for vertical and rocking motions of the structure, since neoprene pads are very stiff in the vertical direction. The claim that the subsoil conditions may assist the neoprene pads in the isolation of vertical motions is thus unquestionably disproved by the above numerical example.

Earthquakes generate three dimensional motions which may contain, close to the epicentral region, vertical accelerations as high as those in the horizontal direction. The structures possess inherently greater strength in the vertical direction thus being sensitive to higher frequency motions. Since the vertical components of earthquake motions contain relatively higher dominant frequencies, in order to prevent any quasi-resonance condition, the nuclear power plants must be appropriately isolated also in the vertical direction.

Helical springs and dashpots are ideally suitable for this purpose, since they may provide any desired amount of flexibility and damping in all three directions. Usually, the horizontal stiffness of helical springs is in the range of 2 to 5 times those in the vertical direction. The dashpots may supply damping values as high as 20% to 30% of that of the critical damping ratio. The coefficient of viscosity of the dashpots in the horizontal direction is normally 60% of that in the vertical direction (11, 13).

6. CONCLUSIONS

Some of the basic advantages of vibration isolation by means of helical springs and dashpots may be summarized as follows:

1) The additional cost of incorporating earthquake resistance to a nuclear power plant by the conventional principle may increase the overall cost by as much as 40% to 60%. The double mat foundations, helical springs, and dashpots, however, may increase the cost by only 3% to 6%.

2) A greater degree of safety and assurance is incorporated into the design, when compared with the conventional principle or the neoprene pads. There is no complex nonlinear behaviour, no possibility of slippage of pads even at accelerations as high as 1.0 g to 1.5 g, no possibility of magnified response in vertical and rocking motions.

3) The number of shut-downs in nuclear power plants will be much less, since the acceleration response in all three directions is greatly reduced. Further, a prompt and immediate restarting of the facilities becomes possible after a major earthquake, since neither the vibration isolation system nor the installations are expected to be damaged. In the case of neoprene pads, a difficult and sensitive adjustment procedure is necessary after a major earthquake.

4) Helical springs and dashpots are durable and less sensitive to temperature changes and to physical conditions of the air. It is very easy to replace any defective helical spring or dashpot.

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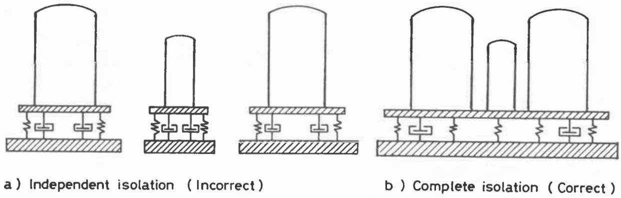

FIG 1.- VIBRATION ISOLATION OF THE NUCLEAR ISLAND

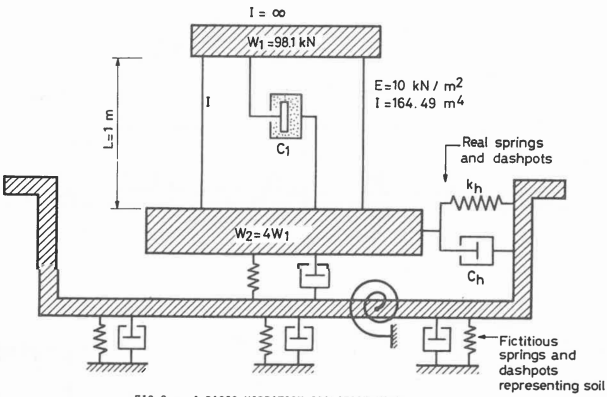

FIG 2.- A BASIC VIBRATION ISOLATION MODEL

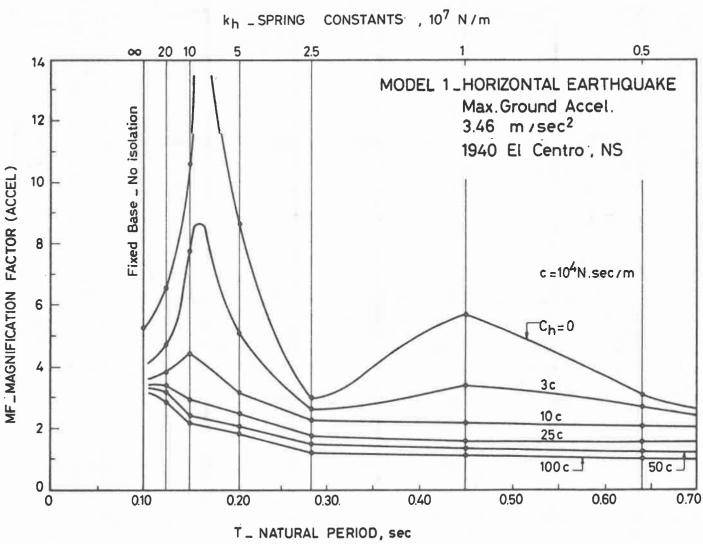

FIG 3.- EARTHQUAKE RESPONSE OF THE BASIC MODEL

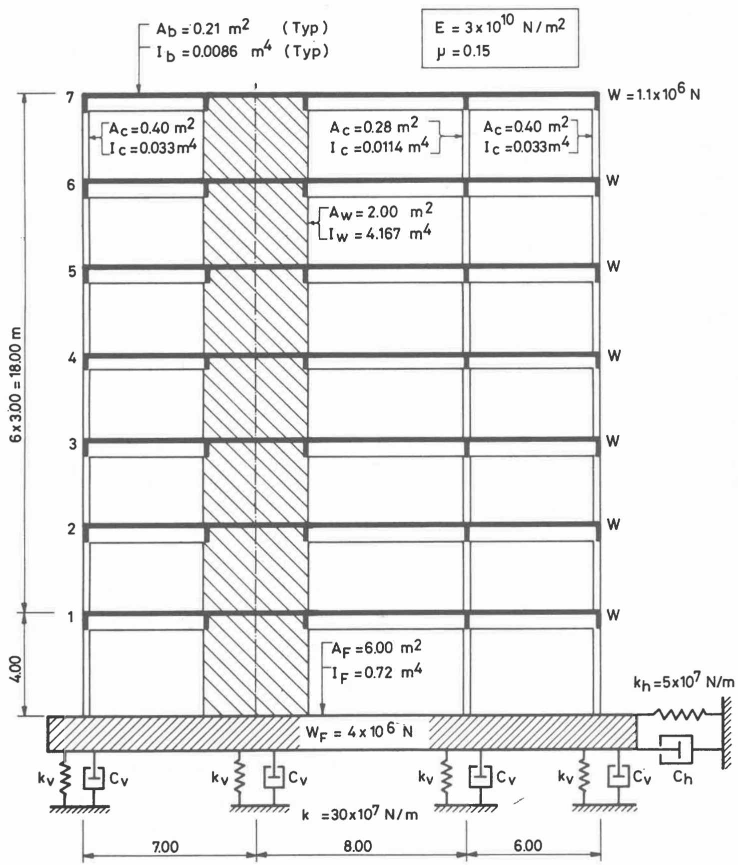

FIG 4.- SEVEN-STOREY BUILDING FRAME

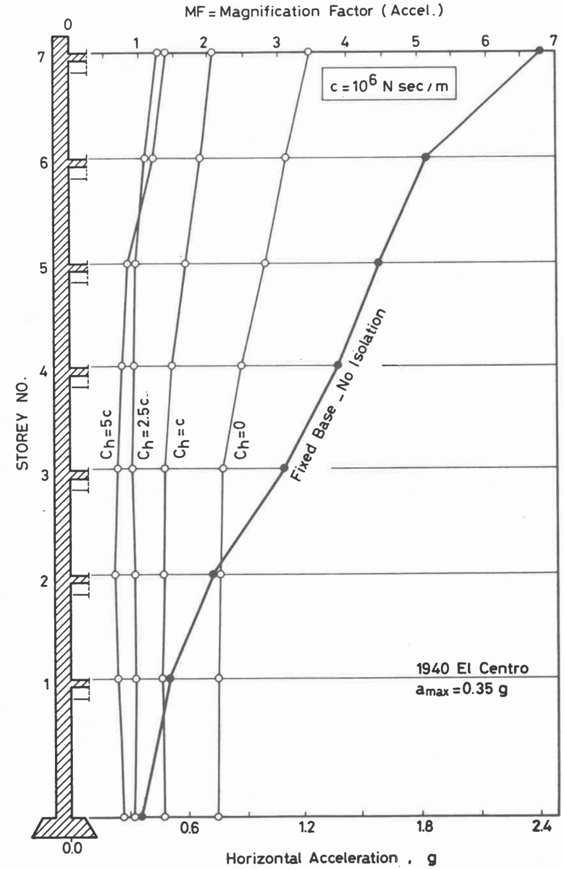

FIG 5.- ACCELERATION RESPONSE OF THE 7-STOREY BLDG

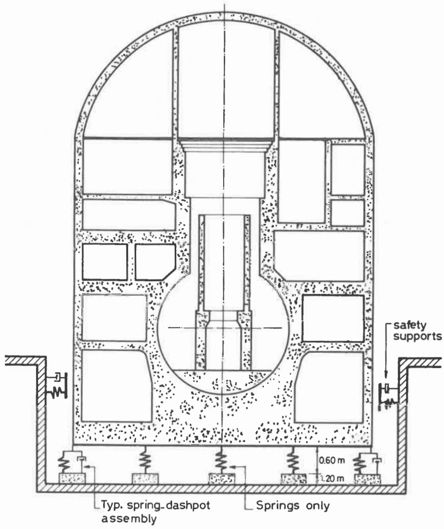

FIG 6.- A TYPICAL REACTOR BUILDING

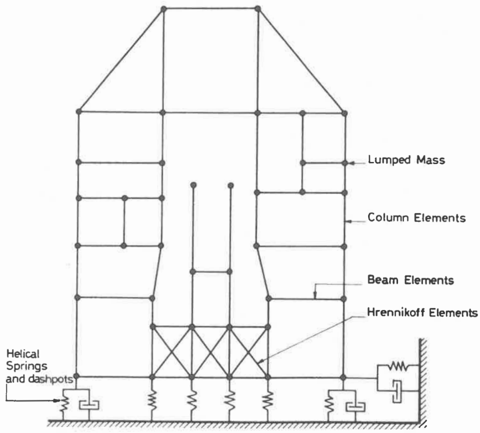

FIG 7.- MATHEMATICAL MODEL OF THE REACTOR BUILDING IN FIG 6.

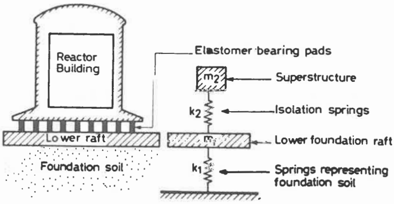

FIG 8.- TWO-MASS ASSEMBLY OF A REACTOR BUILDING