A Numerical Study of Seismic Isolation

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ABSTRACT

The seismic isolation of nuclear structures is an attractive concept and has stimulated a great deal of interest both in practical engineering and research and development. The arguments in its favour suggest a considerable advantage and justify a close examination of the potential and practicability of such systems. This paper presents a summary of isolation systems that have been proposed over the years in the published literature. Three of the most feasible of these systems are selected on the basis of practical considerations of implementation, reliability and other constraints within the nuclear industry. The selected systems are analysed to assess their potential in isolating a simple structure whose masses and springs are chosen to represent the predominant modes of vibration of a reactor building. The results demonstrate some of the dangers of extrapolating results from very simple models. They also show the necessity for considering other sources of dynamic excitation as isolating for one source may make the structure more vulnerable to other sources.

1. Introduction

The design of structures to sustain forces induced by earthquakes is a subject of major concern and a great deal of technical effort has been dedicated to ensuring the integrity of important structures under seismic loading. Two general approaches have been adopted by civil engineers and designers to achieve this aim. The first method employs the conventional procedure of stiffening the structure to cope with the dynamic induced forces. The second method is directed at reducing the forces by special structural elements which may include energy absorbers and isolators that limit the magnitude and frequency of the forces experienced by the structures. This paper is concerned with the second approach with special emphasis for nuclear power plants.

Civil engineers have for many decades considered the isolation or partial isolation of structures from unusual environments. Typical applications have been concerned with vibrations induced by railways and heavy machines. However, it was not until the last decade or so that vibration isolation found practical application in the field of earthquake engineering. Seismic isolation is an attractive concept and it has stimulated a great deal of interest both in practical engineering and research and development. The major arguments that have been put forward for encouraging the consideration of isolation as a practical solution to the problem of aseismic design of structures include:

(a) Isolators reduce the forces induced in the structures and equipment

(b) The use of certain isolators reduces the importance of the uncertainties generally associated with the magnitude and frequency content of the design ground motion.

(c) If the structural forces are limited by the use of the isolators then a standard structural design can be used independent of the seismic environment.

(d) Isolation permits construction of standardised conventional structures in regions of high seismicity where this could not have been previously considered.

(e) The use of isolation devices could have economic benefits in the design of structures in areas of high seismicity.

These arguments suggest a considerable advantage in using seismic isolation devices and justify a closer examination of the potential and practicability of such systems.

The development and implementation of seismic isolation devices is presently an area of active scientific research and development. A number of schemes have been presented in technical publications and some of these have been tested and applied to conventional structures like bridges, schools and high-rise buildings in Europe, Japan and New Zealand. Recent innovative work by a French consortium has broken new ground in suggesting and building two nuclear power plants on isolation bearings.

In this paper isolation devices that have been proposed in the published literature are identified and summarised. Of these, a few systems are selected on the basis of practical consideration, as feasible for use in the nuclear industry. These systems are assessed by analysis of a simple structure comprising lumped masses and springs. The numerical values assigned to the masses and springs are chosen to obtain predominant frequencies of vibration similar to those of a typical nuclear reactor building. The results demonstrate the effectiveness of the selected isolation devices and highlights some of the problems that must be considered when designing such systems.

2. Isolation Systems

A complete review of seismic isolation was performed by Kunar and Maini [1]. From this study five categories of isolation systems were identified:

(1) period lengthening devices

(2) energy absorbing devices

(3) decoupling devices

(4) screening devices

(5) special structural concepts

Period Lengthening Devices:

The dynamic response of structures and their foundations are crucially dependent on the ratio of their fundamental frequencies to the frequency of excitation. The maximum response (resonances) occurs when this ratio is unity. One method of achieving lower structural response (i.e. partial seismic isolation) is to reduce the fundamental frequency of the structures (by employing physical devices like soft springs) so it falls outside the range of frequencies characteristic of strong ground motion. Devices that isolate structures in this way are categorised as period lengthening devices. Such devices include:

(i) Soft springs in the form of helical steel springs, laminates of natural rubber, vulcanised India rubber and neoprene with steel, and air springs.

(ii) Pendulum devices

(iii) Combinations of rubber springs with friction plates, hysteretic dampers and mechanical fuses.

Two practical applications of this system are (i) a three storey reinforced concrete school building in Skopje, Yugoslavia (rubber isolators) (Petrovski et al [2]), and (ii) the Koeberg nuclear power plant complex (rubber isolators in conjunction with friction pads, see fig.1) (Jolivet and Richli [3]).

Energy Absorbing Devices:

The principial purpose of these devices is to reduce structural response by absorbing energy, thereby limiting a build up of vibrations and forces within the structure. Typical practical systems include:

(i) hysteretic dampers

(ii) viscous dampers

(iii) tuned mass dampers

(iv) combination of hysteretic dampers and rubber bearings

Robinson and Greenback [4] reported that a lead extrusion energy absorber has been used for bridges in New Zealand (see fig.2).

Decoupling Devices:

One obvious way to achieve isolation is to directly limit the seismic forces that can be transmitted to the structure by decoupling the structure from its foundation. Possible schemes are to float the structure in water, use friction plates, or use rollers and rockers. The French system (Jolivet and Richli [3]) referred to previously, under period lengthening devices, can also be classified as a decoupling device for high horizontal accelerations.

Screening Devices:

The principle of isolation by screening is to place a barrier between the seismic source and the structure to be protected. Trenches and piles have been suggested in the literature.

Special Structure Designs:

This aspect of the aseismic design of structures does not consider the explicit use of special isolating devices. It concerns design features incorporated into the construction to reduce structural forces. These include:

(i) soft first storey

(ii) double basemat concept

(iii) rod mechanism flexible column system

3. Practical Consideration for Isolation of Nuclear Structures

Any seismic isolation device must satisfy certain fundamental requirements if it is to be considered practical. In the nuclear industry some of these requirements are particularly severe because of the extremely stringent safety standards that must be satisfied.

It is expected that before any seismic isolation is adopted, stringent numerical and laboratory tests or even field tests would have been performed to verify the system. Numerical calculations must take into account any eccentricities and deviations from specifications that may occur during the construction. In the event of minor deviations from expected conditions, it is important that the efficiency and behavioural characteristics of the isolation device are not impaired significantly.

Seismic isolation systems must be guaranteed to function correctly during 30 seconds or so of an earthquake which may occur anytime during the lifespan of the structure. This places a great deal of emphasis on reliability which becomes doubly important when it is recognised that adequate performance of the isolation system is crucial to the integrity of the isolated structure. For this reason, it may be preferable to choose a simple mechanical system rather than a system which relies on a triggering device or external power source. In addition to this, it is important that regular monitoring and maintenance be performed on the system. Routine maintenance should be made as simple as possible if the isolation system requires it during the life of the structure.

One of the more important design requirements for a seismic isolation system is that it must be effective for main earthquake shocks as well as aftershocks assuming no repairs are possible after the main shock. Some devices which rely on plastic deformations for absorption of energy may not meet this requirement. Also some devices that permit permanent off-set displacements after an earthquake (for example, sliding devices), must be designed with this in mind. A further requirement is that after a major earthquake and aftershocks, it must be possible to restore the full effectiveness of the isolation system by replacing devices where and if necessary.

Cost-effectiveness is always an overriding consideration in any project. For a seismic isolation system to be feasible, it must be cheaper overall to construct, monitor and maintain during the life of the structure than a conventional design constructed to withstand the seismic loads. Cost benefits will increase substantially if the isolation system can free the structure design from dependence on the site configuration and the seismic conditions. This will permit the use of a standard structure that would not incur any major modification costs for compatibility with site specific criteria.

A further consideration is related to the question of licenceability. In the nuclear industry the utmost priority is safety, and the licencing bodies are understandably very conservative. Consequently, a great deal of experimental and numerical work must be performed with the isolation system to convince authorities of its behaviour and reliability. All uncertainties must be considered and eliminated wherever possible. It is therefore in the interest of the nuclear supplier to use as simple as system as possible. This will minimise the uncertainties and improve the changes of its acceptance by the licencing authorities.

From the above considerations, the most practical of the identified isolation systems appears to be soft springs or rubber bearings. In practice, this system may be combined with other devices like friction plates or dampers. In this paper, three systems are selected for further assessment: rubber or soft springs; rubber combined with friction elements; rubber combined with hysteretic dampers.

4. Numerical Study of Some Practical Systems

The three practical systems identified above (linear springs, springs with hysteretic dampers and springs with friction elements) are analysed using a simple model of a structure as shown in fig. 3. The masses and the springs of this model are selected to be representative of a nuclear reactor building. Two artificial earthquakes generated to match this USNRC horizontal and vertical spectra are applied simultaneously to the model of the structure and the isolation devices.

Linear Springs:

When soft springs or rubber bearings are used as isolators, the structural response is predominantly a rigid body mode of vibration. The frequency of this vibration is referred to as the isolation frequency. The model shown in fig. 3 was analysed for a range of isolation frequencies. The resulting peak acceleration and displacement responses of mass 2 are plotted in fig. 4 as a function of the isolation frequency. This example demonstrates one of the aspects of seismic isolation that require careful consideration and design. The purpose of this isolation system is to reduce the acceleration response of the structure by shifting the fundamental vibration to a frequency below the predominant earthquake frequencies. In some practical seismic designs, the isolation frequency is selected to be 1Hz or less (Jolivet and Richli [3]). As can be seen from fig. 4, at these frequencies the displacement relative to the ground increases quite significantly. Thus the structure and its connections must be designed to accommodate these large displacements. In addition to this, reducing the first mode of vibration to be less than 1Hz may make the structure more vulnerable to wind loading. It is important therefore to consider other hazards which may not be considered important for conventional designs.

Springs and Hysteretic Dampers:

The same structural model used in fig. 3 was isolated with a model of springs and hysteretic dampers as suggested by Skinner et al [5].

Analyses were performed for different values of stiffness k_1, k_2, k_3 and Q - the damper yield force (see fig. 5). For large values of k_1 (the damper stiffness for small amplitudes) the system is not very effective compared to the spring or rubber on its own ($k_2 = k_1 = 0$). If k_1 is selected such that the isolation frequency for small amplitudes is 5Hz, the response of mass 2 is about 3 times larger than if the rubber isolation alone (tuned to 1Hz) was considered. It is also worth noting that results obtained with different values of Q indicate that if the yield of dampers with large k_1 values is exceeded then it is possible to get higher responses than when yield is not exceeded (i.e. the damper gives adverse rather than beneficial effects). This is due to the sudden large change in stiffness from $(k_1+k_2+k_3)$ to (k_2+k_3). This in itself is a source of dynamic excitation. For small values of k_1 (comparable to k_3) this sudden change is not large and the system becomes more effective.

Springs with Friction Elements:

The model shown in fig.6 was used to represent a spring and friction isolation system typical of that described by Jolivet and Richli [3]. The linear spring was chosen to have an isolation frequency of 1Hz and the coefficient of friction was taken as 0.2. Fig.7 compares the acceleration response of mass 2 with and without the friction elements. The friction elements clearly increase the effective isolation. It should be noted that the peak accelerations exceed the value of 0.2g which would be predicted by a simple 1-DoF resonator. This shows the danger of extrapolating from a very simple model. The friction element is used to limit the horizontal force that can be transmitted to the structure. It will give little or no isolation to the structure for a mode of vibration which is predominantly a rocking of the foundation.

Such a mode of vibration can be excited by a horizontally travelling SV wave. Evidence of such waves playing an important role in damaging structures is discussed by Takada et al [4]. Consider the example of a typical model of a PWR building as shown in fig.8. The reactor building is constructed on a flexible upper raft which is isolated from the lower raft by springs and friction plates as suggested by Jolivet and Richli [3]. This model which is qualitatively similar to ref. [3], was analysed for simultaneous horizontal and vertical seismic excitations. Firstly, the motions were input as vertically propagating waves and then the same motions were phased along the base of the model to simulate an effective travelling velocity of 1000m/sec. The results obtained show that for the travelling waves the horizontal response at the top of the structure was about 3 times larger than when the waves were assumed to be vertically propagating. These results contradict the conclusions reached by Richli et al [5] but are consistent with general trends observed by Wolf and Obernhuber [6].

This last example highlights the need to consider all potentially hazardous dynamic modes of excitation. Isolating a structure for one particular mode may very well result in a vulnerable structure for other modes.

5. References

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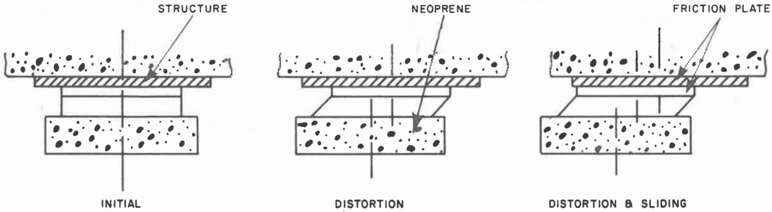


Figure 1 Rubber and friction plates isolation systems (after Jolivet and Richli [3])

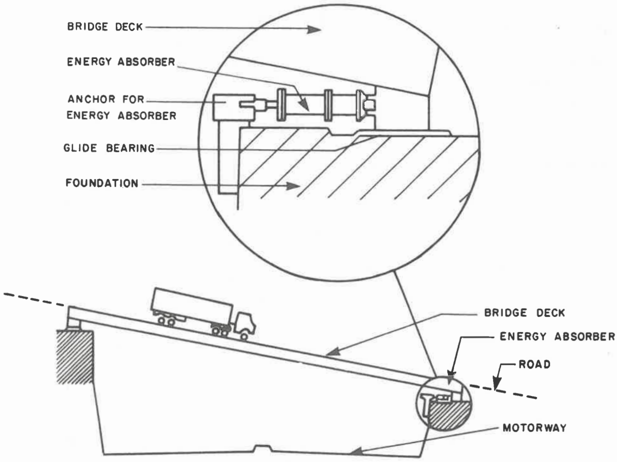


Figure 2 Application of extension energy absorbers (after Robinson and Greenback [4])

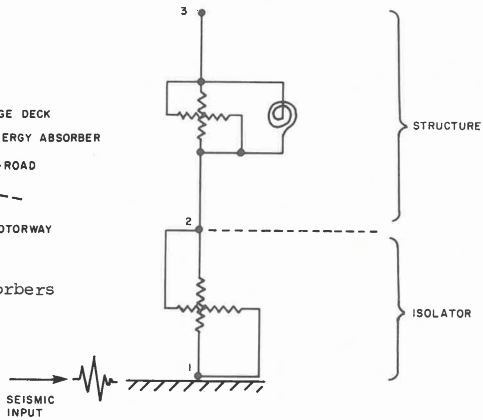


Figure 3 Simple structural models and spring isolation system

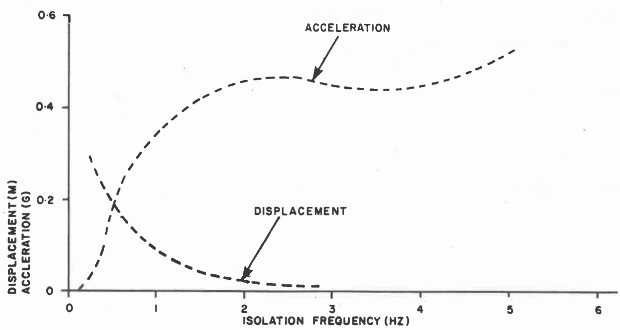


Figure 4 Peak acceleration and relative displacement vs isolation frequency for mass 2 - spring isolation

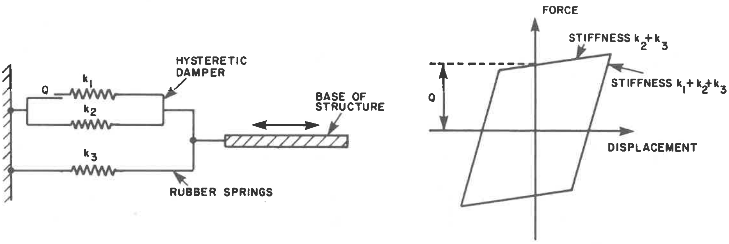


Figure 5 Model of spring and damper isolation systems

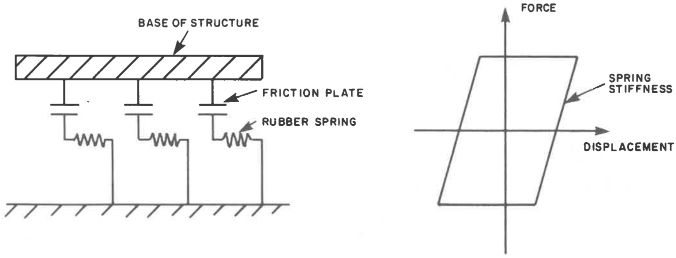
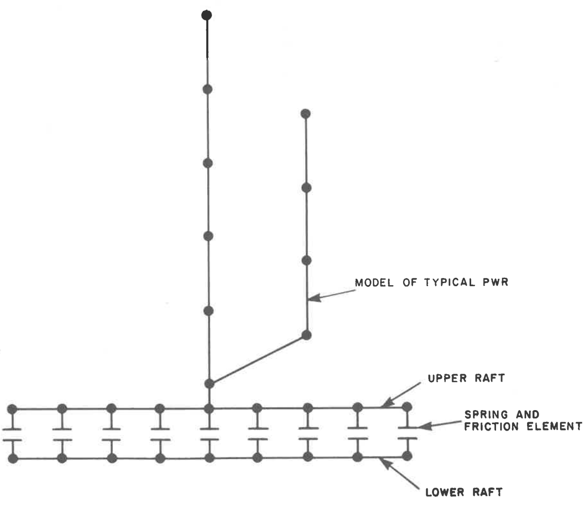


Figure 6 Model of spring and friction element isolation system



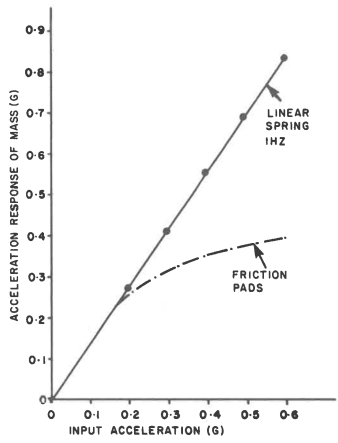


Figure 7 Structural response for spring and friction isolation system

Figure 8 Model of PWR reactor building used for travelling wave study