Shake Table Tests of Long Period Isolation System for Nuclear Facilities at Soft-Soil Sites

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ABSTRACT

Shake table tests of a 1/6 scale model of a base isolated nuclear facility at a soft soil site were carried out to verify that the benefits that base isolation can bring to the design of equipment and piping still hold when the concept is applied to a facility at a soft site. Ground motions characteristics of a soft site, including the effects of site frequency, possible embedment, and soil-structure interaction, were used as inputs to the shake table study. It was shown that the floor spectra of the structure are flat over the range of equipment frequencies and no amplification of acceleration occurred at any frequency significant to the qualification of piping and equipment.

1 INTRODUCTION

The number of buildings worldwide using base isolation is increasing rapidly. The number of base isolated buildings in Japan either completed, under construction or approved for construction by the Ministry of Construction is now approaching fifty. The concept, after a slow start, is gaining widespread acceptance. It is now generally accepted that a base-isolated building will perform better than a conventional building in moderate and strong earthquakes. The major benefit of isolation in such cases is to reduce damage to contents and sensitive internal equipment and in many buildings, the reduction of damage to equipment is of sufficient importance to justify the increased initial cost of isolated construction.

Nuclear power plants are another class of building in which the reduction of response of internal equipment is of primary concern. The analysis of equipment and piping systems in nuclear plants for seismic loading is one of the most expensive parts of the design process. The analysis is complicated by the fact that with conventional construction, the higher levels of the plant have amplified accelerations and the time histories at each level can be very different. It is generally necessary to analyze piping and equipment using multiple support response spectrum analyses. Base isolation drastically reduces the amplification of acceleration at the higher levels of the plant and would permit the use of simpler design methods and eliminate the need for seismic restraints such as snubbers.

There has been a reluctance, however, to use base isolation for nuclear plants, possibly because of uncertainty in the specification of long period ground motion and the performance of isolation systems under levels of earthquake attack beyond design levels. However, the long period ground motion can be predicted accurately if the site fault mechanisms and the soil type are understood since the mechanics of ground motion in the long period range are very well understood. Additionally, if an isolation system uses high strength elastomers such as natural rubber and high quality bonding techniques, the ultimate capacity can be accurately predicted and very substantial safety margins can be established.

This report describes the results of a test program of shake table studies for the purpose of assessing the safety of base isolation for a facility at a soft site for which a number of site specific ground motion time histories were developed. The example used for this test series is the Savannah River site in South Carolina. The site is a deep soil site which could have significant motion at the range of period generally used for isolated structures. The ground motion time histories of this site incorporated the effects of the soil profile, the site frequency, embedment and the anticipated soil-structure interaction of the isolated structure. The model used represented overall inertial properties of the structure at a scale factor of six. Two isolation systems were used, each based on multilayer natural rubber bearings. One system used a high damping rubber with similar properties to one widely used for civil structures in California. The other system used a newly developed high damping compound with a low shear modulus, which provides a frequency of about twenty-five percent lower than the first system. The test program thus allowed the assessment of long period isolation systems with long period ground motion and the degree to which the isolation system produced structural responses advantageous for equipment and piping design.

2 TEST FACILITIES AND EXPERIMENTAL MODEL

The experimental program described here was carried out on the shaking table of the Earthquake Engineering Research Center at the Richmond Field Station of the University of California at Berkeley. The table measures 20 ft x 20 ft (6.1 m x 6.1 m) in plan and can support test structures weighing up to 100 kips (445.6 kN). Simulated seismic motions can be applied vertically and in one horizontal direction with maximum accelerations of 1.0g vertically and 1.5g horizontally.

The test structure used in this study is a five story frame previously used for testing isolation systems using natural rubber and neoprene isolation bearings. The frame has three bays in the direction of shaking with cross bracing only in the center bay of the first floor. The single bay in the transverse direction is heavily stiffened with double-angles to minimize out-of-plane motion. The entire mass is mounted on a base made of two 8WF girders and rests on eight bearings with load cells that are connected to the shaking table.

The scaling used for shake table tests is based on constant stress so that accelerations in the model are the same as in the prototype. The applied dead load must produce stress levels equal to those in a full scale frame. This dead load is supplied by concrete blocks and lead weights bolted to the frame at different floor levels. The total weight of the concrete blocks, the lead weights and the structural frame is estimated to be 103 kips (459 kN). Figure 1 gives a view of the complete frame mounted on the shaking table with the dead load.

Fifty-three channels of data were recorded during each test to measure the response of the combined shake table-structure system. The goal was to measure the following components of response:

- Earthquake Simulator Response: Shake table displacements and acceleration time histories.
- Bearing Response: Relative top-to-bottom bearing displacements in the direction of shaking. Load cells under all eight bearings measured shear and moment in the direction of shaking.
- Frame Response: Absolute displacements of the base and all five floors of the frame. Displacements relative to the table could then be calculated by subtracting the table displacement from these measurements. Accelerometers at each floor level measured accelerations in the direction of shaking. Additional accelerometers were placed at the southwest and northwest corners of the fifth floor to measure accelerations in the transverse direction and on top of each of the corner columns to measure vertical accelerations.

3 RUBBER COMPOUNDS

Two rubber compounds were used in this test series. The first, designated Compound A, is representative of the type of high damping natural rubber that has been used in several commercial base isolation projects and several experimental programs at EERC. It is compounded to have high stiffness at low strains and to have the degree of damping needed for isolation systems. The shear modulus of Compound A varied from 432 psi (2.98 MPa) at 2% strain through 139 psi (0.96 MPa) at 50% to 101 psi (0.70 MPa) at 125% strain as determined from tests on the bearings before the start of the shake table tests. The level of equivalent viscous damping in Compound A from the individual bearing tests is in the range of 10% at the strain level of 50%.

The shear modulus for the second elastomer, Compound B, as determined from the individual bearing tests, varied from 223 psi (1.54 MPa) at 2% through 84 psi (0.58 MPa) at 50% to 66 psi (0.46 MPa) at 125%. The damping in Compound B is around 8 - 10% in the individual bearing tests. The modulus curves from the individual bearing tests are plotted in Figs. 2a and 2b.

3.1 Bearing designs

The design of the two types of bearings is shown in Fig. 3. Type A, using the stiffer compound, has 16 layers each 0.213 inches (5.4mm) thick for a total of 3.408 inches (86.6mm) and a shape factor of 6.9. Type B uses 18 layers, each 0.198 inches (5mm) thick, for a total thickness of 3.564 inches (91mm) and a shape factor of 7.4.

The stiffnesses at around 100% shear strain are approximately 1.10 kips/in. (19.3 kN/mm) for type A and 0.71 kips/in. (12.4 kN/mm) for type B. Both of these values were measured in tests on individual bearings before the shake table tests were carried out. There is necessarily a significant degree of variability in the mechanical properties of such small bearings made with large scale factors, but taking these numbers as representative for the frame loaded to a total of 103 kips (459 kN), they translate (at a scale factor of 6) into frequencies of 0.4 Hz and 0.3 Hz respectively.

4 EXPERIMENTAL PROGRAM

The base isolated structural model on each set of bearings was subjected to a number of different types of dynamic tests. These can be divided into diagnostic tests comprising free vibration (pull-back), harmonic, random and earthquake tests comprising the special soil-structure interaction signals.

4.1 Artificial earthquake input

The Savannah River Site is a deep soil site with bedrock at a depth of approximately 600 feet (183m). The soil is primarily sand with silt and clay. In an effort to provide shake table input motions that reflect this site condition a special set of artificial earthquake motions were generated for the project. In addition these special earthquake records were designed to include the effects of soil-structure interaction. Four different records were provided. The process of development of the records is as follows.

Four historical California earthquake accelerograms were chosen as the starting point for the process. These were:

(i) Taft, Kern County Earthquake, 1952, S69E component
(ii) El Centro, Imperial Valley Earthquake, 1979, Channel 140
(iii) Hollister Public Library, Central California Earthquake, 1954, S01W component
(iv) Hollywood Storage Parking Lot, San Fernando Earthquake, 1971, N90E component

These are long duration, broad band records.

Twenty seconds of each of these accelerograms were modified iteratively until their 7% damped response spectrum matched the response spectrum of USNRC Reg. Guide 1.60 anchored to a zero period acceleration of 0.25g. The resulting acceleration records were assumed to be surface rock site motions and deconvoluted to the bedrock level. The bedrock motions were then propagated back through a soil column model based on the soil profile at the site. The free field motions that resulted were then applied as input motions for a soil-structure interaction analysis of the base-isolated reactor building. In this analysis the reactor building was modeled as a 10 foot thick reinforced concrete base mat surmounted by an isolated mass with a fundamental frequency of 0.4 Hz. The SSI model was analyzed for the four free field surface ground motions to obtain the horizontal acceleration time histories at the top of the base mat. The resulting four shake table input signals were obtained by double integration and correction of these acceleration records. The table inputs thus reflect to the fullest extent possible the site seismicity, the soil profile and soil-structure interaction.

All four records have peak absolute accelerations of around 0.20g, maximum absolute displacements of about 9 inches (229mm) at the top of the base mat and predict a relative displacement across the 0.4 Hz isolation system above the base mat of about 15 inches (381mm). The four records were converted for use with the shake table at a scale factor of six.

4.2 Artificial earthquake input results

The four artificial signals were input to the table at a wide range of span settings producing table accelerations from around 0.1g to 0.25g. The bearing displacements produced, ranged from very small values up to a maximum of 3.64 inches (92mm) in the stiffer system, equivalent to 107% shear strain and to 3.86 inches or (98mm) 108% in the softer system.

The most extreme displacement for the Type A bearings resulted from the second artificial signal (DIS 243a). In this case the hysteresis loops show no evidence of distress in the bearings. The strain level is high enough to generate a small amount of hardening in the rubber at the extreme displacement but there is no evidence of buckling.

In most cases an isolated structure will experience accelerations that are much lower than it would experience if fixed and generally lower than the input acceleration. Also, the profile of the accelerations in the structure would be expected to be very uniform. In the case of these artificial signals which contain long period motion through the effect of the SSI computation these results may not hold. Nevertheless, only in two of the signals, the first and the second, are the accelerations higher than the table accelerations and in both, the profile is uniform. In the third fourth , the accelerations are lower than the table input and also very uniform. In the case of the softer system, the same general trends are evident. The acceleration amplifications are more nearly constant with increasing input level with the accelerations at the roof level being generally about 10% larger than the base level acceleration. For most inputs the roof acceleration is about the same value as the table acceleration and the base acceleration is slightly less.

The maximum bearing displacement for the softer rubber was also achieved for the second signal. The bearing displacement in this case was 3.86 inches (98mm), corresponding to a strain in the rubber of 108%. In this test the effective stiffness is 4.57 kips/in (80.2 kN/mm) corresponding to a frequency of 0.65 Hz for the model and 0.27 Hz (3.7 sec period) for the prototype. This is a very long period system and the displacements for the prototype would be very large. The acceleration above the isolators in this case is half of the input acceleration reflecting the low base shear.

The interstory drift for every case is extremely small. These results attest to the fact that even in the case where the input has a substantial component at the frequency range of the system the isolation action results in predominantly rigid body motion of the structure is still effective. It indicates that if the isolators are designed to accommodate the large resulting displacements, the isolation concept can still be effective. Large displacements for large structures such as nuclear facilities are not a serious problem and the type of large isolators which would be needed in such a structure the maximum acceptable displacement could be very much larger than any likely to arise in practice. For example, the largest displacement in the experimental program 3.86 inches (98mm) translates to 23 inches (584mm) in the full scale system. This seems at first sight to be a very large displacement but the isolator could be of the order of 40 inches (1,016mm) diameter and such an isolator could easily withstand displacements of 30 inches (762mm) if appropriately designed.

It was also shown by the tests results that the floor spectra in every case is very flat and much lower than the ground response spectra above 2.5 Hz for all frequencies. A slight rise in the spectra at 2.5 Hz is quite negligible in comparison to the spectra that would be obtained if the response from fixed base construction was subjected to these ground motions. In the isolated model, the ZPA of the floor response spectra could be considered to occur at 10 Hz. The usual NRC guideline is 33 Hz. This reduction in ZPA has a potential for greatly reducing the expenses for equipment qualification and piping and electrical raceway supports. This would occur because this three-fold decrease in the ZPA frequency would permit a nine-fold decrease in the stiffness of equipment and internal structures designed to rigid. And, similarly, piping and raceway would be subject to much less amplification with fewer supports.

6 CONCLUSION

The test series has shown that base isolation systems can be used at soft soil sites under circumstances where the isolator loads and consequently isolator sizes are sufficiently large to accommodate the resulting large displacement. The use of long period isolation systems at such sites allows a very substantial reduction in the response of internal equipment and allows equipment response to be analyzed for design purposes by simple methods without the use of multiple support response spectrum methods.

The low modulus high damping elastomer used in the softer of the two isolation systems tested, proved to have highly favorable characteristics in addition to its low modulus. Its use in providing low frequency isolation systems is clear but it could also be used to advantage in isolation systems with moderate frequencies but light loads. It is often necessary to isolate individual equipment items in nuclear facilities and it becomes quite difficult to design a stable system if the loads are light. With this rubber it would be straightforward to design an equipment isolation system with, for example, 0.75 Hz frequency and a displacement capacity of 5 inches (127mm) for an isolated load of 20 kips (89.1 kN).

The high damping natural rubber base isolation system has the advantages of simplicity and low cost relative to systems with supplemental dampers. Isolation as a concept relies on the idea of detuning. Detuning and the concomitant fact of the low participation factor of the higher modes of the isolated structure - not the damping - produces the isolation effect. A totally undamped isolation system will still isolate the structure effectively. The damping is needed only to control the effects of possible resonance at the frequency of the isolation system. It is often overlooked by suppliers of dampers that high damping, particularly high damping generated by non-linear mechanical action or by friction, reduces the efficiency of an isolation system. Moreover, damping allows more energy to bypass the isolation barrier and to generate high frequency accelerations in the structure above the isolation system.

In particular, highly non-linear systems can generate high frequency responses in the structure even if energy at that frequency is not in the ground motion. The detrimental effect of large amounts of non-linear damping are not apparent in analysis if, as is common in practice, the response is predicted by single degree of freedom response spectrum methods. The effects of these high frequencies on internal equipment is obvious. In addition, there is the problem of equipment qualification. In an ideal isolation system the response of the super-structure is uniform, in that all levels have the same floor response spectrum. In a practical system this does not hold precisely, but if the damping is relatively low and smoothly generated, it is closely approximated. One of the primary advantages of the high damping rubber system is that it provides very flat floor response spectra over the range of frequency of interest to the equipment designer. A complete description of the testing and results is given in J.M. Kelly, "Shake Table Tests of Long Period Isolation System for Nuclear Facilities at Soft-Soil Sites," *Report No. UCB/EERC 91/03*, Earthquake Engineering Research Center, University of California, Berkeley, California (1991).

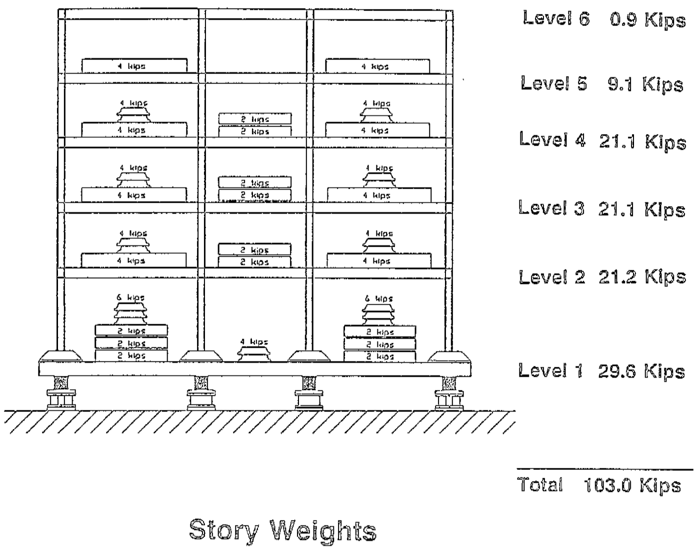

Fig. 1 Five Story Experimental Model and Load Distribution

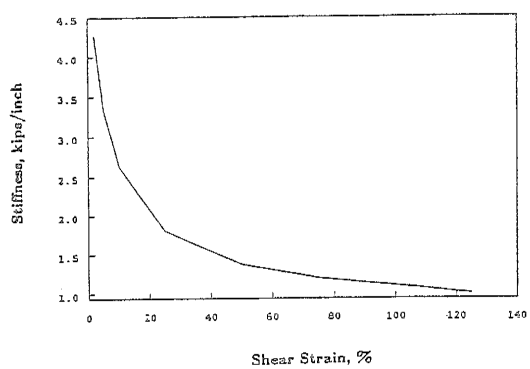

Fig. 2a Shear Modulus vs. Shear Strain - Compound A

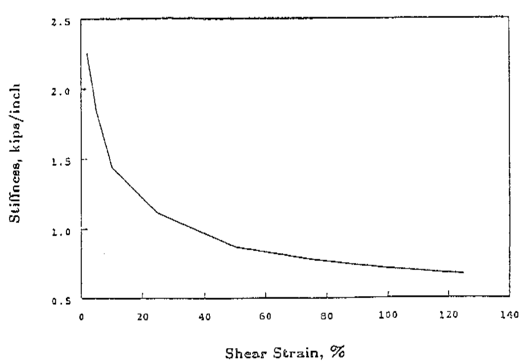

Fig. 2b Shear Modulus vs. Shear Strain - Compound B

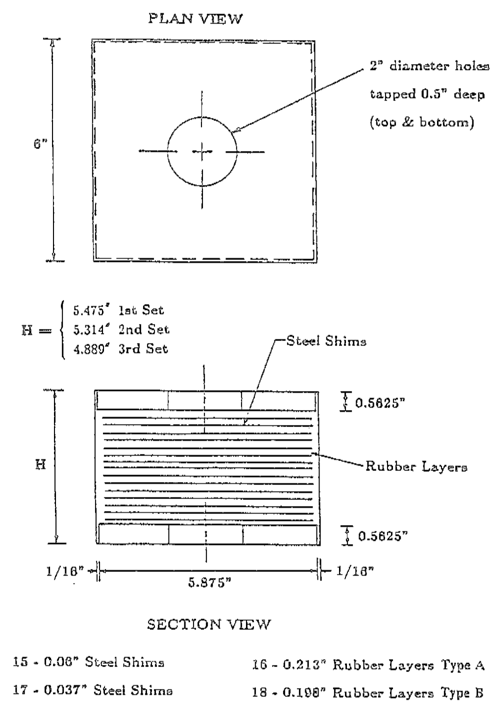

Fig. 3 Bearing Design Details