Foundation Isolation for Seismic Protection Using a Smooth Synthetic Liner

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Abstract: Smooth synthetic materials placed underneath foundations of structures can provide seismic protection by absorbing energy through sliding. Cyclic and shaking table tests were conducted on a variety of synthetic interfaces to identify a suitable liner for use as foundation isolation. It was concluded that a high strength, nonwoven geotextile placed over an ultrahigh molecular weight polyethylene, UHMWPE (geotextile/UHMWPE) constitutes a liner that is well suited for this application. The static friction coefficient of the interface (between the geotextile and the UHMWPE) is about 0.1. The dynamic coefficient is about 0.07 and is insensitive to changes in slip rate and normal stress. A single-story structural model with and without foundation isolation was tested using a shaker table. The results demonstrate the role of foundation isolation in substantially reducing the seismic shear forces in the model. Accompanying this reduction in shear forces are slip displacements along the isolation liner. Permanent slip (final location of the structure relative to its initial position) can be reduced through the use of a small restoring force that could be provided through passive soil resistance. Peak-to-peak slip (maximum slip during shaking) needs to be permitted for foundation isolation to be effective. The experimental and analytical research results demonstrate the technical feasibility of using a smooth synthetic liner in earthquake hazard mitigation.

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Introduction

The devastations that were experienced during the earthquakes in California (1994), Japan (1995), Turkey (1999), Taiwan (1999), and India (2001) are reminders that despite the major achievements in earthquake engineering technology, earthquakes continue to pose serious threats to our communities worldwide.

Ideally, an earthquake-resistant design should ensure that earthquakes, regardless of their size and location, cause negligible or no damage. To achieve this, base isolation and other structural control systems are being developed to reduce seismic structural response, thus minimizing damage. In seismic isolation, the aim is to reduce the earthquake energy transmitted to a structure by placing the structural columns on mechanical isolators. Skinner et al. (1993) and Kelly (1997) have presented comprehensive studies of various aspects of seismic base isolation. Over the years, several types of base isolators have emerged and been installed including natural rubber bearings (NRB), high damping rubber bearings (HDR), lead-rubber bearings (LRB), resilient-friction base isolation (R-FBI), and friction-pendulum system (FPS). Base isolation techniques have been successfully implemented worldwide in buildings, bridges, nuclear power plants, and large storage tanks. Experiences from earthquakes in Japan and the United States have shown that structures with seismic base isolation have suffered little damage. However, conventional seismic base isolation can be quite expensive to implement and maintain and therefore, to date, only important structures have been furnished with these systems.

The writers have conducted a research program that was focused on exploring the technical feasibility of using synthetic materials as an alternative low-cost seismic isolation technique. Hushmand and Martin (1991); Kavazanjian et al. (1991); and Yegian and Lahlaf (1992a,b) proposed the concept of using a smooth geosynthetic liner underneath building foundations to dissipate earthquake energy through sliding along the geosynthetic interface, thus transmitting reduced accelerations to the overlying structure. The scope of this research program was to expand on this concept and identify, through experimental tests, a suitable synthetic liner for the purpose of seismic isolation, explore ways of utilizing such a liner in practice, and demonstrate the technical feasibility and potential benefits of isolation techniques using the synthetic liner.

The research program identified a synthetic liner that is well suited for seismic isolation. Two alternate schemes were explored for the use of the liner. The first was the placement of the liner immediately underneath the foundation of a structure. This approach is referred to as *foundation isolation* and is shown schematically in Fig. 1. In the second approach, the synthetic liner is placed within the soil profile at some depth below the foundation of a structure. This approach is referred to as *soil isolation*. In the research program, both isolation schemes were experimentally evaluated and the practical implications were assessed analytically by using such isolation techniques. This paper focuses on foundation isolation. In a companion paper, by Yegian and Catan (2004), the results of research on soil isolation are presented and discussed.

This paper presents typical experimental test results, which

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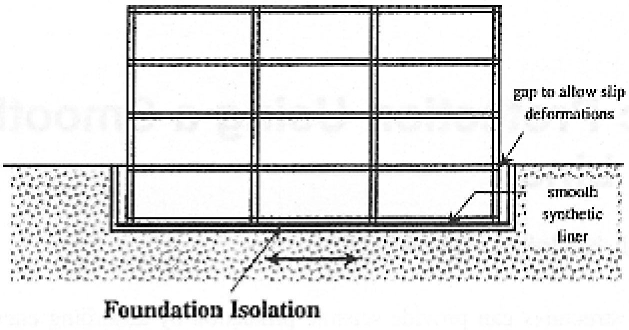

Fig. 1. Foundation isolation for seismic protection of buildings using smooth synthetic liner

support the selection of a synthetic liner most suitable for seismic isolation. The details and results of shaking table experimental tests that were conducted using a rigid block as well as a model structure to investigate the performance of a foundation-isolated structure are presented. Analysis and discussions of the research results are presented demonstrating the technical feasibility of using a synthetic liner to dissipate earthquake energy, thus reducing structural response and minimizing the potential for damage from an earthquake.

Geosynthetic Liners for Foundation Isolation

The selection or development of a proper geosynthetic material for use as foundation isolation was the first important task of the research. Several candidate interface materials were explored for their suitability as foundation isolator. Ideally, foundation isolation material should satisfy requirements including:

- The friction coefficient during sliding should be small to minimize the acceleration transmitted through the interface. In general, friction coefficients between 0.05 and 0.15 would be desirable for the isolation concept to be used worldwide not only in regions of high seismicity, but also where earthquakes pose a moderate threat, and seismic mitigation measures can be cost prohibitive.
- The static friction coefficient should be slightly larger than the dynamic coefficient to prevent sliding under nonseismic loads including wind.
- To simplify introduction of foundation isolation in engineering design, the friction coefficient should be insensitive to several factors including sliding velocity, normal stress, sliding distance, moisture, and temperature.
- The interface material should be resistant to chemical and biological attacks, and to long-term creep effects.
- The maximum and permanent slip displacements induced by an earthquake should be small enough to allow functionality of the structure and its utilities.

In this research, various tests including cyclic loading and rigid block shaking table experiments were performed to evaluate the dynamic response of each interface. The following four interfaces were selected, and are listed in Table 1, as potential candidates for foundation isolation.

- Geotextile/HDPE: A high-strength nonwoven geotextile called "Typar 3601" was used against 1.5 mm smooth HDPE (high density polyethylene).
- PTFE/PTFE: Two layers of 1.5 mm thickness PTFE (polypropylene) sheets were utilized in this interface.
- UHMWPE/UHMWPE: Two layers of 6.4 mm thick UHMWPE (ultrahigh molecular weight polyethylene) "TIVAR 88-2 AntiStatic" were used in this interface.
- Geotextile/UHMWPE: Typar 3601 geotextile was used against TIVAR 88-2, 6.4 mm thick UHMWPE.

Cyclic Load Tests

The purpose of the cyclic load tests was to measure the friction coefficients of the selected geosynthetic interfaces under controlled conditions. Measured friction coefficients can be highly dependent on the testing and loading conditions including sliding distance (or number of cycles), sliding velocity, normal stress, temperature, and geosynthetic surface condition (Yegian and Lahlaf 1992a,b). In the cyclic load tests, the influence of normal stress, number of cycles, and sliding velocity were investigated before more complex shaking table tests were performed. In all the tests, the geosynthetic interfaces were prepared for testing following the procedure described by Yegian and Lahlaf (1992a,b), in which the effect of inadvertent lubrication of the interface through human touch is eliminated. Also, all tests were performed in ambient temperature condition in the laboratory (about 20°C). In this investigation, the effect of temperature was not considered because Lahlaf (1991) has shown that friction coefficient along smooth geosynthetic interfaces only slightly changes with changes in temperature.

The Northeastern University shaking table facility was utilized to carry out displacement- and velocity-controlled cyclic load tests. The table is made of 2.5 cm thick aluminum plate and has dimensions of 1.2×1.8 m. The table moves in a horizontal uniaxial direction powered by a 50 kN capacity hydraulic actuator.

Fig. 2 shows the setup used in the cyclic load tests. As can be seen, the shaker table actuator was used to apply controlled slip displacements along the tested interface that carried a fixed dead load, induced by lead weights, to apply the normal stress. Two

Table 1. List of Synthetic Liners Investigated for Suitability as Foundation Isolators

Interface	Description	Friction coefficient[a]
Geotextile/HDPE	A high-strength nonwoven geotextile, "Typar 3601" against 1.5 mm smooth HDPE (high density polyethylene)	0.15–0.3
PTFE/PTFE	Two sheets of 1.5 mm thickness PTFE (polypropylene)	0.08– 0.15
UHMWPE/UHMWPE	Two layers of 6.4 mm thick UHMWPE (ultrahigh molecular weight polyethylene) "TIVAR 88-2 AntiStatic"	0.09–0.25
Geotextile/UHMWPE	Typar 3601 geotextile against TIVAR 88-2, 6.4 mm thick UHMWPE	0.06–0.08

[a] Range depends on number of cycles, normal stress, and sliding velocity.

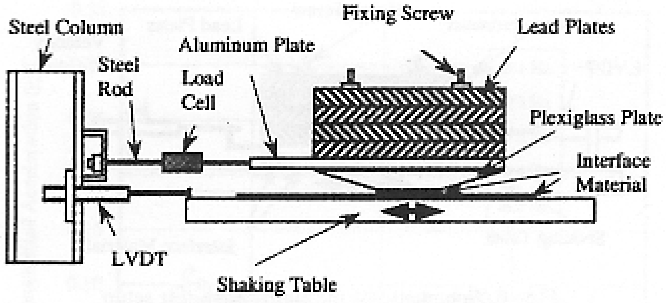

Fig. 2. Schematic of the cyclic load test setup that used the shaking table to apply controlled shear displacements and velocities along the tested synthetic interfaces

quantities were measured during the cyclic load tests: (1) shear forces transmitted along the interface, and (2) relative displacement (slip) between the two geosynthetic interfaces. Discussions on selected test results follow.

Effect of Number of Cycles

Friction coefficients between polymer interfaces can vary significantly with sliding distance. In a cyclic test, sliding distance can be represented by the number of cycles of load application. To identify the effect of number of cycles on friction coefficients, a series of cyclic tests were run using the selected four interfaces. Fig. 3 presents a summary plot showing the variation of friction coefficient as a function of the number of cycles of applications of slip at a sliding velocity of ±2.5 cm/s at 0.25 Hz. The combination of this slip velocity and frequency induced a sliding distance of 5 cm per cycle that was easily accommodated by the test apparatus. It is evident that during the first 10 cycles the friction coefficient varied by about ±30% depending on the interface tested. Beyond 10 cycles, the variation in friction coefficient was negligible.

Effect of Normal Stress

Understanding the effect of normal stress on friction coefficient is important because in real application of foundation isolation, the design level normal stresses can vary significantly depending on the size of the structure, the area of the isolation plane, and the magnitude of the seismically induced overturning moments. The four interfaces were tested under a normal stress varying between 35 and 153 kPa. Due to some experimental difficulties the geotextile/HDPE interface was tested only within the range of 3–33 kPa. This was not a serious shortcoming because the relatively large friction coefficient of this interface ultimately restricted its applicability as a foundation isolator.

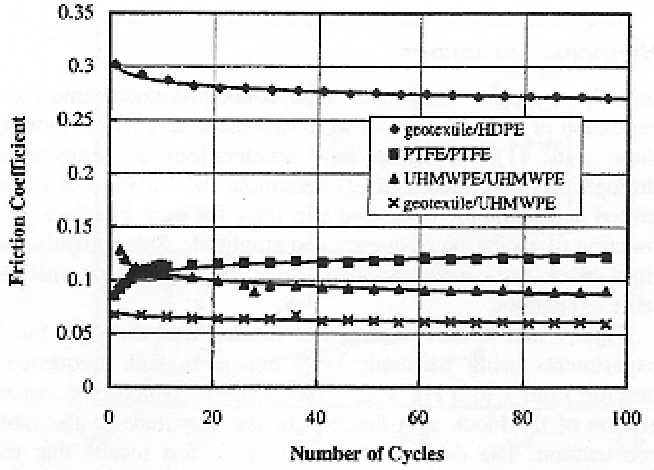

Fig. 3. Effect of number of cycles of application of interface shear on the friction coefficient of the tested interfaces (f=0.25 Hz, sliding velocity=±2.5 cm/s)

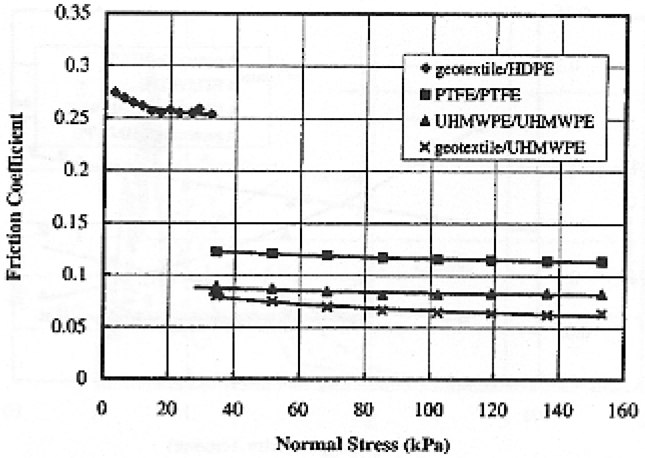

Fig. 4. Effect of normal stress on the friction coefficient of the tested interfaces (f=0.25 Hz, sliding velocity=±2.5 cm/s)

Fig. 4 shows a summary plot of the measured friction coefficients as a function of normal stress. Generally, the friction coefficient slightly decreased with increasing normal stress of up to about 80 kPa, beyond which the friction coefficient remained constant. This decreasing trend of friction coefficient with normal stress was an encouraging result for the application of foundation isolation, since the normal stresses under a typical structure are much larger than those that can be achieved in a laboratory setting.

Effect of Sliding Velocity

Friction coefficients between various materials can change significantly with sliding velocity, which also is referred to as slip rate. Such variations of friction coefficients with sliding velocity may have significant consequences for the foundation isolation application. During sliding, induced by an earthquake excitation, the slip rate between the interfaces may vary substantially. This variation can be extremely large especially when a structure is subjected to a near-field earthquake motion. Corresponding variations of friction coefficients may change the response characteristics of the overlying structure substantially. Therefore, velocity-dependent characteristics of all candidate interfaces were investigated by cyclic load tests. Interfaces with the smallest variation of friction coefficient with sliding velocity were searched for seismic isolation application.

A series of tests were carried out on all interfaces by changing the sliding velocity between 0.001 and 20 cm/s, which is a typical range for static to large seismic loading conditions. Since earlier tests indicated that the friction coefficient decreased only slightly with increasing normal stress, and remained constant beyond about 80 kPa, all tests were run under 69 kPa normal stress.

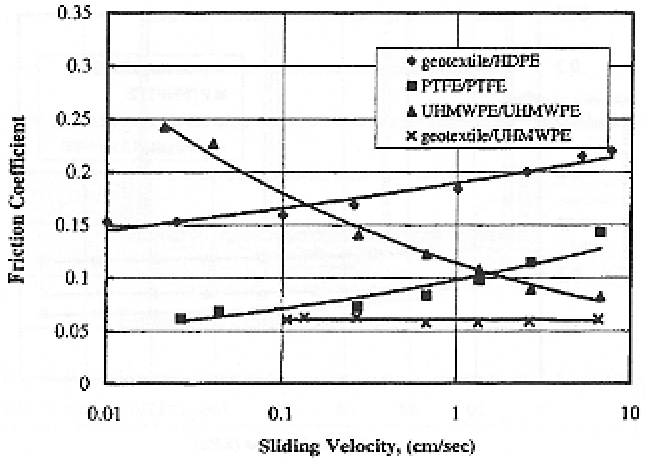

Fig. 5. Effect of sliding velocity on the friction coefficient of the tested interfaces (normal stress=69 kPa)

The velocity amplitude was generated using triangular displacement pulses with an amplitude of ±2.5 cm and varying frequencies.

Fig. 5 presents the measured friction coefficients within the range of sliding velocity between 0.01 and 10 cm/s. This range of sliding velocity was selected for plotting to show more clearly the data (all except for 0.001 and 20 cm/s). The geotextile/HDPE and PTFE/PTFE interfaces exhibited a significant increase in the friction coefficient with increase in sliding velocity. The friction coefficient for the UHMWPE/UHMWPE interface decreased significantly with sliding velocity. The friction coefficient of the geotextile/UHMWPE interface was small and independent of the sliding velocity. This low and almost constant nature of friction coefficient with sliding velocity observed from the geotextile/UHMWPE interface made this liner a leading candidate for foundation isolation because its introduction in engineering design of foundation-isolated structures becomes simple by using a constant friction coefficient for the duration of the seismic shaking of the structure.

In summary, cyclic load tests were conducted on four interfaces that were considered potentially suitable for foundation isolation application. The results from the various tests, in which the number of cycles of application of slip displacement, the normal stress at the interface contacts, and the sliding velocity were varied, are summarized in Table 1. Compared with the other interfaces tested, the friction coefficient of the geotextile/UHMWPE liner not only was smaller than the other interfaces tested but also varied little with the test conditions. The residual friction coefficient of this interface, based on the cyclic tests, ranged between 0.06 and 0.08 depending on the normal stress and the sliding velocity. Thus, it was concluded that the geotextile/UHMWPE liner was the most promising interface for foundation isolation application and was selected for further testing under seismic excitations as is described in the subsequent sections.

Rigid Block Experiments

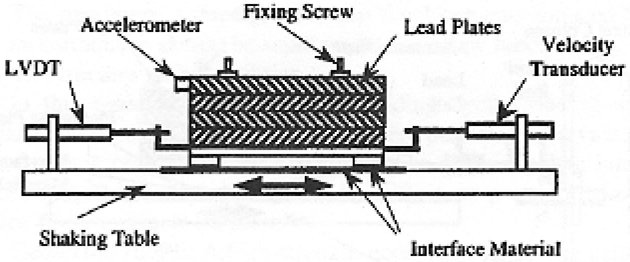

Fig. 6. Schematic of the rigid block test setup

The cyclic load experiments were utilized to obtain the interface friction properties of the four candidate liners. Factors influencing the friction coefficients were also studied. However, displacement-controlled cyclic load tests are usually incapable of providing sufficient information that can be used to estimate the dynamic response of a structure utilizing plastic interfaces. Such information includes: permanent deformations, transmitted accelerations, and effect of excitation frequency and amplitude. Shaking table tests using a rigid block placed on a synthetic liner is a first step to understand how a structure with foundation isolation may behave under dynamic loads such as those induced by an earthquake. Rigid block experiments have been utilized by various researchers to understand the dynamic transmissibility and slip characteristics of several geosynthetic interfaces (Kavazanjian et al. 1991; Yegian and Lahlaf 1992a,b; De and Zimmie 1997).

In this section, the experimental apparatus and the procedures for rigid block tests that were conducted are introduced. Although in the research program all four geosynthetic interfaces were tested, in this paper the results of only the most suitable interface for foundation isolation (geotextile/UHMWPE) are presented.

Experimental Setup

Fig. 6 shows the experimental setup. The rigid block is formed by fixing lead weights on a 20×30 cm aluminum plate. Four small aluminum blocks of 5×5 cm dimensions were attached at each corner of the aluminum plate. The primary function of these blocks was to reduce the contact area, hence to achieve large normal stresses without adding large masses which might cause overturning. Using double-stick tape, the UHMWPE was fixed on the shaking table. Similarly, four pieces of geotextiles were cut and taped at the bottom of the 5×5 cm aluminum blocks. The entire block assembly was then placed over the UHMWPE. The details of the experimental setup and measurement instruments can be found in Kadakal (1999).

Harmonic Excitations

Initially, the rigid block tests were conducted under sinusoidal excitation of the table. There were two main reasons for running these tests: (1) understand how accelerations are transmitted through each interface, and (2) determine the variation of transmitted accelerations, slips, and slip rates for each interface as a function of excitation frequency and amplitude. Subsequently, the rigid block tests were repeated using earthquake-type shaking table excitations.

Figs. 7 and 8 show typical test results from the rigid block experiments using harmonic table excitation with frequencies ranging from 1 to 5 Hz. Fig. 7 shows the measured peak acceleration of the block as a function of the amplitude of the table acceleration. The data confirms the cyclic test results that the block slides at an accelration of about 0.08*g* indicating a dynamic friction coefficient of 0.08. The data also indicates that sliding is initiated only after an acceleration of 0.11*g* is exceeded. This indicates that the static friction coefficient (0.11) of the interface

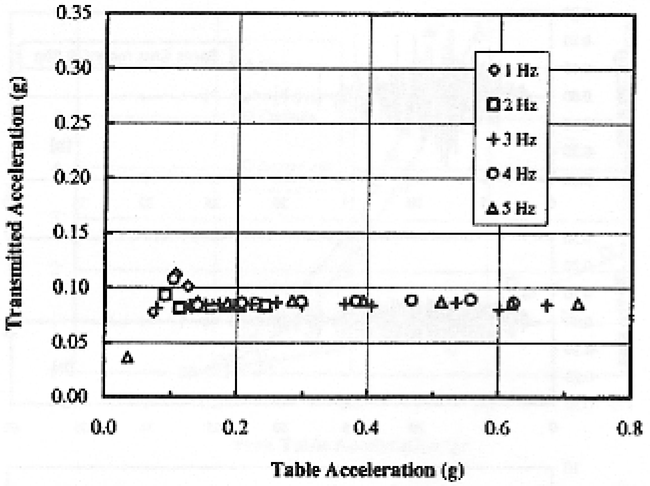

Fig. 7. Variation of transmitted acceleration with table acceleration from rigid block tests on geotextile/UHMWPE interface

is slightly larger than the dynamic friction coefficient (0.08). This observation was also made during the cyclic load tests.

Fig. 8 shows the peak slip displacement of the block as a function of the amplitude of the table acceleration. Again, it is noted that slip displacements were initiated only when the table acceleration exceeded about 0.08*g*. As expected, larger slip displacements were produced by lower excitation frequencies.

Earthquake Excitations

The rigid block tests were repeated using earthquake-type excitations in order to understand the acceleration transmissibility and slip deformations along the interface under more realistic transient motions. Since slip rate and slip amplitude were shown to vary significantly with the frequency of table acceleration, three earthquake records with different frequency bands were selected for the table motion. They were the Corralitos, Capitola, and Santa Cruz records of the 1989 Loma Prieta Earthquake. Fig. 9 shows the response spectra of the shaking table motions scaled to a peak acceleration of 0.25*g*. The Capitola record contains frequencies in a wide intermediate band, while Corralitos and Santa Cruz records have narrow band low and high frequencies, respectively.

Figs. 10–12 show typical responses of the block to each of the three table excitations scaled to 0.25*g*. In all tests, stick-slip motions were clearly observed in the transmitted acceleration records of the block during sliding, resulting in slightly higher transmitted

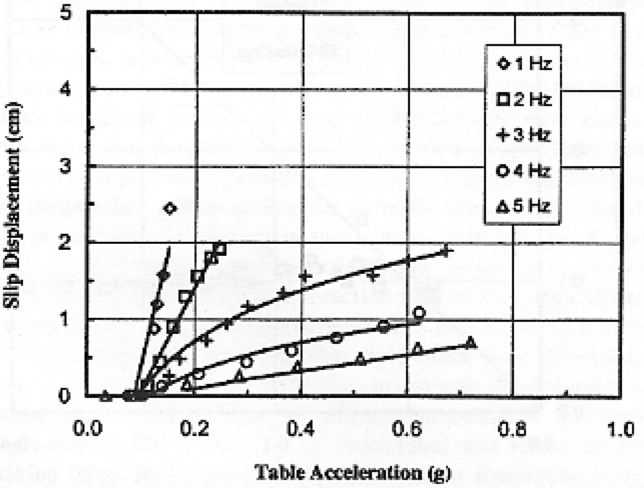

Fig. 8. Variation of slip displacement with table acceleration from rigid block tests on geotextile/UHMWPE interface

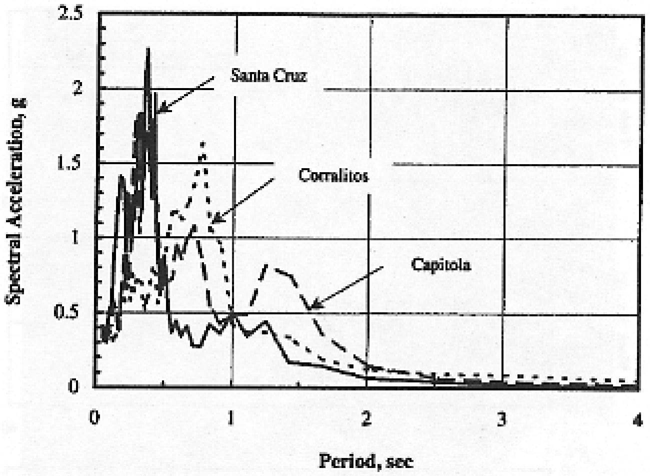

Fig. 9. Response spectra of the three earthquake motions used to excite the shaking table, scaled to 0.25*g* peak acceleration

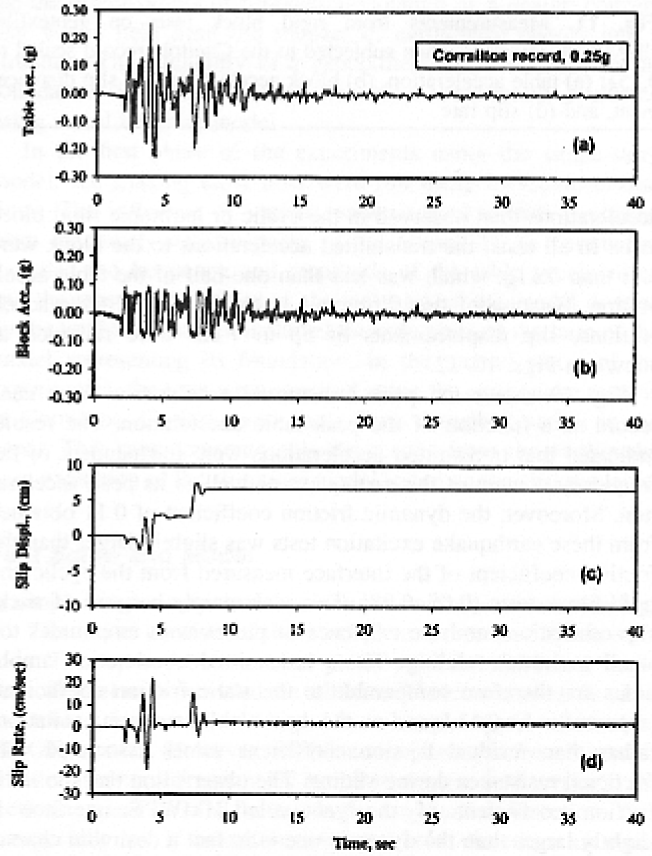

Fig. 10. Measurements from rigid block tests on geotextile/UHMWPE interface when subjected to the Corralitos record scaled to 0.25*g*: (a) table acceleration, (b) block acceleration, (c) slip displacement, and (d) slip rate

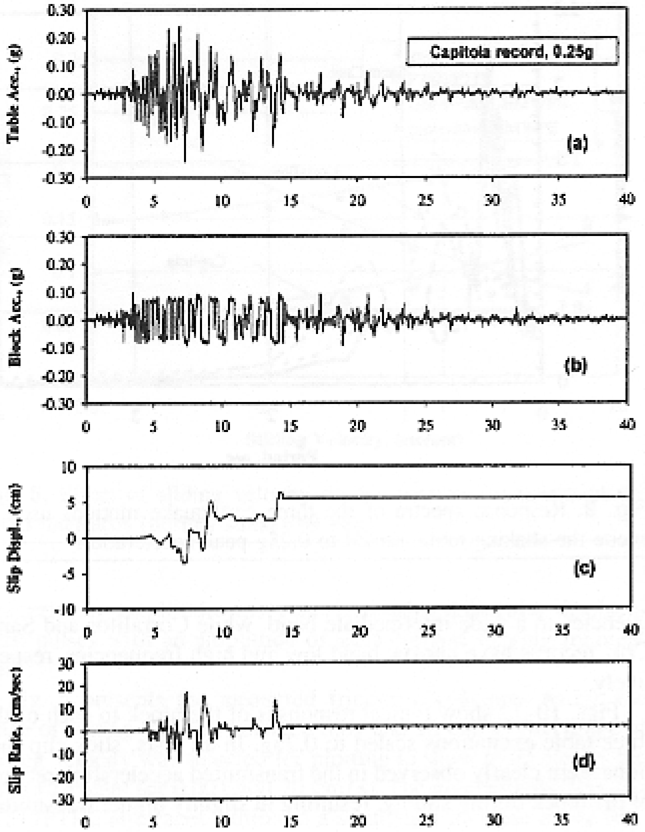

Fig. 11. Measurements from rigid block tests on geotextile/UHMWPE interface when subjected to the Capitola record scaled to $0.25g$: (a) table acceleration, (b) block acceleration, (c) slip displacement, and (d) slip rate

accelerations than observed in the cyclic or harmonic rigid block tests. In all tests, the transmitted accelerations to the block were less than $0.11g$, which was less than one-half of the table acceleration. Because of this difference in the block and table accelerations, slip displacements of up to 7 cm were recorded as shown in Figs. 10–12.

Fig. 13 shows the peak transmitted acceleration from each record as a function of the peak table acceleration. The results indicated that transmitted accelerations were independent of the frequency content of the earthquake as well as its peak acceleration. Moreover, the dynamic friction coefficient of 0.11 obtained from these earthquake excitation tests was slightly larger than the friction coefficient of the interface measured from the cyclic and rigid block tests (0.06–0.08). This was mainly because of stick-slip oscillations and the existence of pulses with amplitudes too small to initiate sliding. These transmitted acceleration amplitudes are therefore comparable to the static friction coefficients (reported to be 0.11 based on the rigid block harmonic excitation) rather than residual friction coefficient values associated with frictional resistance during sliding. The observation that the static friction coefficient of the geotextile/UHMWPE interface is slightly larger than the dynamic one is in fact a desirable characteristic for the interface because it prevents potential sliding when a structure placed over the interface is subjected to weak shearing forces from wind or small earth tremors.

Fig. 14 shows the variation of the measured permanent slip (position of the block at the end of shaking relative to its initial

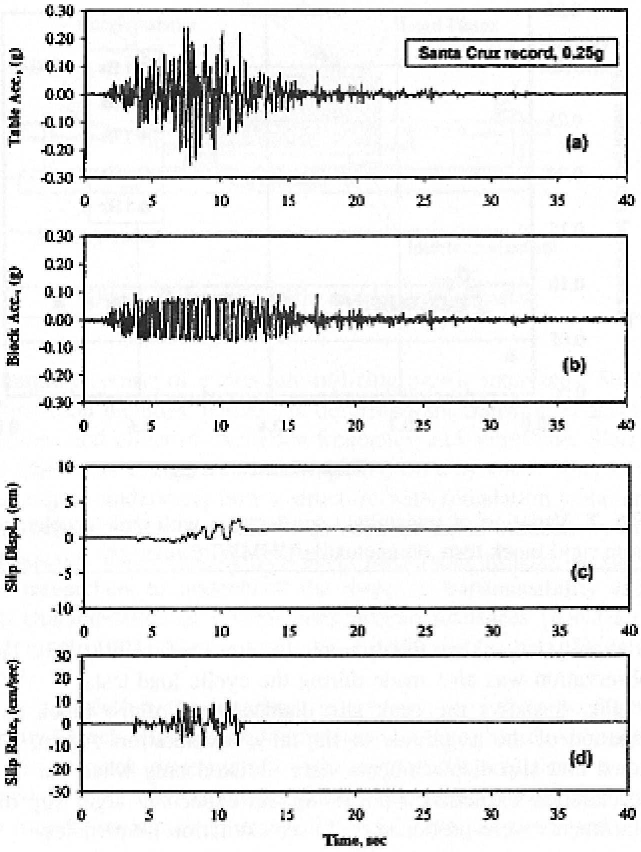

Fig. 12. Measurements from rigid block tests on geotextile/UHMWPE interface when subjected to the Santa Cruz record scaled to $0.25g$: (a) table acceleration, (b) block acceleration, (c) slip displacement, and (d) slip rate

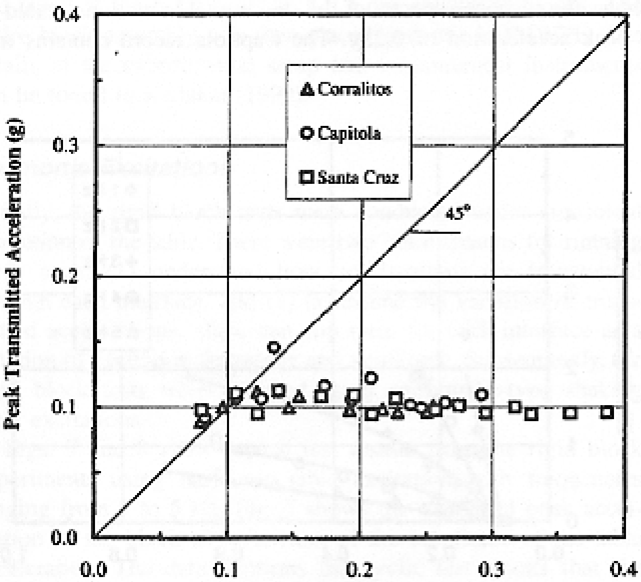

Fig. 13. Variation of peak transmitted acceleration with peak table acceleration from rigid block tests with earthquake excitations, using geotextile/UHMWPE interface

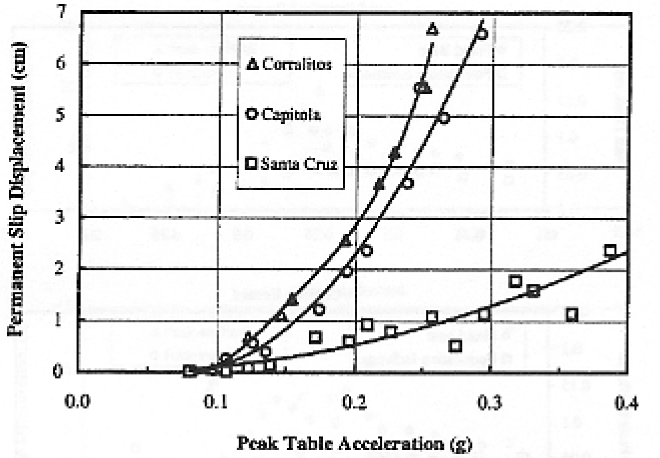

Fig. 14. Variation of permanent slip displacement with peak table acceleration from rigid block tests with earthquake excitations, using geotextile/UHMWPE interface

stationary position) for each earthquake record as a function of the table acceleration. The data shown in Fig. 14 confirm that sliding was first initiated at peak table acceleration of about 0.10g. Beyond that, permanent slips were induced that followed an increasing trend with increasing table acceleration. The permanent slips shown in Fig. 14 indicate a strong dependence on the predominant earthquake frequency. The largest permanent slips were recorded from the lower frequency Corralitos record. Conversely, the high frequency Santa Cruz record produced smaller permanent slips.

In summary, results from the rigid block tests confirmed the conclusions from cyclic load tests that the geotextile/UHMWPE interface is a very suitable liner for foundation isolation. It has a static friction coefficient of about 0.1. Its dynamic friction coefficient is about 0.06–0.08. Furthermore, and most importantly, the friction coefficient is inappreciably affected by normal stress, number of cycles, and slip velocity.

Single-Story Model Tests

The cyclic load tests described earlier provided the basic frictional characteristics of the geotextile/UHMWPE interface including friction coefficients at various sliding velocities and normal stresses, as well as their variation with sliding distance. The dynamic response of a rigid block on a geotextile/UHMWPE interface subjected to harmonic and earthquake-type base excitations were also described earlier. Transmitted accelerations and permanent slips were reported as a function of table accelerations and frequencies. But in reality, the dynamic response of a building on foundation isolation is much more complex due to the effect of the inertial forces induced by the upper story masses. The influence of this inertial interaction may in fact cause deformations and transmissibility characteristics that are substantially different from those obtained from rigid block tests. Therefore, experimental tests were conducted to investigate the dynamic response of a building model on foundation isolation. A simple single-story-building model was constructed and tested on the shaking table. Its responses, with and without foundation isolation, were measured during harmonic- and earthquake-type table accelerations. The geotextile/UHMWPE liner was used as the foundation isolation material. The influence of several parameters on the dynamic response of the structural model was investigated. The change in the structural response was also recorded when a horizontal spring was attached to the base of the structure in order to provide a restoring force which would minimize the permanent slip of the structure. Test results were then used to further evaluate the effectiveness of foundation isolation as a design concept that would help limit the transfer of earthquake energy into a structure. The suitability of a geotextile/UHMWPE interface as foundation isolation material was also analytically evaluated using a real building model.

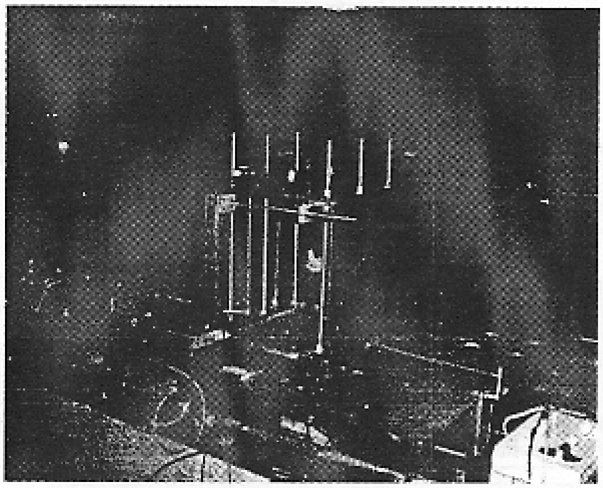

Fig. 15. Photograph of the single-story model structure used in the shaking table tests to evaluate foundation isolation using geotextile/UHMWPE liner

In the first phase of the experiments using the single-story model, the shaking table tests were run using harmonic excitations. The influence of various parameters was then evaluated from the steady-state response of the model. Those parameters included the frequency and amplitude of the table acceleration, and the mass ratio defined as the top mass of the model divided by the total mass, which included the columns and the base of the model representing its foundation. In the second phase of the experiments, the tests were repeated using the earthquake records of Corralitos, Capitola, and Santa Cruz described earlier in the paper. This paper presents only the results from the earthquake base excitation of the structural model tested on the shaking table.

Test Setup and Model

A simple single-story model structure was built as shown in Fig. 15. The model consists of two steel plates connected by six steel rods. The top and bottom steel plates provided the mass, while vertical steel rods provided the stiffness. Therefore, when fixed on the table, the model behaved like a single-degree-of-freedom (SDOF) system. However, SDOF assumption can be violated if additional natural frequencies in the transverse and torsional directions appear close to the one in the longitudinal direction. This is especially true if the stiffness values in two directions are similar. In order to eliminate this effect, two stiffening plates, made of aluminum, were attached on opposite sides of the model as shown in the photograph of Fig. 15. These plates, due to their high, in-plane stiffness, increased the stiffness of the model substantially in the transverse and torsional directions. As a result, trans-

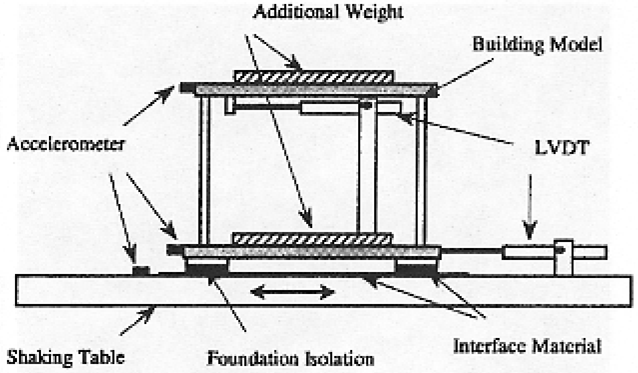

Fig. 16. Schematic diagram of the test setup of the single-story model structure

verse and torsional frequencies of the model were increased beyond 20 Hz, which was the maximum excitation frequency used in the experiments.

Another important feature of the model was the attachment of four steel blocks of 6.7 cm long, 2.4 cm wide, and 3.0 cm high to the base plate. These small blocks were added to reduce the contact area. Hence, higher normal stresses were achieved at the sliding interface without putting large weights on the model. Pieces of geotextiles were taped at the bottoms of the four corner blocks. Four UHMWPE sheets cut in 20 cm × 10 cm dimensions were fixed on the table. Double-stick tape was used for all fastening tasks. The model was then placed over the UHMWPE allowing it to freely slide during shaking.

The model structure was designed such that lead blocks each weighing about 0.18 kN could easily be attached on the top and base plates. The mass ratio (γ), defined as the mass at the top divided by the total mass, could therefore be changed by adding more lead blocks on the base plate. Adding mass on the top plate was avoided to maintain a constant natural frequency of the model.

Measurements were taken by three accelerometers, located on the base and top plates of the model, and on the shaking table. Displacements were also measured by two LVDTs. Fig. 16 indicates the locations of all transducers used. One LVDT was attached between the top and base plates measuring the drift (distortion of the columns of the structure). A second LVDT, mounted on the shaking table, monitored the displacement of the base with respect to the table. A 16-bit data acquisition card was used to acquire the data at a sampling rate of 200 Hz.

Several free vibration tests were carried out to identify the natural frequency and critical damping ratios of the model. The natural frequency of the model was estimated to be 8.6 Hz. The critical damping ratio of the structural model was found to be about 0.01.

Test Results

The three earthquake records, scaled to 0.25g and used in the experiments, were shown in Figs. 10–12. Initially, the model was tested by fixing its base to the shaking table. This allowed the evaluation of the dynamic response of the structure to the base excitation without the effect of foundation isolation. Subsequently, the tests were repeated by allowing the model base to slide along the geotextile/UHMWPE liner.

Fig. 17 shows a comparison of the peak drift of the fixed-base and foundation-isolated models as a function of the peak acceleration of the records used. It is noted that peak drift is the distortion of the columns of the model, and hence a measure of the column shear force induced by the table excitation. The figure indicates that the peak drift from the fixed-base model increases with increasing table accelerations; while the peak drift of the foundation isolated model is much smaller and remains almost constant. Thus, use of foundation isolation can lead to dramatic reduction in column shear forces induced by seismic shaking. However, accompanying such a reduction in transmitted energy are slip displacements along the geotextile/UHMWPE liner interface.

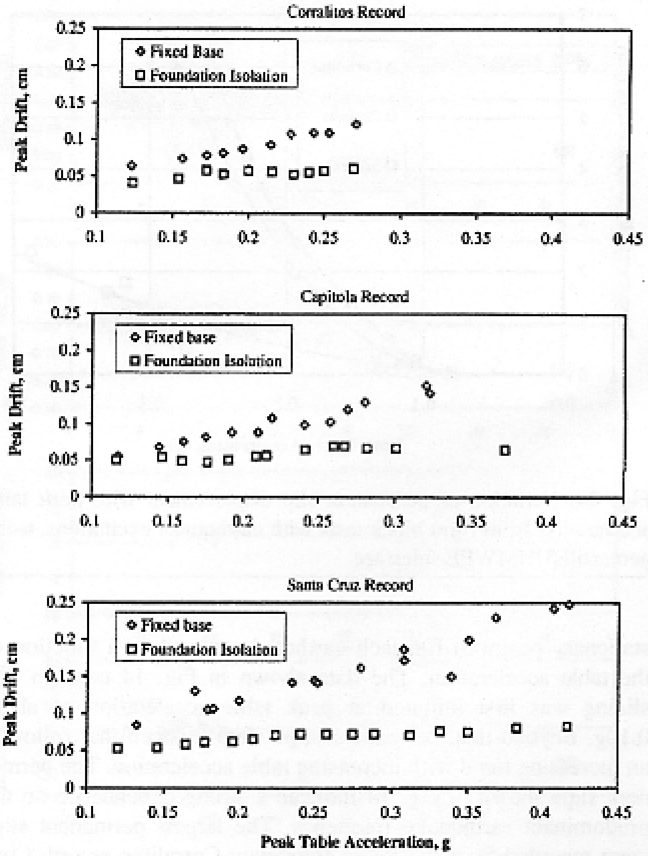

Fig. 17. Comparisons of peak drifts from fixed-base and foundation-isolated structure as a function of earthquake peak table acceleration measured using the Corralitos, Capitola, and Santa Cruz records

Fig. 18 shows the measured peak-to-peak (maximum slip during shaking) and permanent slip displacements (slip at end of shaking). The frequency content and acceleration level of an earthquake record appear to be determining factors in slip displacements recorded along the foundation isolation liner. The low frequency content Corralitos record produced larger levels of peak-to-peak and permanent slip displacements than the other records. In general, an increasing trend of peak-to-peak slip displacements is observed with table accelerations. In all tests, the permanent slips were significantly smaller than the peak-to-peak slips. Hence, for foundation-isolated structures, peak-to-peak slip displacements as well as permanent slip displacements are of crucial importance. Allowance needs to be made in the design of such foundation-isolated structures for the structure to experience the peak-to-peak slip displacements that are associated with reduced transmitted accelerations.

The effectiveness of the foundation isolation in reducing the response of the model during earthquake excitation can be noted

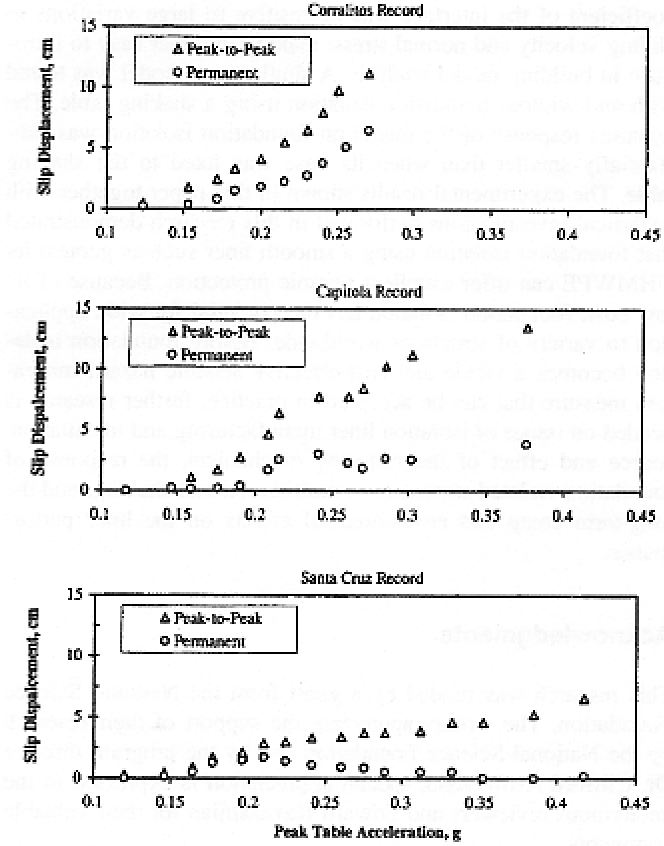

Fig. 18. Variation of slip displacement as a function of earthquake peak table acceleration measured using the Corralitos, Capitola, and Santa Cruz records

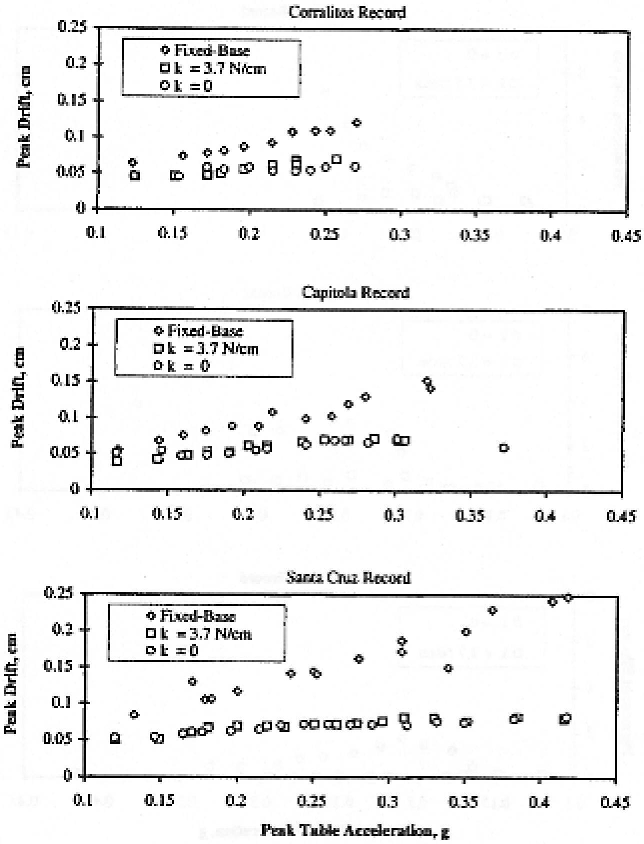

Fig. 20. Influence of base springs on peak drift as a function of earthquake peak table acceleration measured using the Corralitos, Capitola, and Santa Cruz records

in Fig. 19. The figure presents the ratio of the measured shear force in the foundation-isolated model and that of the fixed-base model. The results fall within a certain band that represents the effect of the wide range of frequencies that are present in the three selected records. At a table acceleration of $0.4g$, the shear force in the foundation-isolated model was as small as 30% of that in the fixed-base model. Larger reductions in shear force can be expected for larger table accelerations as the trend in the figure indicates.

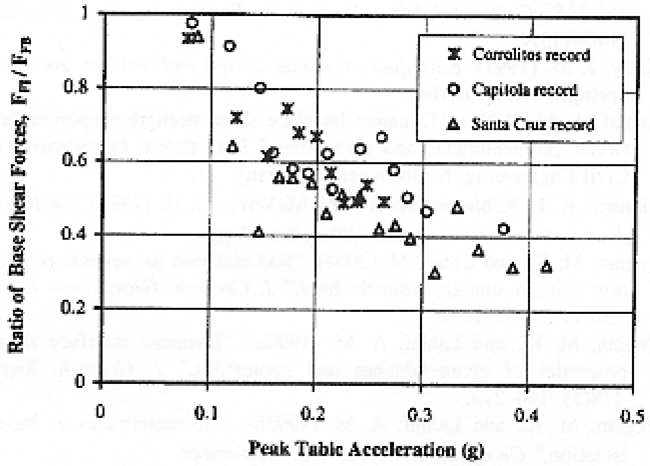

Fig. 19. Ratio of the base shear force in the foundation-isolated model (FFI) and that of the fixed-base model (FFB) as a function of the peak table acceleration, using the Corralitos, Capitola, and Santa Cruz records

Restoring System for Slip Reduction

Tests with earthquake excitations showed that models on foundation isolation may experience significant permanent slip displacements. In practice, these slip displacements may cause several problems including breakage of utility lines and shifting of entrance stairs. In the application of mechanical seismic isolation, restoring force devices are introduced to minimize permanent slips. Helical steel springs and rubber bearings are common restoring force devices. In this research, in order to test the influence of a restoring force on limiting the slip displacements of a foundation-isolated structure, the model was modified such that the base plate was attached to the shaking table through soft steel springs as shown in Fig. 15. The springs were used to provide the restoring force necessary to bring the model to its original position at the end of the shaking.

A series of tests were carried out with earthquake-type excitations to determine the effectiveness of base springs in limiting slip displacements. Tests were run on a fixed-base model, a foundation-isolated model, and on a model with base springs, using three earthquake records of increasing peak accelerations. Fig. 20 shows the peak drift results for a fixed-bas model, foundation-isolated model without restoring spring $(k_b=0)$, and foundation-isolated model with a restoring spring $(k_b=3.7\ \mathrm{N/m})$. The results indicate that almost identical peak drifts are measured

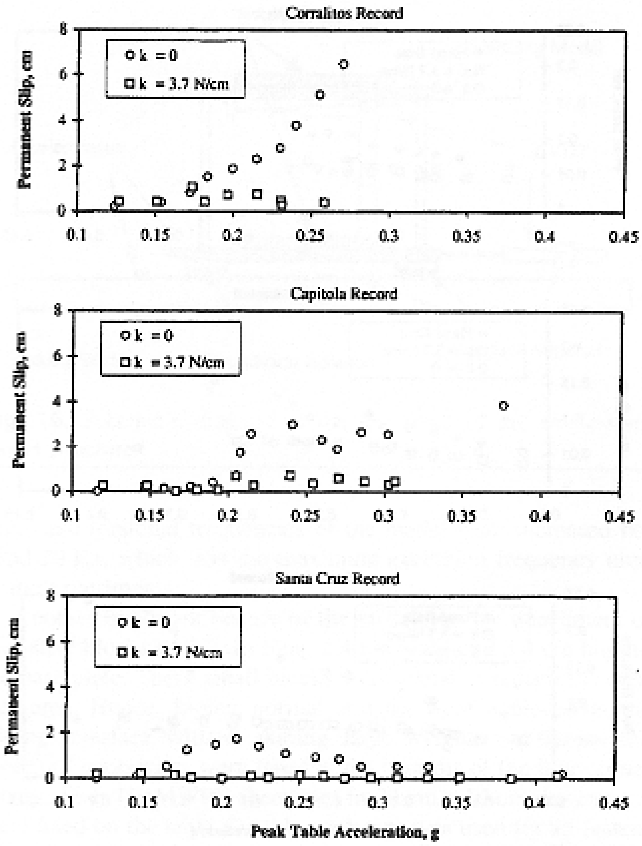

Fig. 21. Influence of base spring stiffness (*k*) on measured permanent slip as a function of earthquake peak table acceleration measured using Corralitos, Capitola, and Santa Cruz records

for models with and without restoring springs. Thus, the use of the restoring spring did not diminish the benefit of foundation isolation. However, the restoring springs substantially reduced the permanent slip as is observed in Fig. 21. Base springs produced almost no change in the peak-to-peak slip displacements and, therefore, need to be accommodated in design as for any other mechanically isolated structure.

A restoring force can be provided in several ways in a building with foundation isolation. One method is to provide the restoring force through the limited, passive resistance of the soil surrounding the foundation of the building. Such an option will be investigated in future research.

Conclusions

The frictional characteristics of various synthetic materials were investigated with the aim of choosing a smooth liner for use in the seismic isolation of structures. Through cyclic and shaking table tests it was determined that a geotextile over an ultrahigh molecular weight polyethylene (geotextile/UHMWPE) liner offered ideal interface frictional properties that make it suitable for foundation isolation application. The static friction coefficient of the interface is about 0.11 and the dynamic one is about 0.08. The friction coefficient of the interface was insensitive to large variations in sliding velocity and normal stress, making the liner easy to introduce in building model analysis. A single-story model was tested with and without foundation isolation using a shaking table. The dynamic response of the model on foundation isolation was substantially smaller than when its base was fixed to the shaking table. The experimental results shown in this paper together with analytical investigations performed in this research demonstrated that foundation isolation using a smooth liner such as geotextile/UHMWPE can offer excellent seismic protection. Because of its low cost, foundation isolation has the potential for wide application to variety of structures worldwide. Before foundation isolation becomes a viable and cost-effective seismic hazard mitigation measure that can be accepted in practice, further research is needed on issues of isolation liner manufacturing and installation, source and effect of the restoring mechanism, the response of foundation-isolated structures to multidirectional shaking, and the long-term creep and environmental effects on the liner performance.

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