Modeling the Stability of Sand Foundations During Earthquakes

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Many of the damages caused to structures during earthquakes are due to the failure of sand foundations. Experience in past earthquakes showed that poorly designed sand foundations can cause large vertical settlement and tilting to buildings. However, research efforts are complicated by the lack of field data about the responses of foundations during earthquakes. Centrifuge modeling has the advantage of being able to replicate field events in a controllable environment. For earthquake centrifuge tests, the boundary effects imposed by a model container need to be addressed carefully. A group of dynamic centrifuge tests was conducted at Cambridge University to study the seismic stability of sand foundations. The tests were conducted in a specially designed model container that could simulate a soil layer of infinite lateral extent. A large data base was established, which can be used for the verification of design calculations and validation of numerical procedures. Failure mechanism similar to that which occurred in the field was observed in the tests. When sand in the foundation was saturated, the risk of failure was significantly increased. There was clear indication of deterioration of the stiffness of sand under cyclic loading and with pore pressure increase. Implications for design are discussed.

Failure of structures based on sand foundations, such as block buildings and bridge foundations, was widely observed during earthquakes. For instance, during the Niigata Earthquake in 1964, the Mexico City Earthquake in 1985, the Loma Prieta Earthquake in 1989, and the Northridge Earthquake in 1994, extensive damage to block buildings was reported. An example of the field failure observed during the Loma Prieta Earthquake is shown in Figure 1. Typical failure of such structures involved excessive settlement and tilting of the foundation.

The frequent occurrence of such failure and the severe damage it caused have provoked widespread research interests among geotechnical engineers, and different types of analyses have been suggested. For example, Seed and Idriss (*1*) conducted a comprehensive analysis of the failure of block buildings during the Niigata Earthquake. To verify the results of these analyses, it is necessary to compare them with the data recorded in the field. However, as an earthquake in the field is unpredictable, recording the response of earth structures and foundations during earthquakes is difficult, time-consuming, and expensive. What is available in most cases is the pre- and post-earthquake information. The most critical information for the analysis, the response of earth structures and foundations during earthquakes, is lacking. For instance, regarding the failure of block buildings in the field, the following critical questions need to be answered in order to improve the design in the future. What were the accelerations on the building? Did the displacement occur during the largest cycles of ground vibration or did it accumulate during the entire duration of the earthquake? What was the magnitude of excess pore pressure in the ground? Was acceleration amplified or attenuated in the foundation soils? Unfortunately, in most cases there are no field data to provide answers to these questions.

This problem has been realized by researchers in many countries and tremendous efforts have been made to instrument sites in the field. In recent years, there have been some cases of success in recording field data during earthquakes. One of the examples is the recording of acceleration and excess pore pressures at the Wildlife site during the Imperial Valley Earthquake, as described by Youd and Holzer (*2*). However, given the infrequent occurrence of earthquakes at a particular site, a number of instruments would have to be installed on a wide range of structures to have a fair probability of recording some data eventually. The considerable cost involved in the installation and maintenance of instruments means that this technique can only be used on limited and highly selective structures. This cannot satisfy the requirements for the development of earthquake-resistant design.

In earthquake-resistant design, it is very important to choose effective and economical engineering countermeasures if a structure is found to be inadequately designed. However, it is difficult and expensive to prove the effectiveness of an engineering countermeasure in the field, especially when there are a number of options available. Different types of designs using a variety of engineering countermeasures would have to be adopted so as to find the most desirable solution. This could be costly and perhaps even risky. It is even more undesirable that the proof would be available only after a major earthquake has occurred at the locations where the engineering countermeasures have been used.

One of the effective methods of analyzing earthquake problems in geotechnical engineering is numerical simulation. Over the past two decades, considerable progress has been made in modeling the behavior of soils under cyclic loading and numerical implementation. There are quite a few established numerical codes available that are specially designed for dynamic problems. Numerical simulation has the advantage of being able to operate easily and identify the influence of individual parameters. The application of numerical simulation has been greatly expanded in recent years with the introduction of fast personal computers. However, it is well understood that the behavior of soils under cyclic loading is very complicated. Therefore, numerical simulation needs to be ver-

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FIGURE 1 Failure of block building during Loma Prieta Earthquake.

ified against experimental results before it can be applied in the field.

ROLE OF CENTRIFUGE MODELING

In the absence of field data, physical modeling techniques have an important role to play in geotechnical earthquake engineering. Physical modeling techniques have been used in the research of geotechnical earthquake engineering since the beginning of this century. Because a model test can be conducted in a controllable environment and transducers can be used at different locations to record the required data, physical modeling provides an effective way to generate experimental results. Data from such tests can be used to verify numerical codes, to improve design procedures, and to help the design in the field.

There are two types of physical modeling techniques widely used in geotechnical earthquake engineering: shaking table tests at normal gravity and shaking table tests mounted on a centrifuge. Shaking table tests conducted at normal gravity ($1g$ tests) have the advantage of being able to make detailed models at a relatively low cost. However, in a $1g$ test the stresses arising from the weight of the soil are much less than those in the field. It is well known that the behavior of soil is stress- and strain-dependent. Certain aspects of soil behavior, such as crushing of soil particles and dilatancy, are highly stress-dependent. Therefore the behavior of soil in a $1g$ test may be quite different from that in the field under high stresses. Although this does not invalidate the $1g$ test, interpretation of the data is difficult, especially if the strain in soil is high.

This difficulty can be avoided by using centrifuge modeling. In a centrifuge test the dimensions of earth structures are reduced while the body force is increased by the ratio of centrifugal acceleration over gravitational acceleration, resulting in the same stress and strain in the model as in the prototype. The principles of centrifuge modeling are well understood now, as demonstrated by Schofield (*3*). It has become a popular research tool in geotechnical engineering (see Corte [*4*] and Ko and McLean [*5*]). Since the early 1980s, a number of centrifuge centers have acquired the capability of earthquake centrifuge modeling, as discussed by Steedman (*6*). With the help of advanced data-acquisition systems and miniature transducers, centrifuge model tests can make valuable contributions by permitting general observations concerning the behavior of soil masses during simulated ground shaking and by providing experimental data against which theoretical analysis can be checked.

In recent years, several research groups have conducted centrifuge simulation on the behavior of shallow foundations during earthquakes. Liu and Dobry (*7*) conducted centrifuge tests on circular shallow foundations based on saturated sand foundations. It was reported that redistribution of excess pore pressure after base shaking played an important role in the displacement of the foundation. Krstelj and Prevost (*8*) carried out centrifuge tests on a square footing based on a saturated sand layer, overlaid by a thin layer of saturated silt. The data were used to verify numerical predictions.

Reported here are some results of centrifuge tests conducted at the Cambridge Geotechnical Centrifuge Center. The operation of the beam centrifuge was described by Schofield (*3*). A series of dynamic centrifuge tests was conducted on block buildings based on sand foundations. All the data in this paper are presented in prototype scale. The soil used in the model tests was Hostun RF sand, a field sand from France. The particle size of this sand ranges between 0.1 and 1 mm, and the average particle size is 0.4 mm. The specific gravity of the sand is 2.677, and the maximum and minimum void ratios are 0.976 and 0.607, respectively. All of the tests were conducted at a centrifugal acceleration of $50g$. The details of the tests and all of the data were reported by Zeng (*9*).

REDUCING BOUNDARY EFFECTS IN EARTHQUAKE TESTS

Although earthquake centrifuge modeling is very useful, it is difficult to model field conditions properly in an earthquake centrifuge test. As a centrifuge model is much smaller than the corresponding prototype structure, the scaling factor may be influential in some tests. For instance, the number of soil particles in contact with a footing would be much lower for the model test than for the corresponding prototype if the same soil is used. While it is possible to change the particle size of soil in the model test to reduce this influence, doing so would create other problems, because some properties of a soil depend on its particle size. A common problem in earthquake tests is to satisfy the scaling relationship for time. While for a dynamic event the model time is reduced by N, the scaling factor of time for consolidation is N^2. This conflict between scaling factors can be solved by increasing the viscosity of the pore fluid.

The unique problem in earthquake centrifuge modeling is how to reduce boundary effects. In the field most geotechnical problems are associated with a soil stratum of large lateral extent, which can be idealized as being of infinite lateral extent. Under base shaking, cyclic shear stresses are imposed on soil elements that are in equilibrium under static loading. A typical loading condition on a section of such a soil stratum is shown in Figure 2*a*. The base shaking would induce shear stresses on both vertical and horizontal planes. The inertial force on soil mass would induce a rocking moment on

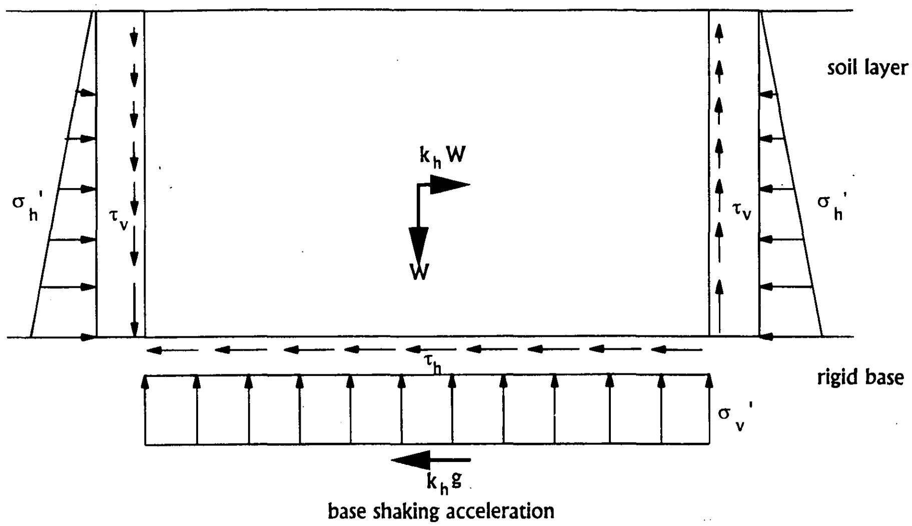

FIGURE 2*a* Distortion in stress field due to smooth end walls: distribution of stresses in a soil layer of infinite lateral extent.

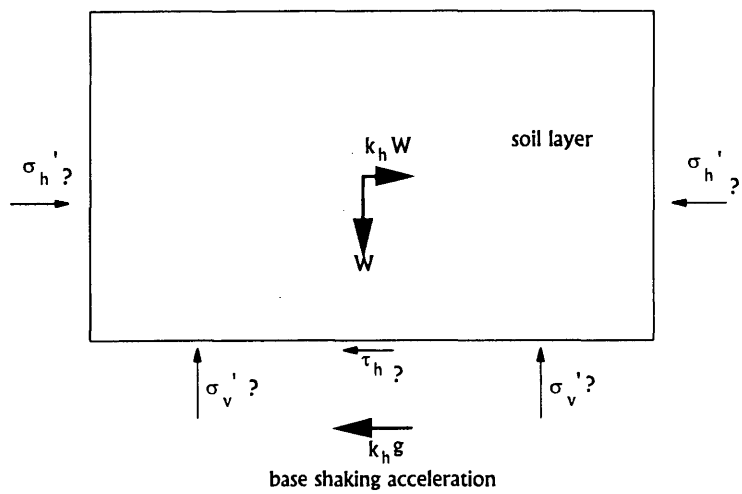

FIGURE 2*b* Distortion in stress field due to smooth end walls: distribution of stresses in model with smooth rigid end walls.

the mass, which would be balanced by the moment of complementary shear stresses on the two vertical planes. However, in a centrifuge test a model is constructed in a model container, and thus artificial boundaries are imposed. If the model container is not properly designed, severe boundary effects may be induced, which can lead to differences in stress and strain distributions between the model and the field conditions. These boundary effects are discussed in detail by Schofield and Zeng (*10*). For instance, if the model container has smooth and rigid end walls, complementary shear stresses cannot be sustained on the vertical end walls. The rock moment induced by the inertial force has to be balanced by the redistribution of stresses on the boundaries, as shown in Figure 2*b*. This complicates the analysis of soil behavior in the model container. Although this effect does not invalidate the results of dynamic centrifuge tests conducted in a rigid model container, the data must be interpreted carefully, especially if the model container is small. For a relatively long model container, it may be suggested that in the central region of the container the influence of boundary effect is small. However, it is difficult to determine the extent to which the boundary effects will affect the data.

To reduce the boundary effects, an equivalent-shear-beam (ESB) model container was designed and tested at the Cambridge Geotechnical Centrifuge Center. The design criteria and the performance of the model container were described by Schofield and Zeng (*10*). A three-dimensional view of the model container is shown in Figure 3. The model container is made of rectangular frames of dural spaced by rubber layers. Under base shaking, the model container moves together with the soil contained, and was designed to have the same lateral deflection and natural frequency

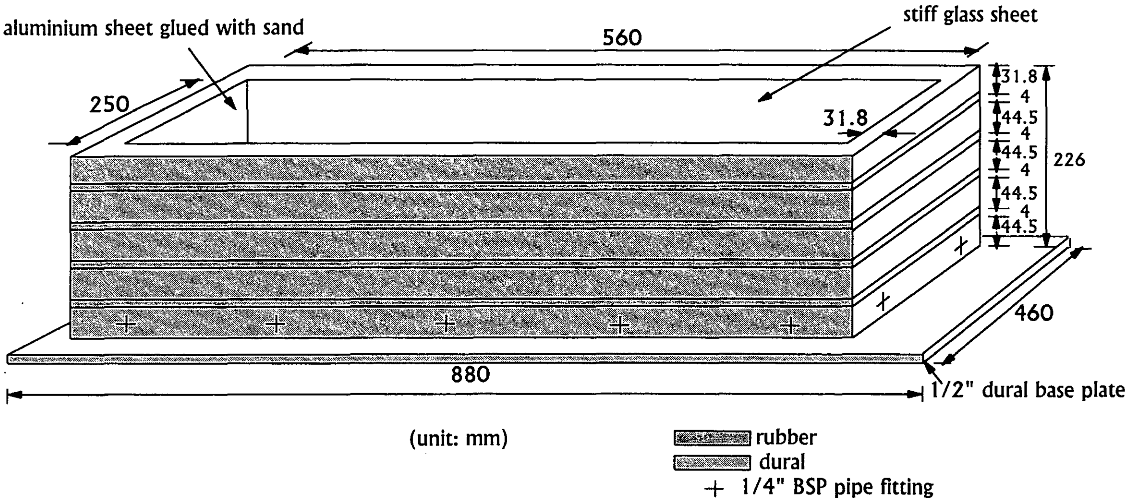

FIGURE 3 A three-dimensional view of the ESB container.

as the soil contained. To sustain complementary shear stresses induced by base shaking, a flexible and inextensible frictional sheet was attached at each end wall and the base of the box was glued with local sand.

A group of centrifuge tests was conducted to study the performance of the ESB container under earthquake loading. One of the centrifuge models is shown in Figure 4. It is a dry sand bed 10 m thick. Two layers of accelerometers were placed across the sand bed and on the model container to check whether a uniform acceleration field is achieved in the model. If the boundary effects are small, accelerations at the same height in the model should be identical. The recording of the accelerometers during one model earthquake is shown in Figure 5. It is clear that accelerations recorded in the sand and on the model container at the same height were almost identical, proving that the design criteria were met. There were other measurements that showed that the performance of the ESB container was satisfactory, as described by Schofield and Zeng (*10*).

BLOCK BUILDING ON DRY FOUNDATION

Test SERC7 was conducted on a block building slightly embedded in a flat, dry sand bed. A cross-sectional view of the centrifuge model and the location of some of the transducers used are shown in Figure 6. The block building was 5 m high and 1.67 m wide, made of steel. The embedment of the building was 0.5 m. The sand in the model had a dry density of 15.01 kN/m^3, which corresponded to a void ratio of 0.743, or a relative density of 63.1 percent. A sequence of earthquakes was applied to the model, with a gradual increase in intensity.

Data recorded by accelerometers during a large earthquake are shown in Figure 7. Accelerometer 1 (ACC1) was fixed at the base of the ESB model container and its recording can be regarded as the earthquake input. As shown in Figure 7, a typical earthquake contains a number of approximate sinusoidal vibrations. The peak horizontal acceleration for this earthquake was 0.31*g*. It is clear that the vibration in the soil was slightly amplified as the shear wave prop-

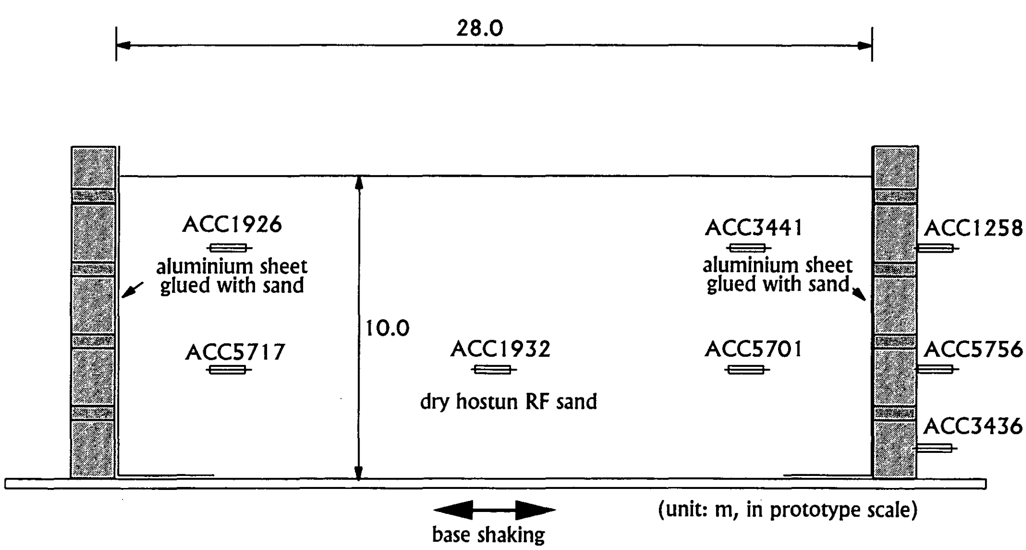

FIGURE 4 Cross-sectional view of centrifuge model, test SERC8.

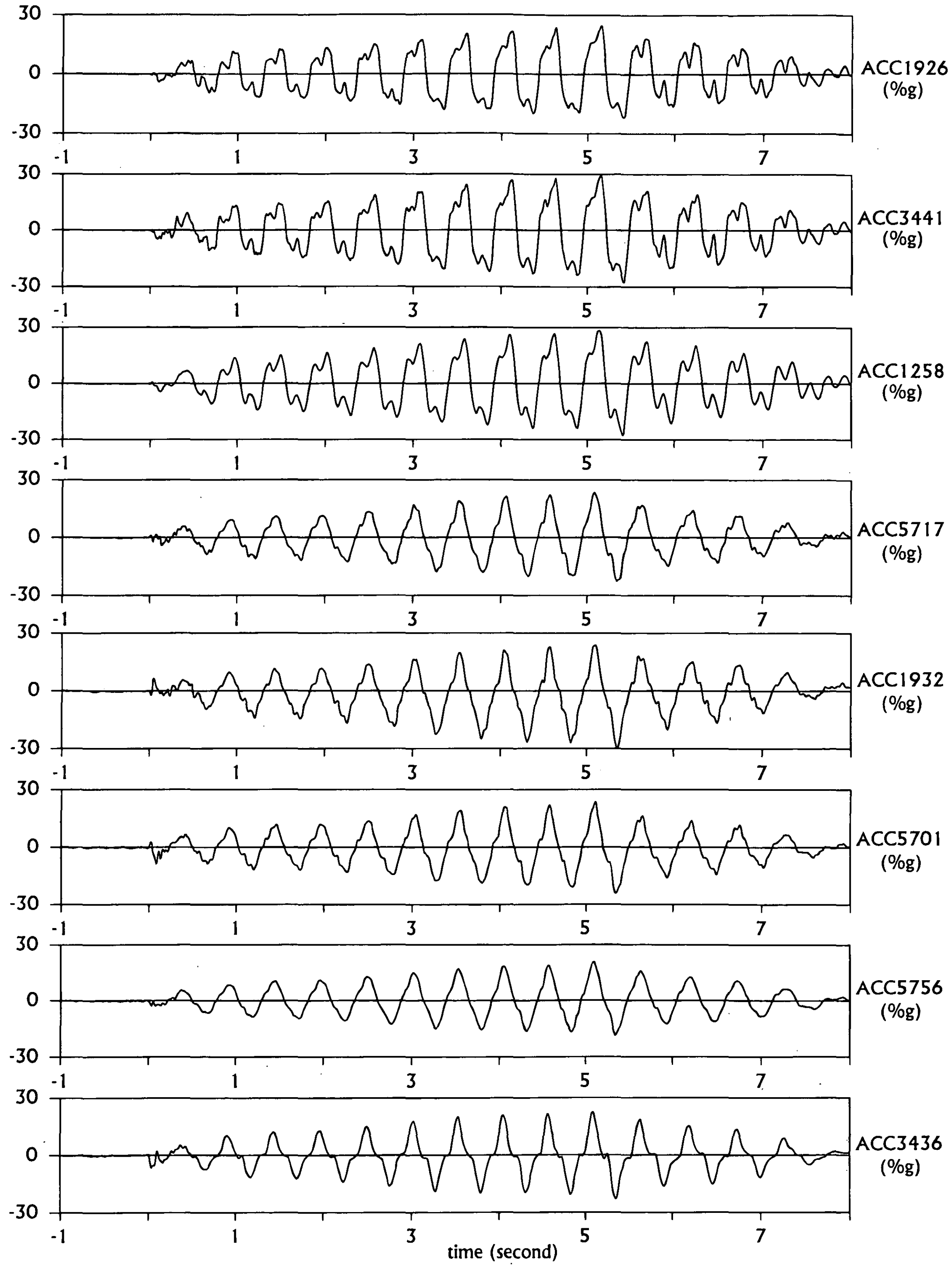

FIGURE 5 Accelerations at two specific heights across the model during EQ2, test SERC8.

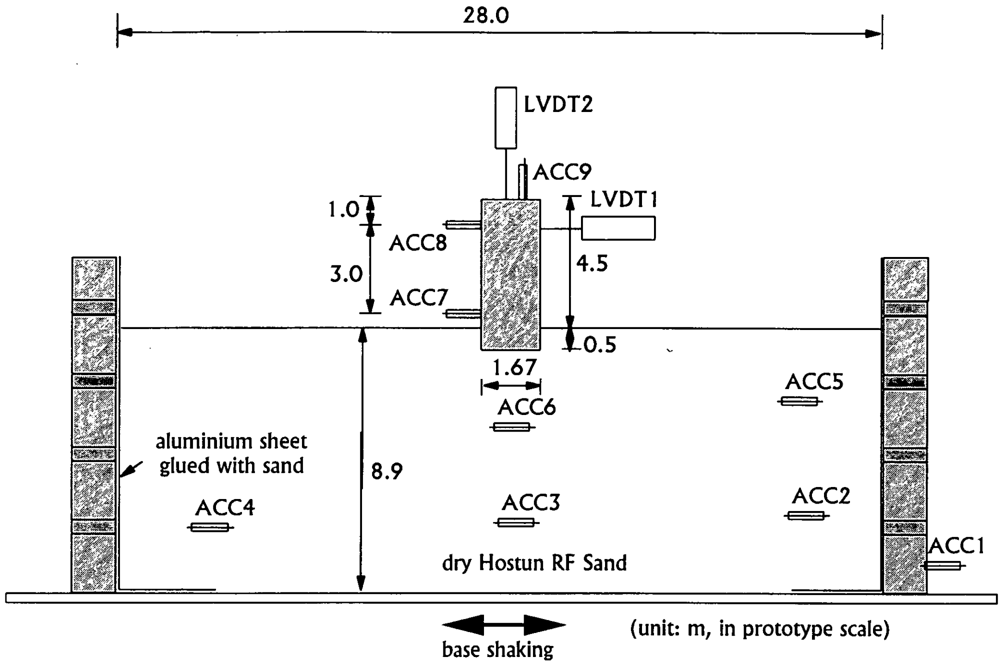

FIGURE 6 Cross-sectional view of centrifuge model, test SERC7.

agated upward. The peak acceleration recorded near the surface was significantly higher than the input motion.

Accelerometers 2, 3, and 4 were in the sand at the same height across the model container. The recordings of ACC2 and ACC4 were almost identical in both amplitude and phase, proving again that the performance of the ESB model container was satisfactory. However, the recording of ACC3 was quite different, showing the strong influence of the vibration of the building. It indicated that the large strain in the soil due to the vibration of the building was limited to the area close to the building. ACC6 was buried in sand underneath the block building. Its recording showed an amplification of nearly 100 percent. Both time history and amplitude were quite different from those recorded in the free field by ACC5.

Both accelerometers and linear variable differential transformers (LVDTs) were fixed on the block building to measure the response of the building. The recording of the transducers during the earthquake is shown in Figure 8. ACC7 was near the base of the structure, hence it predominantly recorded horizontal vibration of the building. As shown in Figure 8, the amplitude of the horizontal vibration was close to that of the base shaking. There was no phase shift indicating that the natural frequency of vibration in the horizontal direction was high. ACC9 was fixed in the vertical direction. Its recording showed that the amplitude of vertical vibration was small. ACC8 was placed near the top of the building, hence its recording included both lateral vibration and rocking motion of the building. ACC8's recording showed that it lagged behind ACC2 by nearly 180 degrees and the amplitude was lower than that of input motion. That was due to the fact that the natural frequency for rocking was lower than the dominant frequency of base shaking.

Two LVDTs were attached to the building to record displacement in the vertical and horizontal directions. As shown in Figure 8, both recorded large displacements during the earthquake. However, the time history showed quite different patterns. The vertical settlement of the building started during the high amplitude cycles and increased continually till the end of the earthquake. On the other hand, the lateral displacement of the building cyclically accumulated during the whole period of base shaking, and the direction of inclination was determined during the first cycle. After the test, measurement of the profile of the model showed that the building model suffered a foundation failure, Figure 9. The total settlement was about 0.3 m and the tilting angle was 6.3 degrees. On the opposite side of the tilting there was a clear heave on the ground. All these data indicate a bearing capacity failure. In the free field away from the structure, there was hardly any ground settlement.

BLOCK BUILDING ON SATURATED FOUNDATION

The centrifuge model for test SERC6 was almost identical to that in test SERC7, except that the sand foundation was saturated with deaired water. A cross-sectional view of the centrifuge model and the locations of some transducers used are shown in Figure 10. The sand in the foundation had a void ratio of 0.774, or a relative density of 55 percent. The model was saturated using a vacuum system. When the model preparation was finished, the lid of the model container was put on and the model container was sealed. A vacuum was applied to the model. After the vacuum had been stabilized, deaired water was slowly introduced into the sand. The whole process

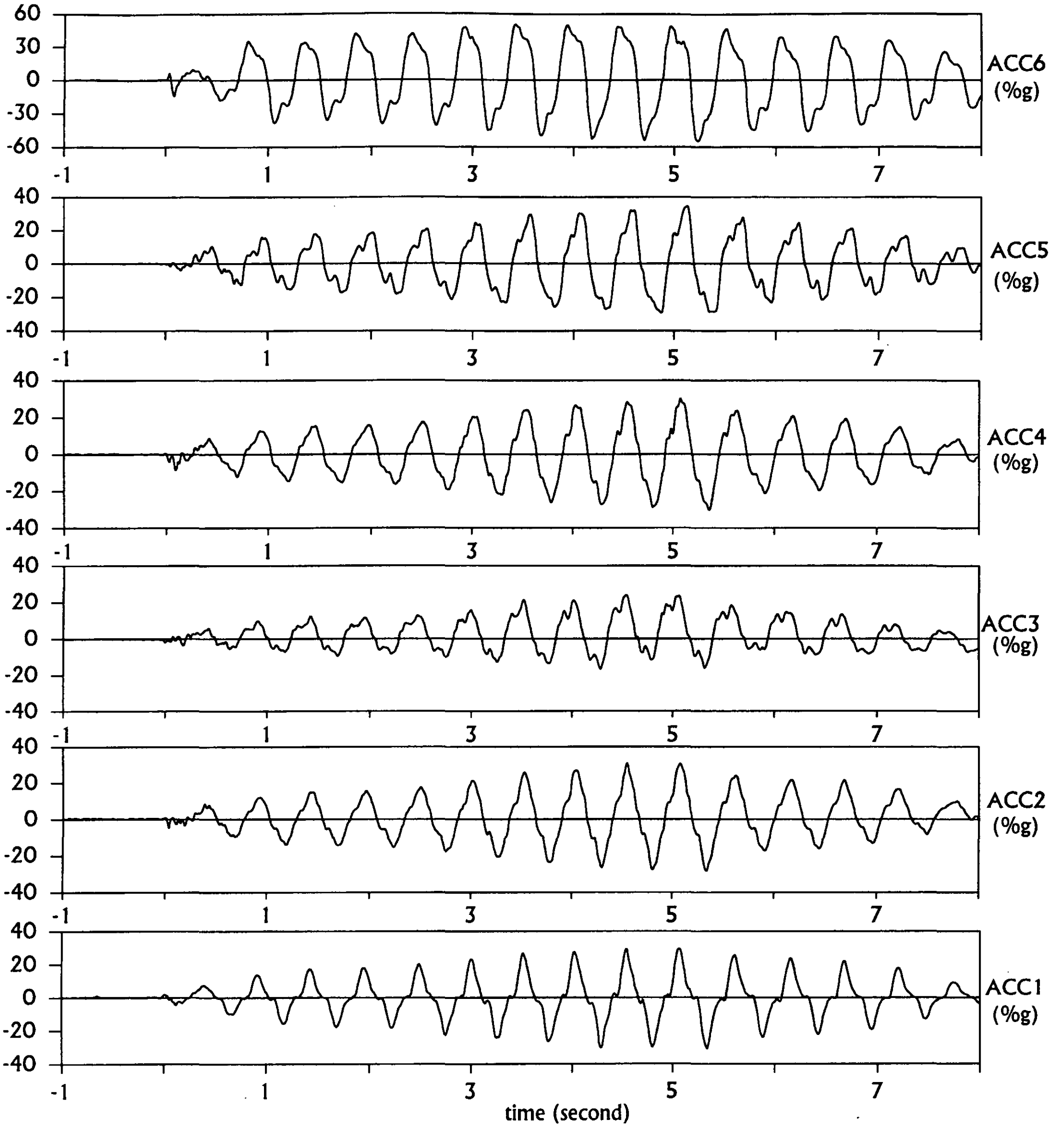

FIGURE 7 Recording of accelerometers during an earthquake, test SERC7.

of saturation took about 12 hours. Because water was used as pore fluid, the permeability of the sand was greatly increased. Therefore, excess pore pressure generated during earthquakes would dissipate fast and the accumulated excess pore pressure was expected to be low.

In this test a number of pore pressure transducers were used to monitor the excess pore pressure in the foundation. The recording of the transducers during a large earthquake is shown in Figure 11. All the transducers recorded cyclic variation of excess pore pressure but no accumulation of excess pore pressure. Pore Pressure Transducers 4 and 5 were in the sand near the two corners of the block building. Their recordings were out of phase with each other. This was due to the rocking motion of the structure, which caused sand on one side to contract while sand on the other side was expanding.

Accelerations recorded in the sand foundation are shown in Figure 12. The results were quite similar to those recorded in the dry test. ACC5, which was right underneath the block building, recorded amplification of vibration. Across the model at the same height, Accelerometers 2 and 4 recorded quite similar results, indicating that desirable boundary conditions were achieved.

The response of the model building to the base shaking is shown in Figure 13. The recordings of the three accelerometers on the building were similar to those during the dry test. A phase shift gradually built up between the lateral vibration of the building (recorded by ACC6) and the input motion, suggesting that the lateral stiffness of the foundation deteriorated under earthquake loading. The two LVDTs recorded large displacements of the structure. After the test the measurement of the profile showed a clear failure mechanism (Figure 14). The building settled 0.5 m and tilted 12

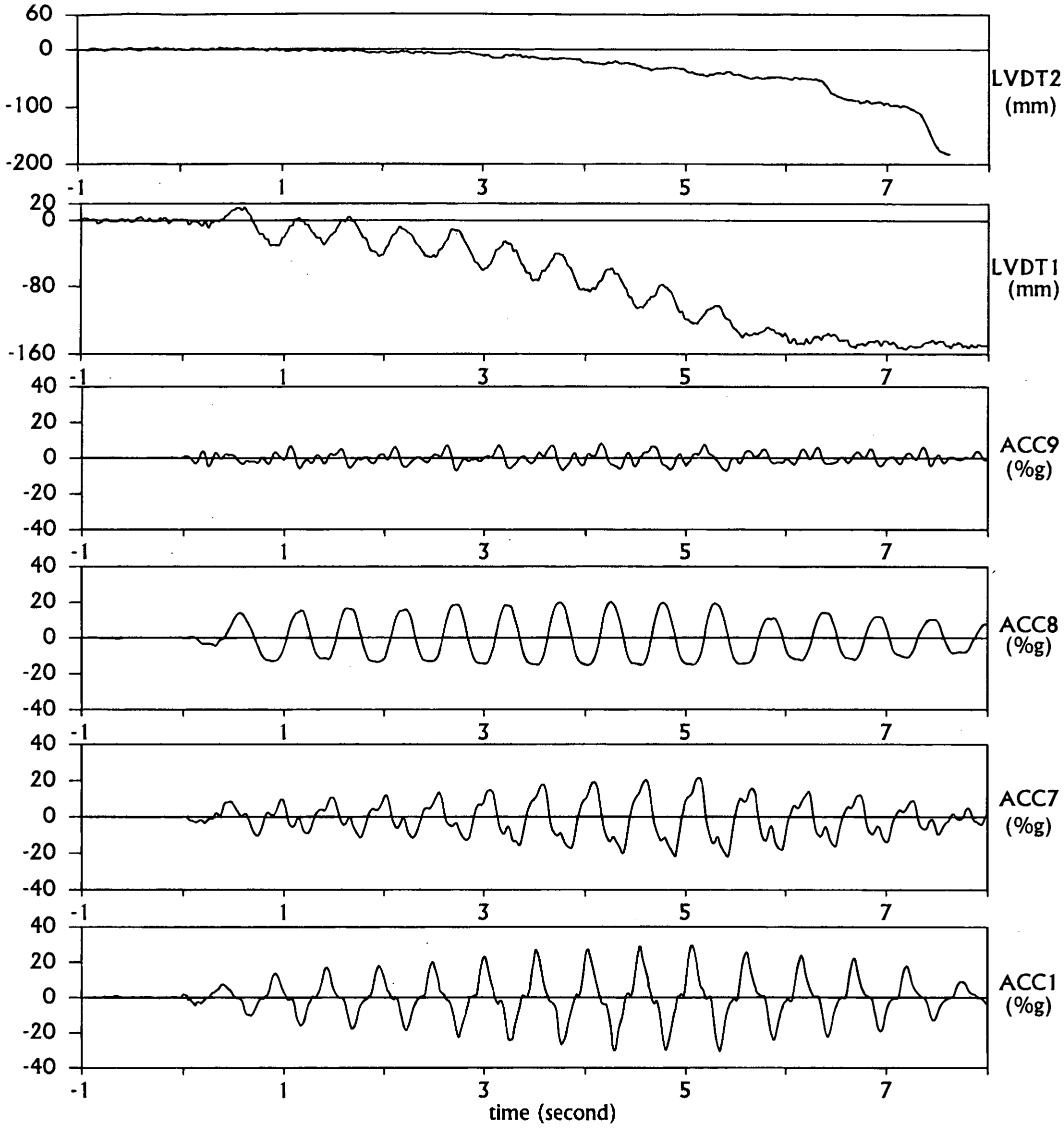

FIGURE 8 **Response of the block building during an earthquake, test SERC7.**

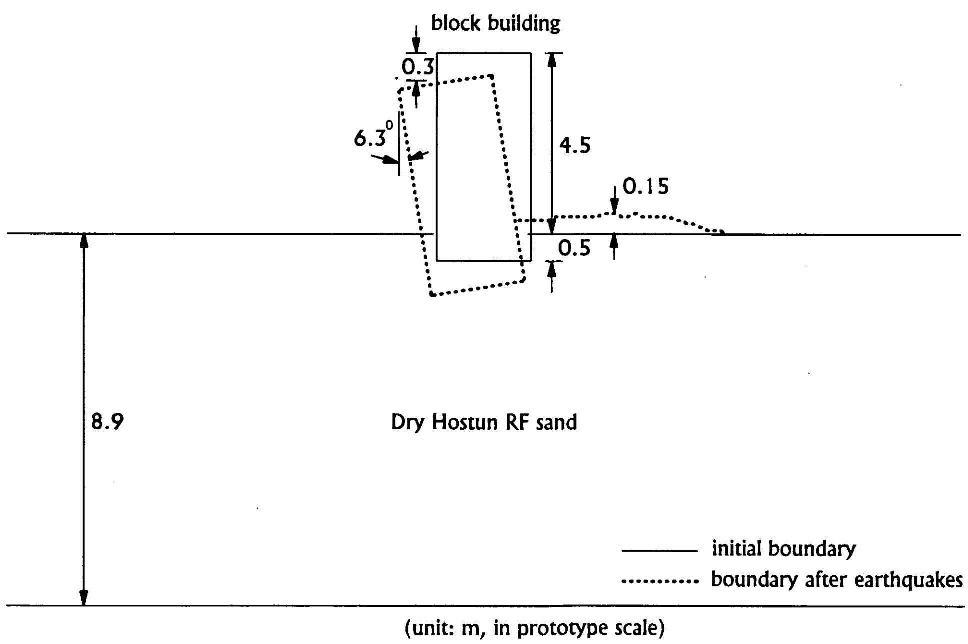

FIGURE 9 **Failure of the block building after earthquakes, test SERC7.**

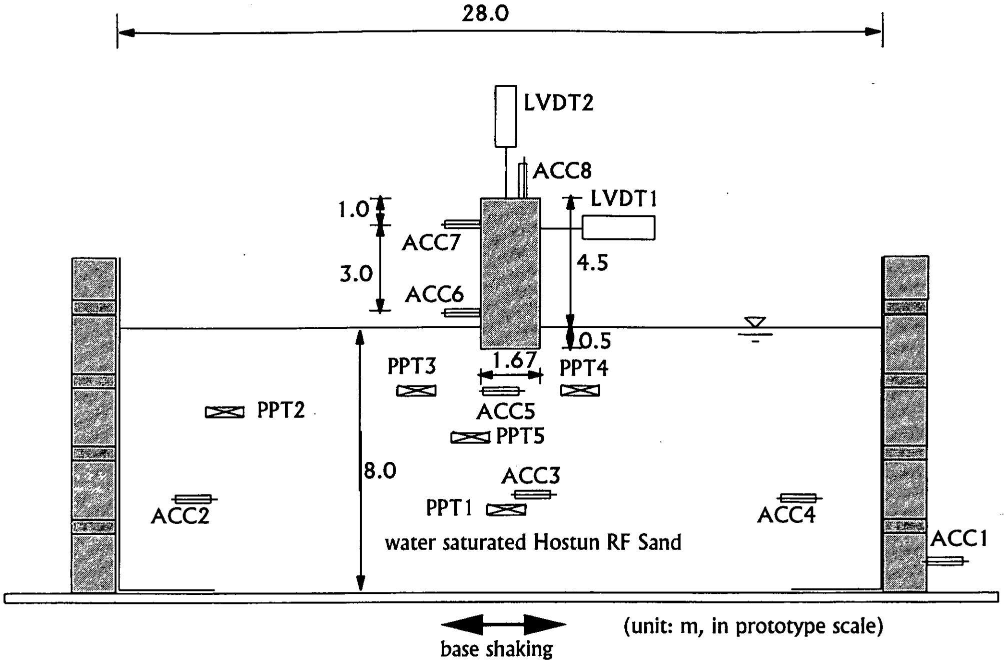

FIGURE 10 **Cross-sectional view of centrifuge model, test SERC6.**

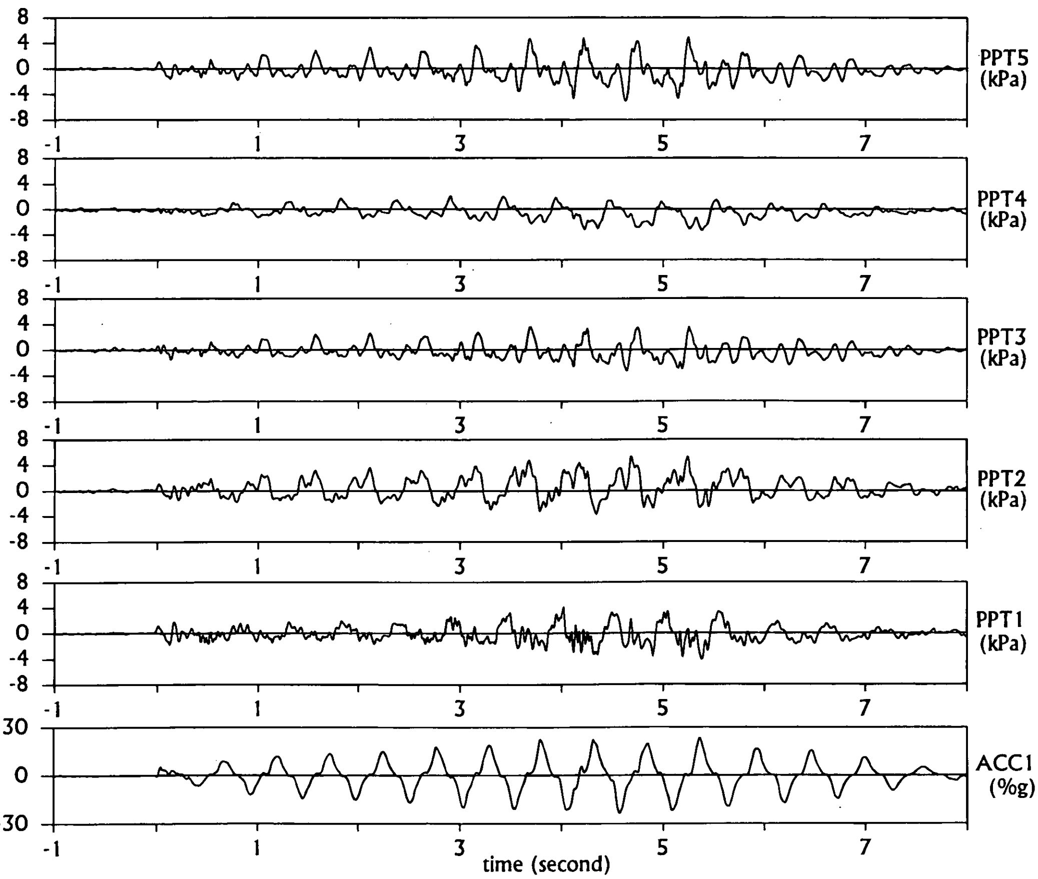

FIGURE 11 **Recording of pressure transducers during an earthquake, test SERC6.**

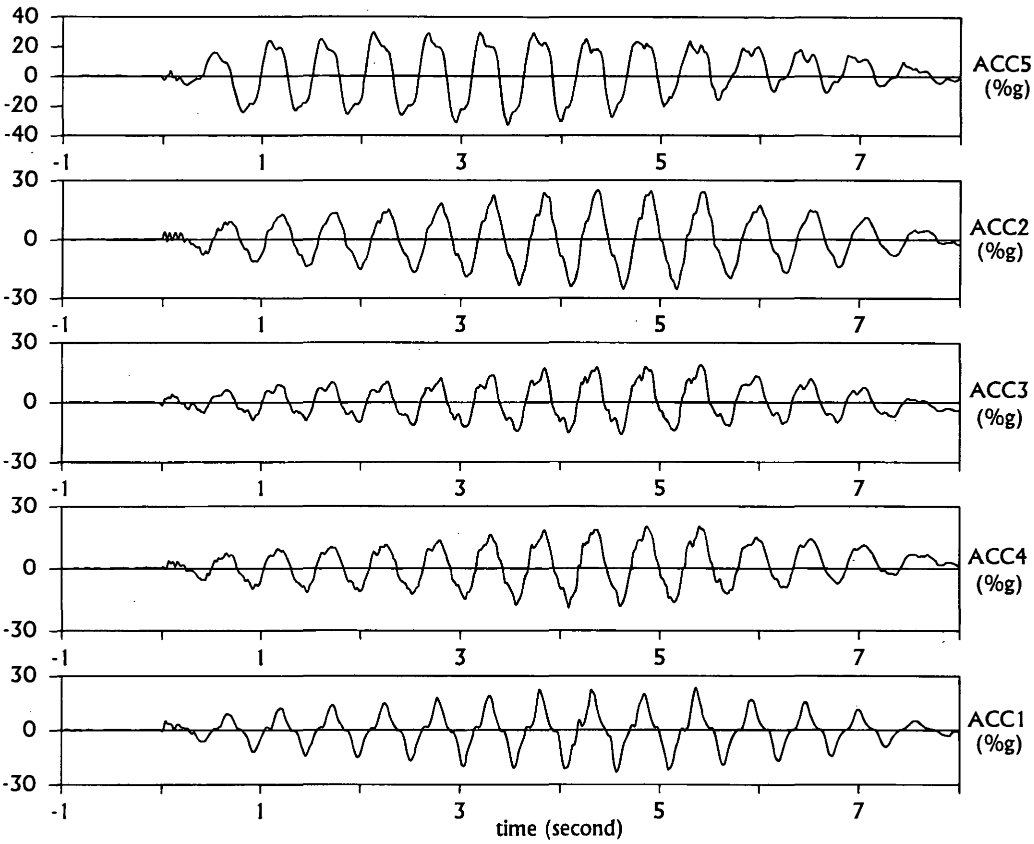

FIGURE 12 Recording of accelerometers during an earthquake, test SERC6.

degrees. On the side opposite of the tilting there was a clear ground heave. The ground away from the building suffered an average settlement of 0.15 m. The failure mechanism was similar to that observed in the field.

Compared with the test on dry foundation, although the amplitude of base shaking was much lower ($0.24g$ versus $0.31g$), the displacement of the structure was significantly larger. Thus the effect of earthquakes on saturated foundations was much more severe than on dry foundations, even without significant accumulation of excess pore pressure. The decrease in effective stress due to both static and dynamic pore pressures reduces the strength and stiffness of the foundation. Moreover, the bearing capacity of the foundation is significantly reduced, which can lead to catastrophic failure.

Therefore, in the design of foundations in the field, special consideration is necessary if the foundation is saturated. Even if the top layer of the foundation is dry, migration of water due to excess pore pressure at lower depths can have a similar effect. To reduce such risks, the foundation can be compacted or installed with a drainage system.

CONCLUSIONS

From the results of this study, the following conclusions can be drawn:

1. Centrifuge tests can generate useful physical data about seismic response of earth structures. These data can help engineers to understand the mechanism of seismic soil-structure interaction and to evaluate the risk of existing structures. In areas related to transportation engineering, centrifuge tests can be used effectively to study complicated problems such as the design of retaining walls and bridge abutments.
2. It is important to ensure that boundary conditions in earthquake centrifuge tests properly replicate the field situation. The concept and the application of the ESB model container proved able to achieve desirable boundary conditions for the type of tests described herein. This model containment can be used for centrifuge tests on models of other structures such as bridge abutments.
3. Foundations of block buildings can suffer bearing capacity failure under earthquake loading, especially when the foundations are saturated.

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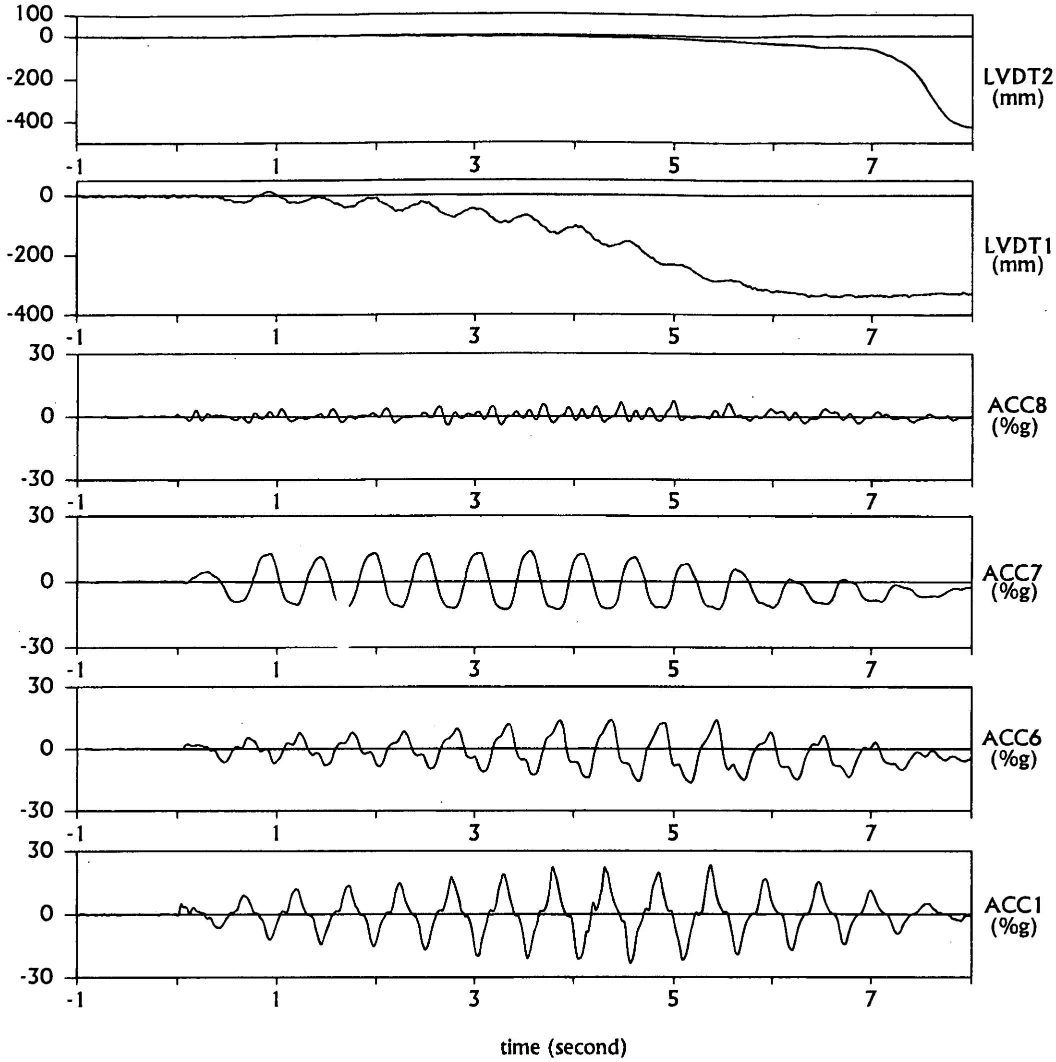

FIGURE 13 Response of the block building during an earthquake, test SERC6.

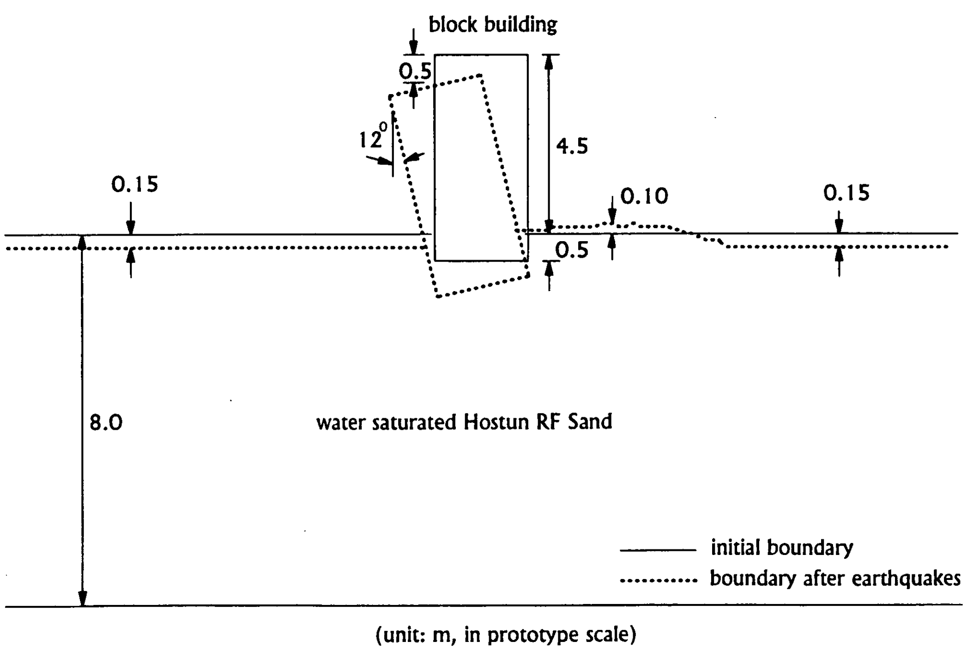

FIGURE 14 Failure of the block building after earthquakes, test SERC6.

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