EARTHQUAKE-INDUCED PERMANENT DISPLACEMENTS IN MODEL REINFORCED EARTH WALLS

by

Dixon Rea[(I)] and William E. Wolfe[(II)]

SUMMARY

The results from a series of shaking table experiments designed to investigate earthquake-induced permanent displacements in reinforced earth walls are described. The 18 in high walls were constructed with plexiglass face elements, 1/2 in wide mylar tape reinforcing ties, and a clean fine sand. The earthquake motion used in the experiments was derived from the N21E component of the Taft (1952) earthquake.

INTRODUCTION

Reinforced earth walls have become an economical means of constructing retaining walls in many regions of the world. Originally developed in countries with relatively low levels of seismic activity (1), reinforced earth construction is spreading to regions liable to experience strong shaking during earthquakes. Thus the response of reinforced earth walls to ground shaking has been receiving increasing attention (2,3).

Reinforced earth walls are usually designed by limit state procedures. During strong earthquake excitation the factors of safety of such walls, like other earthen structures, may become momentarily less than unity. Since the factors of safety are less than unity for only short periods of time, the walls do not necessarily fail; however, they accumulate permanent deformations (4,5). Therefore it would be desirable to add to the limit design procedure a requirement restricting the permanent displacements that reinforced earth walls could incur during earthquakes.

Such a requirement cannot be implemented at present because the seismic behavior of reinforced earth walls is not understood well enough to permit the determination of earthquake-induced permanent deformations by analysis. In order to provide basic data to develop accurate analytical procedures for this purpose, an experimental investigation, (6), was undertaken in which 12 in, 18 in, and 24 in high reinforced earth walls were built in the laboratory and subjected to simulated earthquake motions by means of a shaking table. The walls were subjected to various intensities of four earthquake motions derived from the N21E component of the Taft (1952) earthquake record, and the responses of the walls to these motions were recorded. The results for experiments involving 18 in walls and one of the earthquake motions are presented below.

EXPERIMENTAL EQUIPMENT AND PROCEDURES

The reinforced earth walls were constructed in the laboratory using 1/4 in x 3 in x 30 in plexiglass plates as face elements, 1/2 in wide strips

(I) Associate Professor, University of California, Los Angeles, CA, USA
(II) Assistant Professor, Ohio State University, Columbus, Ohio, USA

of smooth mylar tape as reinforcing ties, and a fine sand with an internal angle of friction of about 35° as backfill. Ties were attached to the front face of the plexiglass plates with masking tape and passed over or under the plate or through a thin slit at mid-height. The horizontal spacing between ties was 6 in at mid-height and 12 in at the top and bottom edges. Ties at the top and bottom edges of the plates were alternated as shown in Fig. 1 so the horizontal and vertical spacings between ties in the sand backfill would be 6 in and 1-1/2 in respectively. The backfill was placed uniformly by letting sand fall through a spreader box from a height of about 18 in. This procedure resulted in a backfill that had an average density in place of 103.5 lb/ft^3 or a relative density of 85%.

The only intended variable in constructing the 18 in walls was the length of the ties, which, while kept constant in a given wall, varied from 12 in to 30 in among the walls subjected to earthquake motions. By a series of static tests it was found that the minimum tie length required to ensure the stability of 18 in walls with the tie configuration shown in Fig. 1 was 6.6 in. Thus the factors of safety of the walls, defined as the ratio of the actual tie length to the minimum length required for static stability, ranged from 1.8 to 4.5.

The walls were built in the wooden box with glass sides shown in Fig. 2. The box is attached to a shaking table consisting of an aluminum plate, 4 ft x 6 ft in plan, and 1 in thick. The aluminum plate is supported by a structural steel grid that rides on four linear bearings. The table is driven in a single horizontal direction by a 5 kip actuator equipped with a 5 gpm servo-valve. The actuator has a 6 in (±3) stroke. The shaking table and part of the actuator can also be seen in Fig. 2.

The earthquake motion used in these experiments was derived from the N21E component of the Taft (1952) earthquake record. The lower frequency components were removed from the original record in order that motions of sufficient intensity to produce permanent displacements in the walls could be generated within the limited stroke of the actuator. This was accomplished by means of a high-pass digital filter with the corner frequency set at 4.0 Hz. In addition, the duration of the filtered motion was halved in the experiments for which results are presented below. The power spectral density of the resulting motion is shown in Fig. 3. The energy in this motion is concentrated in the frequency band 8-15 Hz, well below the fundamental natural frequency of the 18 in walls which, in a series of tests utilizing harmonic motions, was established to be 24 Hz.

The walls were subjected to the earthquake motion at various levels of intensity up to a maximum acceleration of 0.9 g. The acceleration in the backfill was measured by an accelerometer buried just below the surface of the sand, 8 in back from the face of the wall. The displacement of the top face element relative to the shaking table or the base of the wall was measured by a transducer utilizing a differential transformer. The signals from the transducers measuring the response of the walls and from an accelerometer measuring the motion of the table were always recorded on strip chart paper, and in many experiments on magnetic tape as well.

EXPERIMENTAL RESULTS

Time histories of the shaking table acceleration, the acceleration at the surface of the backfill 8 in back from the face of the wall, and the relative displacement between the top face element and the base of the wall are shown in Fig. 4. These data were obtained for a wall with 30 in long ties or a factor of safety of 4.5. A comparison of the acceleration time histories shown in Fig. 4 reveals that each pulse in the surface acceleration coincides with a pulse of the same sense, but not necessarily of the same magnitude, in the table's motion. For example, the pulse in the table's motion with the largest acceleration magnitude, .89 g, which occurs about 5.3 seconds into the record, produced an acceleration pulse of .68 g at the surface of the backfill. The accelerations associated with these pulses, shown in what is usually the negative sense in Fig. 4, acted in the direction from the face elements of the wall into the backfill and henceforth this direction will be designated inward.

Acceleration magnification factors (acceleration magnitudes of pulses at the surface of the backfill divided by the magnitudes of their corresponding pulses in the table's motion) are shown plotted against the acceleration magnitude of the table pulse in Fig. 5. The data represented by dots in Fig. 5 were derived from the acceleration time histories shown in Fig. 4. The data represented by the circles were derived from different earthquake simulation experiments on walls with factors of safety of 4.5, and in fact, they were derived from the pulses with largest outward or inward acceleration magnitudes in these experiments. There is considerable scatter in the data shown in Fig. 5, especially for pulses with small acceleration amplitudes. The scatter may be due to the deterioration in the signal-to-noise ratio in the acceleration records as the magnitudes of the acceleration decreases. However, despite the scatter, trends in the data are evident in both Figs. 5(a) and (b).

The magnification factors for pulses with outward acceleration magnitudes less than 0.1 g are, as shown in Fig. 5(a), greater than 2.0. For acceleration magnitudes greater than 0.1 g, the magnification factors decrease with increasing table acceleration approaching unity asymtotically. The magnification factors are less than 1.2 for pulses with acceleration magnitudes exceeding 0.4 g. The magnification factors for pulses with inward acceleration magnitudes less than 0.1 g are also greater than 2, see Fig. 5(b), and they decrease rapidly after the acceleration magnitude exceeds 0.1 g. The magnification factors become less than unity when the acceleration magnitude of the pulses in the table's motion exceed 0.5 g. Similar results were obtained for walls with factors of safety of 3.4. For these walls, however, the magnification factors for inward table accelerations became less than unity for pulses in the table's motion exceeding 0.4 g.

The displacement time history shown in Fig. 4 consists of a number of displacement pulses superimposed on a base line that shifts in a series of steps in the outward direction. Each pulse in the record corresponds in time to a major pulse in the table's motion; some small pulses in the table's motion produced no discernible displacement at the top of the wall. Outward displacement pulses, shown as positive in Fig. 4, are produced by inward acceleration pulses, shown as negative in Fig. 4, and vice versa.

Acceleration pulses with magnification factors less than unity, i.e. inward pulses with acceleration magnitudes of 0.5 g and greater for the wall in this example, produce large displacement pulses that result in an outward step in the position of the top of the wall. The permanent displacement at the end of the record is the accumulation of the step changes. The inward pulse of greatest magnitude, 0.89 g, produced a step displacement of 0.08 in, 50% of the displacement remaining at the end of the experiment, in an 18 in wall with a factor of safety of 4.5.

The permanent displacements (expressed as fractions of wall height) induced in walls by varying intensities of the earthquake motion are shown in Fig. 6. From this figure it can be seen that in order to cause permanent displacements the acceleration magnitude of the largest inward pulse in the earthquake motion must exceed a threshold value - the so-called yield acceleration (4,5). The yield accelerations can be determined from Fig. 6, and they are 0.23 g, 0.26 g, 0.46 g, and 0.50 g respectively for 18 in high walls with factors of safety of 1.8, 2.3, 3.4, and 4.5.

The experimental data presented in Figs. 4, 5, and 6 pertain to reinforced earth walls subjected to a base excitation having its energy concentrated in a band of frequencies lower than the natural frequency of the walls. The data indicate that under low levels of such excitation a wall vibrates like a continuous elastic body, but under high levels of excitation the behavior of the wall becomes more like that of a rigid body resting on a horizontal surface vibrating horizontally. Such a body will have acceleration magnification factors of unity for accelerations up to a threshold or yield level, and magnification factors less than unity for acceleration levels greater than this level. Reinforced earth walls differ from the rigid body model in having a yield acceleration much smaller for accelerations in one (the inward) direction than for acceleration in the other direction. The rigid body in reinforced earth walls is a wedge of soil, the Rankine zone, immediately adjacent to the face elements.

The yield accelerations for inward accelerations derived from the data shown in Fig. 6 are shown plotted against the factors of safety of the walls in Fig. 7. The data indicate that the yield accelerations increase from zero for walls with factors of safety of 1 and approach a limiting value of about 0.6 g for large factors of safety. The accelerations at which the magnification factors become less than unity for walls with factors of safety of 3.4 and 4.5 have been added to Fig. 7 showing that yield accelerations may also be determined accurately from plots of acceleration magnification factor versus inward acceleration.

The dependence of permanent displacements on factors of safety is shown for the 18 in walls in Fig. 8. The permanent displacements induced by earthquake motions are very sensitive to the factors of safety when these are 2.0 or less. For example, the permanent displacements induced in the 18 in walls with factors of safety of 2.3 are only about 25% of those induced in walls with factors of safety of 1.8. Further increases in the factors of safety become less effective. Walls with factors of safety of 3.0 will experience no permanent displacements in motions if the largest inward peak acceleration is less than 0.4 g and relatively small permanent displacements for motions in which this peak is 0.5 g. The curves shown in Fig. 5 suggest that the anticipated peak acceleration in the design earthquake should govern the selection of the static factor of safety for the design of reinforced earth walls liable to experience strong earthquake motions.

CONCLUSIONS

The shaking table experiments conducted on reinforced earth walls utilized an earthquake motion containing most of its energy in a frequency band lower than the fundamental natural frequency of the wall. The experiments revealed that a reinforced earth wall subjected to such motions at low levels of intensity responds like a continuous elastic body. At high intensity levels, however, it responds like a rigid body resting on a horizontal surface vibrating horizontally, with the exception that slippage occurs for a much smaller acceleration in one direction than for acceleration in the other direction. The rigid body is essentially the soil contained in the Rankine zone immediately behind the face elements. The acceleration at which slippage occurs, the yield acceleration, and the magnitude of earthquake-induced permanent displacements depend principally on the static factor of safety of the walls. It is concluded that the anticipated peak acceleration in the design earthquake should govern the selection of the static factor of safety for the design of reinforced earth walls liable to experience strong earthquake motions.

ACKNOWLEDGMENTS

The authors would like to acknowledge their gratitude to the late Professor Kenneth L. Lee for stimulating their interest in the seismic behavior of reinforced earth walls. They would also like to express their appreciation of the financial support provided by the U.S. National Science Foundation.

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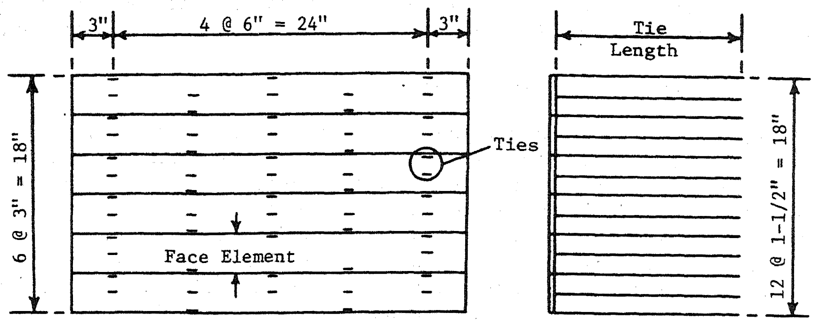

FIG. 1 TIE CONFIGURATION

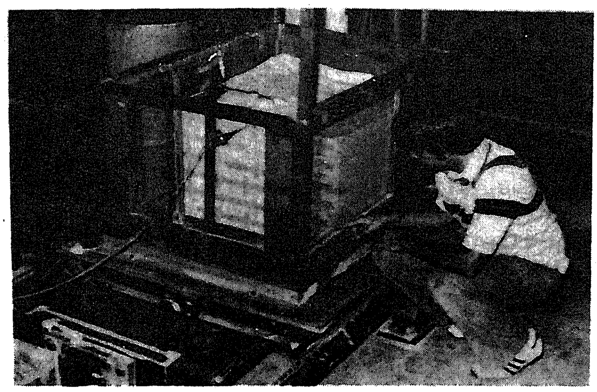

FIG. 2 WALL IN BOX ON SHAKING TABLE

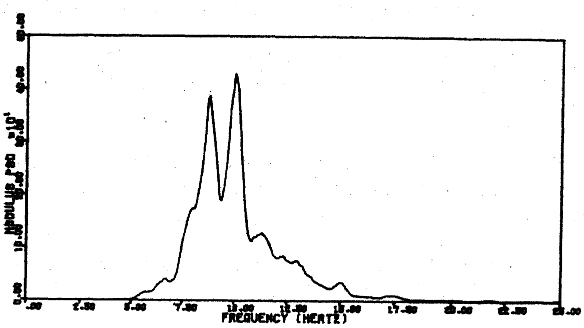

FIG. 3 POWER SPECTRAL DENSITY OF MOTION

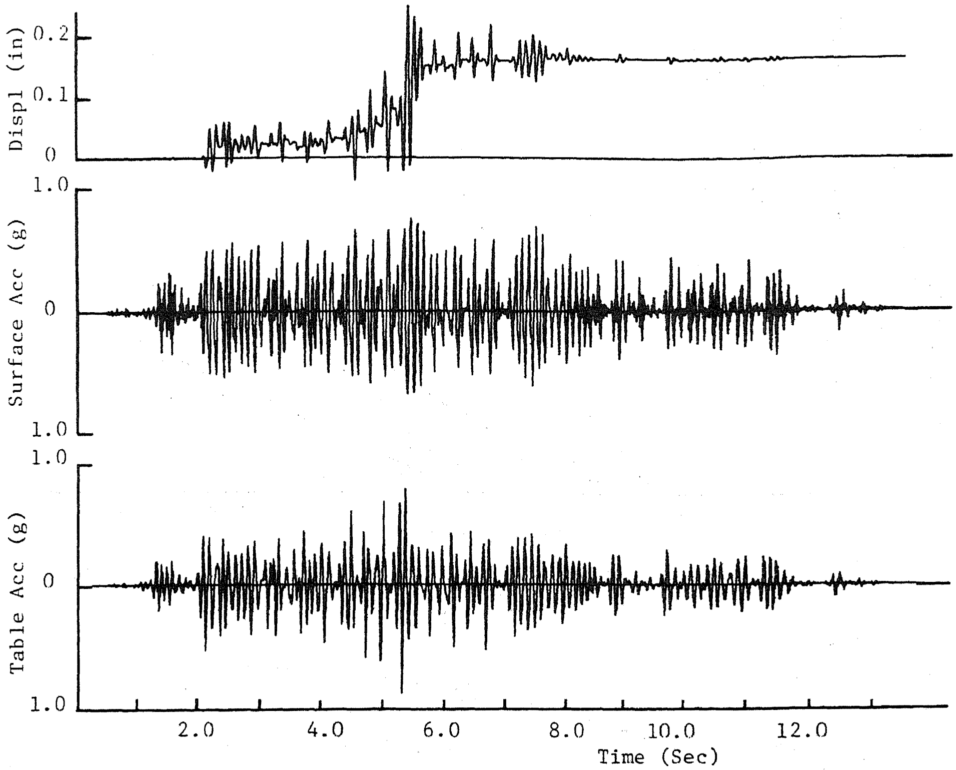

FIG. 4 TIME HISTORIES: 18" WALL WITH FS = 4.5

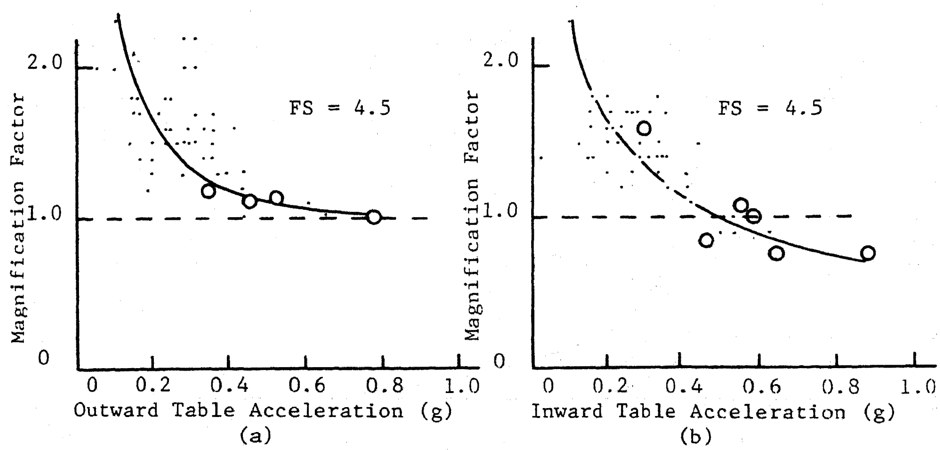

FIG. 5 MAGNIFICATION FACTORS FOR ACCELERATION PULSES

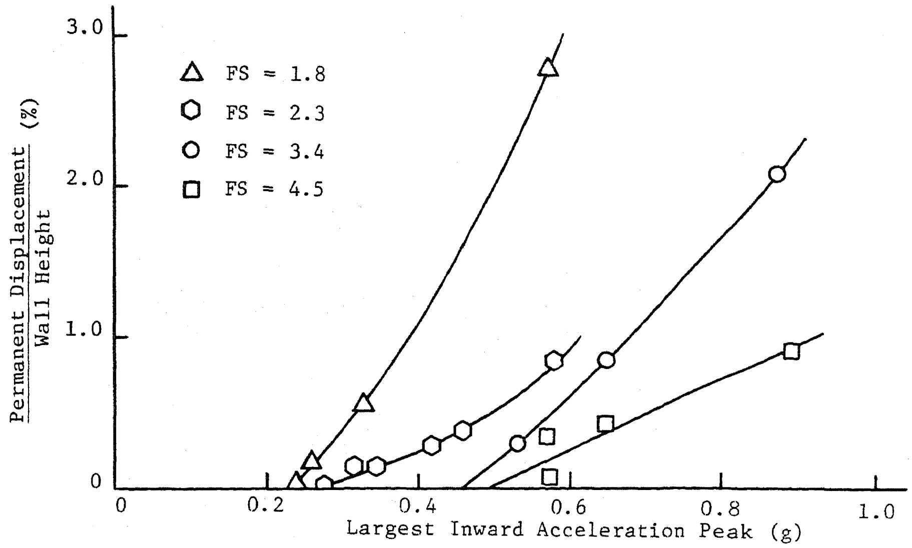

FIG. 6 EFFECT OF ACCELERATION INTENSITY ON PERMANENT DISPLACEMENTS

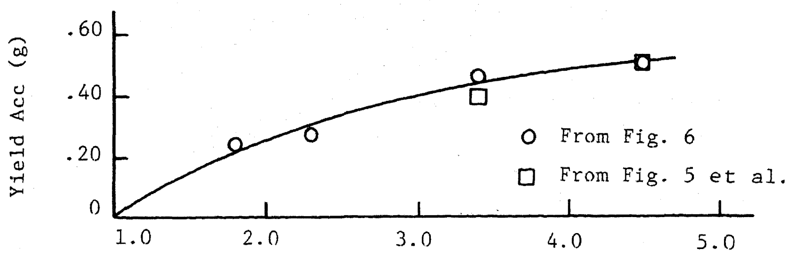

FIG. 7 EFFECT OF FACTOR OF SAFETY ON YIELD ACCELERATIONS

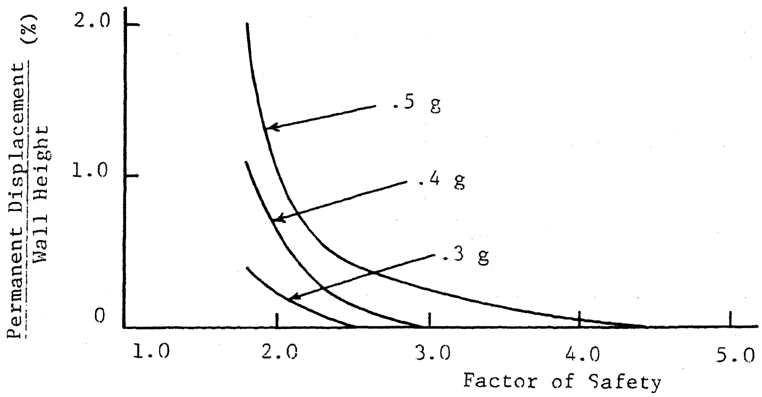

FIG. 8 EFFECT OF FACTOR OF SAFETY ON PERMANENT DISPLACEMENTS