EARTHQUAKE INDUCED RESPONSES OF MODEL RETAINING WALLS

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SUMMARY

The results of shaking table experiments on model retaining walls are presented. The program described was designed to investigate the effects of different input motions on the measured amplification ratios and displacements of model walls. The walls were subjected to motions derived from the El Centro 1940 earthquake and band limited white noise. The results are compared with data from models subjected to a modified Taft 1952 motion. Wall accelerations were found to be a function of the amplitude of the input motion and the ratio of input to wall frequency. Displacements were seen to be dependent upon the type of input motion.

INTRODUCTION

Retaining structures in which the properties of the earth backfill are improved by the inclusion of bars, strips or fibers have become increasingly more popular in recent years. Because the behavior of these structures is not well understood, current design practice assumes satisfactory seismic performance will be achieved by the imposition of large static factors of safety. In order to develop design procedures based on actual behavior of these structures during seismic events, laboratory shaking table experiments were conducted on model earth retaining walls. Deformation of the walls and acceleration of the backfill material are presented as they are related to the type andamplitude of acceleration.

Laboratory tests by Richardson and Lee (Ref. 1) and by Rea and Wolfe (Ref.2) have shown that the loads imposed on model reinforced earth retaining walls by a simulated earthquake motion are similar in distribution and magnitude to those proposed by Seed and Whitman in their 1970 review of the state-of-the-art of seismic stability of gravity retaining walls (Ref. 3). Drawing heavily on the earlier work of Mononobe and Okabe, which defines a destabilizing force proportional to the peak base acceleration, Seed and Whitman presented recommendations which have, to a large extent, become the standards for design practice during the fourteen years since their introduction.

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Richards and Elms (Ref. 4) found that this approach as applied by Seed and Whitman overestimated the safety of gravity walls during a seismic event. Gravity walls and, because they behave similarly, reinforced earth walls as well were included in a class of retaining structures described by Richards and Elms as deformation walls. This classification was based upon whether deformation or load criteria controlled design. In order to describe the behavior of the deformation class of walls they adopted Newmark's approach for determining the behavior of slopes and earth dams during earthquakes (Ref. 5), whereby the identification of a yield acceleration is fundamental. Movement of the wall relative to its base takes place only when this yield acceleration is exceeded. Since the yield acceleration is exceeded only momentarily, displacements should be limited. The fill behind the retaining wall is conceptualized as consisting of two rigid blocks one of which slides with respect to the other. The block boundaries define a Rankine zone immediately behind the wall. Since the blocks are presumed to be rigid, any amplification of the input motion in the backfill is ignored. Richards and Elms further postulated that since movement of a wall away from its backfill could be shown to be related to an active pressure condition whereas movements of the wall into the backfill would require pressures sufficient to overcome passive resistance, any relative wall movement would be expected to be only in the outward direction and therefore permanent. This permanent displacement could be compared with allowable displacements in order to assess the adequacy of the wall design. Nadim and Whitman (Ref. 6) have recently shown that design procedures based upon the Richards and Elms assumptions would likely misestimate the amount of permanent displacement a wall will experience during a seismic disturbance. Finite element studies by Nadim and Whitman on gravity wall as well as experimental studies by Rea and Wolfe on model reinforced earth walls have demonstrated that amplification factors as high as three or more are possible. Further it was observed in the experimental program that relative wall displacements were not only outward. Although the mean wall movement was directed away from the backfill, inward as well as outward motions were measured.

Based upon the results of their laboratory tests, Rea and Wolfe presented design recommendations for reinforced earth walls. The primary input parameters identified were the static factor of safety, peak amplitude of base acceleration and the ratio of fundamental frequency of the retaining wall to the dominant frequencies of the input motion. This paper presents the results of a follow-up laboratory program to the one presented by Rea and Wolfe, in which a number of model walls were subjected to additional simulated earthquake motions. The response of the models showed that seismic designs based upon allowable deformation criteria as proposed by Richards and Elms, Nadim and Whitman and Rea and Wolfe are appropriate for reinforced earth type walls. It was further observed that while the parameters identified by Rea and Wolfe are important in the overall design, different motions can evoke a different response even when the static factor of safety, peak base acceleration and frequency ratio are held constant.

EXPERIMENTAL EQUIPMENT

The model retaining walls tested in the program reported herein were constructed in the laboratory in a wooden box 30 inches wide by 48 inches deep. The walls were 18 inches high and consisted of thin 1/4 inch by 3 inch by 30 inch plexiglass panels which when stacked one on top of the other formed the wall face. Static stability was achieved by attaching 1/2 inch wide mylar strips to the face panels every 1.5 inches vertically, every 6 inches horizontally and extending them a distance of 30 inches into the backfill. The backfill consisted of a medium to fine grained Ottawa sand which was placed in the box at a uniform density of 99.8 lbs/cu.ft. The static factor of safety for this wall geometry was found by Rea and Wolfe to be 4.5.

The model walls were attached to a shaking table capable of movement in one horizontal direction. The motion of the table was controlled by a 5000 lb. actuator equipped with a 10 gpm servo-valve. The actuator has a useful frequency range of from 3 to 40 Hz. The response of the model walls to six different input motions is described. The six motions studied were:

1. two modified records from the N21E component of the Taft 1952 earthquake (test results were taken from Rea and Wolfe)
2. two modified records taken from the N-S component of the El Centro 1940 earthquake
3. two artificial earthquakes derived from a band limited white noise acceleration time history

The El Centro time histories were obtained by decreasing the time step between points in the original digitized time history. This resulted in a compression of the duration of the motion and an increase in the dominant frequencies from 2 to 5 Hz to 6 to 15 Hz and 10 to 25 Hz. The records were then filtered to attenuate all motions below 4 Hz so that large peak accelerations could be accomodated within the 6 inches of allowable actuator displacement. Two time histories typical of the four motions actually applied in this test program are given in Figure 1. Plotted along with the time histories are the response spectra for these two motions.

Instrumentation consisted of one ± 1.0 inch displacement transducer (LVDT) which was mounted to the shaking table and attached to the top of the model wall, and two ± 5g accelerometers. One accelerometer was mounted on the shaking table. The second was buried in the sand backfill one inch below the surface and eight inches behind the wall face. The responses of the three transducers to the input motion were collected digitally as a series of 12 bit words and then stored on magnetic using a MINC PDP-11/23. The rate at which samples were collected was determined by the digitization rate of the input motion. However, in all tests performed, sampling rates exceeded 300 data points per second.

EXPERIMENTAL RESULTS

A total of 25 simulated earthquake motions was applied to the model walls. The input accelerations for these tests ranged between 0.14g and 0.68g. A typical acceleration time history for the table and the for the surface of the backfill as well as a time history of relative displacement between the top of the wall and its base are shown in Figure 2. It can be seen that each peak in the backfill acceleration can be correlated with a peak in the table acceleration in the same direction. A measured time lag of 0.003 seconds between the two responses indicates an average seismic velocity of 500 ft/sec. Results of magnification calculations for the two earthquake time histories with dominant frequencies in the same range as those reported by Rea and Wolfe are plotted along with their data in Figure 3. The same general trends were observed, i.e. backfill magnification factors range between a high of 2.6 for small values of input acceleration down to magnification factors approaching 1.0 for input accelerations larger than 0.5g. The data plotted by Rea and Wolfe are for table accelerations with frequency contents well below the measured natural frequency of the model walls. Magnification factors for additional tests performed as part of this study, wherein model walls were subjected to input motions with strong shaking both well below and in the range of the wall's natural frequencies, are also plotted on Figure 4. It is seen that magnification factors are higher at each input level for those tests near the wall natural frequency indicating that the walls behaved qualitatively as damped elastic systems.

Peak wall displacements for each set of tests are shown in Figure 4. The motions have been grouped according to the dominant frequency range of the input motion. For all the walls tested, a minimum acceleration of approximately 0.25g had to be exceeded before any measureable relative movement between the top of the model wall and its base was observed. This yield acceleration was seen to be relatively insensitive to a specific type or frequency of base motion over the range of tests included in this study which suggests that the yield acceleration for a reinforced earth wall can be determined from the static factor of safety as proposed by Rea and Wolfe.

Further, it can be seen that for the three time histories with strong motion well below the natural frequency of the wall, the wall response is adequately described solely by the peak input acceleration. However, for input motions in the range of the wall natural frequency, the artificial earthquake produced measureably larger displacements than did either of the two actual although modified earthquake time histories. A similar response is also evident for the permanent deformation curves which are shown in Figure 5.

A count was made of the number of peaks in each of the acceleration time histories larger in magnitude than theyield acceleration. A plot of these peak accelerations versus normalized permanent deformations is given in Figure 6. The curve for the tests in which the frequency of input motion was close to the wall natural frequency was more sensitive to the number of peaks than was the curve obtained from the 6-15 Hz data. The artificial earthquake, because it had the greatest number of peaks for a given duration, caused the largest permanent displacements.

CONCLUSIONS

Shaking table experiments were conducted in which model retaining walls were subjected to time varying input accelerations. Two types of table motion were employed. The first, a modification of an historic earthquake motion, the 1940 El Centro N-S time history, was used. The second table motion was an artificial earthquake which was obtained by passing a white noise acceleration record through a band pass filter. The experiments showed that at low levels of excitation, the model walls behaved as damped elastic structures. Magnification factors were found to be somewhat higher for input motions near the natural frequency of the model.

All displacements were shown to be a function of the level of base acceleration with a minimum level of input acceleration required to induce a permanent displacement. It was seen that the amount of permanent displacement observed during base motion is a function of more than the static factor of safety and table peak acceleration levels. Three different input motions, each having the same dominant frequency range, the same peak acceleration levels and the same duration were applied to the model walls. For those records with predominant frequencies well below the natural frequency of the walls, similar response was obtained at each level of table acceleration. When input motions had frequencies of strong motion near the fundamental frequency of the model wall, wall displacement was strongly dependent upon the specific input motion. It was found that a correlation could be made between the number of input acceleration peaks exceeding the yield acceleration and the amount of displacement measures at the end of the disturbance. Application of an artificial earthquake which consisted of a band limited white noise acceleration time history produced the largest permanent deformations.

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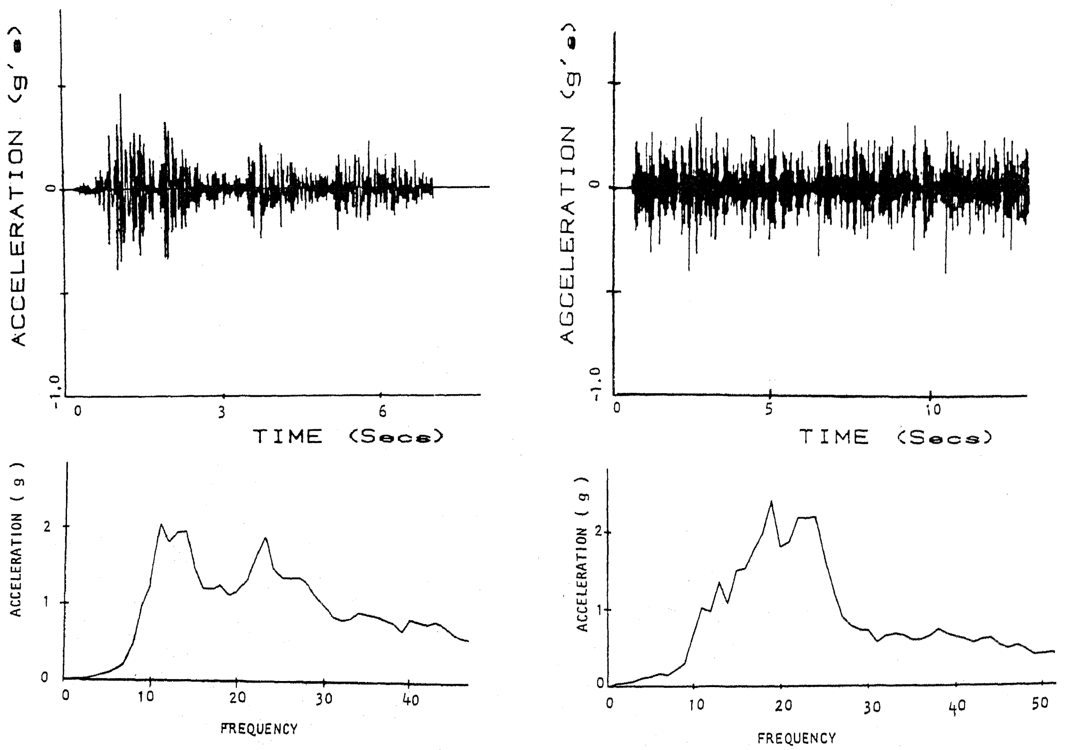


Figure 1. Typical Table Motion

El Centro N-S 10-25 Hz. White Noise 10-25 Hz.

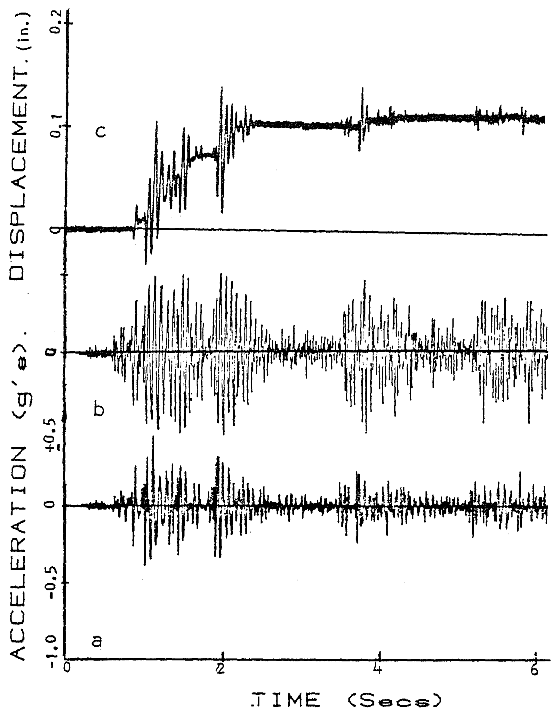
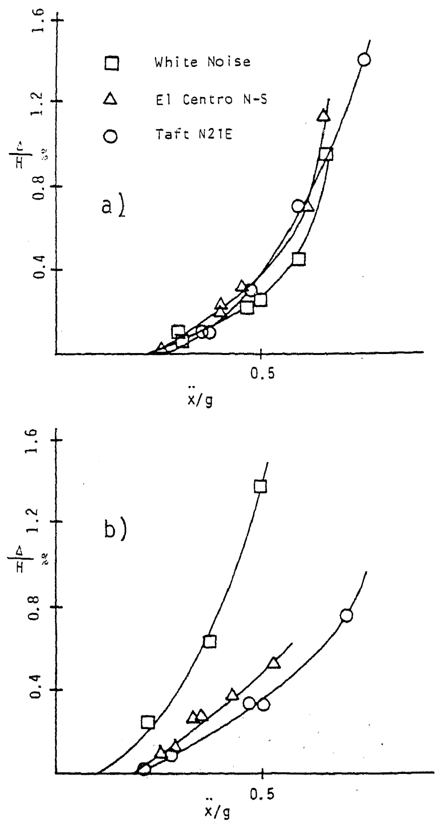


Figure 2. a) Table Acceleration
b) Surface Acceleration
c) Relative Displacement
El Centro 10-25 Hz Input Motion



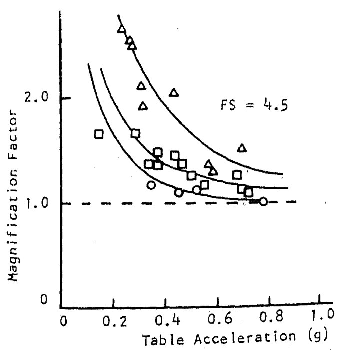


Figure 3. Magnification Factor vs. Table Acceleration for Three Input Motions

Figure 4. Peak Displacement vs. Table Acceleration
a) 6-15 Hz.
b) 10-25 Hz.

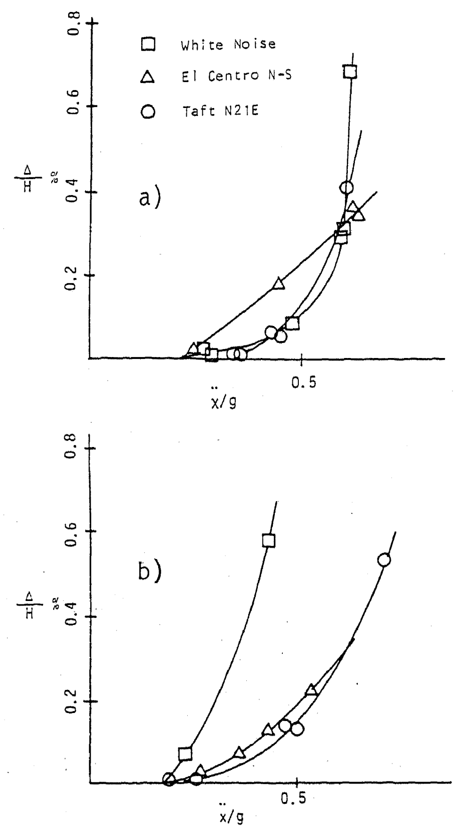


Figure 5. Permanent Displacement vs. Table Acceleration
a) 6-15 Hz.
b) 10-25 Hz.

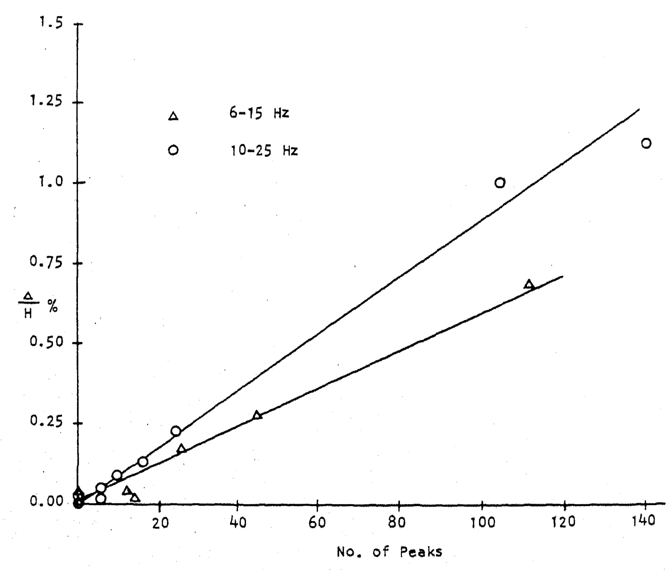


Figure 6.
Permanent Displacement vs. No. of Peaks of Base Acceleration Greater Than Yield Acceleration