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SYNOPSIS Seismic loads on a tall, cantilever retaining wall were studied using centrifuge modeling. An aluminum wall (55' prototype) retaining dry, cohesionless backfill was subjected to two successive dynamic events. The backfill surface was horizontal and even with the top of the wall. The input motion was supplied via a servo-controlled, electro-hydraulic shake table. The input motion was roughly sinusoidal with peak horizontal accelerations of approximately 0.2g and 0.4g for the first and second dynamic events, respectively. The input motion frequency was 1 hz at prototype scale. Lateral earth pressures on the wall, wall displacement, and accelerations of the wall and backfill soil were measured. Pressure transducers were used to directly measure lateral earth pressures on the wall. The magnitudes of the lateral earth pressures were compared with values calculated using the Mononobe-Okabe method. Preliminary results indicate that calculated pressures are higher than the measured pressures.

INTRODUCTION

Retaining walls commonly fail due to seismic loads. These failures are documented in various earthquake damage reports. The damage has included large translational and rotational displacements, buckled walls, settlements of backfill soils, and subsequently, failure of structures founded on the backfills.

Retaining wall damage may be greater than anticipated due to an incomplete understanding of the lateral earth pressures applied to the structure during a seismic event. In particular, the magnitude and distribution of lateral loads are in question. Existing design methods may not adequately account for these issues, and the verification of these methods is incomplete.

Centrifuge model testing was employed in this research to study seismic loads on a tall, cantilever retaining wall. The purpose of the testing was to measure the magnitude and distribution of lateral earth pressures. The measured pressures were compared with pressures determined using the Mononobe-Okabe (M-O) method.

The M-O method is widely used to determine the magnitude of the total dynamic thrust on a retaining wall. The method is based on a modification of the static Coulomb earth pressure theory with dynamic forces treated as additional static forces (Figure 1). The resultant active force P_{AE} is expressed as follows (Seed and Whitman, 1970):

$$P_{AE} = \frac{1}{2} \gamma H^2 (1-k_v) K_{AE} \qquad \ldots (1)$$

where,

$$K_{AE} = \frac{\cos^2(\phi-\theta-\beta)}{\cos\theta \cos^2\beta \cos(\delta+\beta+\theta)\left[1+\sqrt{\frac{\sin(\phi+\delta)\sin(\phi-\theta-i)}{\cos(\delta+\beta+\theta)\cos(i-\beta)}}\right]^2}$$

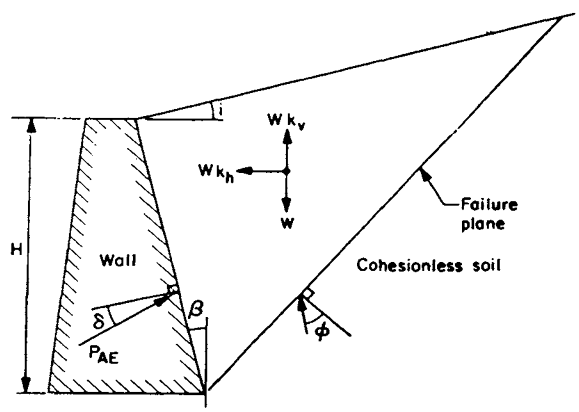

Figure 1: Mononobe-Okabe Analysis

$$\theta = \tan^{-1}\frac{k_h}{1-k_v}$$

H = height of the wall
β = wall inclination
i = backfill slope
γ = unit weight of soil
ϕ = soil friction angle
δ = wall friction angle
k_h = horizontal ground acceleration / g
k_v = vertical ground acceleration / g

The M-O method does not give the distribution of earth pressures. However, a triangular pressure distribution can be assumed as suggested by the nature of the equation. In the absence of any dynamic event (i.e. when k_h and k_v equal zero), the M-O expression reduces to Coulomb's static earth pressure expression.

Dynamic centrifuge experiments were conducted to study the seismic behavior of a cantilever retaining wall. In this paper, results from one of these tests are presented.

EXPERIMENTAL SET-UP

The test configuration is shown in Figure 2a. For convenience, prototype dimensions are given. The actual inside dimensions of the test container were 30" long, 12" wide, and 15.8" deep. A one foot tall, aluminum model wall was used. The model wall width was 11.875". This allowed a clearance of 0.063" between the wall and the sides of the container. At a centrifugal acceleration of 55 times that of earth's gravity, the model wall represented a 55 ft tall, reinforced concrete retaining wall. The model wall satisfied the scaling relation for flexural stiffness. The wall was free to rotate but was restrained against forward sliding, as shown in Figure 2a.

The wall retained dry, Nevada No. 100 Sand with an approximate unit weight of 98 pcf. This corresponds to 60% relative density. The backfill surface was horizontal and even with the top of the wall. The sand was placed behind the wall using dry pluviation and was contained in a latex membrane. Silicone grease was applied on the side walls of the container to minimize frictional effects and better simulate plane strain conditions.

Wall and backfill accelerations, wall displacements, and lateral earth pressures were measured during the test. Accelerations were measured using accelerometers and displacements were measured using miniature linear variable differential transformers (LVDT's). Figure 2b shows the accelerometer and LVDT locations. The accelerometers were deployed along the centerline of the container width; the LVDT's were offset 1.25" from the centerline. All the accelerometers measured horizontal accelerations except AC2, which measured the vertical acceleration at the base. LV1 and LV2 are horizontal LVDT's which measured wall displacements. The assumed positive directions for the accelerometers and LVDT's are given by arrows shown in Figure 2b. Pressure transducers were used to measure lateral earth pressures behind the wall. As shown in Figure 2c, they were deployed in two columns, one along the centerline containing six transducers and one along the quarterline containing four transducers.

The tests were conducted in the geotechnical centrifuge facilities at the University of Colorado, Boulder, U.S.A. on the 400 g-ton centrifuge. Dynamic events were produced by a servo-controlled, electro-hydraulic shake table. Input horizontal base motions consisted of 10 cycles of approximately sinusoidal motion with a 1 Hz prototype frequency. Accelerometer AC1 recorded the horizontal acceleration actually delivered by the shake table. An unavoidable vertical acceleration was measured by AC2.

The test was conducted in five stages. Measurements from the transducers were made during all stages. First, the model was spun to 55 g's and held at a constant g-level. In all subsequent stages, the centrifuge was held at 55 g's. For the second stage, the first earthquake event was triggered (denoted as "D1"). The third stage was a short, "quiet" period where static transducer readings were gathered. In the fourth stage, dynamic event "D2" occurred. The fifth and final stage was another static period.

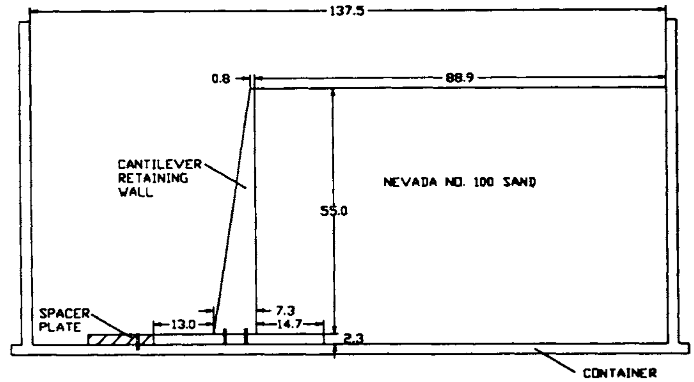

Figure 2a

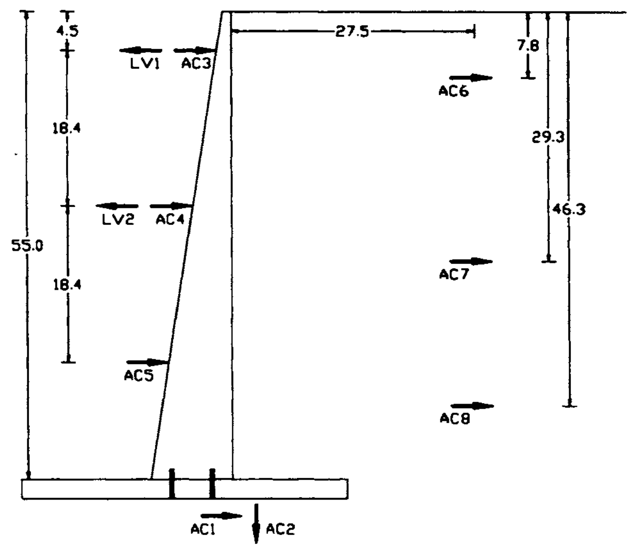

Figure 2b

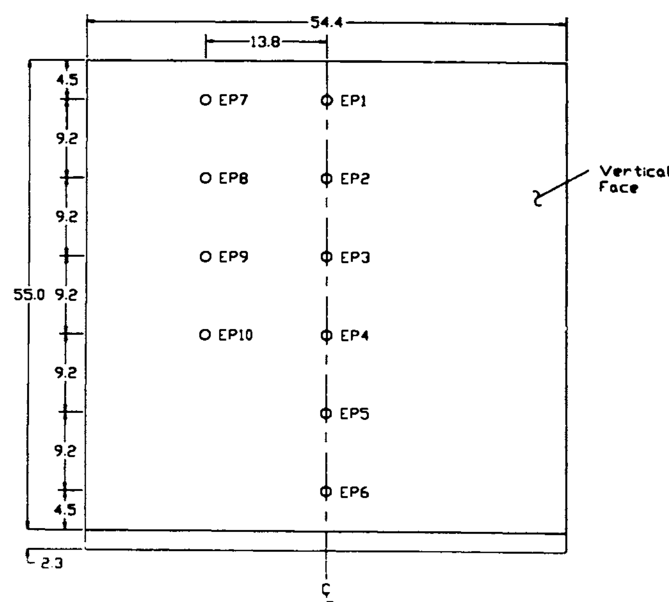

Figure 2c

(Dimensions are in feet.)

Figure 2: Test Configuration

RESULTS

For convenience, all the results are plotted in prototype scale. Figure 3 shows the static earth pressures measured behind the wall. Since, the centerline and quarterline pressure measurements are not identical, plane strain conditions were not fully achieved. However, the pressure profiles are in reasonably good agreement with each other. The pressure distribution is non-linear. For brevity, only measurements from pressure transducers EP1 to EP6 are presented in the remainder of this paper.

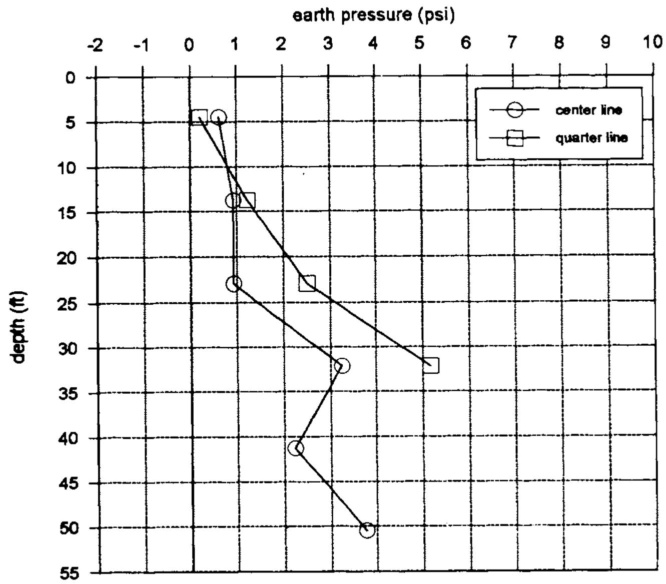

Figure 3: Static Earth Pressures

Figure 4 shows all accelerometer recordings during the first dynamic event D1. AC1 and AC2 give the horizontal and vertical accelerations recorded at the base of the model. AC3, AC4 and AC5 were mounted on the wall. Their measurements show a distinct amplification of acceleration from the bottom to the top of the wall. Similarly, amplification of the acceleration can be seen from the recordings of AC6, AC7 and AC8 which were embedded in the soil backfill.

Figure 5 shows recordings of LV1 and LV2 during the dynamic event D1. The first reading (at zero time) represents the movement of the wall due to static earth pressures. The movement of the wall is substantially higher than that required for the development of active lateral earth pressures.

Figure 6 shows the earth pressures recorded during the first dynamic event D1. The first reading of each plot represents the static earth pressure at that location on the wall. As seen from the figure, earth pressure measurements follow the base motion. At the end of the shaking, earth pressures do not come back to the original static values. These residual earth pressures are higher than the initial static values and are a substantial percentage of the maximum dynamic pressures.

In Figure 7, the maximum and minimum earth pressures measured by transducers EP1 to EP6 are plotted. The maximum values recorded by the individual transducers do not necessarily occur simultaneously. The same is true for the minimum values. These measured earth pressures are compared with calculated pressures using

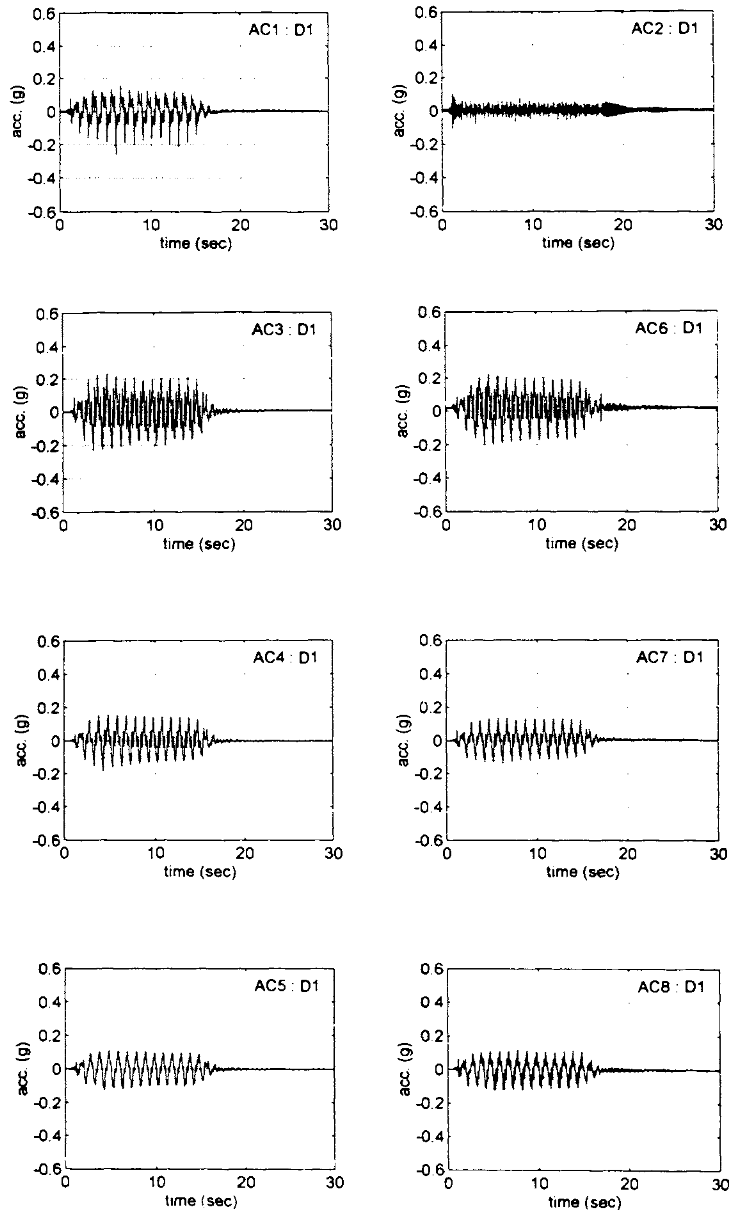

Figure 4: Accelerometer Recordings for D1

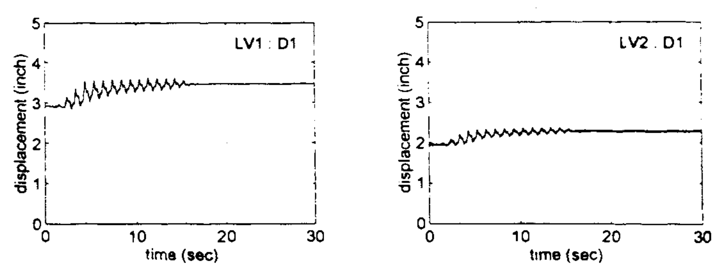

Figure 5: LVDT Recordings for D1

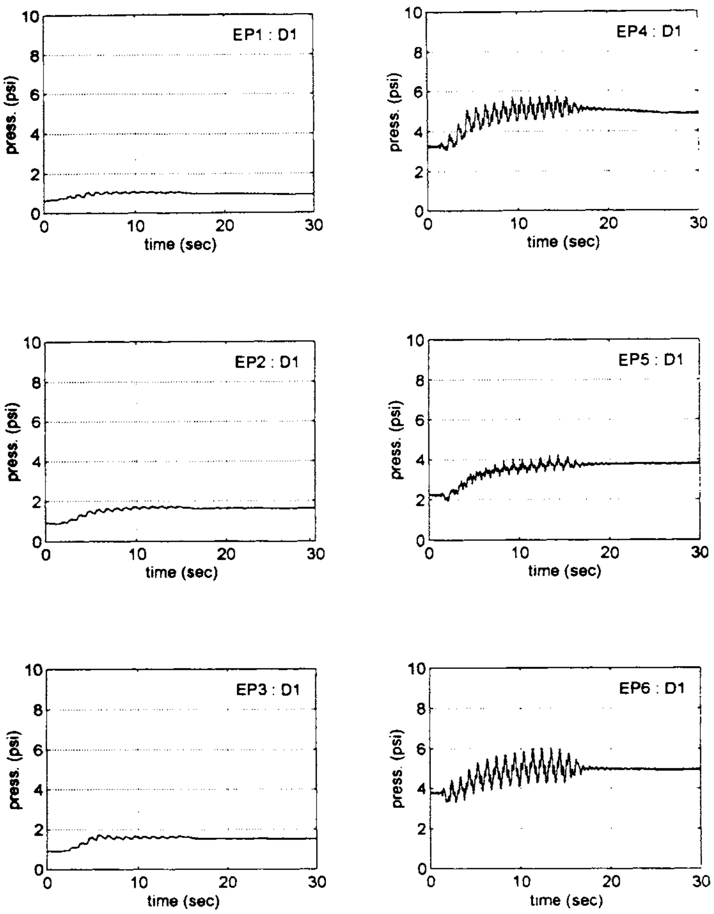

Figure 6: Earth Pressures for D1

Coulomb's theory for the active static earth pressures and the M-O method for the dynamic earth pressures. For Coulomb's theory and the M-O method, it is assumed that the earth pressure distribution is triangular. At 60% relative density, the angle of internal friction, ϕ, for Nevada No. 100 sand is 36^0. Since Equation (1) is not very sensitive to the value of the wall friction, δ, it was assumed to be one half of ϕ as recommended by Seed and Whitman (1970). The maximum positive acceleration recorded by AC1 was assumed to equal k_h in Equation (1). The minimum negative vertical acceleration from AC2 was selected for k_v. Selection of the maximum k_h and minimum k_v gives the maximum possible thrust on the wall. As with the maximum and minimum measured pressures, these values do not occur simultaneously. The measured static pressures are lower than those expected from Coulomb's theory. This affects the comparison between the measured and the calculated dynamic pressures.

To allow better comparison, incremental dynamic earth pressures above the static pressures are plotted in Figure 8. The vertical axis represents the static earth pressure at each pressure transducer location. The incremental dynamic earth pressure distribution from the M-O method is also plotted in Figure 8. From Figure 8 it is seen that the values determined using the M-O method match the experimental values reasonably well. This conclusion is based on the selection of values of k_h and k_v from the accelerations measured at the base. However, since there is an amplification of acceleration from the bottom to the top, the comparison would not be as good if k_h and k_v were selected from the accelerations measured toward the top of the wall.

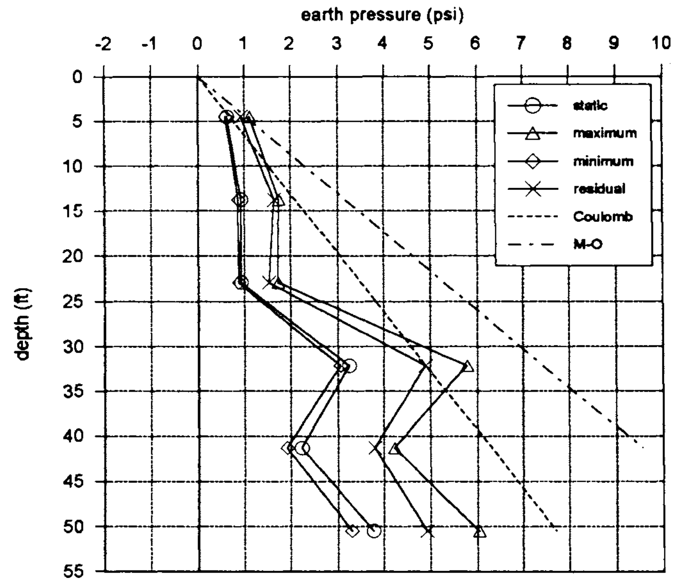

Figure 7: Measured and Calculated Earth Pressures for D1

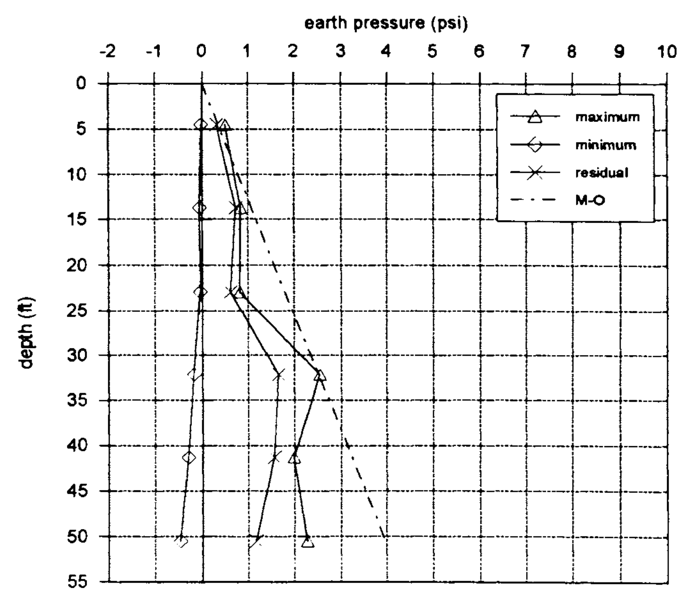

Figure 8: Dynamic Earth Pressure Components for D1

Figure 9 shows the measurements of accelerometers AC1 and AC2 for dynamic event D2. By comparison with the output from dynamic event D1 (Figure 4), the maximum horizontal acceleration recorded in D2 is approximately twice as large as that recorded in D1. The measurements recorded by the other transducers in D2 are not presented here. The output from the other transducers follows the same general trend seen in D1. However, due to the higher intensity shaking, higher magnitudes were measured. Figure 10 displays the measured responses of earth pressure transducers EP1 to EP6 for dynamic event D2 in the same fashion as Figure 8 did for dynamic event D1. The measurements for dynamic event D2 are affected by possible changes in soil properties and residual pressures from dynamic event D1, which had taken place earlier. The trends of maximums, minimums and residual pressures are the same as seen in Figure 8. The magnitudes are higher because of the higher intensity shaking. As was done for dynamic event D1, the pressures determined using the M-O method are also shown in Figure 10. It can be seen that the difference between the measured and calculated pressures is more than that for D1. Figures 8 and 10 show that measured pressures were lower than the calculated pressures.

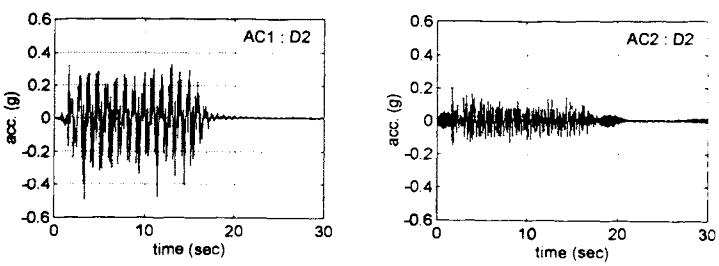

Figure 9: Accelerometer Recordings for D2

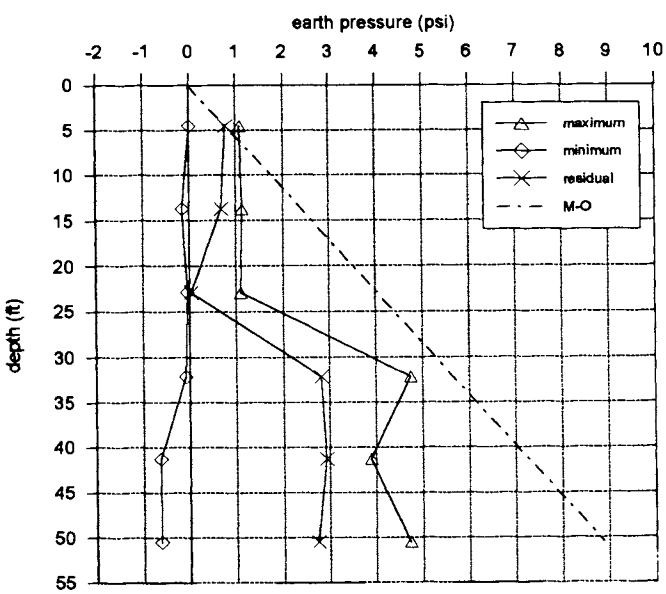

Figure 10: Dynamic Earth Pressure Components for D2

CONCLUSIONS

The following observations can be made from the test results:

- Measured static and dynamic pressures are lower than the calculated pressures using Coulomb's theory and the M-O method, respectively. For the dynamic earth pressures, comparisons can be affected by the choice of k_h and k_v.
- The differences between the measured and calculated pressures are greater in the higher intensity dynamic event (D2). However, results for D2 are affected by residual pressures and possible changes in soil properties due to the event D1 which had taken place earlier.
- Residual pressures are higher than the initial static values and are a substantial percentage of the maximum dynamic pressures.
- Amplification of accelerations occurred from the bottom to the top, both on the wall and in the soil.

Based on the results of other tests conducted at the University of Colorado, Boulder, these observations are generally true. However, some deviations can be expected for other types of test configurations. Further investigations incorporating different model configurations are necessary for more definitive conclusions.

ACKNOWLEDGEMENT

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