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SHAKING TABLE TEST ON SMALL PROTOTYPE OF SOIL RETAINING WALL

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ABSTRACT

A shaking table test was carried out on a 65cm high gravity retaining wall ,arranged in a 3m long tank with glass sides. The wall was put on a 10cm thick layer of San Juan River clean sand and backfilled with the same material. Accelerations of shaking table and wall, horizontal and vertical wall displacements and earth pressure magnitude and distribution were measured during the test.
It was observed that the rocking response played an important role in dissipating the earthquake energy input and preventing from large residual displacement accumulation.The earth thrust record showed an increment of the residual thrust during the test.
The registered behavior of the wall treated as a small prototype, is compared with predicted behavior by some usual analytical aproaches: Mononobe-Okabe expression for earth pressure computation, Richard-Elms method and Zarrabi improved model for residual displacement computation.

KEYWORDS

Retaining wall; shaking table; test; displacements; thrust

INTRODUCTION

The stability analysis of earth retaining walls under earthquake loading requires the determination of earth pressures. The amount of earth pressure depends on the interaction between wall, backfill and foundation.

The traditional way for computing the earth thrust under static loads is the sliding wedge method proposed by Coulomb for frictional materials. Okabe in 1924 and Mononobe and Matsuo in 1929 extended the Coulomb's method to take account of the earthquake effect by means of introducing equivalent static forces in the sliding wedge equilibrium analysis (Fig 1).

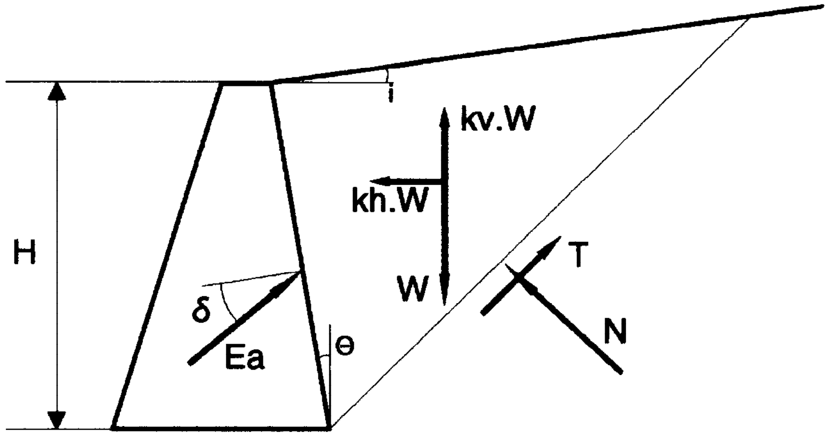

Fig. 1. Coulomb's sliding wedge equilibrium method.

The Mononobe-Okabe analytical expression allows to determine the active thrust as a function of geometry, strength parameters and horizontal and vertical seismic coefficients:

$$E_{AE} = \frac{1/2\ \gamma\ H\,(1-k_v)\ \cos^2(\phi-\psi-\theta)}{\cos\psi\ \cos^2\theta\ \cos(\psi+\theta+\delta)\left[1+\left\{\dfrac{\sin(\phi+\delta)\ \sin(\phi-\psi-i)}{\cos(i-\theta)\ \cos(\psi+\theta+\delta)}\right\}^{\frac{1}{2}}\right]^2} \qquad with\ :\ \psi = \tan^{-1}\frac{k_h}{1-k_v}$$

where γ is the backfill unit weight, k_h and k_v are respectively the horizontal and vertical seismic coefficients, ϕ is the backfill friction angle and δ is the friction angle between wall and backfill. Once the total backfill thrust is computed, the stability of the wall has to be verified against sliding and overturning. The wall inertia forces are usually computed with the same seismic coefficient used to compute the active thrust.

The use of the M-O expression involves the selection of the seismic coefficient that will represent the earthquake effect on the structure. The selection of a seismic coefficient equal to the maximum peak acceleration of the expected earthquake ensures that the wall will not slip at all during the movement. But for most cases, this leads to an excessively conservative and therefore uneconomical design, since most retaining structures allow the occurrence of significant outward displacements which do not mean a failure. Admissible wall displacements and tilting depend on the function of the structure and its importance.

An alternative design criteria is to adopt a reduced seismic coefficient to consider the wall displacement capability in order to get a more economical design. The choose of such a reduced seismic coefficient is a difficult and often arbitary decision and makes the overall security of the structure uncertain.

Considering the above mentioned shortcomings, Richard and Elms (1979) proposed a more rational design criterium consisting in the limitation of the permanent outward displacement of the wall caused by the earthquake, to an admisible value. Richard and Elms developed an extension of the Newmark sliding block method to compute the wall displacements.

The basic assumptions in this approach are: 1) materials behave as rigid-plastic; 2) only the horizontal forces are taken into account in the equilibrium equation; 3) only the horizontal translation movements of the wall are possible; 4) the total earth thrust can be computed with the M-O expression.

A shaking table test on a 25 cm high retaining wall performed by Sim and Berrill (1979) showed that the R-E method often overestimate the permanent displacement. The reason for this is the neglection of the vertical inertia forces acting on the soil wedge due to its down-slip motion following the wall motion. Zarrabi improved the R-E model in its kinematic aspect (Whitman, 1993), taking into account the wall and the backfill displacement compatibility and the vertical inertia forces acting on the soil slip-wedge.

The limitations of the described design methods are: 1) the dynamic amplification effects are neglected since the constitutive laws used are rigid-plastic. 2) The considered wall motion is only horizontal translation, neglecting the rocking response. 3) The possibility of a saturated backfill and liquefaction development are not considered. Other researchers have developed improved models in one or more of these aspects. Prakash (1981) proposed a model for computing displacements in horizontal translation with elastic-plastic constitutive laws for backfill material and wall-soil interfaces. This allows the consideration of the dynamic amplification effects due to the backfill and foundation deformability. He also proposed another similar model for computing wall displacements in rocking. Nadim and Whitman (1984) developed a Newmark-type model including coupled horizontal displacement and rocking wall response.

This paper presents a shaking table test carried on a 65 cm high gravity retaining wall. The main research program aims were: 1) to observe and register the structure behavior during the motion in order to get a better understanding of the failure mechanism and the factors which influence the structure response. 2) to check the validity of the assumptions of the most commonly used stability analysis methods and mathematical models and the degree of accuracy of their results.

TEST SETUP

The test was conducted on a 65 cm high and 82 cm wide gravity wall, arranged in a 3 meters long glass-sided test tank (Fig. 3). The wall and the tank were built with steel sections and sheet. The wall mass is variable by adding weights of 30 Kg. each.

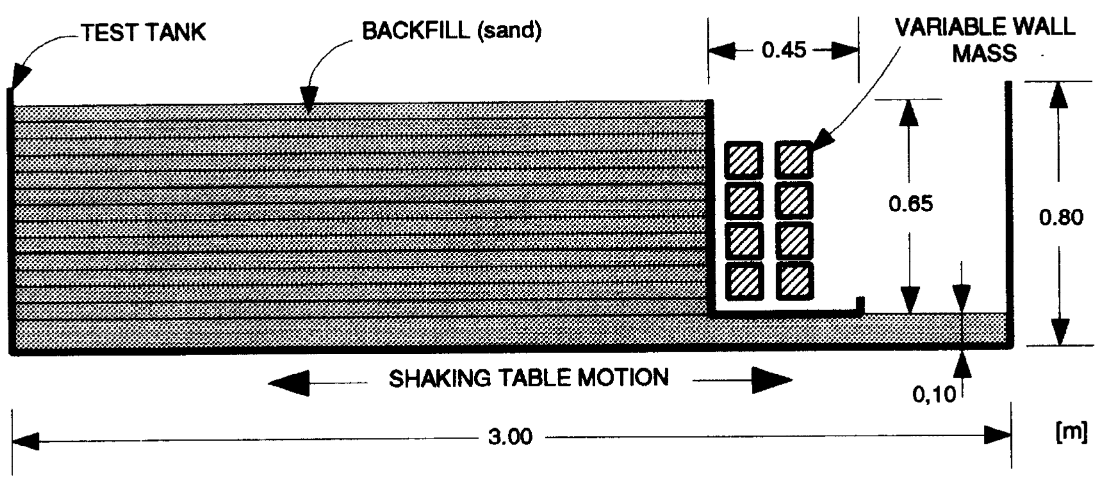

Figure 2. Test setup scheme.

The friction on the wall base-foundation and on the wall vertical face-backfill interfaces was increased by bonding sand with epoxi resin. The friction angle on the wall base was measured by jacking the wall resting on the foundation material and reading the force needed to cause the slip along the base. Measured values ranged between 28° and 33°.

The wall alignment in relation to the test tank was provided by four ball bearings fixed at the wall base corners and resting against the tank glass sides.

TEST PREPARATION

The test tank was mounted on the IDIA shaking table. This is a servo-hydraulic actuated device which can accelerate a 10 ton weight to 0.5g in a frecuency range of 10 to 30 Hz. Motion is controlled by a computer.

San Juan river clean sand was used as foundation and backfill material (Unified Classification: SP). It was placed in 5 cm thick hand compacted layers at 1.81 ton/m3 dry density which corresponds to 60% ASTM Relative Density. The internal friction angle of this material range between 34° and 40°.

The wall was placed on a 10cm thick sand layer, the 8 weights necessary to reach the design mass were fixed and then backfilled. The total weight of the wall was 289.6 Kg. Seals between the wall and the tank glass sides were made with a 5mm thick rubber band.

The test instrumentation comprised:
- Three variable inductance position transducers arranged so as to get a complete record of the wall movements during the test.
- Two strain gage acceleration transducers for measuring the tank (ground) and the wall base acceleration.
- Three full strain gage bridges for measuring the bending moment caused by the earth thrust acting on the vertical wall face at three diferent heights. The record of these bending moments, allowed the calculation of the approximate soil pressure distribution acting on the wall at any time during the test.

The eight transducer analog signals were amplified, converted to digital information and recorded in PC. Recording sample rate was set at 200 data/second. Also, the test was filmed with a video cammera to obtain a register of the whole behavior of the structure. Figure 3 shows the test setup.

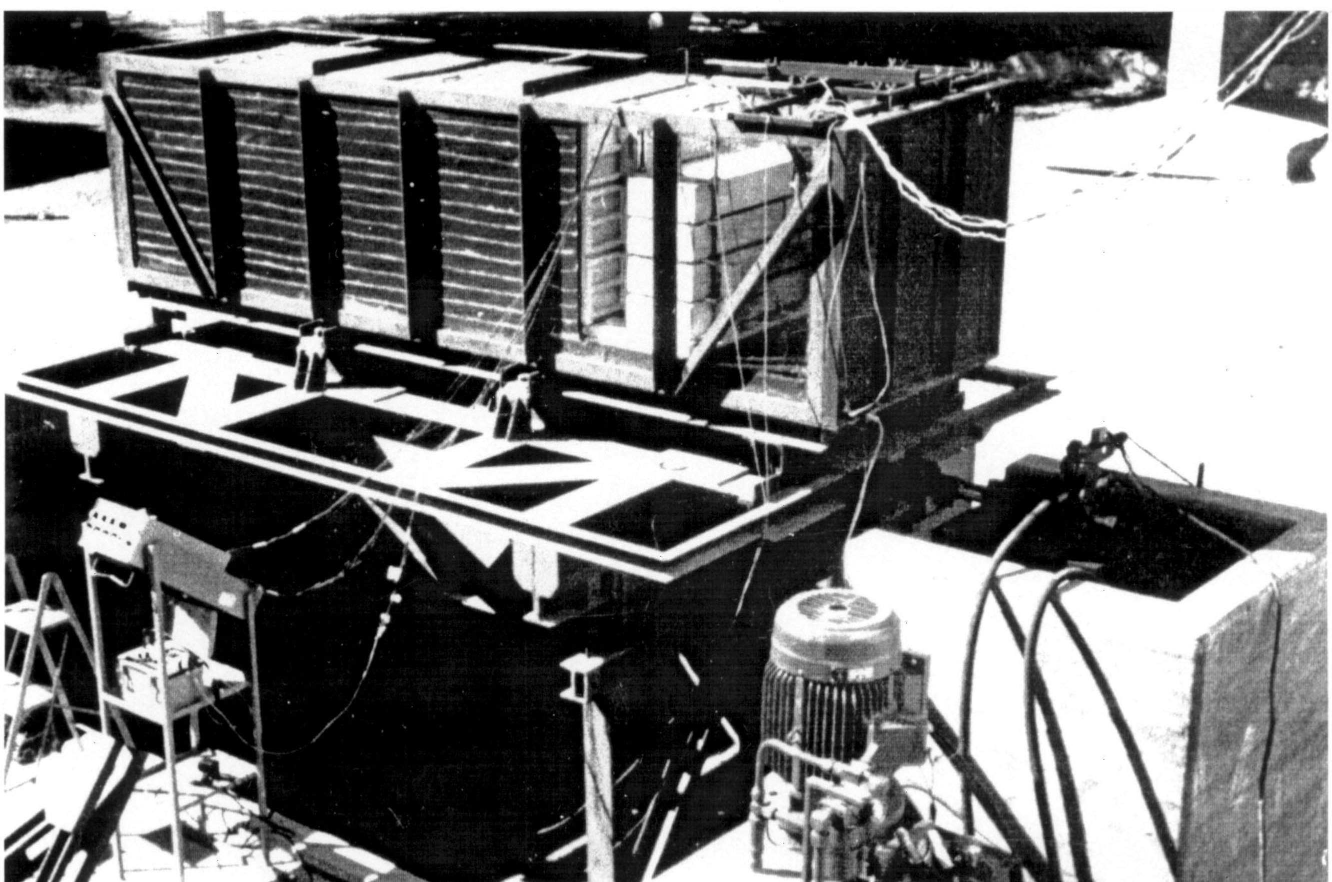

Figure 3. Test setup ready to start the test.

TEST EXECUTION

Analysis of the tested wall treated as a small prototype, was made with the Coulomb method in order to evaluate the pre-test stability condition. The safety factor against sliding under static loads was 2.60 and against tilting was 4.15. The structure yield acceleration -the ground acceleration which initiates the outward slip of the wall- was computed by trials with the M-O expression, with the aim of predetermining the acceleration level to be used in the test motion . Due to the uncertainties in the soil and wall-soil interfaces friction properties, the yield acceleration possible values ranged from 0.15 g to 0.34 g.

The frecuency of excitation motion was fixed at 10 Hertz and its duration at 16 seconds. The test started with 0.25 g of acceleration amplitude which had not any visible effect on the wall or backfill. In successive motions, the amplitude was increased in 0.1 g steps. Cracks appeared on the backfill top surface as the peak acceleration was set at 0.5 g but no permanent displacement of the wall was observed until the last motion which caused the failure. This happened with the 1g amplitude motion showed on Figure 4. The final position of the wall after failure is showed on Figure 5. The wall's head displaced 10 cm from its initial position and the toe 6.8 cm. The permanent outward tilt angle was 2.8°.

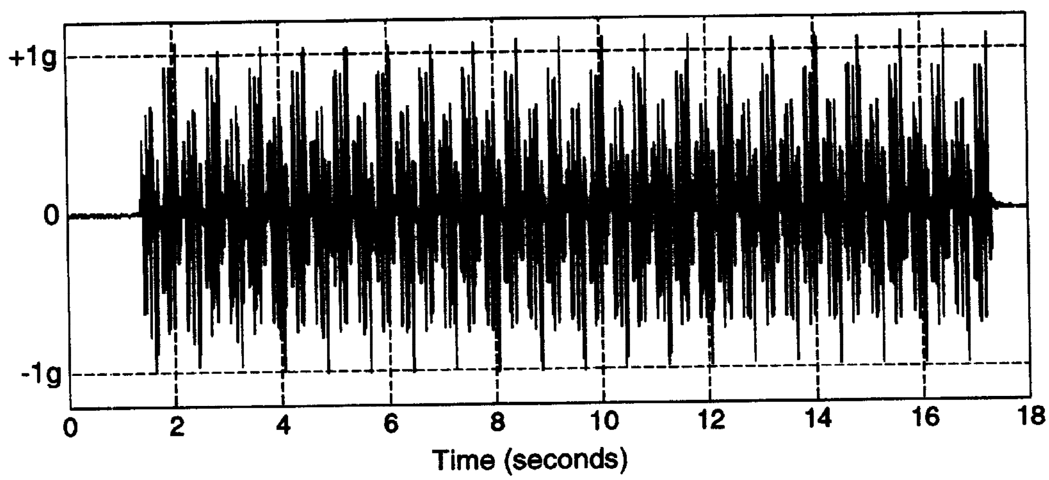

Figure 4. Shaking table acceleration record.

OVERALL BEHAVIOR

Figure 5 shows a photograph of the wall and the backfill after failure with the thirteen fill layers numbered from bottom to top. Failure surfaces were identified and marked on the tank plate-glass sides and a vertical line indicate the initial position of the wall vertical face (white lines).

By procesing the recorded test data, the following results were obtained: wall gravity center horizontal displacement history (Fig. 6a), total earth thrust history (Fig. 6b) and the entire wall motion representation in a PC monitor.

These results and the video tape showed that the structure behavior has two well-defined stages with the following features: a first stage with a duration of 10,5 seconds with low rate of permanent displacement accumulation (1.7 mm/sec.), large rocking response, no evident failure surfaces and increase of the residual backfill thrust -this is the earth thrust which would remain if the test is stopped at any time-. The second stage elapsed the last 5,5 seconds of the test and showed a high rate of permanent displacement accumulation (10 mm/sec), large translation response, well defined failure surfaces and residual backfill thrust remaining nearly constant.

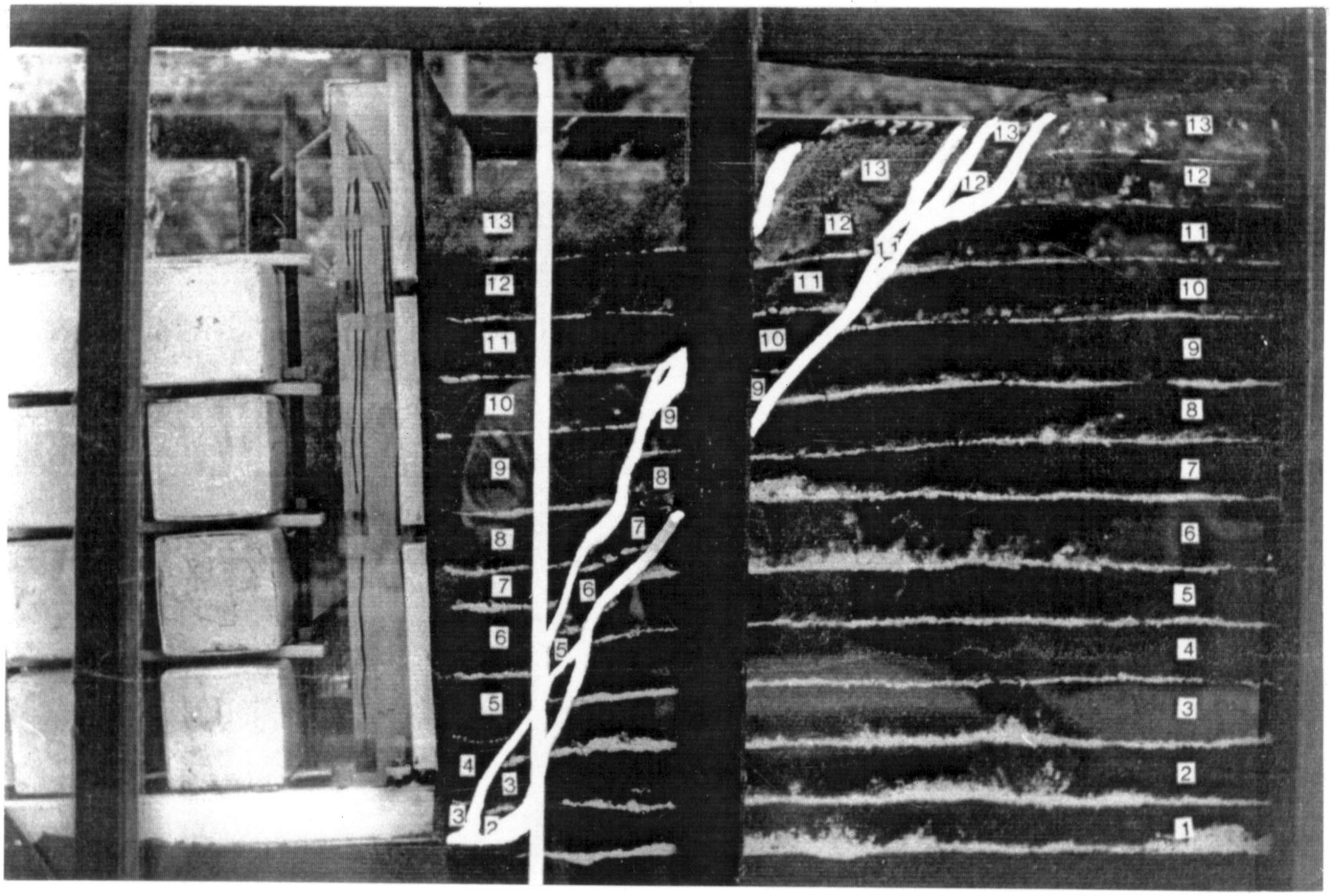

Figure 5. Final position of the structure and backfill after failure.

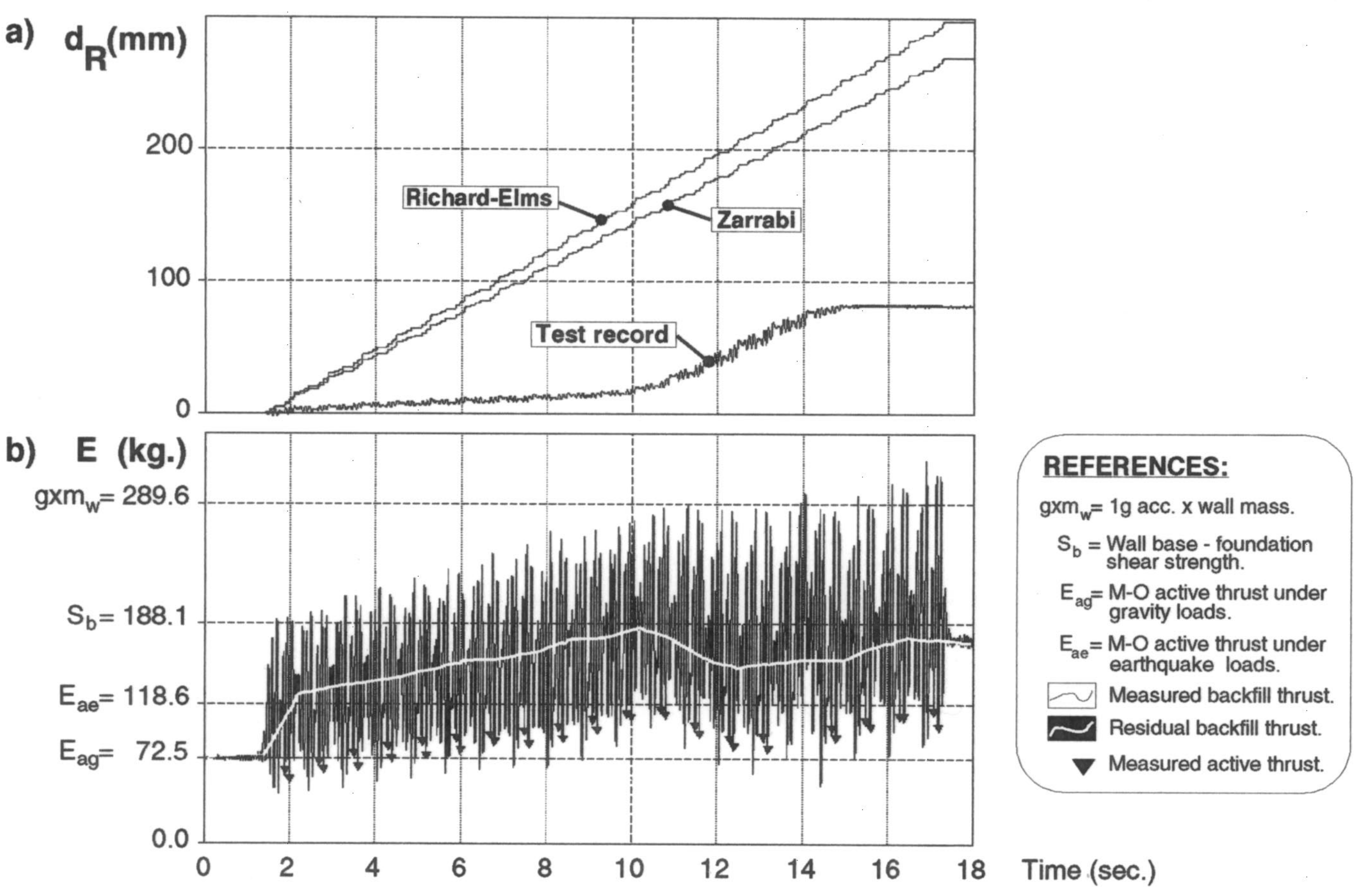

Figure 6. a) Wall gravity center displacement, b) Backfill thrust.

The wall motion representation in a PC monitor was very helpful to observe the response differences between the two stages. In the first stage the response is mainly in rocking and the slow outward displacement accumulation is caused by small slips which occur as the wall starts to rock at each motion cycle. The second stage response is mainly in translation and large horizontal permanent displacements accumulate at each motion cycle while rocking motion amplitude keeps small (Fig. 7).

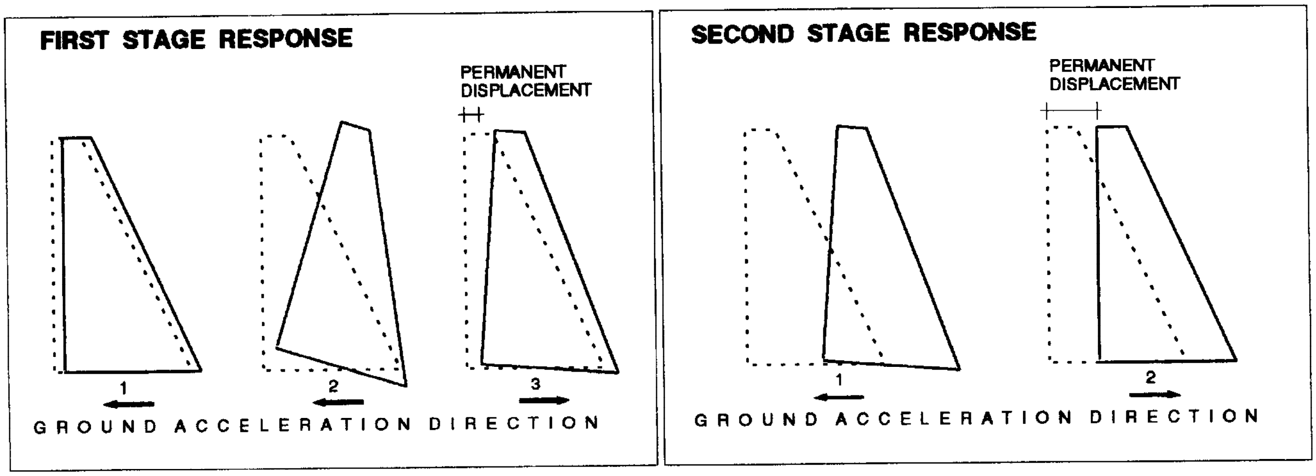

Figure 7. Structure response types (displacements not to scale).

MATHEMATICAL MODELLING

Mathematical modelling of the tested structure treated as a small prototype was carried out in order to compare the predicted with the observed behavior.

The active earth thrust under gravity and earthquake loads were computed by means of the M-O expression. Figure 6b compares those values with the measured backfill thrust plotted for the entire test duration. Marked minimum peaks are dynamic active thrust measured values i.e. the thrust value during each wall slip. At the begining of the test, measured values were smaller than computed ones. Dynamic active thrust peaks become closer to M-O predicted values in the second stage of the test. The same figure shows (white line) the residual backfill thrust increment during the test. Whitman (1993) reported a similar behavior from centrifuge tests observations and suggested that such increase in the residual backfill thrust is associated with the tendency of sands to densify -increasing the minor principal stress- when are shaken or vibrated.

With the aim of predicting permanent displacements the R-E and Zarrabi models were applied, assuming that the failure will occur in agreement with the M-O analysis results, this is a yield acceleration of 0.25g and a 52° inclined failure plane. The shaking table acceleration record was used as input motion. Calculated and measured horizontal displacement of the wall are plotted together in Fig. 6a. Both models overestimate the final permanent displacement, but it is very notable the similitude between the displacement accumulation rate in the Zarrabi model prediction and the recorded rate during the second stage of the test.

CONCLUSIONS

1) Rocking plays an important role in the first stage of the wall response, dissipating most of the earthquake energy input. The observed effect of rocking is the reduction of the permanent displacement accumulation rate due to the attenuation of the inertia forces.

2) This is, at least for the tested structure, the main reason for overestimation of the mathematical models predicted displacements.

3) The R-E model seems to always overestimate the displacements since it neglects vertical slip wedge inertia forces. Zarrabi model overcomes this problem and gives a good approach of the permanent displacement when rocking response is not possible (second stage).

4) There is a residual backfill thrust increase during the motion so that the final static thrust is greater than the initial value.

5) It seems that the structure change its behavior from the first to the second stage as the residual thrust reaches a value high enough to hinder the rocking response.

6) Further research is needed to investigate the factors that determine the structure response type (in rocking or in translation) and the increase of the residual thrust.

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