SEISMIC ANALYSIS OF GRAVITY RETAINING WALLS

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SUMMARY

This paper presents a seismic analysis of gravity retaining walls. A mathematical model was deriven to evaluate the permanent rotation of the wall due to the dynamic pressures generated into the backfill. Several laboratory tests were performed using a retaining wall model resting on a shaking table. An empirical relationship is proposed from the comparison of calculated rotation of the wall and those measured in the shaking table tests. The theoretical model was applied to a field case and it was found that the measured wall rotation at the end of the earthquake could be roughly estimated from calculations.

INTRODUCTION

The stability analysis of retaining walls in earthquake areas has been traditionally performed by pseudostatic calculations procedures. The Mononobe Okabe solution (Ref. 1, 2, 3) has beem applied to obtain the total (static plus seismic) earth pressures acting on the wall. This procedure does not take into account that during earthquakes the acting forces developed in a system normally exceed the resistant forces, making permanent displacements to occur because of the yielding of the materials (Ref.4). To arrive to an appropiate seismic coefficient for the design of a retaining wall, it is necessary to correlate this coefficient with the plastic deformation the engineer can tolerate during an specific earthquake. In this paper it is presented a simple mathematical model for computing permanent displacements of retaining walls based on laboratory model test results. The rotational type of failure is the only one analyzed because this is the mode most likely to occur in the field.

SHAKING TABLE TESTS

Several tests were performed using a model retaining wall resting on a shaking table. The wall was placed on a layer of sand and then it was backfilled by using the same sand. Afterwards, the table was excited by an horizontal-synusoidal type of displacement.

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Properties of the soil used in the tests

A fine uniform dune sand was used, with particles ranging from subangular to subrounded. In Fig.1 it is shown the grain size distribution of the sand, which has the following index properties:

Specific gravity = 2.82
Minimum void ratio = 0.57
Maximum void ratio = 1.01

Several drained lubricated ends triaxial tests were run at different initial relative densities. Figure 2 shows the angle of internal friction of the sand as a function of the initial relative density. For computing earth pressures the triaxial angle of internal friction was corrected for plane strain conditions using the Lade and Duncan theory (Ref. 5, 6).

The shaking table

The shaking table was a box 1.18 m long by 0.59 m wide and 0.45 m height which was mounted on rubber wheels. The horizontal movement of the table was obtained by means of a cranck system which induced a constant amplitude and a constant frequency synusoidal type of displacement. It was possible to chage the frequency from test to test.

The retaining wall model

The retaining wall model was a wooden block 0.581 m long by 0.30 m height and 0.144 m wide wheigting 14.7 kg.

The instruments used in the tests

A small pressure cell was made, which was calibrated using the dune sand placed on layers on top of it. After each layer was placed, the table was shaken for a few seconds in order to destroy the arching effect that would have been developed above the cell diaphragm. The calibration test was done several times and a average was used in the calculations. An LVDT was mounted on the top of the wall to measure the relative horizontal displacement between the top of the wall and the base of the shaking table. The bottom of the wall was indented to prevent an sliding type of failure. Both pressure and displacement were measured and printed on paper in a two channel recorder. The pressure cell was placed between the vertical face of the wall and the backfill.

Static tests

There were static tests performed with the model wall in order to measure experimentally the resisting moment developed in a rotational type of failure. The tests were performed by pulling the top of the wall horizontally and the force was recorded as a function of the displacement. The yielding moment, Mu, was computed as the yielding force times the height of the wall.

In order to measure the angle of friction between the wall and the soil, there were shear tests performed by pulling the wall horizontally, when it was horizontally placed on a layer on sand.

Dynamic tests

Once the soil was placed, the model wall was set up and the transducers were installed, the shaking table was forced to move horizontally with a synusoidal type of displacement. The backfill pressure against the wall and the relative displacement between the top of the wall and the base of the table were recorded while the wall was rotating about the heel.

Test results

At 1/3 of the height of the wall measured from its bottom, static plus dynamic earth preassures were recorded. The total pressure was then computed from Mononobe-Okabe expression assuming the distribution proposed by Seed and Whitman (Ref.3). Both the computed and measured maximum pressures are presented in Table I for loose and dense sand and for several horizontal maximum accelerations of the shaking table.

TABLE I

	Loose sand		Dense sand	
Relative density, Dr	40%		80%	
Dry unit weight, γd	1.5 t/m^3		1.7 t/m^3	
Soil angle of friction for plane strain condition, ϕ	38.5°		44°	
Wall-soil angle of friction, δ	31.5°		31.5°	
Max. horizontal acceleration a_{max}, g's	Calculated pressure t/m^2	Measured pressure t/m^2	Calculated pressure t/m^2	Measured pressure t/m^2
0.22	0.088	0.081		
0.29	0.099	0.102	0.091	0.088
0.40	0.121	0.113	0.112	0.116
0.46			0.126	0.130
0.52			0.143	0.165

The plane strain angles of internal friction were computed from the axi-symetric angles of internal friction by using the procedure proposed by Lade (Ref. 4,5).

The angle of rotation about the heel was obtained dividing the top displacement of the wall by its height. Figure 3 shows the top displacement of the wall as a function of time for a dense sand condition . After a few cycles of shaking the rotation increment per cycle tends to decrease; this fact was due to the decreasing height of the backfill as the wall rotated and the increasing passive pressure at the toe.

MOMENT-ROTATION MODEL

In order to evaluate the rotation of the wall during the shaking of the table, a simple mathematical model is proposed. The model assumes that the earth pressures can be computed according to the Mononobe-Okabe expression with the height distribution proposed by Seed and Whitman (Ref.3). The wall rotates about the heel every time the driving moment exceed the resisting moment which is assumed to have a rigid-plastic behavior.

The differential equation for the permanent rotation can be written as:

$$I\ddot{\theta} = M(t) - Mu$$

I = mass moment of inertia of the wall about the heel
θ = permanent plastic rotation of the wall
$M(t)$ = driving moment due to static plus dynamic earth pressure (the inertia force of the wall can or cannot be included)
Mu = yielding moment obtained experimentally from pulling static tests

The differential equation was integrated for the time interval when $\dot{\theta}$ (angular velocity) > 0.

The double integration was done numerically for time internvals of 0.01 sec., assuming that the acceleration of the shaking table varied linearly during the time interval. Two type of models were integrated, one which assumed that there were no inertia forces acting in the wall and the other assuming an inertia force equal to the mass of the wall times the acceleration of the table, acting in the center of gravity of the wall. The results obtained from the theoretical model were compared with the measured ones

The correction factor χ

The calculated rotation without including the inertia force of the wall was always smaller than the measured one after a few cycles of shaking. On the other hand if the inertia force of the wall is included, the computed rotation was larger that the measured one. This fact is shown in Fig.4 for one of the test performed. In order to have a calculation procedure for the angle of rotation of the wall, a correction factor is proposed such that:

$$\theta_M = \theta_{NIF} \cdot \chi + \theta_{IF} (1-\chi)$$

θ_M = measured angle of rotation of the wall
θ_{IF} = calculated angle of rotation including the inertia force of the wall
θ_{NIF} = calculated angle of rotation without including the inertia force of the wall

The correction factor χ can very from 0 to 1 depending on the amount of plastic rotation per cycle of the wall.

The equation of motion for computing permanent rotation of the wall can be written as:

$$\ddot{\theta} = \frac{Mu}{I} \left(\frac{M(t)}{Mu} - 1\right)$$

Because the value of χ controls de amount of plastic rotation per cycle, it was thought that $\ddot{\theta}_{max}$ would have some relation with χ. Fig.5 shows the relationship between $\ddot{\theta}_{max}$ and χ obtained by comparing the theoretical and experimental results. From this figure 5 it is clear that the higher the acceleration the higher the value of χ. This means that for small accelerations, the retaining wall almost does not rotate and any point of it has an acceleration very close to that of the shaking table. This means χ close to 0. On the other hand, for higher accelerations the wall rotates and important amount in every cycle and the acceleration of its center of gravity is smaller than that of the shaking table. In this case χ close to 1.

APPLICATION TO A FIELD CASE

A field case was selected to check the validity of the theoretical-experimental analysis presented herein. A gravity retaining wall (Ref.7) rotated about 6° during the July 8th 1971 earthquake (epicenter 140 km north-west of Santiago, Chile). The artificial accelerogram selected for the wall location was obtained by the α,β,γ method proposed by Saragoni (Ref.8). This artificial record was also used in slope stability analysis with good success (Ref.9). The acceleration record is presented in Fig.6. By using this acceleration record the total wall rotation at the end of the earthquake was computed with and without including the inertia force of the wall. It was obtained a very small rotation for the case without inertia force and a very large rotation for the case including the inertia force. The χ parameter determined from Fig.5 was used to obtain the corrected rotation, but it was a little too large compared with the rotation measured in the field. This fact was probably due to the large inertia force acting in the wall by its own weight, compared with the Mononobe-Okabe overturning moment.

CONCLUSIONS

1. It seems that the Mononobe-Okabe expression is adecuate to predict earth pressures acting on a gravity retaining wall during earthquakes, at least for small to medium size retaining walls.

2, Gravity retaining walls tends to have a rotational type of failure instead of sliding type failure. Probably this fact is due because engineers usually adopt small angles of friction at the base of the wall, so they underestimate the factor o safety for sliding.

3. Test results showed static pressures at the end of the tests always larger than static active pressures acting before shaking.

4. The overturning moment due to the inertia force of the wall varies from almost cero for large rotations increments per cycle to a value very close to that obtained from the field acceleration for the case of very small rotations per cycle.

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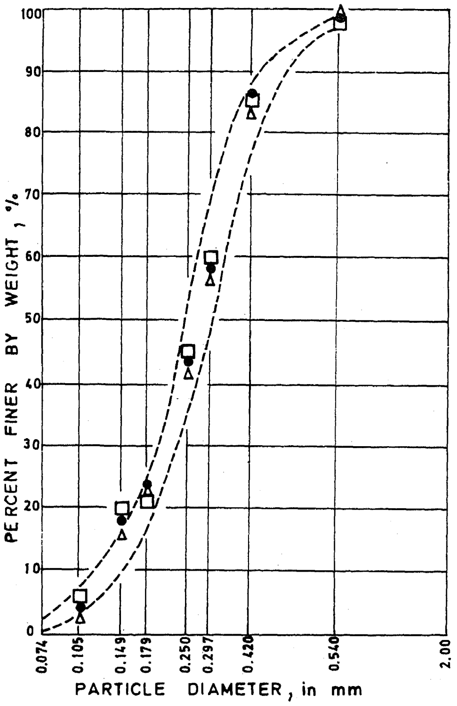


FIG.1 PARTICLE SIZE DISTRIBUTION OF SAND USED IN EXPERIMENTS.

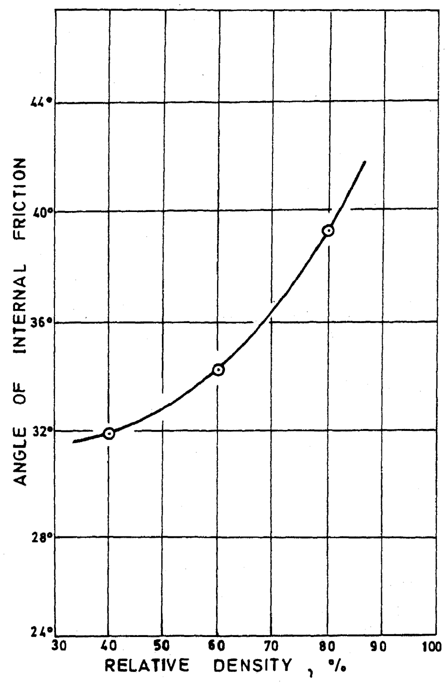


FIG.2 ANGLE OF INTERNAL FRICTION OF THE SAND USED IN EXPERIMENTS.

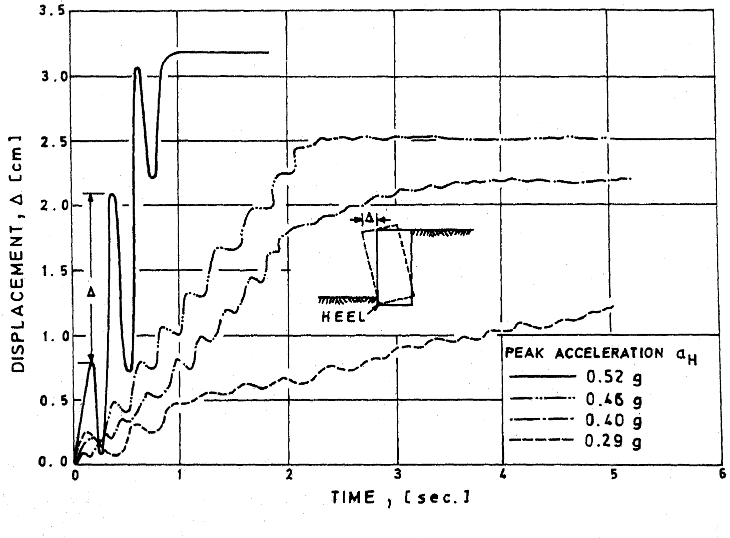


FIG.3 DISPLACEMENT OF THE TOP OF THE WALL AS A FUNCTION OF TIME

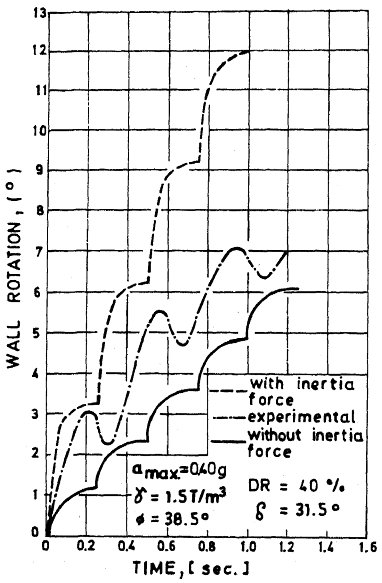
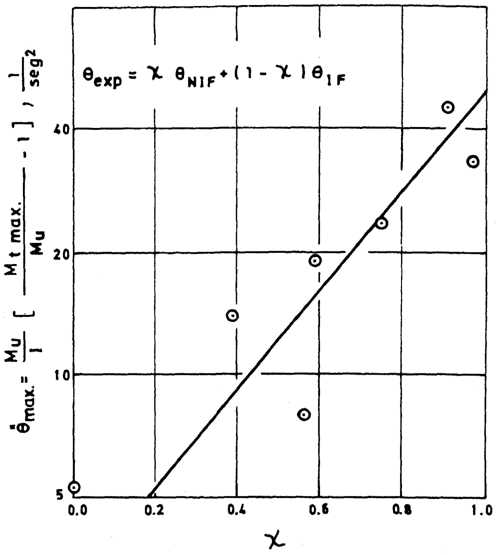


FIG. 4 EXPERIMENTAL ROTATION COMPARED WITH CALCULATED ROTATION, WITH AND WITHOUT INERTIA FORCE ACTING ON THE WALL.



($M_{t\,max.}$ was calculated from Mononobe - Okabe expression)

FIG. 5 RELATION BETWEEN $\ddot{\theta}_{max.}$ AND χ FROM TEST RESULTS.

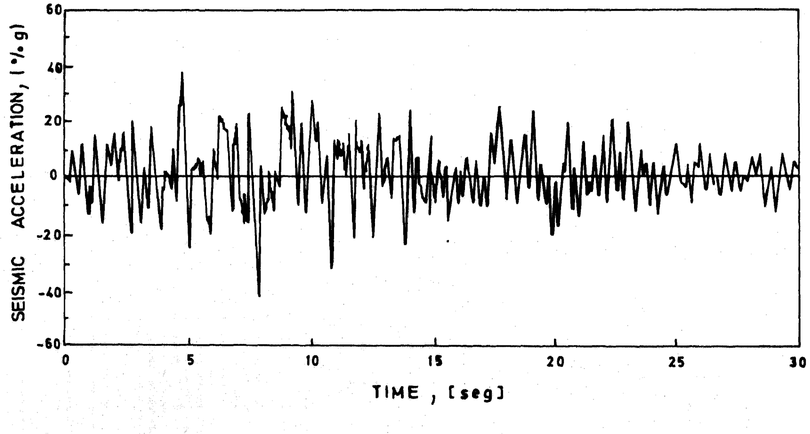


FIG. 6 EARTHQUAKE ACCELERATION RECORD USED FOR THE CALCULATION OF THE WALL ROTATION OF A FIELD CASE.