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SYNOPSIS: Centrifuge tests were conducted to study the displacement of gravity retaining walls during earthquakes. Theoretical analysis based on Newmark's sliding block method was used to analyze the data. For a gravity wall with dry backfill, sliding block method generates reasonable results. However, the method is difficult to apply for a retaining wall with saturated backfill. Comprehensive numerical methods need to be used. A method of calculating the tilting of gravity walls is introduced.

INTRODUCTION

Excessive displacement including lateral movement and tilting has been the major failure mode for gravity walls under earthquake loading. An example of such failure is shown in Fig. 1, which occurred during the Niigata earthquake in 1964. During the earthquake, a gravity quay wall which was made of concrete blocks and 2.4 meters above the sea level before the earthquake sank completely under the sea with large lateral displacement and tilting. Extensive ground settlement was induced in the backfill, which caused further damage to structures based on it. The details of the failure were reported by the Bureau of Ports and Harbors (1989). Similar types of failure were reported in many other earthquakes.

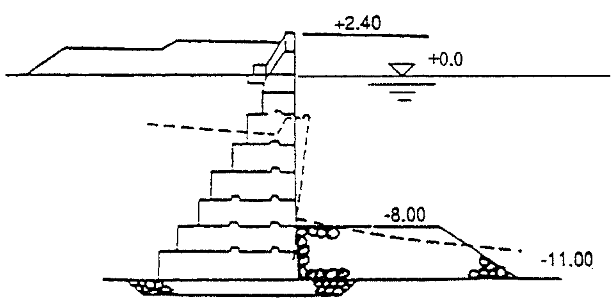

Fig. 1. Cross section of quay wall in A Berth in Niigata Port (after Bureau of Ports and Harbours)

Current design calculation for the lateral displacement of gravity walls is based on the Newmark (1965) sliding block method. It is assumed that a rigid wall would slide along a horizontal surface which has a rigid-plastic friction resistance. The wall will start sliding when the base shaking intensity has reached the level of threshold acceleration. Relative displacement will accumulate until the block and the ground have the same velocity again. This approach was adopted by Richards *et al.* (1979) in the analysis of gravity walls with dry backfill. It was shown that satisfactory results were achieved.

However, if the backfill is saturated, excess pore pressure generated during an earthquake would have strong influence on the calculation. So far there is no design calculation available to take into account the influence of excess pore pressure. At the same time, there is no design calculation developed to estimate the tilting of a gravity wall under earthquake loading.

In this paper, the lateral displacement and tilting of gravity walls with both dry and saturated backfill are studied based on the experimental results of centrifuge tests. The model tests were conducted at the Cambridge Geotechnical Centrifuge Center using the Bumpy Road Earthquake Actuator. The operation of the centrifuge was described by Schofield (1980). The soil used in the model tests was Nevada sand. The model wall was made of aluminum. The tests were conducted at a centrifuge acceleration of 80g and followed the standard procedures of earthquake centrifuge tests. All the data in this paper are presented in prototype scale.

LATERAL DISPLACEMENT OF GRAVITY WALLS

Displacement of a retaining wall induced by an earthquake can be divided into three categories: elastic, plastic residual and sliding displacement. During base shaking cyclic loading is induced on soil, which will cause soil deformation. The soil deformation may result in the displacement of a retaining wall. After a base excitation is over, part of the soil deformation will recover, which can be regarded as elastic deformation. However, large proportion of the displacement developed during base shaking will remain as residual displacement even without sliding. This displacement is caused by the plastic deformation of soil, which may also cause an increase in lateral earth pressure on a retaining wall after an earthquake, as has been observed in many experiments. Experimental data have also shown that plastic residual displacement is usually a substantial percentage of the peak displacement developed during base shaking. If dynamic loading is so large that the equilibrium of forces on the wall cannot be satisfied, severe sliding displacement will occur. The magnitude of this type of displacement can be quite large depending on the intensity and duration of base shaking. Therefore, in most cases it is this type of displacement that is the major concern for design engineers.

Sliding displacement of a gravity wall

Newmark's sliding block method has been widely used to estimate sliding displacement of retaining walls. There are two important assumptions behind this type of calculation. First, the block is assumed to move as a single rigid body with shearing resistance mobilized along a planar sliding surface. The effect of an earthquake can be represented by an inertial force in the direction opposite to base shaking. There is neither amplification nor phase shift of vibration. The second assumption is that the sliding surface is free draining. There is no excess pore pressure. This can be apply to either dry soil or saturated soil but with high permeability.

In the case of a gravity wall with saturated backfill, the loading condition on the wall is quite complicated and hence the calculation of displacement is not straightforward. A general loading condition is illustrated in Fig. 2. The only two forces that can be derived directly are the weight of the wall and hydrostatic pressure. Although there are methods to estimate other forces the following three important factors need to be considered:

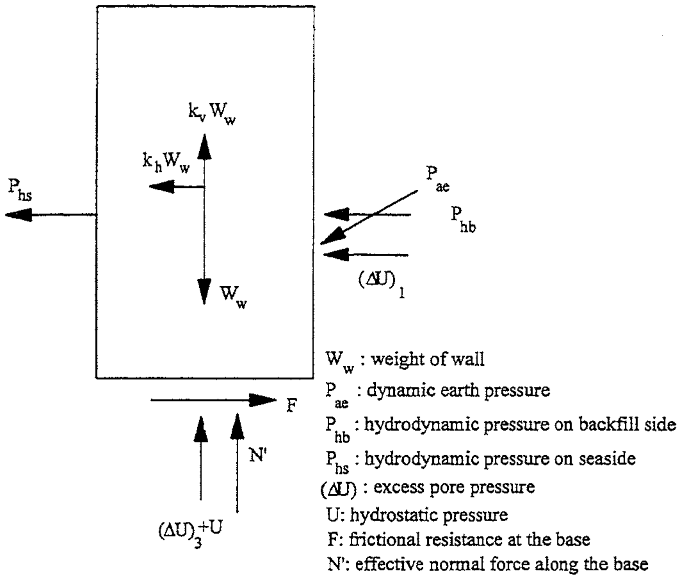

Fig. 2. Forces acting on a gravity quay wall

1) strain softening: to estimate the dynamic earth pressure on a retaining wall and the frictional resistance at the base, it is necessary to know the friction angle of the backfill and the friction angle between the wall and soil. As the strength of soil is dependent on the effective stress and strain, the friction angle of backfill may vary with location. To estimate the peak friction angle the dilatancy theory proposed by Bolton (1986) can be used.

$$\phi_{max} = 33 + 5\, I_R \tag{1}$$

where I_R is the relative dilatancy index which is defined as

$$I_R = I_D(10 - \ln\sigma_m') - 1 \tag{2}$$

where σ_m' is the mean effective confining pressure and I_D relative density of soil. Frictional angle between sand and aluminum can be expressed in a similar formula

$$\delta_{max} = 17.7 + 2.4\, I_R \tag{3}$$

The stress and strain state at mid-height in the backfill can be used to estimate the average peak friction angle. However, soil is a strain softening material and with the increase in the displacement of a wall the friction angles are expected to drop towards the critical value.

2) amplification of vibration: to calculate inertia force of the wall, dynamic earth pressure and hydrodynamic pressures shown in Fig. 2, it is necessary to know the earthquake acceleration coefficients. The magnitude of acceleration used in the calculation of each force may not be identical and they may be different from the base shaking input depending on the nature of dynamic soil-fluid-structure interaction. If the natural frequency of the soil-structure system is much higher than the dominant earthquake frequency, the acceleration at the base can be used. Otherwise the possible amplification and phase shift of vibration has to be taken into account in the calculation.

3) influence of excess pore pressure: excess pore pressures generated in soil has strong influence on the stability of a retaining wall. First, it increases the total horizontal force on the wall, which will reduce the threshold acceleration. Secondly, excess pore pressure generated at the base reduces the effective weight of the wall and hence further reduces the threshold acceleration.

For a gravity wall with dry backfill the influence of the first two factors can be estimated. For example, if there is enough initial displacement of the wall to cause a full strain softening, a unique threshold acceleration can be worked out. If there is strain softening during base shaking the threshold acceleration will be reduced gradually as shown by centrifuge tests reported by Steedman (1984). However, for saturated backfill the combined effect of these three factors is very difficult to estimate by simple calculations. Since the magnitude of excess pore pressure is difficult to predict, the threshold acceleration cannot be derived directly. The resulting displacement will depend on a number of factors. Under such circumstance it is necessary to use physical modeling or comprehensive numerical techniques.

Experimental data

Test XZ7 was conducted on a gravity retaining wall with dry backfill. A cross-sectional view of the model is shown in Fig. 3. The relative density of the backfill is 33%. The recordings of some transducers during a model earthquake are shown in Fig. 4. ACC11 was fixed at the base and its recording can be regarded as the base shaking input. ACC2 was fixed on the wall beneath mid-height and hence it recorded the lateral vibration of the retaining wall. Compared with input motion there were obvious differences. While in the negative half cycle the amplitude of base shaking and wall vibration was approximately the same there was considerable difference in the positive half cycle. The acceleration recorded on the wall had a flat peak started from the fifth cycle and this flat peak lasted for a period of time. During the half cycle the base acceleration was first larger and later smaller than the acceleration on wall, indicating the buildup and decline of a relative velocity between the wall and its base. As the result, displacement of the wall relative to the base was accumulated.

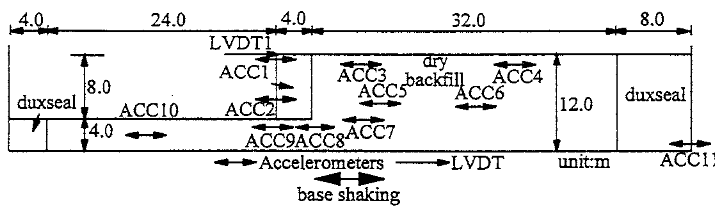

Fig. 3. Cross-sectional view of centrifuge model XZ7

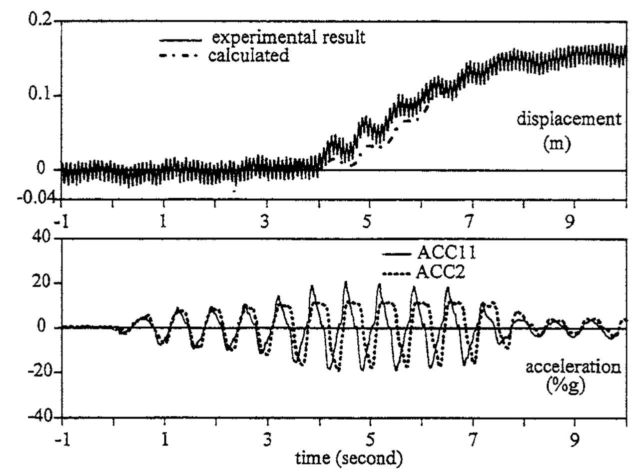

Fig. 4. Response of gravity wall during EQ2, test XZ7

The peak flat acceleration recorded on the wall had a magnitude of 12.5% which can be regarded as the threshold acceleration in the sliding block method. From equilibrium of forces on the wall and after considering strain softening of soil, the threshold acceleration calculated is 14.8%. That is quite close to the experimental result. The displacement of the retaining wall can be derived by integrating twice the difference in acceleration. The calculated displacement of the wall is also shown in Fig. 4, which shows a good agreement with experimental data.

As discussed above, for a gravity retaining wall with saturated backfill, excess pore pressures have strong influence on the stability of a retaining wall. As excess pore pressures vary with time the threshold acceleration will also change. Therefore there will not be a flat top type recording for acceleration on the wall during sliding. Text XZ9 was conducted on a wall with saturated backfill, Fig. 5. The relative density of the backfill is 32.7%. The recordings of some transducers during a large earthquake are shown in Fig. 6. During this earthquake pore pressure transducers in the backfill recorded considerable excess pore pressures. As shown in Fig. 6, there is no flat peak (or a unique threshold value) for acceleration on the wall. Displacement of the wall was recorded during both large cycles and small cycles as excess pore pressure continued to build up. The magnitude of permanent displacement under such circumstance is difficult to estimate by simple calculations.

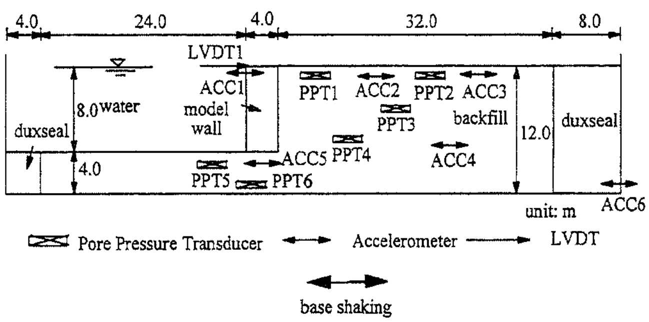

Fig. 5. Cross-sectional view of centrifuge model XZ9

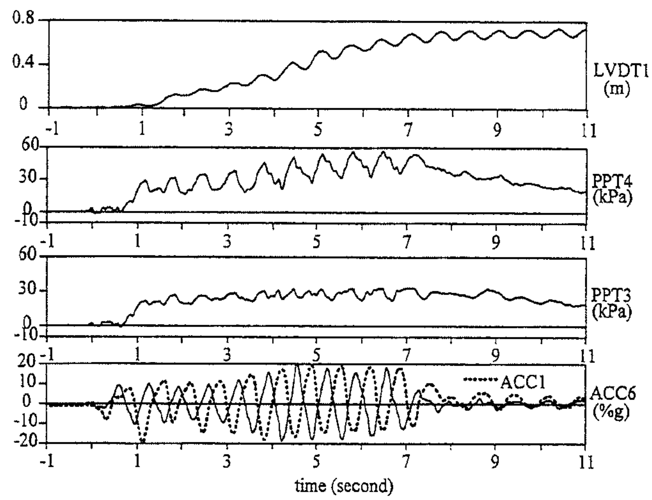

Fig. 6. Recording of some transducers during EQ1, test XZ9

Numerical simulation

Numerical simulation can provide reasonable solutions for complex geotechnical problems. In recent years, a number of numerical codes have been developed to study earthquake problems. For retaining wall problems, a comprehensive numerical analysis can take into account soil behavior under cyclic loading, dynamic soil-fluid-structure interaction and the influence of excess pore pressure. For the problem discussed in this paper, a numerical simulation was conducted by Madabhushi *et al.* (1993) using the finite element code SWANDYNE-II. Some of the results are shown in Fig. 7. It is clear that the finite element calculation achieved reasonable results for acceleration, excess pore pressure and displacement.

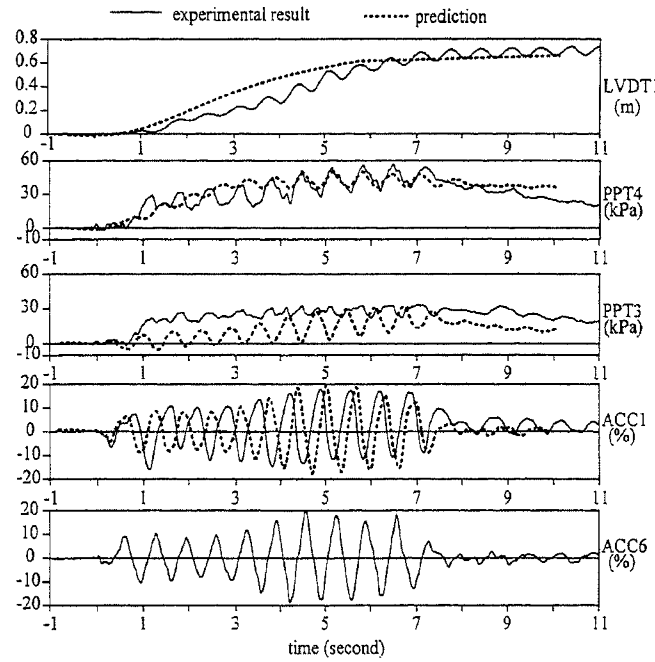

Fig. 7. Comparison between prediction and experimental data, test XZ9

TILTING OF GRAVITY WALLS

Tilting of a gravity quay wall under earthquake loading is harmful. Here the method used in calculating the rotation angle of a footing suggested by Dean *et al.* (1989) is modified to estimate the rotation angle of a gravity wall. For virgin loading rotation angle and moment has a hyperbolic relationship which can be expressed as:

$$\theta = \frac{M/K_I}{1 - M/M_{max}} \tag{4}$$

in which M is the rotating moment, θ the rotation angle, M_{max} the ultimate overturning moment and K_I the elastic rocking stiffness of the foundation which is given by Wolf (1988) as

$$K_I = \frac{GB^2}{8(1-\mu)}(3.2L + 0.8B) \tag{5}$$

where G is the shear modulus of foundation soil, μ Poisson's ratio, B and L the width and length of the foundation respectively. The maximum shear modulus of foundation soil can be derived by an empirical formula suggested by Hardin *et al.* (1972)

$$G_{max} = 3230\frac{(2.973 - e)^2}{(1+e)}(\sigma_m')^{0.5}\ (kN/m^2) \tag{6}$$

in which e is void ratio of soil and σ_m' mean effective confining pressure. The relationship between moment and rotation angle is illustrated in Fig. 8. The unloading-reloading path follows a line of linear elastic with a modulus assumed to be equal to the initial rocking stiffness of a footing. The ultimate rocking moment depends on the combined loading condition on the wall and the approach suggested by Dean *et al.* (1992) is used here

$$\sqrt{\left[\frac{M}{BV_M}\right]^2 + 0.39\left[\frac{H}{V_M}\right]^2} = 0.35\frac{V}{V_M}\left[1 - \frac{V}{V_M}\right] \tag{7}$$

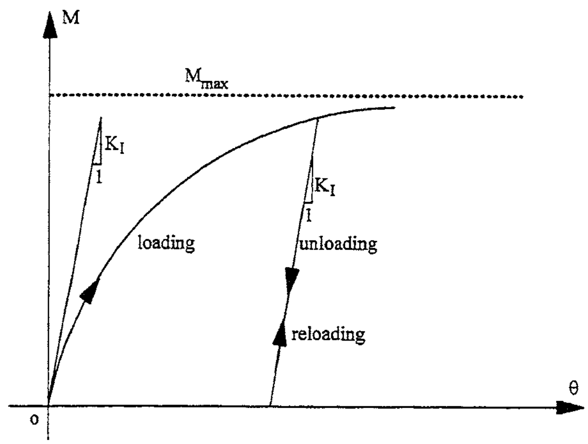

Fig. 8. A hyperbolic model for calculating tilting of a retaining wall

where V_M is the vertical bearing capacity with vertical loading only, V is vertical bearing capacity with eccentricity and H the horizontal load. The vertical bearing capacity with or without eccentricity is given by:

$$V = 0.5(B - 2e)^2\gamma' N_\gamma \qquad (8)$$

where e is the eccentricity of the applied load and N_γ is the bearing capacity factor. To estimate the tilting angle of a retaining wall it is necessary to work out the magnitude of each force on the wall shown in Fig. 2 and thereafter the magnitude and acting point of the combined load. Then following the method described above it is possible to calculate the maximum rotation angle. If the backfill is dry the calculation is straightforward. But when the backfill soil is saturated effective stresses varies with time as excess pore pressure builds up. Both the stiffness and bearing capacity of a footing is difficult to predict. The calculation can not be applied directly.

Experimental data of tilting

For test XZ7 which had a loose dry sand backfill the final rotation angle of the wall was 4 degrees after the earthquake. Following the procedures of calculation described above the calculated rotation angle of the wall was 2.5 degrees, which had correct magnitude compared with experimental data. It needs to point out that when large residual rotation occurs the moment on the wall would be near the ultimate moment of the foundation. In that range the calculation is sensitive to the magnitude of loading on the wall.

CONCLUSIONS

The following conclusions can be drawn from this study:

1) Centrifuge tests generated useful data about the displacement of gravity walls with dry and saturated backfill.

2) For a gravity wall with dry backfill, Newmark's sliding block method can generate reasonable result about the sliding displacement.

3) For a gravity wall with saturated backfill, the influence of excess pore pressure makes it difficult to apply such simple calculation. Comprehensive numerical simulation is needed.

4) A method is suggested to estimate the tilting angle of a gravity wall with dry backfill, which showed promising result.

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