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# Evaluating tilt of gravity retaining walls during earthquakes

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ABSTRACT: An analytical model is developed to analyze the seismic response of gravity walls retaining and founded on dry sand, with special emphasis on tilting behavior. A well verified two dimensional finite element code is used for this purpose. The proposed model is verified comparing predictions to results from three dynamic centrefuge tests, with satisfactory agreement. The proposed model is used in a parametric study on the dynamic response of an 8.0 m high and 3.0 m wide gravity retaining wall for sinusoidal and earthquake acceleration input motions. The results from the analysis of the different cases show that outward tilting of gravity retaining walls is the dominant mode of response during dynamic shaking and that these walls end up with a permanent outward tilt at the end of shaking. Based on the results from the analysis in the study, a practical and approximate method is suggested for evaluating the permanent outward tilt of gravity retaining walls during earthquakes.

## 1 INTRODUCTION

The dynamic response of gravity walls that experience tilting and the effect of tilting on the overall displacement of these walls has received little analytical study.

A well verified, general purpose, two dimensional finite element computer code named FLEX (developed by Weidlinger Associates) is used in "constructing" a finite element model for the gravity retaining wall dynamic problem. The model is developed for understanding the dynamic response of gravity retaining walls with special emphasis on tilting behavior. The backfill and foundation soils are dry in this study. The proposed model is verified by comparing its predictions to results from three dynamic centrifuge tests conducted by Andersen et al. (1987) on a tilting gravity wall.

The proposed model is used in studying the dynamic response of an 8.0 m high and 3.0 m wide gravity retaining wall subjected to a sinusoidal and earthquake acceleration input motion. The effect of tilting on the overall displacement of the wall is assessed. A parametric study is carried out to define the factors affecting the dynamic tilt of the wall and to establish practical guidelines for identifying situations for which tilting is important.

The results from all the analyzed cases of the 8.0 m high gravity retaining wall together with those from the analysis of the tilting wall centrifuge tests are discussed and used for proposing a practical method for evaluating permanent tilt of gravity retaining walls during earthquakes.

## 2 BACKGROUND REGARDING DYNAMIC LATERAL EARTH PRESSURES AND ASEISMIC DESIGN OF GRAVITY RETAINING WALLS

Gravity retaining walls are usually designed for earthquake loading using either of two methods. The first method is called the traditional approach to design in which (static plus dynamic) lateral earth pressure is evaluated using a simplified equation of the Mononobe-Okabe formula as recommended by Seed and Whitman (1970) together with an assumed horizontal acceleration coefficient. In addition, an inertial force on the wall is included, using the same acceleration coefficient. Moreover, for the purpose of evaluating the overturning moment on the wall, the dynamic lateral earth pressure is assumed to be located at 0.6 H above the wall base, where H is the height of the wall. The wall is proportioned to resist the total earth force and overturning moment for certain factors of safety against sliding and overturning. Usually, the factors of safety recommended for use are less than that required for static forces alone. Recommended acceleration coefficients typically range 0.05 to 0.15, corresponding to 1/3 to 1/2 of the peak acceleration of the design earthquake.

The second method is called the

limited-displacement approach to design proposed by Richards and Elms (1979) using Newmark's block-on-plane model. Here, the wall performance is considered satisfactory if the earthquake induced relative translational displacement (i.e. sliding) is less than an allowable amount. The total (static plus dynamic) lateral earth force is computed using the Mononobe-Okabe method or the Seed-Whitman formula. Many studies at the Massachusetts Institute of Technology were carried out to modify the Richards-Elms method but with the same basic assumption regarding failure by sliding.

## 3 A PROPOSED MODEL FOR EVALUATING TILT OF GRAVITY RETAINING WALLS DURING EARTHQUAKES

A well verified finite element code named FLEX (Vaughan and Richardson, 1989) is used in developing an analytical model to study the tilting response of gravity retaining walls for earthquake loading. The proposed model has the following characteristics (see Figure 1 for a typical 2-D finite element grid used in the analysis of the gravity retaining wall dynamic problem. This figure shows the different features of the proposed model in this study):

1. The soil (dry sand in this study) is modeled by a two dimensional finite element grid.
2. The gravity retaining wall is modeled as a rigid substructure.
3. The strength and deformation of the soil are modeled using a viscous cap constitutive model. This model consists of a failure surface and hardening cap together with an associated flow rule. The cap surface is activated only for the soil under the wall to represent compaction during wall rocking. In addition, visco-elastic behavior is provided for representing the hysteretic-like damping of soil during dynamic loading. (For more details on this constitutive model, see work by Isenberg, Vaughan, and Sandler, 1980; Sandler and Rubin, 1979; and Vaughan and Isenberg, 1982).
4. Interface elements are used between the between the wall and the soil to allow for sliding and for debonding/recontact behavior.
5. The finite element grid is truncated by using an absorbing boundary approximation developed by Lysmer and Kuhlemeyer (1969). Using this boundary at both sides of the grid simulates the horizontal radiation of energy scattered from the wall and the excavation. Shear beams are placed adjacent to the lateral boundaries from each side which give the far-field ground motion.

The procedure for carrying out the analysis is presented in detail by Al-Homoud (1990). The results of the different quantities from the analyses are obtained and presented in the form of time histories.

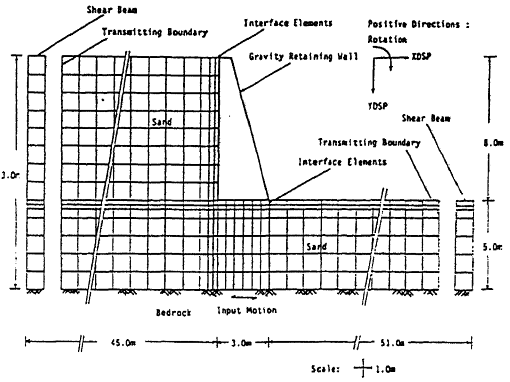

Figure 1. Proposed 2-D finite element grid for the gravity retaining wall problem which shows the different features of the proposed model in this study.

## 4 COMPARISON BETWEEN MODEL PREDICTIONS AND RESULTS FROM CENTRIFUGE TESTS ON TILTING GRAVITY WALL RETAINING DRY SAND

The proposed model is verified by analyzing three "Prototype" dynamic centrifuge tests on a tilting gravity retaining wall model conducted by Andersen et al. (1987). The simulated, rigid wall was hinged at its heel, and supported by a spring near the toe to provide resistance to tilting. The spring spring stiffness has a different value in each of the three centrifuge tests which was used to represent soft, medium, and stiff foundation, respectively. The soil was 14/25 Leighton Buzzard dry sand. Shaking in each test consisted of 10 not-very-uniform cycles which was applied to the base of wall and backfill.

The "Prototype" tilting gravity retaining wall centrifuge test set-up is modeled by a 2-D finite element grid using the proposed model. The sand used in the analysis is 120/200 Leighton Buzzard dry sand at a relative density of about 80% due to lack of laboratory test results on the cyclic shear strength of 14/25 Leighton Buzzard sand. The angle of friction for this sand at this density is about 40 degrees and its dry density is about 1530 kg/m3. The input parameters of the viscous cap constitutive model are evaluated from monotonic compression tests on 120/200 Leighton Buzzard sand conducted by Gately et al. (1986) and cyclic triaxial compression tests on the same sand conducted by Pahwa et al. (1986). The shear and bulk moduli are chosen to vary with depth as a function of the initial effective stress, and correspond to the levels of strains expected in the dynamic analysis. A damping ratio of 8.5% is used in the analysis.

The following main predicted and measured "Prototype" dynamic quantities are compared for each of the three analyzed centrifuge tests resulting in an overall average absolute error of about 26% :

1. Peak and permanent outward displacement at top of wall.
2. Peak and residual dynamic horizontal earth force.
3. Peak and residual increase in toe spring force.
4. Location of residual total (static plus dynamic) earth force above the wall's base.
5. Maximum horizontal acceleration at different locations in the backfill.

The phasing relations between the different quantities in the problem are found to be the same in both the results from the dynamic analysis using the proposed model and the measurements from the centrifuge tests. These are summarized below:

1. The maximum earth pressure behind the wall occurs when the wall is at its maximum displacement towards the backfill, which occurs also at the time of a maximum outward horizontal acceleration at the base.
2. The minimum earth pressure occurs when the wall is at its maximum displacement away from the backfill, which also occurs at the time of a maximum inward horizontal acceleration at the base.
3. The highest location of the resultant earth force above the bottom of the wall occurs at the time of maximum earth pressure, while the lowest location occur at the time of minimum earth pressure.

It is important to emphasize that the phasing relations in (1) and (2) above are just the opposite of the result reached using the Mononobe-Okabe (1929) approach, assuming active conditions at all times, and the result observed during shaking table tests such as those by Sherif et al. (1981).

The results from the comparison between the main predicted and measured "Prototype" dynamic quantities reflect a success of the proposed model knowing that there are some inaccuracies and difficulties encountered in the tests and approximations and drawbacks in the proposed model. The inaccuracies encountered in carrying out the centrifuge tests were given by Andersen et al. (1987). The drawbacks in the proposed model are: (1) the inability of the viscous cap constitutive model to include the hysteretic volumetric strains which develop in the sand during dynamic loading (e.g. Stamatopoulos, 1989), (2) the inability to model nonlinear soil behavior within the failure surface of the viscous cap constitutive model, and (3) the predicted dilatancy when yielding occurs in the soil is larger than the estimated value based on triaxial test results.

## 5 TILTING OF GRAVITY RETAINING WALLS SUBJECTED TO SINUSOIDAL GROUND MOTION

### 5.1 The problem and traditional approach for seismic design

The proposed model is used to carry out a parametric study on the dynamic response of an 8.0 m high and 3.0 m wide gravity retaining wall proportioned using the traditional approach to seismic design for an earthquake with a peak acceleration of 0.2 g. The wall retains 120/200 Leighton Buzzard dry sand with a relative density of 80% and has a 5.0 m foundation of the same sand, too.

The width at the top of the wall is chosen to be 0.80 m. In order to choose the proper wall width (3.0 m in this case) the traditional approach to seismic design is used with an acceleration coefficient equal to 1/2 of the peak acceleration of the design earthquake. Moreover, a safety factor between 1.1 and 1.2 is chosen based on recommended factors of safety by NAVFAC, 1982 design manual. The chosen wall has static safety factors against sliding and overturning of 2.88 and 2.50, respectively. The corresponding total (static plus dynamic) safety factors are 1.70 and 1.29, respectively.

### 5.2 Analysis of the problem using the proposed model

Figure 1 shows the 2-D finite element grid for the gravity retaining wall problem, which shows the different features of the proposed model. The input motion is prescribed at the base of the grid. This is chosen to be a certain number of cycles of a sinusoidal acceleration with a known frequency and peak amplitude.

At the beginning a sensitivity analysis is carried out to optimize the finite element grid size and the thickness of the interface elements. The optimum grid size (i.e. width of the grid) is found to be about 100 m ; which corresponds to truncating the grid at about 6.0 H from each side. The optimum thickness of the interface elements is found to be 25 cm; which corresponds to a maximum aspect ratio (length/width of a finite element) of 4.0.

The input parameters of the viscous cap constitutive model are the same as those used in the analysis of the tilting wall centrifuge tests. In the current analysis, the cap failure surface is activated only for the foundation soil under the wall base to represent compaction due to wall's rocking during dynamic shaking. The shear and bulk moduli are chosen to vary with depth as a function of the initial effective stress, and correspond to the levels of strains expected in the dynamic analysis.

The natural frequency of the backfill layer is computed to be 3.76 Hz, *corresponding to a shear wave velocity of* 195.6 m/s. The angle of friction and cohesion for the interface elements behind the wall are 26.8 degrees, and zero, respectively. The corresponding values for the interface elements under the wall are 40.0 degrees and zero, respectively.

Table 1 summarizes the cases studied. The detailed results from the dynamic analysis of these cases is given by Al-Homoud (1990). These results include time histories of the following quantities: horizontal acceleration at top and bottom of wall, absolute and relative displacements (both vertical and horizontal) at top, toe and heel of wall, rotation of wall, sliding of wall, gaping between the soil and wall (underneath and behind the wall), total (static plus dynamic) horizontal earth pressure behind the wall, total (static plus dynamic) vertical stress under the wall, dynamic response at many points in the backfill and far field (this include horizontal and vertical displacements, horizontal acceleration and horizontal and vertical total pressure). Moreover, for each case, the distribution of total horizontal earth pressure behind the wall is given by Al-Homoud (1990) for the following conditions: initial geostatic, at time of maximum outward displacement of wall, at time of maximum inward displacement of wall, at end of shaking and as evaluated using the Seed-Whitman (1990) approach.

**Table 1. Summary of dynamic gravity retaining wall problem cases studied for a sinusoidal acceleration input motion.**

| Case No. | Base Width of Wall (m) | Description of Sinusoidal Input Motion | | |
|---|---|---|---|---|
| | | Acceleration Amplitude (g's) | Excitation Frequency (Hz) | No. of Cycles |
| I | 3.0 m | 0.2 | 4 | 3 |
| II | 3.0 m | 0.2 | 2 | 3 |
| III | 3.0 m | 0.2 | 4 | 6 |
| IV | 3.0 m | 0.1 | 4 | 6 |
| V | 3.0 m | 0.3 | 4 | 6 |

The analysis using the proposed model for the cases in Table 1 showed that outward tilting of gravity retaining walls is the dominant mode of response, and that there is a permanent outward tilt for these walls. The permanent wall tilt is found to be accompanied by:

1. A permanent increase in horizontal earth force behind the wall. This was also observed by Andersen et al. (1987) and by those who conducted analytical studies on the problem (e.g. Nadim and Whitman, 1983).
2. A permanent upward displacement of the wall's heel.
3. *A permanent downward displacement of* the wall's toe.
4. A permanent increase in the vertical stresses under the toe accompanied by a permanent decrease in the vertical stresses under the heel.

The phasing relations between the different quantities are found to be exactly the same as these observed in the centrifuge tilting wall tests by Andersen et al. (1987). These are summarized previously.

In studying the effect of excitation frequency on the dynamic wall response, it is found that the permanent outward tilt is 0.02 degrees for a three cycle input motion which has an acceleration amplitude of 0.2 g and a frequency of 2Hz; while it is 0.36 degrees for an input motion which has three cycles of acceleration with an amplitude of 0.2 g and a frequency of 4 Hz.

In studying the effect of the number of cycles of the input motion on the dynamic wall response, the permanent outward wall tilt is decreased to 0.22 degrees for an input motion which has six cycles of acceleration with an amplitude of 0.1 g and a frequency of 4 Hz. In another case for which the input motion amplitude is increased to 0.3 g, the permanent outward wall tilt is increased to 1.61 degrees. All these results emphasized the nonlinearity in the dynamic wall response.

In studying the effect of the initial factor of safety against overturning on the dynamic response of the wall, by increasing the wall base by 33.0% (i.e. from 3.0 m to 4.0 m), the permanent outward wall tilt is increased to 0.61 degrees for an input motion which has six cycles of acceleration with an amplitude of 0.2 g and a frequency of 4 Hz.

In all the above cases, the Seed-Whitman (1970) method for estimating the dynamic earth force and its location above the base is found to be an upper bound when the wall is at its maximum inward displacement towards the backfill.

An analysis is carried out to understand the effect of the cap constitutive model parameters on the wall tilt; these parameters are those which define the following: initial position of the cap surface, shape of the cap surface, and maximum plastic volumetric compaction. The results from the analysis showed that the permanent outward wall tilt is not affected by the variation in these parameters.

## 6 TILTING OF GRAVITY RETAINING WALLS SUBJECTED TO EARTHQUAKES

The proposed model is used in studying the dynamic response of the gravity retaining wall problem of Figure 1 using three well known earthquakes normalized to different values of maximum acceleration amplitude. The detailed results from the analysis in these cases are given by Al-Homoud (1990). The results from the analysis are consistent with the fact that the traditional approach for the design of gravity retaining walls is conservative and that walls designed using this approach can survive earthquakes stronger than the one used in the design. In order to check this hypothesis, an analysis is carried out for an earthquake normalized to 0.4 g. The gravity wall of Figure 1 survived this earthquake but with relatively large permanent outward tilt compared to the one with 0.2 g.

## 7 PROPOSED PRACTICAL METHOD FOR EVALUATING PERMANENT OUTWARD TILT OF GRAVITY RETAINING WALLS

Based on a detailed study of the results from all of the cases analyzed using the proposed model, the following simplified and approximate procedure is proposed to evaluate the permanent outward tilt of a gravity retaining wall as a result of an earthquake. (This procedure is not valid for the situation in which the peak outward tilt of the wall may exceed 5.0 E-03 radians or for strong earthquake input motions. This is because the wall in these situations is close to failure. Here, the authors recommend using the code FLEX with the procedure proposed in this study):

I. Estimate the maximum value of the amplified horizontal acceleration at H/2 below the top surface of the far field behind the wall, where H is the wall height. This can be obtained using the computer code SHAKE developed by Schnabel et al. (1971).

II. Estimate the maximum horizontal acceleration at the center of gravity of the wall at the time of its maximum outward displacement to be equal to that obtained in step I. The corresponding horizontal inertia of the wall is computed as the multiplication of the mass of the wall and the estimated horizontal acceleration.

III. Compute the dynamic overturning moment due to horizontal wall inertia at time of maximum outward displacement Mo as the multiplication of the maximum horizontal inertia of the wall obtained in step II and the height of the center of gravity of the wall above the base. This assumption is based on the results from the analyses of the centrifuge tilting wall tests and the gravity retaining wall problem of Figure 1, which showed that most of the dynamic overturning moment comes from the horizontal inertia of the wall.

IV. Estimate the initial value of the dynamic rotational stiffness of the wall as 80% of that evaluated using the equation recommended by Dobry and Gazetas (1986), for a strip footing resting on an elastic homogeneous half space.

V. Compute the overturning moment increment required to initiate uplift of the wall by carrying out regular static computations considering the wall weight and initial earth pressure.

VI. Compute the outward wall tilt which corresponds to initial uplift condition $\theta_o$ as a division of the overturning moment increment obtained in step V by the rotational stiffness estimated in step IV.

VII. Estimate the ultimate dynamic resisting moment of the wall Mu by assuming:

a. A contact pressure distribution under the wall base as proposed by Meyerhof (1951).

b. At ultimate condition, only about 20% of the wall base is in contact with the soil.

c. The ultimate soil pressure under the wall is computed using the Terzaghi (1943) bearing capacity equation for an infinitely long shallow strip footing with the bearing capacity factors as given by Meyerhof (1963).

VIII. Estimate the peak outward tilt of the gravity retaining wall from Figure 2 as follows:

a. Enter the plot with the ratio Mo/Mu computed by dividing the dynamic overturning moment obtained in step III by the ultimate resisting moment obtained in step VII. Obtain from the plot the ratio $\theta/\theta_o$.

b. Compute the peak outward wall tilt by multiplying the ratio $\theta/\theta_o$ by the outward wall tilt which corresponds to initial uplift condition obtained in step VI.

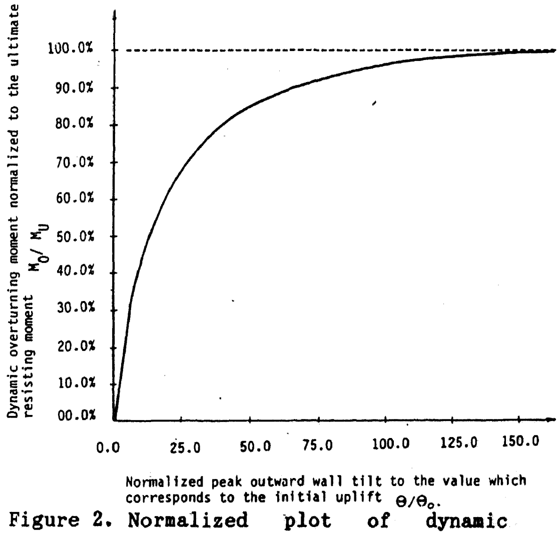

**Figure 2. Normalized plot of dynamic overturning moment to the ultimate resisting moment versus peak outward wall tilt to the value which corresponds to the initial uplift.**

IX. Compute the permanent outward tilt of the gravity retaining wall as the multiplication of a reduction factor (given by Figure 3) by the peak outward tilt computed in step VIII.

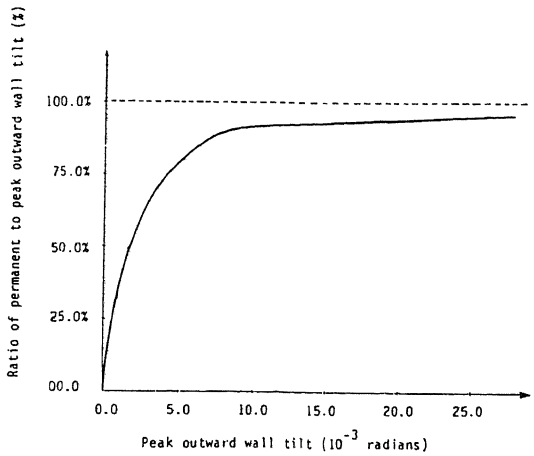

Figure 3. Ratio of permanent outward wall tilt to peak value versus peak outward wall tilt as obtained from the analysis in this study.

## 8 CONCLUSIONS

On the basis of the results and discussions of the current study, the following conclusions can be made:

1. An analytical model is developed in this study to analyze the seismic response of gravity walls retaining and founded on dry sand, with special emphasis on tilting behavior. The model considers all aspects of the dynamic gravity retaining wall problem. The model is verified by comparing predictions to measurements from three "Prototype" dynamic centrifuge tests on a tilting gravity retaining wall, with satisfactory agreement.
2. The results from the current study showed that the Seed-Whitman (1970) simplified formula for estimating the maximum dynamic earth force is conservative, while the Seed-Whitman (1970) recommendation for using an 0.6 H value above the base for the location of this force is close to that obtained from the analysis.
3. The proposed model is used in studying the dynamic response of an 8.0 m high and 3.0 m wide gravity retaining wall, subjected to sinusoidal and earthquake acceleration input motions. The results from the analysis showed that outward tilt of gravity walls is the dominant mode of response during dynamic shaking and that these walls end up with a permanent outward tilt at the end of shaking.
4. Based on the results from the analysis in this study an approximate practical method is suggested for evaluating the permanent outward tilt of gravity retaining walls during earthquakes.

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