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Displacement Based Design of Retaining Walls

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SYNOPSIS: A relatively simple rigid plastic model to study deformation behavior of rigid retaining wall is outlined. Both sliding and tilting modes of deformation are included. The study clearly reveals that wall movement caused by tilting can be substantial. But for high values of foundation soil friction angle, the tilting component of deformation can be omitted. Since the wall movement is affected by the characteristics (strength and frequency) of the excitation history, a number of excitation histories should be considered in retaining wall designs.

INTRODUCTION

Post earthquake damage reports give details of distortion and even collapse of superstructures such as bridges brought on by the failure of earth retaining structures. These damage accounts have been summarized by a number of researchers including Richard and Elms (1979), Ortiz (1982), and Whitman and Christian (1990). The main culprit in the failure of past retaining walls has been the loss of strength in the foundation soil coupled with substantially increased wall disturbing forces. Both components of disturbing forces, namely, the backfill thrust and wall inertia forces can be large enough to cause wall movement. The loss of strength in the foundation soil has been often associated with liquefaction. However, damage caused to retaining walls resting on non-liquefiable soils is also common. The paper presented here is limited to walls under such circumstances.

The current methods available for the design of rigid retaining wall can be divided broadly into either strength based or deformation based models. The strength based model is a pseudo-static method exemplified by Seed and Whitman (1970). The basic assumptions and limitations of this model have been described elsewhere (Seed and Whitman, 1970; Richard and Elms, 1979). Two major limitations of this method are (1) the lack of a rational basis for selecting seismic coefficients and (2) the inability of the model to provide any information on the displacement of the wall.

Richard and Elms (1979) proposed the displacement based approach for retaining wall. According to their rigid plastic model, the wall translates when the inertia force on the wall plus the total backfill thrust on the wall is more than the shear resistance at the base of the wall. On this basis, Richard and Elms proposed the design of retaining wall such that the wall displacement is within a specified limit. Unfortunately, only wall translation can be considered using this approach. However, past earthquake damage reports and laboratory observations readily indicate that the wall movement by rotation is also very common.

In the paper presented here, a displacement model that accounts for both sliding and tilting modes of deformation is outlined. The paper also presents results of a parametric study carried out using the proposed model. Finally, some conclusions are drawn relative to displacement based retaining wall design.

PROPOSED MODEL

The proposed model is similar to Richard-Elms model in the sense that the wall movement (in sliding and tilting) is assumed to occur only after the resisting forces or moments or both have been overcome. In other words, a rigid plastic behavior is assumed for the soil. When movement under passive condition caused by wall moving into the backfill is neglected, the wall progressively moves away from the backfill whenever the yield resistance is exceeded. This type of characterization of wall movement has been used in the model proposed by Siddharthan, et al., (1990 a, b). Since detailed description of this model is available elsewhere, only a brief outline is presented below.

The problem of deformation response of rigid retaining wall is statically indeterminate and nonlinear. In the proposed model, the wall translation and rotation about a point along the base (center of rotation) are selected as the unknowns (Fig. 1). The factors such as resistance against rotation offered by the foundation soil, moment of inertia of the wall and the disturbing moments depend on the point to rotation. Therefore the selection of center of rotation will affect the computed wall displacement. In the procedure proposed, the center of rotation is selected before starting the dynamic analysis and the sliding and rotation of the wall about this point are computed. From these results, the wall top displacement is

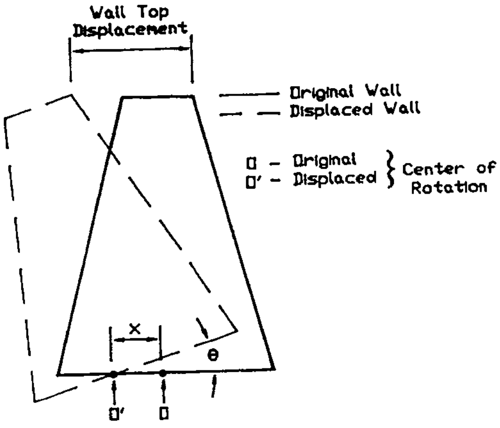

Fig. 2 Forces and Moments Acting on the Wall

evaluated as a function of time. By varying the location of the center of rotation along the base of the wall, a number of wall top displacement values at the end of the excitation are noted. The maximum wall top displacement at the end of the excitation is considered to be the design wall displacement.

Figure 2 shows a rigid retaining wall of height H subjected to base excitation. The ground accelerations $\ddot{X}_g(t)$ and $\ddot{Y}_g(t)$ are shown in the figure. Inertia forces have been applied according to d'Alembert's principle which permits the problem to be treated as a static problem. The response of the wall is given in terms of wall translation x (relative to the input excitation), and rotation, Θ about the center of rotation, O, which is located along the base of the wall. Here, CG is the center of gravity of the wall; R is the distance from O to the CG; I_{CG} is the mass moment of inertia of the wall about the CG; δ is the wall-backfill friction angle; α is the angle that the back of the wall makes with respect to the vertical; g is the acceleration due to gravity; W is the weight of the wall; and P_{AE} is the total backfill thrust on the wall. The base reaction is given in terms of the vertical and horizontal forces P_v and P_h and a moment of resistance, M_o. The passive resistance provided by the soil in front of the wall can be incorporated in the same manner as the lateral active wall thrust. For simplicity, the passive resistance is not included in the development of the equations.

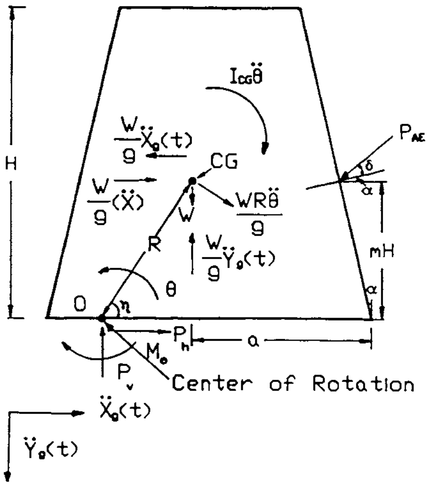

Fig. 1 A Simplified Model for Wall Displacement

After some algebraic manipulations, the dynamic equilibrium equations (or equations of motion) for the horizontal and vertical directions and the rotation about point O can be written as

$$\frac{W}{g}(\ddot{X}) + \left[\frac{W}{g}\,\frac{R\sin(\phi_b + \eta)}{\cos\phi_b}\right]\ddot{\Theta} = \frac{W}{g}\ddot{X}_g(t) + P_{AE}\cos(\alpha + \delta) - [W - W\ddot{Y}_g(t)/g + P_{AE}\sin(\alpha + \delta)]\tan\phi_b \tag{1}$$

and

$$\frac{W}{g}R\sin\eta(\ddot{X}) + \left(I_{CG} + \frac{WR^2}{g}\right)\ddot{\Theta} = \frac{W}{g}R\sin\eta\ddot{X}_g(t) - \frac{W}{g}[g - \ddot{Y}_g(t)]R\cos\eta + P_{AE}(mH)\cos(\alpha + \delta) - P_{AE}\sin(\alpha + \delta)[R\cos\eta + a - mH\tan\alpha] - M_{yo} \tag{2}$$

in which a is the horizontal distance between the CG and the heel of the wall η is the angle that the line joining O and CG makes with the horizontal (Figure 2). ϕ_b is the friction angle at the interface between the wall base and foundation soil, M_{yo} is the yield moment of resistance, and mH is the location of the line of action of the backfill thrust from the base.

It should be noted that equation 1, which is the equation of motion for the horizontal direction, can be uncoupled by omitting the second term (rotational term) from the left side of the equation. This uncoupled equation is identical to the equation used by Richard and Elms (1979). On the other hand, when the first term (sliding) from the left side of equation 2 is omitted, one gets the uncoupled equation for rotation about point O (the center of rotation). Equations 1 and 2 are coupled equation for $\ddot{X}$ and $\ddot{\Theta}$. The procedure used to solve for $\ddot{X}$ and $\ddot{\Theta}$ are presented elsewhere (Siddharthan 1990 a,b).

One of the input parameters in equation (2) is M_{yo}. Using a strip foundation model resting on Winkler springs Siddharthan, et al. (1990b), showed that M_{yo} can be written as:

$$M_{yo} = \frac{1}{6q_{ult}}(4P_v - q_{ult}B)(q_{ult}B - P_v) - P_vd \quad \text{for} \quad P_v \geq \frac{q_{ult}B}{2} \tag{3a}$$

and

$$M_{yo} = \frac{P_v}{6}\left(3B - \frac{4P_v}{q_{ult}}\right) - P_vd \quad \text{for} \quad P_v < \frac{q_{ult}B}{2} \tag{3b}$$

in which d is the distance from the center of base to the center of rotation and q_{ult} is the ultimate bearing capacity. For this value of M_{yo}, both ultimate bearing pressure and lift off conditions have been reached at the base of the foundation. If M_{yo} computed by equation 3 is negative, M_{yo} is set to zero.

Equation (3) implies that M_{yo} is a function of P_v and q_{ult}. Both P_v and q_{ult} vary with time during the excitation and they depend upon the wall inertia forces. Under these circumstances, the solution to equation 2 requires an iterative procedure. A solution for this equation is achieved when the initial guess and the computed (after solution) values of M_{yo} and $\ddot{\theta}$ are within a few percent.

APPLICATION OF THE MODEL

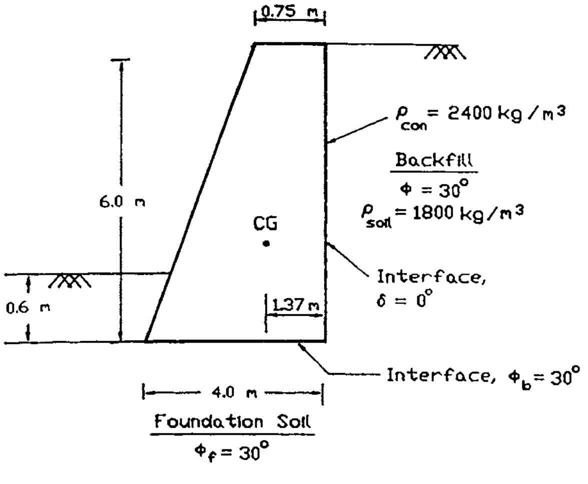

Fig. 3 Retaining Wall Used in the Study

Figure 3 shows a rigid retaining wall that was used in the study. The wall is 6m in height and has a base width of 4.0m. The height of soil in front of the wall is 0.6m. Both the backfill and foundation soil are assumed to have a friction angle of 30°, the backfill-wall interface was assumed to be smooth. The static factors of safety of the wall against sliding along the base and tilting about the toe assuming full mobilization of active (backfill) and passive conditions, are 1.9 and 4.2 respectively. In the first part of the study, 1940 El Centro earthquake motion (N-S component) scaled to 0.1g was used as the input motion. The vertical component of the motion was also scaled by the scale factor used for the horizontal component.

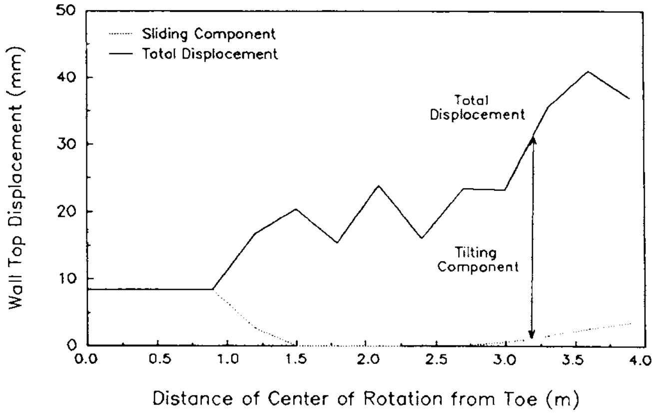

Fig. 4 Components of Wall Displacement

Figure 4 shows the wall top displacement as a function of the location of the center of rotation computed using the model. The total wall top displacement is computed as the sum of the sliding component (x) and the tilting component (Htanθ). Both of these components are shown in the figure. A number of observations can be made on the basis of the Figure 4. Firstly, the selection of the center of rotation can affect the wall top movement substantially. If the center of rotation is located less than 0.7m from the toe, only sliding wall top displacement is present. But as the center of location is located further from the toe, total wall top displacement increases to 42mm. The contributing mode of deformation is tilting. The maximum wall top displacement occurs when the center of rotation is located at 3.6m from the toe.

To investigate the influence of the vertical component of excitation, the wall top displacement was computed using both horizontal components of 1940 El Centro earthquake with and without the vertical component of acceleration. The wall top displacement history obtained with these excitations are presented in Figure 5. Only the time histories of the maximum wall top displacement obtained with the model and plotted. It may be noted that the wall movement with East-West component of excitation is much greater than with North-South component. The vertical excitation in the analysis increases the wall movement in the case of East-West component, while its influence in the case of North-South component is negligible. The direction of the wall inertia force due to the vertical acceleration during wall movement can act as a destabilizing force causing an increase in wall movement.

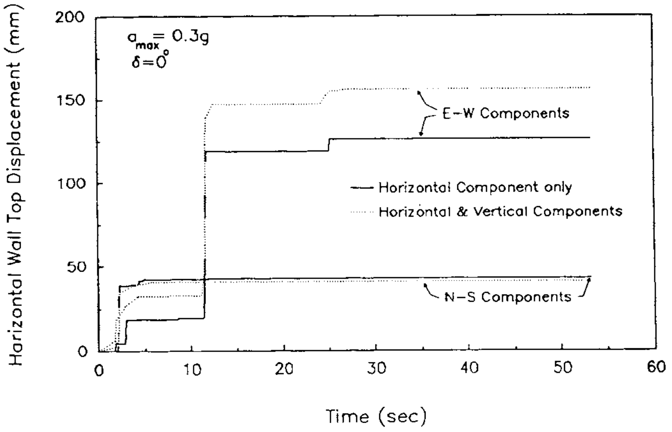

Fig. 5 Wall Top Displacement for 1940 El Centro Excitations

The influence of the foundation soil friction angle, ϕ_f is shown in Figure 6. All wall and soil properties except, the ϕ_f were assigned the previous values. The wall top displacement computed with the model, along with those obtained with Richard-Elms model are shown. Since the Richard-Elms model assumes sliding mode of deformation only, the results are unaffected by ϕ_f. However, the results given by the proposed model are substantially affected. Since the increase in ϕ_f results in an increase in q_{ult}, the yielding movement M_{yo} also is increased. When ϕ_f exceeds 35^o, the wall top displacement due to tilting disappears and only sliding component of deformation is present.

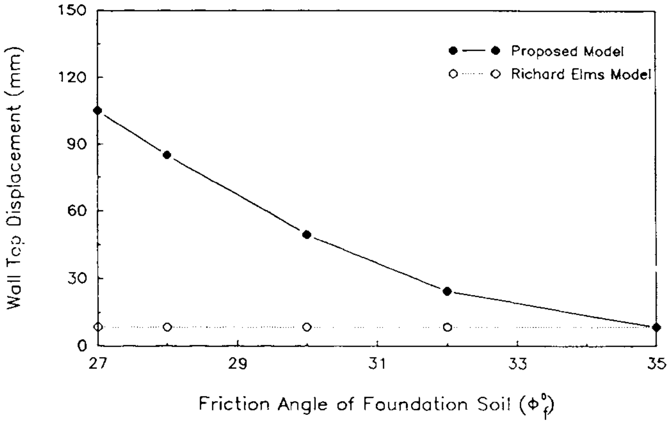

Fig. 6 Influence of Foundation Soil Friction Angle

Figure 7, shows the wall top displacement computed using the model for five earthquake excitations. These excitation histories were selected from earthquakes with magnitude varying in the range 6.4 to 7. The wall and soil properties used are shown in Figure 3. Table 1 gives details about the earthquakes. These earthquake excitations are considered to be representative of excitations caused by moderate to large earthquakes. Since there are two horizontal components for each earthquake, in essence there are ten horizontal excitation histories. All horizontal excitation histories were scaled to 0.3g and the same scale factor was used to scale the vertical acceleration histories.

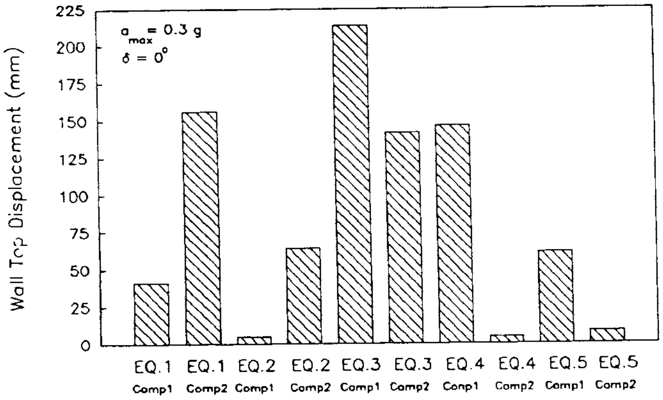

Fig. 7 Wall Displacement for Five Earthquake Records

The largest wall movement of 212mm was computed with the N11^{o}W component of the 1954 Eureka earthquake record. It may be noted that even though the horizontal earthquake motions were scaled to a constant value, the wall displacement is substantially affected by the excitation history. This is true mainly because the

Table 1: Description of Earthquakes Used

Earthquake Information

Earth- quake #	File Reference	Recording Station and Year	Component	Richter Magnitude
1	2A001*	Imperial Valley (1940)	S 00° E S 90° W Vertical	Mw = 7.0 ML = 6.4 Ms = 7.1
2	2B040*	Borrego Mountain (1968)	N 33° E N 57° W Vertical	Mw = 6.7 ML = 6.7 Ms = 6.7
3	2C041*	San Fernando (1971)	S 16° E S 74° W Vertical	Mw = 6.6 ML = 6.4 Ms = 6.6
4	2A008*	Eureka (1954)	N 11° W N 79° E Vertical	ML = 6.6
5	SMR20425	San Marcos, Mexico (1989)	E-W N-S Vertical	Mw = 6.8 Ms = 6.9
6	CPDR0425	Cerro de Piedra, Mexico (1989)	E-W N-S Vertical	Mw = 6.8 Ms = 6.9

* California Institute of Technology, Vol. 2 Record Identification Number

frequency components of the excitations are quite different. Since it is known that the frequency components of a record are affected by the location of the site with respect to the fault rupture and also by the media through which the waves travel through, care should be taken in selecting design earthquake excitation histories for retaining wall design.

CONCLUSIONS

The paper outlines a relatively simple rigid plastic model for predicting the seismic displacements of rigid retaining walls supporting and resting on dry cohesionless soils. The retaining wall deformation response is evaluated in terms of sliding and tilting deformations in a coupled manner.

A parametric study using the proposed method reveals that the selection of the center of rotation can substantially affect the wall response. If the center of rotation is assumed to be located near the toe of the wall, only the sliding mode of deformation is present. However, when the center of location is away from the toe of the wall, tilting mode of deformation is also present. The largest horizontal displacement is computed when the center of rotation is located close to the heel of the wall. The vertical acceleration component may be important since it can sometimes lead to larger wall displacement.

When the foundation soil friction angle is increased, the wall displacement due to tilting decreases and only sliding component of displacement is present above 35° for the wall considered in the study. The wall movement was also found to be strongly dependant upon the characteristics of excitation history (strength and frequency), indicating that a number design excitation histories should be considered in the design.

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