Modified Two Wedge Failure Mechanisms for Reinforced Soil Walls

Jayasree, P.K.  Rajagopal, K. Joy, Sibi
Senior Lecturer, Professor and Head Postgraduate Student
e-mail: jayasreepk@yahoo.com e-mail: gopalkr@iitm.ac.in e-mail: joy.sibi@gmail.com
Department of Civil Engineering, College of Engineering, Thiruvananthapuram
Department of Civil Engineering, IIT Madras, Chennai

ABSTRACT

The contribution of the wall facing to the stability of reinforced soil retaining walls is not accounted for in the current design methods. Design calculations for the dynamic lateral earth pressure on a retaining wall, which use a pseudo-static approach, assume that the backfill experiences a uniform acceleration throughout. This accounts for the dynamic nature of earthquake loading in an approximate way. The pseudo dynamic method overcomes these limitations by accounting the phase difference and amplification effects within the backfill. This method is more realistic and gives the non-linear seismic active earth pressure distribution behind the retaining wall. Hence, the pseudo dynamic analysis is used in this work to develop the design criteria of reinforced soil walls considering the facing effects. The two-wedge failure mechanism theory for seismic analysis of reinforced soil retaining walls considering the facing effect was modified incorporating the pseudo dynamic approach.

1. INTRODUCTION

The use of reinforced soil retaining structures has increased immensely, throughout the world especially in seismic prone areas. The present accepted method of analysis of reinforced soil retaining walls under seismic loading is the pseudo-static method of analysis in which the dynamic effect of seismic loading is accounted by seismic acceleration coefficients.

The recently developed pseudo-dynamic method of analysis considers the dynamic nature of seismic force and is a more sensible approach for the analysis of reinforced soil structures subjected to seismic loading. A worldwide-accepted standard analysis and design procedure for reinforced soil retaining walls under dynamic loading is yet to be developed. For determining the seismic forces induced due to earthquake different methods were proposed and developed by scientists. The contribution of facing towards the stability of the reinforced retaining wall is an emerging aspect and not much study has been done in this field.

The current design methods do not account for the contribution of wall facing to the stability of geosynthetic-reinforced retaining walls. A facing is constructed to prevent soil erosion at the face of a retaining wall. A more efficient design can be obtained by including the contribution of facing in the stability calculations of the wall. The stability of a geosynthetic reinforced wall is highly dependent of the type of facing system, the care with which it is designed and constructed, and the ability of the wall to safely transform the stresses from the soil to the facing element. Tatsuoka (1993) stated that full-height precast or cast-in-place concrete facings have increased the stability of geosynthetic reinforced walls. Tatsuoka (1993) proposed the two-wedge failure mechanism method of analysis to consider the effect of facing rigidity on stability. Ismeik & Guler (1998) examined the results of a seismic stability analysis of geosynthetic reinforced walls subjected to different seismic loading conditions. The effect of wall facing thickness on stability was investigated for a full height concrete facing by using the two-wedge failure mechanism. An analytical method was developed to correlate the effect of facing thickness with the amount of geosynthetic reinforcement required using the pseudo-static approach.

Huang & Wu (2007) found out that the extent of the facing’s contribution to the stability and displacement of the wall is influenced by factors other than those related to the facing itself such as, internal frictional angle of backfill soils and the length of the reinforcing layers. Nimbalkar & Chowdhury (2008) used the pseudo dynamic approach for the determination of lateral earth pressure considering the facing rigidity as one of the factors.

In this paper the modifications done in the two wedge failure mechanism theory for seismic analysis of reinforced
soil retaining walls by considering the facing effect and by adopting the pseudo dynamic approach are discussed.

2. TWO WEDGE FAILURE MECHANISM THEORY

The two-wedge failure mechanism shown in Figure 1 has been adopted to analyse geosynthetic reinforced retaining walls which is explained by Ismeik & Guler (1998). Considering the equilibrium of wedge 1 and resolving the forces acting on wedge 1 parallel and perpendicular to the lower side of the wedge, the total geosynthetic reinforcement force in wedge 1 is obtained as:

\[
T_{1r} = \frac{(W_1 + q_1 - C_{1z}) (\tan \alpha_1 - \tan \phi) + (U_1 \tan \phi - C_1)}{1 + \tan \alpha_1 \tan \phi} \tag{1}
\]

Similarly considering the equilibrium of wedge 2 and resolving the forces acting on wedge 2 parallel and perpendicular to the wedge, the geosynthetic reinforcement force in wedge 2 is obtained as:

\[
T_{2r} = \frac{(W_2 + q_2 + C_{2z} - V)(\tan \alpha_2 - \lambda_2 \tan \phi) + (U_2 \tan \phi - C_2)}{1 + \lambda_2 \tan \alpha_2 \tan \phi} \tag{2}
\]

where \(T_{total} = T_{1r} + T_{2r} - P\) is the total force required to stabilize the wall when the facing contributes to the wall stability, \(T_{1r}\) and \(T_{2r}\) are the total sum of the geosynthetic reinforcement forces required to stabilize wedges 1 and 2, respectively, \(V\) is the shear force between the facing and the backfill, \(\alpha_1\) and \(\alpha_2\) are the angle at the base of wedges 1 and 2 with respect to the horizontal, respectively and \(P\) is the force contributed by the facing to the wall stability.

Non-dimensionalising, the tensile forces can be written in terms of the geometry factors as:

\[
\frac{T_{1r}}{0.5\gamma H^2} = \frac{\left(1 - \frac{Y}{H}\right)^2 (\tan \alpha_1 - \tan \phi)}{\tan \alpha_1 (1 + \tan \alpha_1 \tan \phi)} \tag{4}
\]

where \(g_{f1}\) and \(g_{f2}\) are the geometry factors defined as:

\[
g_{f1} = \left(\frac{X}{H}\right) \frac{Y}{H} + \left(1 - \frac{Y}{H}\right) \left[\frac{X}{H}\right] \tag{5}
\]

\[
g_{f2} = \left(\frac{Y}{H}\right) \frac{Y}{H} - \lambda_2 \tan \phi \tag{6}
\]

X is the x coordinate of the two wedge node, Y is the y coordinate of the two wedge node, \(\lambda_2\) is the coefficient of base sliding for soil over reinforcement.

Seismic Loading

The use of a continuous rigid facing was experimentally found to increase stability of a geosynthetic reinforced soil retaining wall. In the current study, the stability of a geosynthetic reinforced wall under seismic conditions was analysed. The pseudo-dynamic analysis was used to calculate the additional dynamic forces acting on wedges 1 and 2 and the facing. The additional horizontal seismic forces acting on the facing and wedge 1 and 2 are obtained by the pseudo-dynamic method for calculation of seismic forces. They are denoted as \(Q_{df} , Q_{h1}\) and \(Q_{h2}\) respectively. Using the pseudo-dynamic approach, the horizontal seismic forces acting on the facing and wedge 1 and 2 were obtained by considering each wedge separately and integrating the product of mass and acceleration over the height of the wedge.

For a sinusoidal shaking, acceleration at depth \(z\) and time \(t\) is given by,

\[
A_h(z, t) = k_h g \sin \omega \left( t - \frac{H - z}{V_s} \right) \tag{8}
\]

where \(V_s\) the shear wave velocity \(V_s = \sqrt{\frac{G}{\rho}}\), where \(\bar{n}\) is the density of backfill soil. In the present study, the shear wave velocity is assumed to act within the soil media due to earthquake loading. Also, it is assumed that \(\omega\) is the angular frequency of base shaking which is equal to \(2\alpha f / T\), where \(T\) is the period of lateral shaking. For most geotechnical structures \(T = 0.3\) s is a reasonable value (Nimbalkar et al., 2006 and Ghosh, 2008).

For wedge 1 the horizontal seismic inertial force is obtained as
and is the angle at the base of wedges 1 with respect to the horizontal. Figure 2 shows the plot between the reinforcement force coefficient $K$ and facing thickness to wall height for different values of horizontal seismic acceleration coefficient, $k_s$. As the value of horizontal seismic acceleration coefficient, $k_s$, increases from 0 to 0.5 there is an increase in the reinforcement force coefficient.

4. RESULTS AND DISCUSSION

The force coefficient $K$ is evaluated according to the geometric design and the assumed loading conditions where a wider range of seismic loading conditions were taken into account with different wall thickness. This was achieved by optimizing the force coefficient using the optimizing tool Solver in MS Office Excel for each case.

The analysis was carried out for facing thickness ratios, $L_w / H$, varying from 0 to 0.25. The failure wedge angle of wedge 1, $\alpha_1$ was varied from 10 to 80. The normalised $X$ coordinate was varied from 0.1 to 0.9. The normalised $Y$ coordinate was varied from 0 to 5.

Effect of Horizontal Seismic Acceleration Coefficient

Figure 2 shows the plot between the reinforcement force coefficient $K$ and facing thickness to wall height for different values of horizontal seismic acceleration coefficient, $k_s$. As the value of horizontal seismic acceleration coefficient, $k_s$, increases from 0 to 0.5 there is an increase in the reinforcement force coefficient.

![Fig. 2: Results of Seismic Stability Analysis for Different Value of a Horizontal Seismic Acceleration Coefficient, $k_s$.](image-url)
During static condition, the reinforcement force coefficient $K$ decreases by 71% as it increases from 0 to 0.25. During a mild earthquake when the horizontal seismic acceleration coefficient, $k_h$ value 0.1, the reinforcement force coefficient $K$ decreases by 62% as it increases from 0 to 0.25. Even under very intense earthquake for horizontal seismic acceleration coefficient, $k_h$ value 0.5 the reinforcement force coefficient $K$ decreases by 38% as the wall thickness increases from 0 to 0.25. Hence as the thickness of the wall increases the reinforcement force coefficient is reduced even under very intense magnitude of earthquake.

**Effect of Friction between the Facing and Foundation**

The friction between the facing and foundation was varied from $\delta_f = 0$ to $\delta_f = \phi$ and the plot between the reinforcement force coefficient $K$ and facing thickness to wall height was plotted as shown in Figure 3. As the value of friction between the facing and foundation increased from $\delta_f = 0$ to $\delta_f = \phi$, the reinforcement force $K$ decreases by 97% for a $L_w/H$ value of 0.2.

![Figure 3: Results of Seismic Stability Analysis for Different Value of Friction Between the Facing and the Foundation](image)

For a smooth wall it is observed that the thickness of the wall increases there is no decrease in the reinforcement force coefficient. But for a friction angle between the facing and foundation, $\delta_f = 1/3 \phi$, the reinforcement force coefficient decreases by 21% as the $L_w/H$ increases from 0 to 0.25. But for a higher friction angle between the facing and foundation, $\delta_f = \phi$, the reinforcement force coefficient decreases by 97% as the $L_w/H$ increases from 0 to 0.25.

5. **CONCLUSIONS**

The effect of facing rigidity was studied by modifying the two wedge failure mechanism theory and by incorporating the pseudo-dynamic nature of earthquake.

The maximum value of the force was obtained by optimizing the force coefficient by varying the geometry using the optimizing tool solver in MS office excel. As the wall friction angle increases the reinforcement force decreases with the increase in thickness of the wall. For a wall friction angle, $\delta = \phi$, the reinforcement force $K$ decreases by 74% as the $L_w/H$ increases from 0 to 0.25. with an increase in friction between the facing and foundation, the reinforcement force decreases with an increasing thickness of the facing. For a higher friction angle between the facing and foundation, $\delta_f = \phi$, the reinforcement force coefficient decreases by 97% as the $L_w/H$ increases from 0 to 0.25.

**REFERENCES**


