Permanent Displacement Based Seismic Design Chart for Cantilever Retaining Walls

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Abstract. The primary aim of this paper is to suggest a suitable design procedure using a seismic sliding displacement based chart for the design of cantilever retaining walls. Permanent displacement based design chart have been proposed by Franklin and Chang for slopes and have been used by Richards and Elms for the seismic design of gravity retaining walls. Engineers have been using the same chart for seismic design of cantilever retaining wall without understanding the implications of such considerations and hence may result in unreliable design. The suitability of design procedure to be adopted would depend upon its closeness with the actual mechanism taking place. Experimental investigations have witnessed the formation of a V-shaped wedge in the backfill of cantilever retaining walls. The Double wedge model computes displacements considering the formation of this wedge and its relative movement with the wall during seismic loading. The upper bound curve has been developed on the basis of Double wedge model by analyzing 153 earthquakes for four different heel-length to height ratio and compared with Franklin and Chang's chart. The procedure followed for the development of this chart has been explained in the paper. This study has been performed to understand the suitability of Franklin and Chang's chart for the design of cantilever retaining walls. A suitable design procedure has been suggested on the basis of the V-shaped mechanism for the seismic design of cantilever retaining wall.

Keywords: Design chart · Permanent sliding displacement
Cantilever retaining walls · Double wedge model · V-shaped wedge
Seismic loading

1 Introduction

Seismic design philosophies are gaining confidence in the direction of deformation based approach as failure can be measured in terms of displacements. Newmark's sliding block model [1] has been widely used to compute the permanent displacements for slopes. Franklin and Chang analyzed 169 earthquake motions using Newmark's sliding block theory with unsymmetrical resistance for earth fill dams and have proposed a design chart to be used by engineers [2]. Richards and Elms [3] proposed methodology for the seismic design of gravity retaining walls on the basis of Franklin and Chang's chart. According to their design philosophy, yield acceleration of wall to be designed can be obtained from the chart for the allowable displacements. This yield acceleration

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can be used to compute the required weight of wall using pseudostatic force equilibrium equations. The pseudostatic forces are computed according to the M-O theory which considers equilibrium of V-shaped wedge, exerting thrust on the predefined back face of gravity retaining wall. However, the applicability of Franklin and Chang's chart for cantilever retaining walls is yet to be established. There is a need to understand if the existing charts can be used directly for the design of cantilever retaining walls. In order to use such charts reliably, one needs to consider a suitable mechanism that can occur in the backfill. There is an ambiguity regarding what mechanism to be taken place for the design of cantilever retaining walls. Some of the current design philosophies suggest to adopt ad hoc arrangement wherein soil above the heel is considered to be a part of the wall and analyze cantilever retaining walls as gravity retaining walls [4–8]. The implications of this assumption may result in the over-conservative design of cantilever retaining walls. Experimental investigations for cantilever retaining walls have shown that there is a formation of inverted V-shaped rupture planes in the backfill [9, 10]. A Double wedge model has been proposed which simulates the formation of these rupture planes and computes yield acceleration and hence displacements separately for the wall and sliding soil wedge considering its relative movement with respect to the wall [11]. Seismic design procedure has been proposed on the basis of formation of the V-shaped wedge in the backfill for cantilever retaining walls.

2 Double Wedge Model

Double wedge model has been proposed by Jadhav and Prashant [11] to compute seismic sliding displacements of a cantilever retaining wall. This model computes dynamic yield accelerations for wall and soil wedge separately. The computed yield accelerations depend not only on the geometry and soil properties but also on the ground acceleration at that time instant. During ground motion, two rupture planes, AB and BC as shown in Fig. 1 would be developed from the heel of the wall.

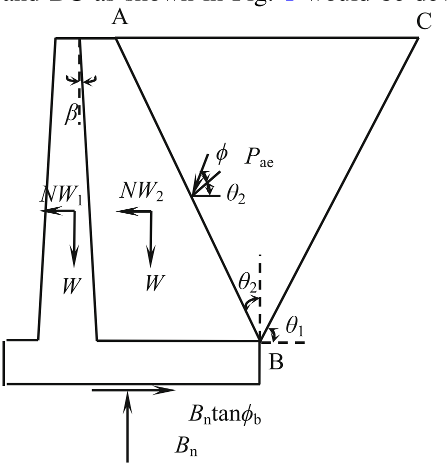

Fig. 1. Schematic diagram showing outer rupture plane not intersecting wall

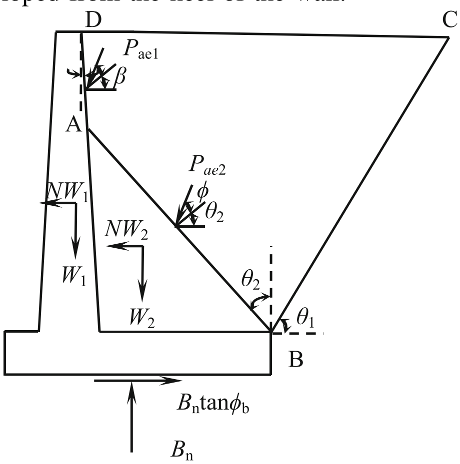

Fig. 2. Schematic diagram showing outer rupture plane intersecting wall

The inner rupture plane BC would develop from the heel towards the backfill and the outer rupture plane AB would develop from the heel towards the back face of the wall. The critical angles of inclination of rupture planes are determined at which the wall has minimum yield acceleration. The model computes displacement for two cases, i.e., when the outer rupture plane does not intersect the back face of the wall as shown in Fig. 1 and the other when this plane intersects the back face of the wall as shown in Fig. 2. The formulation has been accordingly developed to compute the yield acceleration of wall. The model assumes that the developed soil wedge slides tangentially with respect to the wall with locked soil mass along AB as shown in Figs. 1 and 2, and it remains in contact with it throughout the motion. The model ensures both acceleration and velocity compatibility to be maintained during the motion. Double wedge model has been validated for centrifuge tests performed by Sitar et al. [12, 13] at UC Davis on a geometry of wall subjected to Takatori, Kobe earthquake motion [14] shown in Fig. 3. The rigid body translation measured was 0.0165 m for the considered geometry and PGA 0.64 g. The Double wedge model estimated 0.018 m which is quite close to the measured value thus imparting enough confidence on the Double wedge model.

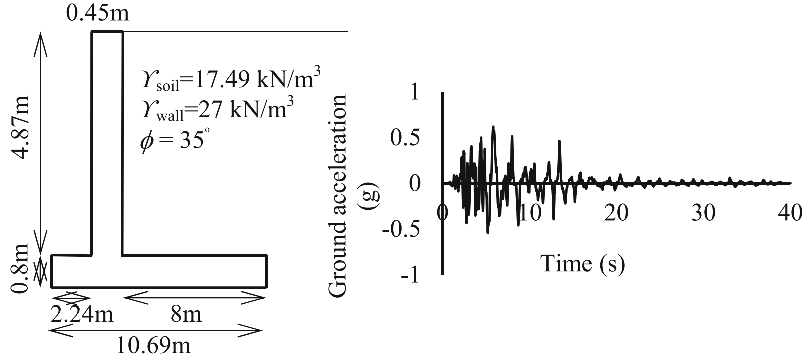

Fig. 3. Geometry of wall and ground motion used in case study

2.1 Verification of the Earthquake Data Used for Developing Franklin and Chang's Chart

The upper bound envelope using Newmark's sliding block has been redeveloped in this study. This chart predicts the displacements computed using Newmark's sliding block theory for a *N/A* value wherein, *N* represents yield acceleration, and *A* represents expected PGA at the site. The yield acceleration considered in the chart is computed at the factor of safety with respect to sliding equal to one which is a function of geometry and soil properties and hence remains constant throughout the ground motion. This exercise has been performed to gain confidence in the earthquake data to be used for the development of curve using Double wedge model which would be compared with Franklin and Chang's [2] curves. It was possible to obtain 153 earthquakes data from PEER [13] out of 169 earthquakes used by Franklin and Chang. All the ground motion accelerations have been scaled to 0.5 g, and computed displacements have been scaled with respect to scaling velocity of 0.762 m/s. The displacement curves from Franklin and Chang have been digitized to get the data points for comparison. The digitized curves and the computed upper bound envelope have been plotted in Fig. 4, which showed a good match for 153 earthquakes.

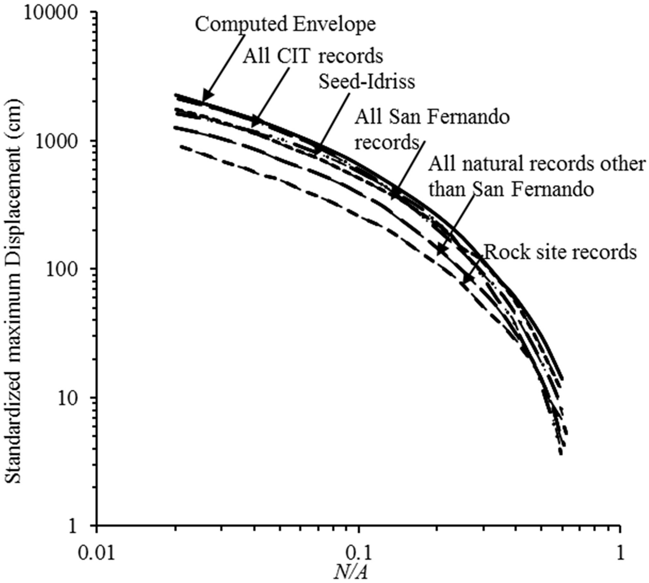

Fig. 4. Comparison of obtained curve with Franklin and Chang's upper bound curves

2.2 Methodology to Develop Design Chart Using Double Wedge Model for Cantilever Retaining Walls

A design chart has been developed for cantilever retaining walls using Double wedge model. The implementation of Double wedge model involves two-step calculation of yield acceleration. The first step involves computation of cutoff yield acceleration, *N* which is a function of geometry and soil properties only. During ground motion, if this cutoff yield acceleration is exceeded, dynamic yield acceleration of wall which is a function of ground acceleration at that time instant, is computed. If dynamic yield acceleration coefficient is also exceeded, then corresponding velocity and displacement of the wall is computed. As dynamic yield acceleration would vary at each time instant, the chart has been developed for different cutoff yield acceleration coefficient values but displacements have been computed only when the dynamic yield acceleration is exceeded. This assumption is in convergent with the physical situation, wherein, the wall-soil wedge would not undergo any movement, unless the cutoff yield acceleration is exceeded. Once cutoff yield acceleration is exceeded, the system would undergo displacements with respect to the dynamic yield acceleration of wall. In this paper, 12 m height, *H*, of the wall and four different heel lengths, *L*, viz., 3 m, 4 m, 4.5 m and 6 m, supporting a backfill with friction angle 30° and unit weight 16.67 kN/m^3 have been considered. These configurations with *L*/*H* ratios 0.25, 0.33, 0.375 and 0.5 have been considered with an idea that there would be significant change in the developed mechanism and hence the magnitude of displacements with different *L*/*H* ratios. Following steps have been executed for developing chart.

Step 1: Consider *N*/*A* values same as Franklin and Chang chart, where *N* is the cutoff yield acceleration coefficient, and *A* is the scaled peak ground acceleration value which has been considered as 0.5 g. Using *N*/A values from the chart and *A* as 0.5 g, the values of *N* have been computed.

Step 2: Compute pseudostatic earth pressure force using *N* at different values of inclination of outer rupture plane, θ_2 using M-O equation. The maximum value of pseudostatic earth pressure force, P_{ae} and the corresponding value of θ_2 has been chosen for further calculations as shown in Fig. 5.

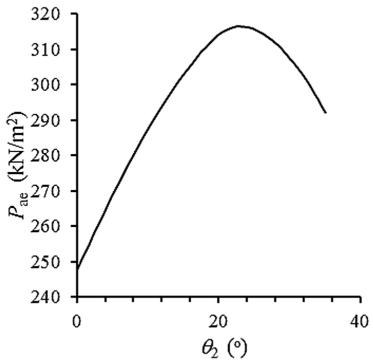

Fig. 5. Variation of lateral earth pressure force with inclination of outer rupture plane

Step 3: The weight of wall, W_1 has been computed by solving the equilibrium equation for both the cases when outer rupture plane is not intersecting and intersecting the back face of the wall as shown in Figs. 1 and 2. The Eqs. (1) and (2) have been derived to compute the weight of wall, W_1 using pseudostatic earth pressure force and inclination for outer rupture plane from step 2 for outer rupture not interesting and intersecting wall respectively. In these equations, β represents the inclination of back face of the wall and W_2 represents the weight of locked soil mass which can be calculated from the geometry. ϕ and ϕ_b represent friction angles for backfill soil and foundation soil respectively, and δ represents interface friction angle between wall and soil. δ and ϕ_b have been considered two-third ϕ in this analysis.

$$W_1 = \frac{P_{ae}(\cos(\delta+\beta) - sin(\delta+\beta)tan(\emptyset_b))}{(tan(\emptyset_b) - N)} - W_2 \tag{1}$$

$$W_1 = \frac{P_{ae1} K_1 + P_{ae2} K_2}{N - tan_b} - W_2 \tag{2}$$

$$K_1 = sin(\delta + \beta)tan\phi_b - cos(\delta + \beta)$$

$$K_2 = \sin(\phi + \theta_2)tan\phi_b - cos(\phi + \theta_2)$$

Step 4: Compute seismic sliding displacement for cantilever retaining walls using the obtained values of weight of wall following the steps in Double wedge model [11] for different *N*/*A* values. According to the formulation in Double wedge model, dynamic yield accelerations are obtained for wall and soil wedge for critical wedge by iterating the inclination of rupture planes. The displacements are computed only when the yield acceleration of wall is exceeded by the considered ground motion at that instant by using numerical integration. These steps have been repeated for 153 different earthquakes, and the upper bound curve has been plotted for four *L*/*H* ratios as shown in Fig. 6. The upper bound curve for Franklin and Chang has also been plotted in Fig. 6 with the curve for cantilever retaining walls on the log-log scale and normal scale to understand the difference in magnitudes of displacement.

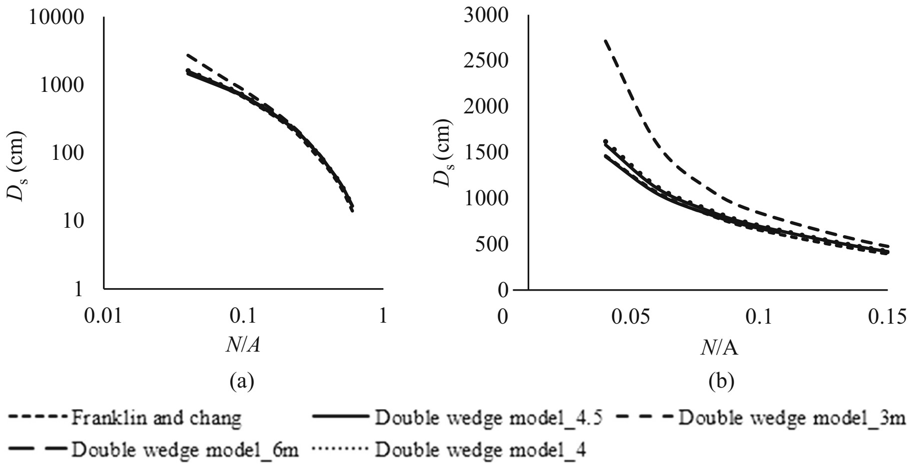

Fig. 6. Upper bound curves representing standardized maximum displacement, D_s versus *N*/*A* ratio obtained from Double wedge model and Franklin and Chang in (a) log-log scale, and (b) normal scale

3 Results and Discussions

It can be observed that the displacements computed by Double wedge model for *L*/*H* ratio greater than 0.3 matches well with the displacements obtained from Franklin and Chang. The upper bound curve for lower *N*/*A* value shows significant variation for *L*/*H* ratio less than 0.3. This shows that wall with smaller *N/A* and lesser heel length is susceptible to undergo more sliding displacement than the wall with same *N/A* and greater heel length. With the decrease in heel length, the mechanism gets switched from case1 to case2 as shown in Figs. 1 and 2. When the outer rupture plane is not intersecting the back face of the wall, i.e., $L/H > 0.3$, the wall undergoes nearly same magnitude of displacement owing to the soil-soil friction angle ϕ along the outer rupture plane. For *L*/*H* less than 0.3, there is reduced wall-soil interface friction angle along the outer rupture plane which is in contact with wall thus resulting in an increased magnitude of displacements at lower *N/A*. At higher *N/A* values, which is quite uneconomical, the wall would undergo nearly same displacements irrespective of the heel length due to the sufficient resistance by the geometry of wall. Thus, Franklin and Chang's curve can be directly used for the estimation of sliding displacements for the wall geometries with *L*/*H* ratio greater than 0.3.

4 Suggested Design Procedure for Cantilever Retaining Walls

The upper bound curve for cantilever retaining walls with *L*/*H* ratio greater than 0.3 has been observed to match well with the Franklin and Chang's curve. The Franklin and Chang's curve with this limitation can be used directly for the design of cantilever retaining walls. Use of this chart in design would require assumption of suitable mechanism in the backfill. Owing to the experimental observations, formation of inverted V-shaped wedges has been assumed in this paper. Accordingly, following steps can be followed to compute the required weight of wall using the proposed chart.

- Estimate the maximum seismic sliding displacement that the wall would be allowed to undergo during ground shaking. Consider height of the wall according to the site requirement and assume heel length such that *L*/*H* greater than 0.3.
- Depending upon the site location, estimate a suitable PGA for the ground motion.
- Determine the *N/A* ratio from the proposed chart for the corresponding expected displacement. Using the value chosen for PGA, determine the value of cutoff acceleration, *N*, for the wall.
- Compute the lateral earth pressure force values from the M-O equation using the obtained value of *N* for different values of θ_2. The value of earth pressure force and θ_2 at which earth pressure is maximum would be used for further calculations.
- Depending upon the value of θ_2, either of Eqs. (1) or (2) can be used to compute the required weight of the wall.
- If the weight of the considered geometry is greater than the required weight of the wall, then the geometry would undergo less than or equal to expected displacement. The charts are applicable to walls resting on soil with properties taken in the range of this study. The authors are further continuing to perform the required computations to improve the design recommendations.

5 Conclusion

The permanent displacement based seismic design chart has been developed for cantilever retaining walls for different heel-length to height ratio using Double wedge model. The developed chart can be used for walls with backfill properties lying in the range of this study. The upper bound curves for cantilever retaining walls matched closely with the Franklin and Chang's curve with $L/H > 0.3$ whereas the curve for $L/H < 0.3$ showed significant variation at lower N/A ratio. The proposed design procedure considers the formation of V-shaped mechanism in the backfill and is suitable for geometry with $L/H > 0.3$.

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