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Seismic displacement of gravity retaining walls

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Abstract Seismic displacement of gravity walls had been studied using conventional static methods for controlled displacement design. In this study plain strain numerical analysis is performed using Plaxis dynamic program where prescribed displacement is applied at the bottom boundary of the soil to simulate the applied seismic load. Constrained absorbent side boundaries are introduced to prevent any wave reflection. The studied soil is chosen dense granular sand and modeled as elasto-plastic material according to Mohr–Column criteria while the gravity wall is assumed elastic. By comparing the resulted seismic wall displacements calculated by numerical analysis for six historical ground motions with that calculated by the pseudo-static method, it is found that numerical seismic displacements are either equal to or greater than corresponding pseudo-static values. Permissible seismic wall displacement calculated by AASHTO can be used for empirical estimation of seismic displacement. It is also found that seismic wall displacement is directly proportional with the positive angle of inclination of the back surface of the wall, soil flexibility and with the earthquake maximum ground acceleration. Seismic wall sliding is dominant and rotation is negligible for rigid walls when the ratio between the wall height and the foundation width is less than 1.4, while for greater ratios the wall becomes more flexible and rotation (rocking) increases till the ratio reaches 1.8 where overturning is susceptible to take place. Cumulative seismic wall rotation increases with dynamic time and tends to be constant at the end of earthquake.

Introduction

Limit-state analysis method based on Pseudo-static approach is among several methods that have been used to study seismic stability of gravity retaining walls (Mononobe, and Matuo [1]; Okabe [2]; Choudhury et al. [3] and Ortigosa [4]).

Pseudo-dynamic approach has the capability of considering the dynamic nature of the earthquake loading in an approximate and simple manner compared with other methods. The phase difference and the amplification effects within the soil mass are considered along with the accelerations causing inertia forces (Steedman and Zeng [5]).

Closed form solutions using elastic or viscous elastic behavior analyzed the response of a rigid non-yielding wall retaining a homogeneous linear elastic soil and connected to a rigid base. For such conditions Veletsos and Younan [6] concluded that the dynamic amplification is insignificant for

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relatively low-frequency ground motions (that is, motions less than half of the natural frequency of the unconstrained backfill), which would include many or most earthquake problems.

Numerical analyses by finite element numerical model have been developed for gravity walls found on dry sand (Al-Homoud and Whitman [7]) using two-dimensional (2D) finite element computer code, FLEX. Dynamic analyses in FLEX are performed using an explicit time integration technique (Green and Ebeling [8]). Other numerical models have been developed using FLAC finite difference code.

Gazetas et al. [9] applied numerical models using the commercial finite-element package ABAQUS for two dimensional plane-strain conditions.

Displacement-based analysis considers the earthquake motion vibrates with the backfill soil, and the wall can easily move from the original position due to this earthquake motion. The methods available for displacement based analysis of retaining structures during seismic conditions are based on the early work of Newmark [10], and Kramer [11]. The basic procedure was developed for evaluating the deformation of an embankment dam shaken by earthquake based on the analogy of sliding block-on-a-plane. Richards and Elms [12] model proposed the basic Newmark's model, developed originally for evaluation of seismic slope stability and modified it for the design of gravity retaining walls.

Some guidelines for permissible displacement based on experience or judgment (Huang [13]) are used for the design of retaining walls which failed during earthquakes by sliding away from the backfill or due to combined action of sliding and rocking displacements.

The permissible horizontal displacement according to Eurocode [14] equals $300.a_{\max}$ (mm), while according to AASHTO [15] it equals $250.a_{\max}$ (mm), where $a_{\max}$ is the maximum horizontal design acceleration.

Wu and Prakash [16] predict that permissible horizontal displacement equals 0.02 H and the failure horizontal displacement equals 0.1 H, where H is the height of retaining wall.

JRA [17] suggested that the permissible differential settlement equals 0.1–0.2 m, and that the severe differential settlement $\geqslant$0.2 m (damage needing long term retrofit measures).

Rafnsson and Prakash [18] developed a model for a rigid wall resting on the foundation soil and subjected to a horizontal ground motion and analyzed the problem as a case of combined sliding and rocking vibrations including the effect of various important parameters such as soil stiffness in sliding, soil stiffness in rocking, geometrical damping in sliding, geometrical damping in rocking, material damping in sliding, and material damping in rocking. The cumulative displacement of retaining walls due to combined sliding and rocking for negative back slope of walls is smaller compared to the case of vertical face or positive back slope.

Wu [19] lists the cumulative displacements for gravity walls 4 m to 10 m high walls with a typical granular backfill subjected to 3 earthquakes. He found that for 8 m high wall and base width 4.6 m when subjected to El-Centro earthquake, it undergoes 0.135 m sliding, 0.286 m rocking with total combined displacement equals 0.42 m. The later value is greater than the permissible displacement 300 $a_{\max} = 0.349 \times 300$ - mm = 0.104 m according to the Eurocode.

Nadim [20], Nadim and Whitman [21] recommended determining the frequency ratio between fundamental ground motion (f) and fundamental frequency of backfill (f_1). If the ratio is less than 0.25, neglect the ground amplification, if the ratio is approximately 0.5, increase the peak acceleration by 25–30% and if the ratio is between 0.7 and 1.0, increase $a_{\max}$ and V (ground velocity) by 50%.

Based on the previous literature survey the objective of the present work is to carry out modified seismic numerical analysis for gravity retaining walls and comparing the resulted displacements with the corresponding values given by previous work, also to introduce an additional analysis for both active and limited passive earth pressure for the aim of reducing seismic wall displacement to be within the permissible values.

Pseudo-static analysis of gravity retaining walls

Fig. 1 shows a sketch for a trapezoidal gravity retaining wall of dimensions A, B and height H undergoing sliding and rocking displacement. The ground backfill is inclined by angle β. The back surface of the wall is inclined by angle θ with the vertical. The sliding is represented by the translation from point 1 to 1′ while rocking of the wall is represented by the inclination angle 'i' with the vertical.

Mononobe–Okabe developed the total static and dynamic active coefficient of earth pressure acting on rigid retaining walls

$$a_{max} = K_h\, g = \text{maximum ground acceleration} \tag{1}$$

K_h and K_v are coefficients of horizontal and vertical ground accelerations, $K_v = 0$ or half K_h.

$$\psi = \tan^{-1} \frac{K_h}{1 - K_v} \tag{2}$$

The total active static and dynamic pressure on the back surface of the wall is P_{AE}

$$P_{AE} = \frac{1}{2} K_{AE}\, H^2\, \gamma(1 - K_v) \tag{3}$$

$$K_{AE} = \frac{\cos^2(\phi - \theta - \psi)}{\cos\psi \cos^2\theta \cos(\delta + \theta + \psi)\left[1 + \sqrt{\frac{\sin(\delta+\emptyset)\sin(\emptyset-\beta-\psi)}{\cos(\delta+\theta+\psi)\cos(\beta-\theta)}}\right]^2} \tag{4}$$

$$\begin{aligned} a_y &= N \times g \\ &= \left[\tan\phi_b - \frac{P_{AE}\cos(\delta + \theta) - P_{AE}\sin(\delta + \theta)\tan\phi_b}{W}\right] g \end{aligned} \tag{5}$$

where: a_y = the critical or yield ground acceleration causing sliding of the wall

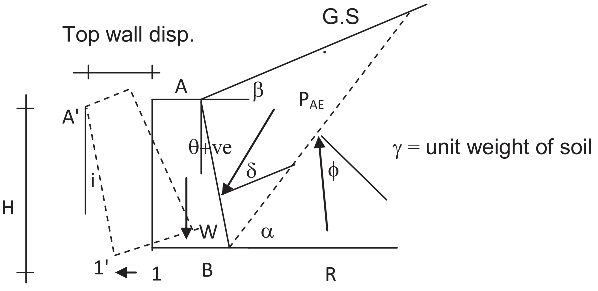

Fig. 1 Seismic displacement of gravity retaining wall.