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Seismic rotational stability of gravity retaining walls by modified pseudo-dynamic method

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ABSTRACTS

Seismic stability analysis is an important aspect for design of safe retaining walls in earthquake prone areas. In this study, limit equilibrium method is used for rotational stability analysis of gravity retaining wall on rigid foundation supporting dry cohesionless backfill with modified pseudo-dynamic seismic forces. Proposed method satisfies the zero stress boundary condition at free ground surface and considers the amplification of acceleration. Stability factor F_W is proposed to determine the safe weight of the retaining wall against rotational failure under seismic conditions. If the safe weight of the retaining wall is known under static condition then by simply multiplying that with F_W can give the safe weight of the retaining wall against rotational failure under seismic condition. Present study shows that wall-soil interaction in various seismic conditions may or may not be in-phase for the entire duration of the input motion. It depends on the properties of the backfill soil, properties of the wall material and also on the frequency content of the input motion. A modified rotating block method is proposed to obtain the rotational displacement under seismic conditions. Present results give higher values of rotational displacements of the wall when compared with the available results by pseudo-static analysis. Hence the present study may be used to design seismically stable retaining wall.

1. Introduction

Evaluation of seismic active earth pressure is integral part of retaining wall design in seismically active region. The most popular and widely used method for computation of seismic earth pressure is Mononobe-Okabe method [1]. Seed and Whitman [2] proposed a methodology for earth retaining structures by separating the static and dynamic component of total earth pressure. Seismic inertia force in both backfill soil and retaining wall was first considered by Richards and Elms [3] for sliding stability analysis. Caltabiano et al. [4] considered the effect of surcharge on the stability of retaining wall. Seismic displacements of retaining wall were reported by Huang [5]. Researchers had proposed a new method for back analysis of two retaining walls situated on slopes. Both the walls were severely damaged during the 1999 Chi-Chi earthquake. Based on experimental and analytical work Huang et al. [6] proposed a seismic displacement criterion for conventional soil retaining walls. Li et al. [7] determined the yield acceleration for translation failure of gravity retaining walls based on the upper bound theorem of limit analysis. The researchers had concluded that the wall roughness has remarkable influence on the yield acceleration. Caltabiano et al. [8] obtained the angle of the active slip surface, the critical acceleration coefficient and the coefficient of active earth pressure under seismic conditions for different surcharge configurations using limit equilibrium analysis. Recently, a new analytical model for sliding displacement of retaining wall was proposed by Conti et al. [9]. The researchers had assumed that the wall and the active soil wedge will act as two separate bodies. Comparison of the method with Newmark's sliding block theory showed higher values of sliding displacement.

Most of the researches considered pseudo-static seismic inertia force. Pseudo-static seismic inertia force is a very crude approximation. A pseudo-static based approach assumes that the maximum inertia

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Nomenclature

$a_h(z, t)$	Horizontal acceleration in the backfill at depth z and time t
b	b_w/H
b_w	Top width of the retaining wall
C_R, $C_{RD}(t)$	Static and seismic wall rotational factor
F_T, F_R, F_W	Soil active thrust, wall rotational and combined dynamic factor
$FSRD$	Dynamic factor of safety against rotation failure
f_a	Amplification factor
g	Acceleration due to gravity
G	Shear modulus
H	Height of retaining wall
I_c	Polar moment of inertia of the wall about centroid
K_a,$K_{ae}(t)$	Static and seismic active earth pressure coefficient
k_h	Seismic acceleration coefficient at the base
k_{hc}	Critical seismic acceleration coefficient at the base
$k_{h,g}$	Seismic acceleration coefficient at the ground surface
$P_{ae}(t)$	Seismic active thrust
$Q_{hs}(t)$, $Q_{hw}(t)$	Horizontal inertia forces in the active wedge and wall due to seismic acceleration
r_c	Radial distance between centroid and rotation center E
t	Time
t_s	Duration of input motion
T	Period of lateral shaking
V,V_s, V_{sw}	Shear wave velocity, shear wave velocity in the soil and wall respectively
W_w	Weight of the wall
$W_{w,static}$, $W_w(t)$	Weight of the wall required for equilibrium against rotation under static and seismic conditions
W_s	Weight of active soil wedge
z	Depth from the top of the backfill or wall
α	Rotational acceleration
α_f	Angle of inclination of failure plane with horizontal
β	Rotational velocity
γ_s	Shear strain
γ,γ_b,γ_w	Unit weight, unit weight of the backfill and wall material
ρ	Density
δ	Wall friction angle
τ	Shear stress
ϕ	Soil friction angle
θ	Wall inclination angle
ξ	Damping Ratio
ξ_s, ξ_w	Damping ratio of backfill and wall material
ω	Angular frequency of motion = $2\pi/T$
μ	Viscosity
η	Angle of inclination of radial distance between centroid and rotation center E with horizontal
ψ	Rotational displacement

force in wall and maximum seismic earth pressure are simultaneous. Nakamura [10] conducted a series of centrifuge model tests to re-examine this assumption. Based on these experimental results Nakamura [10] concluded that the maximum values of wall inertia and maximum value of seismic earth pressure do not occur simultaneously. Experimental results of Nakamura [10] were numerically validated by Athanasopoulos -Zekkos et al. [11]. Al-Atik and Sitar [12], using the results of centrifuge experiments on cantilever retaining walls in open channels, also suggested that design of retaining walls for maximum dynamic earth pressure increment and maximum wall inertia is overly conservative.

Steedman and Zeng [13] proposed a simple pseudo-dynamic method to consider vertically upward propagating wave. The method considers the propagation of shear waves behind a retaining wall under the active mode of failure. Choudhury and Nimbalkar [14] improved the solution by considering vertical acceleration. Using the proposed methodology sliding and rotational stability of retaining wall was studied for both active and passive cases [15–20] under dry condition. Baziar et al. [21] re-examined and rectified the expression of wall inertia forces proposed by Nimbalkar and Choudhury [16].

But pseudo-dynamic method lacks in certain aspects. For example, pseudo-dynamic method proposed by Steedman and Zeng [13] does not satisfy the boundary conditions [22–24]. And pseudo-dynamic method follows a simple approach to consider the acceleration amplification. In that approach one need to assume an amplification factor value and a linear variation of the acceleration is considered in the analysis. And pseudo-dynamic method in any form does not consider the damping properties of the retained fill.

Bellezza [23,25] solved the 1D wave equation assuming the dry homogeneous cohesionless backfill as Kelvin-Voigt solid to derive the acceleration distribution within the retained fill. The differential equation is solved using boundary conditions and the author showed that the acceleration distribution is non-linear in nature. Pain et al. [26] showed that the maximum active thrust from the backfill soil and maximum value of wall inertia force may or may not be simultaneous for sliding mode of failure. For the active condition, the researchers had assumed a planar failure surface.

All the approaches discussed previously are limit equilibrium based. Another approach of solving the retaining wall problem was proposed by Veletsos and Younan [27] which is popularly known as soil-structure interaction based approach. Veletsos and Younan [27] developed an analytical approach for evaluating the seismic earth pressure on retaining wall subjected to horizontal shaking. The researchers also considered the uniform stratum as a visco-elastic medium. Numerical validation of the analytical model was done by Psarropoulos et al. [28]. The researchers had reported the effect of inhomogeneity in the retained soil (in terms of variation in the shear modulus) and the properties of foundation soil on the dynamic earth pressure. Reduction in the earth pressure was observed by Psarropoulos et al. [28] for very flexible wall due to inhomogeneity. Reason for the good performance of flexible earth retaining systems subjected to short-duration moderately strong excitations was reported by Gazetas et al. [29]. Jung et al. [30] extended the analytical solution of Veletsos and Younan [27] by including the horizontal translation of the wall. Also the effects of the different parameters such as vertical translation, interface and seismic input were evaluated numerically with a finite element based numerical model. Giarlelis and Mylonakis [31] compared the experimental and analytical results to understand the dynamic response of rigid and flexible walls retaining dry cohesionless soil.

Literature is available on the sliding stability of gravity retaining wall but very few literature is available on the rotational stability of gravity retaining wall. Zeng and Steedman [32] proposed rotating block method with pseudo-static seismic force. Rotating block method is used to compute the rotational displacement of gravity retaining wall under seismic conditions. The limitations of pseudo-static method are already discussed. To the best of author's knowledge no analytical model is available for rotational stability analysis of gravity retaining wall that addresses the issue pointed out by Nakamura [10] and Athanasopoulos-Zekkos et al. [11]. In the present study an attempt is made to develop an analytical model for rotational stability of gravity retaining wall to examine whether the maximum seismic inertia force in the wall and the maximum seismic active earth pressure from the backfill is coinciding or not. The inertia force in the active soil wedge