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Effect of dynamic soil properties and frequency content of harmonic excitation on the internal stability of reinforced soil retaining structure

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The effect of dynamic soil properties and frequency content of harmonic excitation on the internal stability of reinforced soil retaining structure is investigated. Arc of a log-spiral is considered as the failure surface in the present limit equilibrium analysis. Backfill and reinforced soil is modeled as a visco-elastic material. The whole structure is considered to be resting on a rigid stratum. Backfill soil and the reinforced soil retaining structure are subjected to harmonic shaking at the base. Present methodology satisfies the stress boundary condition at the ground surface. In the present study, amplitude and phase of the horizontal and vertical seismic accelerations change with depth and the variation of accelerations along the depth is found to be time dependent and nonlinear. All the four possible combinations of horizontal and vertical seismic inertia force directions are considered to determine the total reinforcement force and critical length of the reinforcement. In the present study, amplification of accelerations towards the ground surface depends on the dynamic soil properties and frequency content of input excitation. Detailed parametric study is done to understand their implications on the solution. An algorithm is proposed at the end of this paper which uses strain dependent equivalent linear values of shear wave velocity (V_s) and damping ratio (ξ) to compute the total reinforcement force and critical length of the reinforcement. The limitation of equivalent linear based approach is that it only considers vertically propagating shear wave. Comparison of present method with other theories is also presented showing the merit of the present study.

1. Introduction

Reinforced soil retaining structure is very popular across the globe. In a reinforced earth retaining structure, different reinforcing element such as, geogrid or metallic strips are laid at a regular or irregular interval throughout the depth of the backfill soil. The friction between the earth and the reinforcement is the essential phenomenon in the reinforced earth structure. The stresses built up in the soil mass are transferred to the reinforcement through the interface friction. The advantages of reinforced soil retaining structures include savings in cost, ease of construction, design flexibility, capacity to sustain large deformations without structural distress and aesthetics. All these made them suitable for a variety of civil engineering applications. The reinforcement in the soil retaining structures must be designed with adequate strength and length to resist different possible modes of failure, namely, tieback, direct sliding and pull out failure. In last few years, numbers of methods were proposed for the design of reinforced soil retaining structure under static and seismic conditions.

Using limit equilibrium method, Leshchinsky et al. (1995) demonstrated the contribution of facial panels on the stability of reinforced soil walls. A comprehensive design approach for reinforced soil structures under seismic condition was proposed by Ling et al. (1997). Using the same pseudo static approach Ling and Leshchinsky (1998) had highlighted the importance of vertical

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Notations

$a_h(z,t)$	Horizontal acceleration at depth z and time t
$a_v(z,t)$	Vertical acceleration at depth z and time t
C_i	Soil-reinforcement pull out coefficient
G	Low strain shear modulus
G_{sec}	Secant shear modulus
g	Acceleration due to gravity
H	Height of the reinforced soil retaining structure
K	$\frac{\sum_1^n t_j}{0.5\gamma H^2}$
k_h and k_v	Horizontal and vertical seismic acceleration coefficients at the base of the reinforced soil retaining structure
l_c	Critical reinforcement length from tie back analysis
L_c	l_c/H
$l_{a,j}$	anchorage length of reinforcement against direct pull out
Q_h, Q_v	Horizontal and vertical seismic inertia forces
V_s, V_p	Shear and primary wave velocity
T	Period of lateral shaking
t	Time
t_j	Tensile force in the jth layer of reinforcement
z	Depth from the top of the backfill soil
u_{h0}	Amplitude of the horizontal displacement of the rigid stratum
u_h	Horizontal displacement
u_{v0}	Amplitude of the vertical displacement of the rigid stratum
u_v	Vertical displacement
α	Inclination angle of reinforced soil retaining structure with vertical
γ	Unit weight of soil
γ_s	Shear strain
ρ	Density
τ	Shear stress
ϕ	Soil friction angle
ξ	Damping Ratio
ω	Angular frequency of motion $= 2\pi/T$
λ	Lamé constant
η_s, η_l	Viscosity

component of seismic acceleration on the design of reinforced soil retaining structures. The researchers had concluded that for tieback analysis, direction of vertical seismic acceleration in upward and downward are equally important. Vahedifard et al. (2012) proposed a limit equilibrium based solution for reinforced soil retaining structure with inclined backfill. The researchers considered the failure surface to be a trace of a log-spiral. Seismic forces were simplified and considered to be pseudo-static in nature. Recently, Vahedifard et al. (2016) proposed a simplified method to optimize the profiling facing element of reinforced soil retaining structure under static condition. Authors concluded that concave profile is best suited for practice.

Shahgholi et al. (2001) had proposed a simplified horizontal slice method (HSM). In the proposed method whole reinforced zone is divided into a number of horizontal slices. Vertical equilibrium of each slice was satisfied and by satisfying the global horizontal equilibrium, the number of equations and unknown were reduced to $2N+1$, where N is the number of horizontal slices. It should be noted that in this proposed method moment equilibrium was not satisfied.

Nouri et al. (2006) had proposed a number of different HSM. The formulation ($5N$-1) was found to be the most efficient approach. Further, Nouri et al. (2008) had used ($5N$-1) formulation to calculate the critical reinforcement length required to resist the internal failure of reinforced soil walls. The researchers had assumed the horizontal seismic acceleration to vary linearly from the base to the top of the backfill. The amplification of acceleration considered in the study was in accordance with the centrifuge experiments reported by Nova-Roessig and Sitar (1999). Effect of cohesion of backfill material on the design strength and length of reinforcement required for seismic internal stability of inclined rigid faced retaining wall was explored by Ghosh and Debnath (2016) using the HSM method. Khosravizadeh et al. (2016) proposed an optimization procedure to identify the most probable multilinear failure surface using HSM.

Different formulations of HSM were proposed and applied for internal stability of reinforced soil structure under seismic conditions. Pseudo-static approach was mostly used by the researchers. Garg (1998) proposed an analytical formulation for the design of rigid retaining wall with reinforced backfill soil. The researcher had documented the design, construction and cost economics of an 11 m high retaining wall in Indian Himalaya. Shekarian et al. (2008) proposed a HSM for the seismic analysis of rigid retaining wall with reinforced backfill soil. The researchers had considered the seismic forces to be pseudo-dynamic in nature. Using HSM, Ahmadabadi and Ghanbari (2009) proposed the design methodology for reinforced and unreinforced rigid retaining wall with c-ϕ backfill soil. The solution was further extended for reinforced c-ϕ backfill soil with line surcharge by Ghanbari and Taheri (2012). Wang et al. (2015) performed large scale shake table experiments on geogrid reinforced rigid retaining wall with saturated backfill soil. The researchers had observed accelerated dissipation of excess pore water pressure due to the inclusion of geogrid in the backfill soil. The researchers also emphasised on the importance of the connection of geogrid with the rigid retaining wall on better seismic performance.

Pseudo-dynamic method was used to determine the reinforcement length required to resist direct sliding and overturning of reinforced soil walls under seismic condition by Choudhury et al. (2007). Though, the method proposed by Choudhury et al. (2007) did not consider the effect of amplified seismic acceleration but it considered the phase difference in both primary and shear wave propagating through the backfill and the reinforced zone. Nimbalkar et al. (2006) had used ($2N+1$), HSM formulation for the tieback analysis of reinforced soil structure. Length of the reinforcement required to resist the internal failure was reported to be higher than those obtained using the pseudo-static method of Ling and Leshchinsky (1998). Mojallal et al. (2012) proposed a new methodology to compute the yield acceleration and permanent displacement of rigid facing reinforced soil retaining structure using a multi-wedge failure mechanics.

Basha and Babu (2010, 2011) had used target reliability approach (TRA) for the internal stability of reinforced soil structure system. Seismic forces were pseudo-dynamic in nature. Log-spiral failure surfaces were optimized based on two angular quantities. Soil reaction along the log-spiral failure surface was assumed to be constant. By solving the force equilibrium equation total strength of the reinforcement required to resist the failure along the log-spiral failure surface was estimated. Reliability index against tension failure, pull out failure and total pullout failure was proposed. The