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Evaluation of seismic passive earth pressure of inclined rigid retaining wall considering soil arching effect

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ABSTRACT

Evaluation of seismic passive earth pressure is an important topic of research in geotechnical engineering. In this study seismic passive pressure on an inclined rigid retaining wall supporting horizontal cohesionless backfill is estimated considering arching effect. A planar failure surface is considered in the present analysis. Seismic forces are considered to be pseudo-static in nature. The effect of different parameters on the seismic passive earth pressure is studied in details. The normal stress distribution along the depth of the backfill is found to be nonlinear in nature. Friction angle between wall and the backfill soil has the most significant effect on the distribution of normal stress along the depth of the backfill. The point of application of seismic passive pressure shifts gradually downward for higher seismic forces. Present method is validated with the experimental results available in the literature for static conditions. Comparison of present method with other theories is also presented showing the merit of the present study. Arching effect in the backfill should be considered for high values of wall inclination angle as the present seismic passive resistance is found to be the lowest as compared to other theoretical solutions.

1. Introduction

Evaluation of seismic passive earth resistance is crucial for safe design of retaining walls. These walls serve as part of foundation of bridge deck, girders and roads. It is very essential to maintain the serviceability of these constructed facilities under seismic condition, which renders the problem more complex. Various researchers have employed analytical/numerical methods to estimate the passive earth resistance on a rigid retaining wall under seismic conditions. The most popular and easily adoptable method is Mononobe-Okabe [1]. The simplicity of the method lies in basic assumptions of a planar rupture surface and pseudo-static approximation of time-dependent irregular seismic forces. Many researchers considered a planar failure surface in their limit equilibrium solution [2–10] to obtain the passive resistance under seismic conditions. Many of these researchers considered pseudo-static seismic forces in their solution [2,6,9]. The solutions proposed by Shukla and Habibi [6] and Shukla [9] are for cohesive frictional (c-ϕ) backfill. These solutions are very easy to implement but they suffer from few limitations like simplification of earthquake force, assumption of planar failure surface which put some constrains on the application of these solution for very rough walls, solutions don't consider the arching effect in the backfill etc. The pseudo-dynamic solution proposed by Choudhury and Nimbalkar [4] eliminates the simplification of earthquake force. Pseudo-dynamic solution considers only the vertically upward propagating shear and primary wave in a homogeneous medium. The solution of Choudhury and Nimbalkar [4] was further used for the design of retaining wall under seismic condition [11,12], design of waterfront retaining wall under seismic condition [13] and to determiner uplift capacity of shallow strip anchors in sand [14]. The pseudo-dynamic solution is also implemented for non-linear failure surface [15–17]. A nonlinear failure surface is found to be more suitable for very rough walls and inclined away from the backfill. Non-linear failure surface is also implemented by many researchers with pseudo-static seismic forces and method of analysis for all of these solutions are limit equilibrium based [18–22]. Rajesh and Choudhury [23] used the critical failure surface under passive condition proposed by Subba Rao and Choudhury [21] for the design of seawall against non-breaking wave force.

Choudhury et al. [24] and Bellezza [25] pointed out the shortcomings of pseudo-dynamic method. The seismic waves considered in pseudo-dynamic method do not satisfy the boundary condition of zero shear stress at the free ground surface. Pseudo-dynamic method is not

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Nomenclature

c	Cohesion	γ	Unit weight of the backfill soil
dG	Weight of the differential element	δ	Wall friction angle
G	Weight of the sliding wedge	σ_w	Normal stress acting on the differential element EF at point E
H	Height of the retaining wall	σ_s	Normal stress acting on the differential element EF at point F
h	Point of application of passive earth pressure	σ_1	Major principal stress
K_p,K_{pe}	Static and seismic passive earth pressure coefficients	σ_3	Minor principal stress
k_h	Seismic horizontal acceleration coefficient	σ_v	Vertical stress acting on the differential element
k_v	Seismic vertical acceleration coefficient	τ_w	Shear stress acting on the differential element EF at point E
q	Surcharge at the ground surface	τ_s	Shear stress acting on the differential element EF at point F
q_n	Normalized surcharge ($q/\gamma H$)	ϕ	Soil friction angle
y	Depth from the ground surface	ε	Wall inclination angle
dy	Thickness of the differential element		
β	Inclination of the failure plane with horizontal		

capable of handling the reflection of seismic waves at the free surface. And the effect of material damping on seismic forces was neglected. Recently, Pain et al. [26] and Rajesh and Choudhury [27] addressed most of the limitations of pseudo-dynamic method and showed that the acceleration distribution in the backfill soil may or may not be in-phase for the minimum value of seismic passive earth pressure. But the method does not address the effect of soil arching on the value of passive resistance under seismic condition.

There are few other methods of analysis such as the solution proposed by Kumar and Chitikela [28]. The methodology proposed by Kumar and Chitikela [28] is based on the method of stress characteristics. A closed-form solution using plasticity theorem was proposed by Mylonakis et al. [29] for gravity retaining walls under seismic conditions. Theorem of plasticity was also used for computing the passive earth resistance on rigid retaining walls under seismic conditions [30–32].

Fang et al. [33] conducted passive earth pressure test for three different wall movements, translation, rotation about a point above the top of the wall and rotation about a point below the bottom of the wall. Tests were conducted on dry cohesionless soil. Two passive pressure load tests in field were conducted by Duncan and Mokwa [34]. One test was performed in natural ground and the other test was performed in compacted gravel backfill. Gutberlet et al. [35] used Particle Image Velocimetry (PIV) to identify the shear band formed under passive earth pressure condition. The researchers conducted the experiments on homogenous and layered cohesionless soil. All the experiments were done under static condition. High values of passive earth pressure were recorded during the experiments as compare to the theoretical predictions. The researchers attributed this difference to interlocking of the grains at low stress levels as the experiments were conducted on reduce scale retaining walls.

Arching is a process of redistribution of stresses in the soil mass. The most classical work is presented by Terzaghi [36], where he described the arching effect involved in the soil mass that resists its downward movement through a moving plate at the bottom of a rigid box. As it is apparent from the general meaning of arching that signifies stress transfer from the moving soil mass to the adjacent stationary areas, its occurrence caused by numerous factors involved in the movement of soil mass is completely different. The cause related to the arching can be various in geotechnical issue. The common examples of arching in the geotechnical engineering problems may be seen in earth dams, retaining wall, reinforced soil slopes, trenches and tunnels. Handy [37] was among the first who estimated the active thrust exerted by a rigid retaining wall considering arching effect. Later, Paik and Salgado [38] estimated the active thrust under translation mode of failure considering the arching effect. The researchers had assumed a planar failure surface and obtained the pressure distribution under active condition. A circular arch was assumed in the analysis. The researchers showed that the distribution of active earth pressure is not linear and it depends on the mode of wall movement. Goel and Patra [39] implemented the same procedure for two different combination of parabolic arch and (planar and parabolic) failure surface and found that the combination of a planar failure surface and a parabolic arch provided close agreement with experimental results. Through a series of physical model tests Khosravi et al. [40] validated ‘arch-action’ based theories under active condition for horizontal translation of retaining wall. Recently, several other researchers [41–43] used ‘arch-action’ based theory to compute the active/passive thrust exerted by c-ϕ soil.

However, the passive earth resistance under seismic condition considering the arching effect is still scarce. Hence, seismic passive earth resistance is obtained in the present study considering the arching effect for a non-vertical rigid retaining wall supporting horizontal dry cohesionless backfill. Horizontal translational movement of the wall is considered. A planar failure surface is considered in the analysis. Effect of a wide range of parameters on the seismic passive resistance is studied. A comparison of present results with experimental data of Fang et al. [33] is presented under static condition. Passive earth coefficients under seismic condition are compared with the other available literature.

2. Methodology

2.1. Theoretical model

A non-vertical rigid retaining wall ‘AB’ is considered to support horizontal cohesionless backfill (Fig. 1). AB is inclined at an angle ε from vertical. H is the height of the retaining wall. BD is slip surface and it is inclined at an angle β. EF is the differential element of thickness dy at a depth y from the ground surface. k_h and k_v are the pseudo-static horizontal and vertical acceleration coefficients respectively. Reduction in the weight of the differential element EF due to the vertical seismic inertia force is considered in the present study. And to account that the weight of the element EF is considered as $(1\text{-}k_v)dG$, where dG is the gravitational weight of the element EF. σ_w and τ_w are the normal and shear stress acting on the differential element EF at point E. Similarly, σ_s and τ_s are the normal and shear stress acting on the differential element EF at point F. The resultant of normal and shear stress is acting at an angle δ and ϕ to the normal component. δ is the friction angle at the soil-wall interface and ϕ is soil friction angle.

According to soil arching principle, the direction of major principal stress (σ_1) in the soil sliding body in passive limit state under earthquake load is no longer horizontal, but deflection occurs (Fig. 2). Under the translation mode, no shear stress on the surface of the differential sliding element is considered; only normal stress is acting on the element. At given depth, the principle stress is assumed to be constant. Fig. 3 is the Mohr circle representation of stresses due to soil arching