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Uplift capacity of horizontal strip plate anchors adjacent to slopes considering seismic loadings

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Abstract

For computing the uplift capacity of strip anchors buried adjacent to sloping ground surface in the presence of pseudo-static earthquake body forces, theoretical solutions have been developed by using the upper bound theorem of limit analysis based on a simple rigid wedge collapse mechanism. The influence of the ratio of anchor edge-distance from the crest of slope to the width of anchor (ε) and earthquake acceleration coefficients (k_h, k_v) on the dimensionless seismic uplift factor (f_γ) due to soil unit weight have been examined for different combinations of the internal friction angle of soil (ϕ), slope angle (β), and the embedment ratio (λ) of anchors. The magnitude of f_γ was found to decrease continuously with increases in the slope angle and earthquake acceleration coefficients; whereas, as expected, f_γ increases with increases in the soil friction angle, edge-distance ratio (ε) and the embedment ratio of anchors. Under the static condition, the angle of slope has no influence on the magnitude of uplift resistance when $\varepsilon \geq \lambda \tan \phi$. The present solutions are in good agreement with the results reported in the literature.

Keywords: Strip anchors; Limit analysis; Pseudo static; Slopes; Seismic uplift capacity

1. Introduction

Anchors are often recommended as an economical solution for structures requiring uplift resistance such as transmission towers, dry docks and pipelines under water, etc. Numerous studies have been conducted to obtain the static and seismic uplift capacity of anchors embedded in soil with horizontal ground surface (Meyerhof and Adams, 1968; Rowe and Davis, 1982; Murray and Geddes, 1987; Subba Rao and Kumar, 1994; Kumar, 2001; Merifield and Sloan, 2006; Ghosh, 2009; Rangari et al., 2013; Pain et al., 2015). On the other hand, few studies have been reported on determining the ultimate uplift capacity of anchors embedded in sloping ground (Kumar, 1997; Choudhury and Subba Rao, 2004; Yu et al., 2014). Based on the upper bound limit analysis with rigid block failure mechanism, Kumar (1997) has developed closed form solutions for computing the static uplift capacity of plate anchors buried in sandy slopes either horizontal or parallel to the slope with the pullout force perpendicular to the plate. Choudhury and Subba Rao (2004) obtained the seismic uplift capacity factors of horizontal strip anchors embedded in an inclined ground surface using the limit equilibrium method based on the logarithmic rupture surface with the pseudo-static approach. Yu et al. (2014) provided the pullout capacity together with the failure surfaces for horizontal and inclined strip plate anchors in sandy slopes by applying three upper bound approaches: the simple upper bound mechanisms, the block set mechanism approach, and the finite element upper bound limit analysis. By conducting a few laboratory model

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Nomenclature

k_h	earthquake acceleration coefficient in the horizontal direction
k_v	earthquake acceleration coefficient in the vertical direction
k_{eh}	modified earthquake acceleration coefficient to account the combined effect of k_h and k_v
ψ	dilatancy angle of sand
ϕ	internal friction angle of sand
ϕ'	effective internal friction angle of sand
ϕ^*	modified internal friction angle of soil to account ψ
γ	unit weight of sand
γ'	effective unit weight of sand
γ_e	modified unit weight of soil to account the combined effect of k_h and k_v
β	angle of slope with horizontal
f_γ	dimensionless seismic uplift factor
b	width of anchor
d	depth of anchor
λ	embedment ratio of anchors (d/b)
e	edge distance of anchor plate from the slope crest
ε	edge-distance ratio of anchors (e/b)
ε_{cr}	critical edge-distance ratio of anchors
H	height of slope
P_u	ultimate vertical uplift force per unit length of the anchor
p_u	ultimate uplift capacity per unit length of the anchor (P_u/b)
W_0	weight of soil block *OIJ*
W_1	weight of soil block *OJK*
W_2	weight of soil block *OLMI*
V_0	velocity of soil block *OIJ*
V_1	velocity of soil block *OJK*
V_2	velocity of soil block *OLMI*
V_{01}	relative velocity between soil blocks *OIJ* and *OJK*
V_{02}	relative velocity between soil blocks *OIJ* and *OLMI*
θ	inclination of V_0 with respect to vertical
θ_{cr}	critical uplift inclination angle
η_1	inclination of linear rupture surface *JK* with the horizontal plane
η_2	inclination of linear rupture surface *IM* with the horizontal plane
μ_1	inclination of velocity discontinuity line *JO* with the horizontal plane
μ_2	inclinations of velocity discontinuity line *IO* with the horizontal plane

tests, Sawwaf (2007) examined the uplift behavior of horizontal anchor plates located near sandy slopes with and without the inclusion of geosynthetic reinforcements under static loading. Besides the investigations of Sawwaf (2007), no attempt has been made to study the effect of the edge-distance of anchors from the crest of slope. Again, it seems that hardly any literature is available as a guideline for computing the uplift capacity of anchors embedded adjacent to sloping grounds with the inclusion of earthquake body forces. Hence, in the present work, with the application of the upper bound theorem of the limit analysis by employing a simple rigid wedge collapse mechanism bounded by planar rupture surfaces, theoretical solutions have been produced under static and pseudo-static body forces. The dimensionless uplift factor, f_γ due to the unit weight of soil have been provided for different combinations of the internal friction angle of soil (ϕ), slope angle (β), edge-distance of anchor from crest to width ratio (ε), embedment ratio (λ) of anchors and earthquake acceleration coefficients.

2. Problem definition

A rigid strip plate anchor of width b is embedded horizontally in homogenous sand near a sloping surface at a depth d as illustrated in Fig. 1. The edge of anchor plate is kept at a distance e from the slope crest. The sloping surface makes an angle of β with the horizontal plane. The depth of anchor d is assumed to be less than the height of slope H so that the rupture surface does not pass through the base of the slope at the ultimate shear failure of the anchors. The thickness of anchor plate is considered to be negligible compared to its width. For horizontal plate anchors, Rowe and Davis (1982) reported that the magnitude of the uplift resistance is not affected by the roughness of the horizontal plate anchors, and Merifield and Sloan (2006) have found that interface roughness has little or no effect (< 4%) on the uplift capacity for all the embedment depths and angle of the internal friction of the soil mass. Based on the findings of Merifield and Sloan (2006), a smooth anchor-soil interface was assumed in the pseudo-dynamic analysis performed by Rangari et al., 2013 for determining the seismic uplift capacity of horizontal strip anchors. In the present analysis, it is assumed that the anchor plate is smooth. The soil medium is assumed to be rigid perfectly plastic, and it obeys the Mohr-Coulomb failure criterion and an associated flow rule.

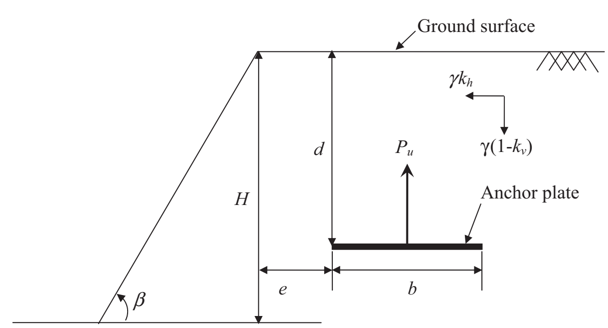

Fig. 1. Definition of problem.