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Seismic uplift capacity of shallow strip anchors: A new pseudo-dynamic upper bound limit analysis

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ABSTRACT

Using a new pseudo-dynamic approach for the inclusion of seismic body forces, the seismic vertical uplift capacity of horizontally placed strip plate anchors in sand at shallow depths has been computed with the application of upper bound theorem of limit analysis. Unlike the earlier pseudo-dynamic approaches, in this study, the nonlinear variation of both horizontal and vertical acceleration along the depth of soil layer, and in the values of amplitude and phase of accelerations has been considered with the satisfaction of stress boundary condition at the ground surface. The seismic uplift factor $F_{\gamma s}$ due to the unit weight of soil for different combinations of seismic acceleration coefficients, internal friction angle of soil, and the embedment ratio of anchors has been obtained. The solutions indicate that the magnitude of $F_{\gamma s}$ decreases substantially with an increase in seismic acceleration coefficients; whereas as expected, increases with an increase in embedment ratio of anchors and soil friction angle. This study produces the least upper bound solutions in comparison to the earlier reported results in the literature.

1. Introduction

Anchors are often used as a foundation system for various important structures requiring uplift resistance such as transmission towers, dry docks and buried pipelines under water etc. In addition to static forces, the anchors located in a seismically active zone are also subjected to seismic body forces during the event of an earthquake. Under static condition, the uplift capacity of anchors has earlier been computed by different researchers [1–15]. In the presence of seismic loadings, the uplift capacity of anchors have been computed by using pseudo-static approach [16–19] and pseudo-dynamic approach [20–24]. In the pseudo static approach, the magnitude and phase of acceleration are assumed to be uniform throughout the soil medium and this unrealistic assumption can be tackled using a simple pseudo-dynamic approach proposed by Steedman and Zeng [25]; and also the approach extended by Choudhury and Nimbalkar [26]. However, this pseudo-dynamic approach again involves disadvantages such as,

(i) The stress boundary conditions (i.e. shear and normal stresses are equal to zero; $\sigma_{xz} = 0$ and $\sigma_{zz} = 0$) at ground surface are not satisfied

(ii) A simplified linear variation for amplification of vibration is assumed

This simplified pseudo-dynamic approach was employed for solving anchor problems [20,21]. Very recently, Bellezza [27,28] proposed a new pseudo-dynamic approach based on a more realistic behavior of soil modeled as a Kelvin–Voigt solid, which overcomes the aforementioned disadvantages. Using this new pseudo dynamic approach, Pain et al. [22] have computed seismic uplift resistance of strip anchors in a limit equilibrium framework similar to Choudhury and Subba Rao [17,18]. However, their analysis requires assumptions regarding the selection of (i) wall friction angle, and (ii) point of application of seismic passive resistance [23,24]. Moreover, the effect of vertical acceleration was not taken into consideration. Hence, following new pseudo dynamic approach of Bellezza [27,28] and taking into account the effect of both horizontal and vertical accelerations together with the application of kinematic theorem of limit analysis, this note presents the upper bound solutions for the seismic uplift capacity of horizontal strip plate anchors. The results obtained from the present analysis are compared with those results reported in the literature.

2. Problem statement

A rigid strip plate anchor having width B buried horizontally in a homogeneous sand layer at a depth H from the ground surface is illustrated in Fig. 1. The ultimate uplift load carrying capacity P_u of this plate anchor needs to be determined in the presence of pseudo dynamic

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Notations

V	velocity of soil block MNOP
α	inclination of velocity of soil block V with the vertical
θ_1, θ_2	inclination of linear rupture surfaces OP and MN with horizontal plane
ϕ	internal friction angle of soil
γ	unit weight of soil mass
ρ	soil density
f	amplification factor
G	shear modulus of the soil
λ	first Lame´ constant
g	acceleration due to gravity
B	width of strip anchors
H	embedment depth of anchors
ε	embedment ratio of anchors = H/B
z	depth from the ground surface
$W(\alpha)$	weight of soil block MNOP
$m(\alpha,z)$	mass of the differential element dz
$P_u(\alpha,t)$	vertical seismic uplift resistance
α_c	α corresponding to minimum value of $P_u(\alpha,t_c)$
$F_{\gamma s}$	seismic uplift factor
k_h, k_v	acceleration coefficient at anchor base in horizontal and vertical directions
$k_{h,avg}$, $k_{v,avg}$	weighted average acceleration coefficient in horizontal and vertical directions
$a_h(z,t)$, $a_v(z,t)$	horizontal and vertical accelerations at any depth z and time t
u, v	horizontal and vertical displacements
u_0, v_0	horizontal and vertical displacements at the level of anchor base
$Q_h(\alpha, t)$, $Q_v(\alpha, t)$	horizontal and vertical inertia forces
$\omega_s H/V_s$, $\omega_p H/V_p$	normalized frequency of shear and primary waves
ξ_s, ξ_p	damping ratio of shear and primary waves
ω_s, ω_p	angular frequency of shear and primary waves
T_s, T_p	period of shear and primary waves
V_s, V_p	velocity of shear and primary waves
η_s, η_p, η_1	soil viscosities
t	time
t_c	time (t) corresponding to minimum value of $P_u(\alpha_c,t)$

earthquake forces. For simplifying the analysis, it has been assumed that (i) the mass of the anchor is negligible, (ii) the soil mass is dry and follows Mohr-Coulomb failure criterion with an associated flow rule, and (iii) the occurrence of an earthquake does not affect the magnitude of soil parameters.

3. Analysis

3.1. Wave equation

The horizontal and vertical accelerations are obtained from the concept of viscoelastic wave propagation in a soil medium, which is modeled as a Kelvin–Voigt solid represented by a purely elastic spring and a purely viscous dashpot connected in parallel [29]. The motion equations of a wave propagating along the z-axis in xz plane for the Kelvin–Voigt viscoelastic medium can be written as

$$\rho\frac{\partial^2 u}{\partial t^2} = G\frac{\partial^2 u}{\partial z^2} + \eta_s\frac{\partial^3 u}{\partial z^2\partial t} \tag{1}$$

$$\rho\frac{\partial^2 v}{\partial t^2} = (\lambda + 2G)\frac{\partial^2 v}{\partial z^2} + (\eta_1 + 2\eta_s)\frac{\partial^3 v}{\partial z^2\partial t} \tag{2}$$

where u and v are the displacements in the horizontal (x-axis) and vertical (z-axis) directions; respectively, ρ refers to the soil density, G and λ account as the Lamé constants, η_1 and η_s are the soil viscosities and t is the time.

Following Bellezza [27], for a harmonic horizontal vibration of angular frequency ω_s and period $T_s = 2\pi/\omega_s$ by imposing the boundary

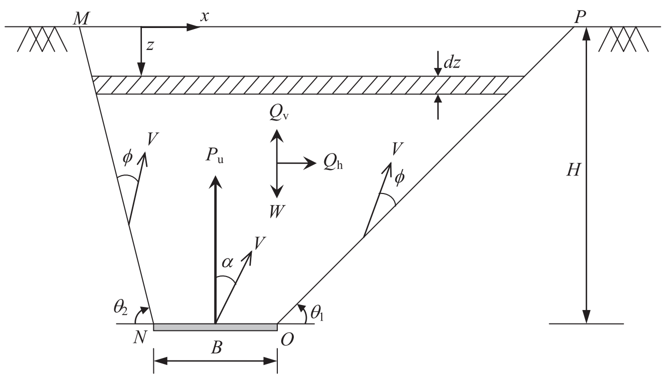

Fig. 1. Definition of the problem.

conditions (i) at $z = 0$, $\sigma_{xz} = 0$ and (ii) at $z = H$, displacement coincides with that of anchor plate, the horizontal accelerations at any depth z and time t can be expressed as

$$a_h(z, t) = \frac{k_h g}{C_s^2 + S_s^2}[(C_s C_{sz} + S_s S_{sz})\cos(\omega_s t) + (S_s C_{sz} - C_s S_{sz})\sin(\omega_s t)] \tag{3}$$

By satisfying the boundary conditions (i) at $z = 0$, $\sigma_{zz} = 0$, and (ii) at $z = H$, displacement coincides with that of anchor plate and following Bellezza [28], for a harmonic vertical vibration of angular frequency ω_p and period $T_p = 2\pi/\omega_p$, the vertical accelerations at any depth z and time t can be written as

$$a_v(z, t) = \frac{k_v g}{C_p^2 + S_p^2}[(C_p C_{pz} + S_p S_{pz})\cos(\omega_p t) + (S_p C_{pz} - C_p S_{pz})\sin(\omega_p t)] \tag{4}$$

In Eqs. (3) and (4), $k_h g = -\omega_s^2 u_0$ and $k_v g = -\omega_p^2 v_0$

where k_h and k_v are the horizontal and vertical acceleration coefficients at the base of the anchor plate, respectively; u_o and v_o are the amplitudes of horizontal and vertical displacements at the base of the anchor plate, respectively.

The other parameters introduced in Eqs. (3) and (4) are defined as follows;

$$C_{az} = \cos\left[\frac{y_{a1}z}{H}\right]\cosh\left[\frac{y_{a2}z}{H}\right] \tag{5a}$$

$$S_{az} = -\sin\left[\frac{y_{a1}z}{H}\right]\sinh\left[\frac{y_{a2}z}{H}\right] \tag{5b}$$

$$C_a = \cos(y_{a1})\cosh(y_{a2}) \tag{6a}$$

$$S_a = -\sin(y_{a1})\sinh(y_{a2}) \tag{6b}$$

$$\begin{matrix} y_{a1} \\ y_{a2} \end{matrix} = \pm\frac{\omega_a H}{V_a}\sqrt{\frac{\sqrt{1 + 4\xi_a^2} \pm 1}{2\,(1 + 4\xi_a^2)}} \tag{7}$$

In the Eqs. (5)–(7), the subscript ‘a’ is replaced with the subscripts ‘s’ and ‘p’ to define the parameters of Eqs. (3) and (4), respectively. The dimensionless quantities y_{s1} and y_{p1} in Eq. (7) is a function of damping ratios $\xi_s = \eta_s\omega_s/2G$ and $\xi_p = (\eta_1 + 2\eta_s)\omega_s/2(\lambda+2G)$; normalized frequencies $\omega_s H/V_s$ and $\omega_p H/V_p$ of a vertically propagating shear and primary waves with velocities V_s and V_p, respectively. In this study, both horizontal and vertical accelerations at any depth z have been