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Stability of non-vertical waterfront retaining wall supporting inclined backfill under earthquake and tsunami

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ABSTRACT

The stability analysis has been carried out for generalized non-vertical waterfront retaining wall supporting inclined backfill under combined action of earthquake and tsunami forces. Closed-form design solutions for factor of safety against sliding have been obtained using limit equilibrium method. For estimating seismic passive earth pressure and the wall inertia force, the pseudo-dynamic approach has been adopted. Different methods available in literature are used to estimate tsunami wave pressure and hydrodynamic pressure. It has been observed that parameters like seismic accelerations in both horizontal and vertical directions, time period, soil and wall friction angles, wall batter, ground inclination, pore pressure ratio, tsunami wave height have significant effect on the sliding stability of the waterfront retaining wall under combined action of earthquake and tsunami. Comparison of results with available results in literature for special case of vertical waterfront retaining wall supporting horizontal backfill has indicated a very good agreement. It is expected that the proposed design charts and tables presented in this paper will be helpful for the design engineers to design waterfront retaining wall against sliding mode of failure under combined action of earthquake and tsunami.

1. Introduction

A waterfront retaining wall is a very important structure. When it is subjected to the combined action of an earthquake and a tsunami, the stability may get affected severely. The evidence of the enormous damage of the waterfront retaining walls can be found from the recent South Asian earthquake of 2004 and Japan earthquake of 2011, which triggered very big tsunami waves due to earthquake. Hence a typical waterfront retaining wall can be subjected to both earthquake and tsunami and the combined effect of a number of forces/pressures such as (i) the seismic forces, (ii) the tsunami force, and (iii) the hydrostatic and hydrodynamic pressures need to be considered for design. Except two recent research works reported by Choudhury and Ahmad (2007a) and Ahmad and Choudhury (2008), all other works available in literature considered either only one force/pressure or just a combination of a few of these forces/pressures at a time *i.e.* only earthquake or tsunami. Combined action of earthquake and tsunami were hardly considered. Choudhury and Ahmad (2007a) considered all these forces/pressures, but the seismic passive earth pressure was calculated using the conventional pseudo-static approach, which was established by various researchers like Choudhury and Subba Rao (2002) and Subba Rao and Choudhury (2005). Also recent work of Ahmad and Choudhury (2012) considers only pseudo-static approach. Whereas, Ahmad and Choudhury (2008) and Choudhury and Ahmad (2008) also considered all these forces/pressures, but the seismic earth pressure was calculated using more realistic pseudo-dynamic approach, where in addition to the seismic accelerations, duration, frequency of earthquake, body waves traveling during earthquake were also considered. As a result of that, the pseudo-dynamic approach provides less conservative result as compared to the conventional pseudo-static approach (Steedman and Zeng, 1990; Choudhury and Nimbalkar, 2005, 2007; Nimbalkar and Choudhury, 2007, 2008). But, Choudhury and Ahmad (2007a) and Ahmad and Choudhury (2008) have considered only an ideal case of perfectly vertical wall with perfectly horizontal backfill, which is the main limitation of these two available research works. Hence in the present study, an attempt has been made to propose a methodology to study the sliding stability aspect of a generalized non-vertical waterfront retaining wall supporting inclined backfill, exposed to the combined effects of earthquake and tsunami, including the hydrostatic and hydrodynamic pressures, using the limit equilibrium method in combination with the pseudo-dynamic approach.

2. Methodology

Fig. 1 shows a typical non-vertical face rigid waterfront retaining wall supporting an inclined backfill. The height of the wall is *H*

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Nomenclature

a_h	amplitude of seismic acceleration of the backfill soil in the horizontal direction
a_v	amplitude of seismic acceleration of the backfill soil in the vertical direction
$a_h(z,t)$	backfill soil acceleration in the horizontal direction at depth z and time t
$a_v(z,t)$	backfill soil acceleration in the vertical direction at depth z and time t
a_{hw}	amplitude of seismic acceleration of the wall in the horizontal direction
a_{vw}	amplitude of seismic acceleration of the wall in the vertical direction
$a_{hw}(z,t)$	wall acceleration in the horizontal direction at depth z and time t
$a_{vw}(z,t)$	wall acceleration in the vertical direction at depth z and time t
b	width of the wall at the top
F	resultant of all the forces acting on the failure wedge
F_{dC}	total driving force by considering the CRATER (2006) approach for the estimation of the tsunami wave pressure
F_{dF}	total driving force by considering the Fukui et al. (1962) approach for the estimation of the tsunami wave pressure
F_r	total resisting force
FS_C	factor of safety in sliding mode of failure of the wall by considering the CRATER (2006) approach for the estimation of the tsunami wave pressure
FS_F	factor of safety in sliding mode of failure of the wall by considering the Fukui et al. (1962) approach for the estimation of the tsunami wave pressure
g	acceleration due to gravity
H	height of the wall
h_t	tsunami water height on the upstream side of the wall
h_{wd}	height of the water on the downstream side of the wall
h_{wu}	height of the water on the upstream side of the wall
k_h	seismic acceleration coefficients in the horizontal direction
k_v	seismic acceleration coefficients in the vertical direction
k_h^*	modified seismic acceleration coefficient in the horizontal direction
K	a constant as described in text
K_p	passive earth pressure coefficient under static conditions
$K_{pe}(t)$	seismic passive earth pressure coefficient
$m(z)$	mass of the thin shaded zone of the backfill material having thickness dz, and located at a depth z below the top of the wall
$m_w(z)$	mass of the thin shaded zone of the wall having thickness dz, and located at a depth z below the top of the wall
P_{dyn}	hydrodynamic pressure
P_p	total passive earth pressure under static conditions
$P_{pe}(t)$	total seismic passive resistance
P_{std}	hydrostatic pressure on the downstream side of the wall
P_{stu}	hydrostatic pressure on the upstream side of the wall
P_{tC}	tsunami wave pressure by considering the CRATER (2006) approach for the estimation of the tsunami wave pressure
P_{tF}	tsunami wave pressure by considering the Fukui et al. (1962) approach for the estimation of the tsunami wave pressure
$Q_h(t)$	seismic inertia force on the backfill soil in the horizontal direction
$Q_v(t)$	seismic inertia force on the backfill soil in the vertical direction
$Q_{hw}(t)$	seismic inertia force on the wall in the horizontal direction
$Q_{vw}(t)$	seismic inertia force on the wall in the vertical direction
r_u	pore pressure ratio
SWL	sea water level
t	time (duration)
T	period of lateral shaking
V_p	the velocity of the primary wave propagating through the soil
V_s	the velocity of the shear wave propagating through the soil
V_{pw}	the velocity of the primary wave propagating through the wall
V_{sw}	the velocity of the shear wave propagating through the wall
W_w	weight of the wall
α	angle of inclination of the inclined backfill
β	angle which the failure wedge plane makes with the horizontal at the base of the wall
β_c	β for the critical collapse mechanism
δ	wall friction angle
ϕ	soil friction angle
γ_c	unit weight of concrete
γ_d	dry unit weight of the soil
γ_s	unit weight of soil
γ_{sat}	saturated unit weight of the soil
γ_w	unit weight of water
γ_{we}	the equivalent unit weights of water, modified due to submergence of the backfill
$\bar{\gamma}$	the equivalent unit weights of the soil, modified due to submergence of the backfill
μ	coefficient of base friction
ν	Poisson's ratio
θ	inclination of wall with vertical
ω	angular frequency $=2\pi/T$

and the width at the top is b. The inclination of wall with vertical is θ. The inclination of the inclined backfill is α. The inclined backfill is submerged with water to a height h_{wd}. The upstream water height is h_{wu}. The tsunami water wave height is h_t. Following Ahmad and Choudhury (2008), the corresponding total pressure/force due to h_{wu} and h_t would, respectively, be hydrostatic pressure P_{stu}, and tsunami wave pressure P_t. The hydrostatic pressure P_{std}, the hydrodynamic pressure P_{dyn}, the seismic passive earth pressure/resistance $P_{pe}(t)$ and the wall inertia forces $Q_{hw}(t)$ and $Q_{vw}(t)$ are also indicated in that figure. The objective of the study is to provide a methodology for assessing the sliding stability of a general non-vertical waterfront retaining wall supporting inclined backfill under the combination of all these forces. It has been assumed that the wall rests over a rigid foundation. The possibility