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A finite element performance-based approach to correlate movement of a rigid retaining wall with seismic earth pressure

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ABSTRACT

The paper presents a unique finite element model-based investigation and development of a relationship between the seismic active and passive earth pressure and the movement of a rigid retaining wall. A hardening soil with small strain model with consideration of the Rayleigh damping has been adopted for modelling soil. Validation of the finite element model has been carried out by using centrifuge test results already available in the literature. Unique design charts have been proposed highlighting the relationship between the seismic earth pressure and the wall movement. It is observed that the seismic active earth pressure is independent of the seismic input motion and hence does not depend upon the wall movement during an earthquake, while on the contrary the seismic passive earth pressure is significantly affected by it. Comparison of the results of the present study with the Mononobe-Okabe and pseudo-dynamic methods clearly highlights that the latter overestimates the seismic earth pressure. The proposed design charts and other results provide an important cue to the design engineers.

1. Introduction

Retaining walls are one of the most important civil engineering structures constructed to provide lateral support to soil and are widely used in transportation systems, mines, underground structures, and military defences. In order to assess the stability of these structures, an accurate estimation of the lateral earth pressure is very important. Pioneering work on the estimation of lateral earth pressure was done by Coulomb and Rankine [1,2]. From the classic literature on earth pressure, it is noted that the mode, direction, and magnitude of the retaining wall displacement have a significant effect on the development of active and passive lateral earth pressures. For example, through analytical work presented by [3–5] and experimental work presented by [6,7], it is found that the magnitude of lateral earth pressure is highly influenced by the direction of the retaining wall movement while the mode of the retaining wall movement controls the distribution of lateral earth pressure along the height of the retaining wall. Numerical modelling techniques like the finite element and finite difference methods have been used to provide an in-depth understanding of the relationship between the lateral earth pressure and the displacement of retaining walls [8–11], and interesting findings have been made about the different modes and amount of the movement of the retaining wall on the magnitude and distribution of earth pressure. In the earthquake prone areas, an accurate estimation of the seismic earth pressure becomes pivotal for the design of such retaining walls. Okabe and Mononobe [12,13] pioneered a method for estimating the earth pressure by extending the Coulomb's static earth pressure theory. The method proposed by Okabe and Mononobe is very widely used in current practice and is often called as the Mononobe-Okabe or simply the MO method. In this method, the effect of the earthquake is simulated by introducing additional forces called as the seismic inertia forces on a soil wedge which exert lateral earth pressure on the retaining wall, called as the seismic earth pressure. Over the past many years, many researchers like [14–20] have modified and extended the MO method to propose new analytical solutions like the pseudo-dynamic method to compute the seismic earth pressure, while, other researchers like [21–24] developed experimental and numerical methods to compute the seismic earth pressure by using the MO method. Further, [25,26] have developed numerical methods for studying the phasing issues for the seismic response of yielding and non-yielding gravity retaining walls. However, it is important to highlight that the MO method does not take into account the displacement of the retaining wall under seismic conditions and hence, it is categorised as a force-based method. Real field observations as reported by [21,27] have shown that the retaining walls undergo large displacements during earthquakes. Richards and Elms [28] proposed an analytical

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List of symbols

a	acceleration
a_{CG}	acceleration at the centre of gravity of the retaining wall
b_f	a reference point in the foundation soil, located 0.5 m below the base of the retaining wall
b_m	a reference point, located at the base of the FE model
b_w	a reference point, located at the bottom of the retaining wall
c'	effective cohesion of the soil
$[\boldsymbol{C}]$	damping matrix of the system
d_{active}	horizontal displacement in the active direction
$d_{passive}$	horizontal displacement in the passive direction
D_r	relative density of the soil
E	modulus of elasticity of the wall
E_{50}	modulus of soil at 50% of the soil's strength at failure
E_{50}^{ref}	modulus of soil at 50% of the soil's strength at failure, corresponding to a reference confining pressure p^{ref}
E_i	initial modulus of the soil
E_{oed}	modulus of the soil obtained from an oedometer test
E_{oed}^{ref}	modulus of the soil obtained from an oedometer test, corresponding to a reference confining pressure p^{ref}
E_{ur}	modulus of the soil for unloading-reloading conditions
E_{ur}^{ref}	modulus of the soil for unloading-reloading conditions, corresponding to a reference confining pressure p^{ref}
f	frequency of the seismic input motion
f_{max}	maximum frequency of the seismic input motion
F	horizontal seismic inertia force of the retaining wall
F_a	horizontal seismic inertia force of the retaining wall, acting away from the backfill soil
F_p	horizontal seismic inertia force of the retaining wall, acting towards the backfill soil
g	gravity acceleration
G	shear modulus of the soil
G_o	initial small strain shear modulus of the soil
G_o^{ref}	initial small strain shear modulus of the soil, corresponding to a reference pressure p^{ref}
G_{ur}	shear modulus of the soil for unloading-reloading conditions
h	thickness of the foundation soil
h_{ei}	height of the element
he_{max}	maximum height of an element of the FE mesh
H	height of the retaining wall (and backfill soil)
$[\boldsymbol{K}]$	stiffness matrix of the system
K_o	at-rest earth pressure coefficient
m	mass of the retaining wall
$[\boldsymbol{M}]$	mass matrix of the system
n	number of elements of the backfill soil which are in contact with the back of the retaining wall
p_a	static active earth pressure
p_{ae}	seismic active earth pressure
p_o	static at-rest earth pressure
p_{pe}	seismic passive earth pressure
p^{ref}	reference confining pressure ($=100\ \mathrm{kN/m^2}$)
P	seismic earth pressure force
P_a	static active earth pressure force
P_{ae}	seismic active earth pressure force
P_{ei}	seismic earth pressure force for the element
P_o	static at-rest earth pressure force
P_{pe}	seismic passive earth pressure force
P_{re}	residual seismic earth pressure force
q_a	asymptotic value to the soil's strength at failure
q_f	soil's strength at failure
R_f	failure ratio
t	time
t_b	a reference point, located at the top of the backfill soil
t_w	a reference point, located at the top of the retaining wall
ν	Poisson's ratio of the retaining wall
v_s	velocity of the shear wave
ν_{ur}	Poisson's ratio of the soil for unloading–reloading conditions
W	weight of the retaining wall
y	a constant, to account for the stress-level dependency of the stiffness of soil
z	height of the wall measured above its base
α, β	Rayleigh damping parameters
Δb_w	horizontal displacement at the base of the retaining wall
Δt_w	horizontal displacement at the top of the retaining wall
ΔP	seismic earth pressure force increment
ΔP_{ae}	seismic active earth pressure force increment
ΔP_{pe}	seismic passive earth pressure force increment
γ_s	unit weight of the soil
γ	shear strain
$\gamma_{0.7}$	reference shear strain, corresponding to 70% of G_o^{ref}
γ_w	unit weight of the retaining wall
ξ	damping ratio
θ	rotation of the retaining wall about an axis passing through location b_w
θ_{active}	rotation of the retaining wall in the active direction
$\theta_{passive}$	rotation of the retaining wall in the passive direction
λ_{min}	wavelength of the shear wave
σ'_3	effective confining pressure
σ_{hei}	horizontal stress for element i
$\sigma_{ha,b}$	horizontal stress computed at the Gauss integration points a and b which are in contact with the retaining wall
ϕ'	effective friction angle of the soil
ψ	dilatancy of the soil
ω_{z1}, ω_{z2}	first two natural circular frequencies of the finite element model

Abbreviations

2D	two-dimensional
CG	centre of gravity of the retaining wall
FE	finite element
HSsmall model	hardening soil with small strain model
MO	Mononobe-Okabe theory
PGA	peak ground acceleration

solution by extending the Newmark sliding block method [29] to estimate the displacement of a retaining wall during an earthquake. Many researchers like [30–41] have also provided analytical, experimental, and numerical work based on the Newmark sliding block method and thereby applying the displacement-based approach to compute the displacement and rotation of a retaining wall under seismic loading; and as such assessing the stability of retaining structures based on allowable displacement.

Like for the static case, researchers over the years have tried to investigate the relationship between the retaining wall displacement and development of seismic earth pressure. For example, an elastic solution to study the influence of retaining wall flexibilities on seismic earth pressure was presented by [42] and the analysis showed that the maximum wall force was significantly smaller than that obtained by the conventional force-based method. Similarly, [43] proposed the intermediate wedge approach to consider the mobilization of frictional