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Influence of non-breaking wave force on seismic stability of seawall for passive condition

B. Giridhar Rajesh, Deepankar Choudhury*

Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai 400076, India

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ABSTRACT

Proper design of seawall in earthquake prone region is one of the major concerns in geotechnical earthquake engineering. This paper presents the stability analysis of seawall under the combined action of earthquake forces, non-breaking wave force, hydrostatic and hydrodynamic forces and uplift force. Stability of seawall is assessed in terms of its factor of safety against landward sliding and landward overturning modes of failures. Seismic passive earth resistance has been calculated using pseudo-static approach. A detailed parametric study has been conducted to study the effect of non-breaking wave height, depth of water on seaward and land ward sides, soil and wall friction angles, and horizontal and vertical seismic accelerations. The factor of safety against overturning mode of failure decreases by about 52%, for a change in the ratio of non-breaking wave height to the depth of water on seaward side from 0 to 0.60. Present study shows that the seismic stability of seawall is more sensitive to non-breaking wave height, soil friction angle, wall friction angle and horizontal seismic acceleration. Proposed closed-form solutions and design charts can be used for the seismic design of seawall for passive case under the combined action of earthquake and non-breaking wave forces.

1. Introduction

Gravity type seawalls are the most common type of construction used to defend shoreline against wave attack. Poor performance of the many seawalls can be noticed from the past major earthquakes like Loma Prieta in 1989, Northridge in 1994, Kobe in 1995, Bhuj in 2001, South Asian Sumatra in 2004 and Tohoku in 2011 (Werner, 1998; Dakoulas and Gazetas, 2008; Sheth et al., 2006; Cilingir et al., 2011; Kang et al., 2014). The movement of a seawall can be either seaward side or landward side depending on various factors such as the weight of the seawall, the combination of forces acting on the seawall and the strength of the backfill and foundation soil (Ghalandarzadeh et al., 1998; Dakoulas and Gazetas, 2008). The present study deals with the landward movement of seawall during the earthquake which has not been received much attention so far. Two seawalls of Kobe port during the 1995 earthquake had experienced similar mode of failure (Ghalandarzadeh et al., 1998; PIANC, 2001). Landward overturning of seawall due to 1993 Hokkaido Nansei-Oki earthquake tsunami has been reported by Shuto and Matsutomi (1995). The seawall on the Ryoishi coast, Iwate Prefecture has also failed by landward overturning due to the 2011 Great East Japan Earthquake and Tsunami (Kato et al., 2012). In the normal conditions, i.e., when there is no earthquake, seawalls will be continuously experiencing wave forces which are time varying in nature. When these waves overtop the seawall, they might cause lee ward scour leading to loss of passive resistance from the backfill. This in turn with wave forces on the seaward side might cause landward movement of the seawall (USACE, 2005). So, seawall must be designed to be safe against landward movement as well. The wave forces acting on seawalls can be divided into non-breaking wave forces, breaking wave forces and broken wave forces. This paper focuses on the stability of seawall under the influence of non-breaking wave force in succession with earthquake forces. Seawall will be subjected to a non-breaking wave force when the depth of water at the wall is greater than 1.5 times the maximum design wave height. Most of the seawalls support the submerged backfill, in such cases an extra hydrodynamic pressure will be generated during the seismic event in addition to the lateral earth pressure on landward side and the hydrodynamic pressure from water on the seaward side. Due to the complications of the combination of these forces acting simultaneously, the design of seawall becomes challenging to the geotechnical engineers. In the present study, seismic design of gravity type seawall subjected to the combined action of earthquake forces, non-breaking wave force, hydrostatic and hydrodynamic forces and uplift force using the pseudo-static method is presented.

* Corresponding author. Tel.: +91 22 2576 7335/8335; Fax: +91 22 2576 7302.
E-mail addresses: bgrajesh@iitb.ac.in (B. Giridhar Rajesh), dc@civil.iitb.ac.in, dchoudhury@iitb.ac.in (D. Choudhury).

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Nomenclature

b, h width and height of the wall
H height of non-breaking wave
d_S, d_L height of water on seaward and landward sides of the seawall
F_{dr}, F_{df} driving force for restrained and free water conditions
F_r resisting force
FS_{sr}, FS_{sf} factor of safety against sliding mode of failure in restrained and free water cases
FS_{or}, FS_{of} factor of safety against overturning mode of failure in restrained and free water cases
k permeability of soil
k_h, k_v horizontal and vertical seismic acceleration coefficient
K_{pe} seismic passive earth pressure coefficient
K a constant$=0.5K_{pe}\overline{\gamma}(1-k_v)(1-r_u)$
K_1, K_2, K_3 numerical constants
L wave length of non-breaking wave
P_1 increase in water pressure due to wave crest at the wall
P_{pe} seismic passive resistance
P_{dynS}, P_{dynL} hydrodynamic pressure on seaward and landward sides of the seawall
P_w non-breaking wave pressure including hydrostatic water pressure on seaward side
P_{stL} equivalent hydrostatic pressure on landward side
u_S, u_L pore water pressure at the seaward and landward sides of the seawall
U_b uplift pressure at the base of the seawall
r_u pore pressure ratio
W weight of the wall
y_{pe} point of application of P_{pe}
x point of application of uplift pressure
h_o height of mean water level above the still water level at the wall
χ wave reflection coefficient$=1$(assuming complete reflection of incident wave)
y_c depth of wave crest$=d_S+h_o+\left(\frac{1+\chi}{2}\right)H=d_S+h_o+H$
δ,ϕ wall and soil friction angles
δ_b friction angle at the base of the seawall
γ_w,γ_c unit weight of water and concrete
$\gamma_d,\gamma_{sat},\gamma_{sub}$ dry, saturated and submerged unit weight of soil
$\gamma_{we},\overline{\gamma}$ equivalent unit weight of water and soil due to submergence
θ wall inclination with respect to vertical
μ coefficient of base friction
α scaling factor that correlates PGA and k_h

2. Review of literature

Okabe (1924) and Mononobe and Matsuo (1929) did the pioneering work on seismic lateral earth pressures. They extended the conventional coulomb's static earth pressure theory to seismic case by considering two additional forces, seismic horizontal and vertical inertia forces (k_hg and k_vg), which is commonly known as Mononobe-Okabe method (see Kramer (1996)) and is widely used worldwide for seismic design of retaining walls. But, this study is valid only for dry backfills. A subsequent study of Chakrabarti et al. (1978) proposed the methodology for seismic design of gravity-type cellular cofferdams considering both water in front and in the backfill soil by extending simple static design techniques to seismic case. The authors recommended the factor of safety values against sliding and overturning away from backfill to be greater than 2 and 3 respectively. However, their work is only applicable to cellular coffer dams founded on rock. Further, the excess pore pressure and the hydrodynamic pressure generated in the backfill were neglected in the study. Later on, the issue of hydrodynamic pressure in the submerged backfill was addressed by Matsuzawa et al. (1985). Depending on the permeability of backfill, the authors defined free water and restrained water conditions and suggested calculating the hydrodynamic pressure by Westergaard (1933) formula and adding it to seismic earth pressure in the case of free water conditions of backfill. But, the study of Matsuzawa et al. (1985) only confined to hydrodynamic pressure in the backfill and its relation to the permeability of the backfill and did not address the stability and design aspects of waterfront retaining wall with excess pore pressure generated in the backfill. Further, the study of Ebeling and Morrison (1992) presented the design aspects of waterfront retaining wall in detail. The authors suggested new computational procedures to consider excess pore water pressure and partial submergence in the backfill. However, it did not address the effect of wave forces on the stability of waterfront retaining wall. The present study focuses to address the existing limitations in literature of omitting wave forces in the stability analysis of waterfront retaining wall along with the seismic earth pressures considering curved failure surface.

Choudhury and Ahmad (2007) and Chakraborty and Choudhury (2014) discussed the design of seawall for passive case under the combined action of earthquake and tsunami. These works presented the closed-form design solutions for vertical and inclined seawall respectively. But, these studies considered only the front force of the tsunami and neglected the force due to tsunami from the backfill side furthermore the authors have used the same seismic inertia angle in both irrespective of backfill conditions. Kang et al. (2014) estimated tsunami force numerically to overcome the shortcoming and proposed the factor of safety equations for sliding and overturning stability in active case. All these studies presented the combined effect of tsunami wave force and seismic inertia forces on stability of seawall. But, the combined effect of most common waves such as non-breaking, breaking and broken waves during the earthquake has not yet investigated thoroughly. The probability of occurrence of non-breaking wave from seaward side along with the earthquake main shock may be unlikely, but there is always a possibility of occurrence of moderate non-breaking wave along with earthquake main-shock or consequent foreshocks or aftershocks (PIANC, 2001). The recent 2015 Lamjung and 2011 Tohoku earthquakes show the importance of aftershocks which are of comparable magnitude with main-shocks, to consider in the design with wave forces. Rajesh and Choudhury (2015) studied the stability of seawall under the combined action of non-breaking wave force and seismic active earth pressure. However, the stability of seawall under the influence of non-breaking wave in passive condition of earth pressure is still scarce. Hence, in the present study an attempt has been made to propose a methodology for the design of seawall under the combined action of non-breaking wave force, uplift force, hydrostatic and hydrodynamic forces and seismic passive resistance and seismic inertia forces in the wall due to an earthquake or subsequent aftershocks.