Applied Ocean Research 65 (2017) 154–165

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

Stability of seawalls using modified pseudo-dynamic method under earthquake conditions

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ARTICLE INFO

Article history:
Received 20 July 2016
Received in revised form 11 March 2017
Accepted 3 April 2017
Available online 17 April 2017

Keywords:
Sliding
Overturning
Seismic active earth pressure
Factor of safety
Hydrodynamic pressure
Hydrostatic pressure

ABSTRACT

By using the modified pseudo-dynamic method for submerged soils this paper explores the seismic stability of seawall for the active condition of earth pressure. Different forces such as seismic active earth pressure, seismic inertia forces of the wall, non-breaking wave pressure, hydrostatic and hydrodynamic pressures are considered in the stability analysis. Limit equilibrium has been used, and expressions for the factor of safety against sliding and overturning mode of failure have been proposed. The proposed methodology overcomes the limitations of existing pseudo-dynamic method for submerged soils. A detailed parametric study has been conducted by varying different parameters and results are presented in the form of design charts for computation of factor of safety against sliding and overturning mode of failures. It was noticed that the influences of soil friction angle, seismic acceleration coefficient, wall inclination and excess pore pressure are significant when compared to the other parameters. The value of factor of safety against the sliding mode of failure is increasing by about 62% when the value of soil frictional angle is increased from 30° to 40°. It was also found that the factor of safety against overturning mode of failure is decreasing by about 22% as the value of excess pore pressure ratio increases from 0 to 0.75. The proposed method with closed-form solutions can be used for the seismic design of seawalls.

1. Introduction

Seawalls are one of the most common marine concrete structures, which are typically constructed along the shorelines to safeguard ports and harbors. Proper design of seawalls in the earthquake prone areas is one of the most complex and challenging problems in geotechnical earthquake engineering. Damages of the many seawalls were seen in the past major earthquakes such as South Asian Sumatra earthquake in 2004 and Tohoku earthquake in 2011.

The current seismic design and analyses procedures on the subject of waterfront retaining structures can be broadly divided into three categories (PIANC [1]): simplified method, simplified dynamic method, and dynamic method. Dynamic methods can be considered as more sophisticated methods possible to estimate the seismic response of the wall and the soil system. In general, these methods are based on numerical methods such as Finite element method (FEM) or Finite difference method (FDM) which incorporate soil-structure interaction in the analysis. The major limitations of these methods are these need great effort, time and selection of suitable input parameters. Simplified method is conventional pseudo-static force balance design approach. Simplified method is adopted in the conventional seismic design codes and guidelines such as Eurocode 8 (EN 1998-5 [2]), technical Standard and commentaries for port and harbor facilities in Japan (OCDI [3]), the seismic design of waterfront retaining structures (Ebeling and Morison [4], which is a basis of the design practice in North America), code of practice for maritime structures by British Standards (BS 6349 [5]) and Italian building code (D. M. 14/01/08 [6]). In these simplified methods the influence of earthquake ground motions are considered by peak ground acceleration (PGA) or an equivalent seismic coefficient (k_h and k_v in horizontal and vertical directions respectively). In most of the seismic design guidelines, this equivalent lateral seismic coefficient is computed by multiplying the design PGA by commonly named "reduction factor." It is widely accepted in the literature that the pseudo-static method does not account for the dynamic nature of seismic loading, ignoring the effect of time completely (Steedman and Zeng [7]; Choudhury and Ahmad [8]; Basha and Babu [9,10]; Bellezza et al. [11]). Furthermore, the equivalent lateral seismic coefficient is not directly related to the displacement of the wall though it is a fact that

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http://dx.doi.org/10.1016/j.apor.2017.04.004
0141-1187/

Nomenclature

$u_{hs}(z,t)$, $u_{vs}(z,t)$ Horizontal and vertical seismic displacements in the backfill at depth z and time t
$a_{hs}(z,t)$, $a_{vs}(z,t)$ Horizontal and vertical seismic accelerations in the backfill at depth z and time t
$Q_{hs}(t)$, $Q_{vs}(t)$ Horizontal and vertical seismic inertia forces in soil
$Q_{hw}(t)$, $Q_{vw}(t)$ Horizontal and vertical seismic inertia forces in wall
T Period of lateral shaking
t Time
V_{Ss},V_{Ps} Shear and primary wave velocities in the backfill
V_{Sw},V_{Pw} Shear and primary wave velocities in the wall
z Depth from the ground surface
ξ_s Damping ratio of soil
ξ_w Damping ratio of wall
b, h Width and height of the wall
H Height of non-breaking wave
d_w Depth of submergence level
F_d Summation of driving forces acting on the seawall
F_r Summation of resisting forces acting on the seawall
FS_s Factor of safety against sliding mode of failure
FS_o Factor of safety against overturning mode of failure
k_h, k_v Horizontal and vertical seismic acceleration coefficient
C_1 Numerical constant
$P_{ae}(t)$ Total seismic active earth pressure
P_{dynL} Hydrodynamic pressure from landward side of the seawall
P_{dynS} Hydrodynamic pressure from seaward side of the seawall
P_w Non-breaking wave pressure including hydrostatic water pressure on seaward side
P_{stL} Equivalent hydrostatic pressure on landward side
P_{stS} Hydrostatic pressure on seaward side
r_u Excess pore water pressure ratio
W_W Weight of the wall
y_{ae} Point of application of P_{ae}
δ,ϕ Wall and soil friction angles
γ_w, γ_c Unit weight of water and concrete
y_{s1}, y_{s2}, y_{p1}, y_{p2} Dimensionless constants
η_1, η_s Viscosities
ρ Density
γ_d, γ_{sub} Dry and submerged unit weight of soil
γ_{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
(x_c, y_c) Centroid of the seawall
h_o Height of mean water level above the still water level at the wall
y_t Depth of wave trough = $d_w + h_o - H$
α Angle of failure wedge with the horizontal at the base of the seawall

sufficient amount of wall movement is essential to produce an active earth pressure state in soil. To overcome these limitations, researchers have come up with displacement based approaches and pseudo-dynamic methods which belong to the category of simplified dynamic method (Richards and Elms [12]; Whitman and Liao [13]; Steedman and Zeng [7]; Choudhury and Ahmad [8]; Bellezza et al. [11]). The displacement-based approaches are based on rigid block model of Newmark [14]. Richards and Elms [12] and Whitman and Liao [13] proposed the closed-form empirical formulae for computing permanent displacements which are the function of peak ground acceleration (PGA), peak ground velocity and threshold acceleration of the wall (Kramer [15]). But, it is a well-known fact that the permanent displacement also depends on the seismic ground motion parameters such as frequency and duration (Ahmad and Choudhury [16]). Moreover, the empirical formulae proposed for computing final displacements in the literature do not account for water in front of the wall and submergence in the backfill, which cause the hydrodynamic force on waterfront retaining structures. The present study belongs to the group of pseudo-dynamic methods which focuses on the limitation of neglecting time in the conventional simplified analysis of seismic waterfront retaining structures.

During an earthquake, a typical seawall can experience seismic inertia forces of the wall, seismic earth pressure, hydrostatic pressures and hydrodynamic pressures. In addition to them, a seawall may also be subjected to the wave forces on the seaward side during an earthquake. The probability of experiencing a major wave attack from the seaward side along with the earthquake mainshock may be unlikely, but there is always a possibility of occurrence of moderate wave force along with subsequent seismic aftershocks (PIANC [1]).The recent 2015 Gorkha (Nepal) and 2011 Tohoku earthquakes show the importance of aftershocks which are of the practically identical magnitude of mainshocks. Hence, in the present study, all the above-mentioned forces including wave force from the seaward side are considered, and a new design methodology for the seismic design of seawall is proposed.

2. Review of literature

Chakrabarti et al. [17] proposed a methodology for designing gravity-type cellular cofferdams under the action of earthquake forces. This research is a basic extension of static design techniques of gravity-type cellular cofferdams to seismic condition and is based on the Mononobe-Okabe method (Kramer [15]). Ebeling and Morison [4] described the seismic analysis and design of waterfront retaining structures in detail by addressing various design aspects such as wall displacements, backfill submergence, excess pore water pressure and hydrodynamic pressure generated in the backfill. Choudhury and Ahmad [18,19] proposed the closed-form design solutions for the seismic stability of waterfront retaining wall in the active and passive condition of earth pressures respectively. But, all these studies are based on pseudo-static method. In the pseudo-static method, the influence of earthquake is considered by adding a set of equivalent static forces (pseudo-static forces) to the other non-earthquake forces. The pseudo-static forces in soil are computed by multiplying the weight of the failure wedge with the equivalent seismic coefficients (k_h and k_v). Similarly, the seismic inertia forces in the wall are calculated by multiplying the weight of the wall with the equivalent seismic coefficients. The centrifuge tests conducted by Steedman and Zeng [7] showed the phase change in lateral acceleration in the backfill behind the retaining wall as shear wave propagate from bottom of the wall to ground surface. There is no possibility to consider this aspect in the pseudo-static analysis. Further, it considers the effect of earthquake in a very approximate way and the effect of time period of earthquake and duration are neglected (Steedman and Zeng [7]; Choudhury and Ahmad [8]; Bellezza et al. [11]).

To overcome these limitations of pseudo-static method, Choudhury and Ahmad [8] proposed a pseudo-dynamic method by considering phase difference in the submerged backfill behind a vertical waterfront retaining wall and time period of the earthquake. For illustration, if the base of a retaining wall of height h retaining a submerged backfill soil having shear wave velocity V_{Ss}