Ain Shams Engineering Journal (2014) **5**, 343–354

Ain Shams University

Ain Shams Engineering Journal

www.elsevier.com/locate/asej
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CIVIL ENGINEERING

Probabilistic pseudostatic analysis of pile in laterally spreading ground: Two layer soil profile

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Received 9 August 2012; revised 18 December 2013; accepted 23 December 2013
Available online 23 January 2014

KEYWORDS

Reliability analysis;
Response surface method;
Single pile;
Lateral spread;
Pseudostatic approach

Abstract Coupling the finite element model of pile under lateral spread with the Monte Carlo Simulation is frequently prohibited by excessive lengthily computations. In the present paper, a simplified pseudostatic method is integrated with an improved response surface scheme to evaluate the reliability of pile subjected to lateral spread. The pseudostatic model takes both geometric and soil nonlinearities into account, while, the response surface formulation takes; load, geometry, material and model uncertainties into consideration. First; the improved response surface scheme is suggested and validated with the help of a simple example. Then, the pseudostatic model of a full size pile under lateral spread is integrated with the improved response surface scheme in order to assess the pile reliability. In the considered example, for both operational and structural possible modes of failure, it has been found that the most influential random variables are lateral displacement, and pile radius, respectively.

1. Introduction

Liquefaction-induced lateral spread can cause substantial amount of damage to pile-foundations of buildings and bridge piers. The lateral spread is very unpredictable and its kinematic interaction with the pile may induce significant residual horizontal deflections, shear forces and bending moments to the pile. The analysis and design procedure of pile in liquefying grounds is inherently burdened by many uncertainties such as; ground motion induced loads and displacements, material properties of piles and the pile–soil interaction characteristics. Therefore, rational design decision cannot be made without taking these uncertainties into account. In other words, to obtain a least-cost pile which recognizes the presence of uncertainties over its expected life time, the design of pile should be based on reliability concept, where the uncertainties can be recognized and treated adequately in a probabilistic-based format.

Bradley et al. [1] have proposed a probabilistic framework for pseudostatic analysis of pile foundations in liquefied and lateral spreading soils. Where a pseudostatic method involves applying static displacements and forces to a typical beam-spring/ Winkler model, has been integrated with Monte Carlo Simulation. It has been observed that the significant uncertainties involved in pile in laterally spread soil result in significant uncertainty in pile-head displacement and pile bending moment for a given level of input ground motion. Consequently the

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Peer review under responsibility of Ain Shams University.

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http://dx.doi.org/10.1016/j.asej.2013.12.010

Nomenclature

A, A_b and A_s	the cross sectional area of pile, beam and solid elements, respectively
b_0, b_i, b_{ii}, and b_{ij}	unknown coefficients of a polynomial to be determined
CCD, SD	central composite design and saturated design
Dh	the maximum liquefaction-induced lateral displacement
D_p	the pile diameter
E, E'	the Young's modulus of pile material and solid element, respectively
EA, EI	the axial stiffness and the flexural rigidity of the pile, respectively
$g(\mathbf{X})$	explicit expression of the limit state function
$\hat{g}(\mathbf{X})$	response surface function
$g_m(X)$	the limit state function of moment
$\hat{g}_{\mathrm{m}}(\mathbf{X})$	the response surface function of moment
$g_{ux}(X)$	the limit state function of drift
$\hat{g}_{ux}(X)$	the response surface function of drift
h_i	an arbitrary factor that defines the experimental/sample region
H_{liq}	the thickness of the liquefiable soil layer
I, I_b and I_s	second moment of inertia of the pile, beam, and the solid elements, respectively
k	the number of random variables
k_r	the rotational stiffness of the base
m	total number of most sensitive random variables
M_u	the moment capacity of the pile section
MCS	Monte Carlo Simulation
p	the numbers of coefficients necessary to define a polynomial
P_f	the probability of failure
q	assumed uniform distributed pressure
r	the pile radius
t	the pile thickness
ux	the pile head deflection
X_{all}	the allowable drift
$\mathbf{x}_{C_2}$	second center point
$\mathbf{x}_{D_1}$	the coordinates of the first checking point
X_i $(i = 1, 2, \ldots, k)$	the ith random variable
X_i^C	the coordinates of the center point, i
$X_d = Y_d = Z_d$	the dimensions of soil domain in x, y and z directions, respectively
α	distance $\alpha = 2^{k/4}$ from the center point on the axis of each random variable
α_m	the model correction factors for the estimation of moment
α_u	the model correction factors for the estimation of drift
β	β-index = reliability index
ε	pre-selected convergence criterion
σ_{x_i}	the standard deviation of a random variable X_i

decision making based on a single reference model is potentially erroneous.

Although, the Winkler model is simple and can be practically coupled with Monte Carlo Simulation, it needs a soil resistance–lateral displacement curve (p–y curve). This curve should be back-figured from either the field or a model test. Also, the beam-spring model is clearly a gross simplification of the highly non-linear dynamic response of an entire soil–pile system. The uncertainty of force–displacement response can be accounted as uncertainty in both the equivalent stiffness and strength.

To the author knowledge, the above mentioned method is the only method in the literature to determine the reliability of pile under lateral spread. As an alternative to the spring model-based simulation method, the present paper aims to integrate an improved response surface scheme with a pseudo-static based 3-D elasto-plastic model of pile under lateral spread to compute the pile reliability.

First, an improvement in the response surface scheme of Lee, and Haldar [2] is initially suggested and verified using a simple example, (example 1) [3]. Then, the probability of failure is computed for a pseudostatic based 3-D elastoplastic model of pile under lateral spread from the literature Hussein et al. [4], (example 2). This model is chosen to avoid complexity and lengthily time consuming in long running of the finite element code which governs the reliability assessment. Moreover, this 3-D elasto-plastic model is more realistic, it needs no soil resistance-lateral displacement curve and it can take the soil elastic modulus and angle of internal friction into consideration. The pseudostatic approach involves applying static displacements on a 3-D elastoplastic finite element model. Moreover, both the geometric and soil nonlinearities are taken into account. In the formulation of response surface, the uncertainties of loads, geometrical details, material properties and modeling are explicitly incorporated. Finally, the most influential random variables are determined.

In other words, the paper suggests an improvement of the response surface scheme of Lee and Haldar [2], then integrates the improved scheme with a simplified pseudostatic-based model of pile under lateral spread of Hussein et al. [4] to compute an approximated value of the probability of failure in one computer session.

2. Pile embedded in two layer soil profile

In practice, two cases are commonly encountered; a 2-layer soil profile and a 3-layer soil profile. While, the 2-layer soil profile is manipulated in the present paper, the pile embedded in 3-layer soil profile is handled in another ongoing paper. A 2-layer soil profile represents a thick liquefiable soil layer which lies upon a non-liquefiable bed. To resist deformations of the lateral spread, free head piles are driven through the liquefiable soil layer and firmly embedded into the non-liquefiable bed. This case is usually encountered in practice when river or lake banks, is covered by poorly consolidated natural deposits or fills [5], as shown in Fig. 1a. This design case can be represented by a simple model called a limit equilibrium model which was suggested by Dobry et al. [6]. In this model, the pile will respond as a partially fixed column of length equal to the thickness of the liquefiable soil layer H_{liq}, and with rotational spring at the base of rotational stiffness, k_r, as shown in