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Practical applications of a nonlinear approach to analysis of earthquake-induced liquefaction and deformation of earth structures

Zhi-Liang Wang*, Faiz I. Makdisi, John Egan

Geomatrix Consultants, Inc., 2101 Webster Street, 12th Floor, Oakland, CA 94612, USA

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Abstract

Seismic stability, liquefaction, and deformation of earth structures are critical issues in geotechnical earthquake engineering practice. At present, the equivalent linear approach is considered the 'state of practice' in common use. More recently, dynamic analyses incorporating nonlinear, effective-stress-based soil models have been used more frequently in engineering applications. This paper describes a bounding surface hypoplasticity model for sand [Wang ZL. Bounding surface hypoplasticity model for granular soils and its applications. PhD Dissertation for the University of California at Davis, U.M.I. Dissertation Information Service, Order No. 9110679; 1990; Wang ZL, Dafalias YF, Shen CK. Bounding surface hypoplasticity model for sand. ASCE, J Eng Mech 1990;116(5):983–1001; Wang ZL, Makdisi FI. Implementing a bounding surface hypoplasticity model for sand into the FLAC program. In: Proceedings of the international symposium on numerical modeling in geomechanics. Minnesota, USA; 1999. p. 483–90] incorporated into a two-dimensional finite difference analysis program [Itasca Consulting Group, Inc. FLAC (Fast Lagrangian Analysis of Continua), Version 4. Minneapolis, MN; 2000] to perform nonlinear, effective-stress analyses of soil structures. The soil properties needed to support such analyses are generally similar to those currently used for equivalent linear and approximate effective-stress analyses. The advantages of using a nonlinear approach are illustrated by comparison with results from the equivalent linear approach for a rockfill dam. The earthquake performance of a waterfront slope and an earth dam were evaluated to demonstrate the model's ability to simulate pore-pressure generation and liquefaction in cohesionless soils.

Keywords: Stability of dams; Earthquake performance; Nonlinearity of soils; Plasticity model; Liquefaction

1. Introduction

The state-of-practice for evaluating the seismic stability of earth dams was developed in the early and mid-1970s by the late Professor Seed and co-workers at the University of California at Berkeley [5]. The basic elements of this analysis included the following steps: (a) earthquake ground motions are estimated at bedrock underlying the dam and its soil foundation; (b) the response of the embankment to the base rock excitation is computed to estimate the dynamic stresses induced in representative elements of the embankment; (c) the cyclic strength of the embankment soils is evaluated using in situ tests and liquefaction resistance correlation curves based on observed performance during past earthquakes; (d) by comparing the dynamic-induced shear stresses to the cyclic strength, the potential for liquefaction of the embankment and foundation soils is estimated; (e) for the zones of the embankment that are determined to have liquefied during the earthquake, a residual strength is assigned based on the density of the soil; (f) the stability of the embankment and its foundation is evaluated using limit equilibrium stability analyses; if the embankment is found to be stable, earthquake-induced permanent displacements are estimated using Newmark-type deformation analyses. In this procedure, the dynamic response of an embankment is estimated using an iterative equivalent linear approach [6] to model the nonlinear strain-dependent modulus and damping properties of the soils. With this approach, however, the computed seismic response and shear stresses within embankment soils do not reflect the effects of induced pore pressure during earthquake shaking. The amount of induced pore pressure and the potential for liquefaction are estimated at the end of the specified duration of shaking.

* Corresponding author. Fax: +1 510 663 4141.
E-mail address: zlwang@geomatrix.com (Z.-L. Wang).

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Nomenclature

a	model parameter
b	model parameter
A	constant
c_1, c_2, c_3, c_4	constants
$C(\xi)$	modulus degradation function
d	dilatancy
$\mathrm{d}\varepsilon_{ij}$, $\mathrm{d}\varepsilon^{\mathrm{e}}_{ij}$, $\mathrm{d}\varepsilon^{\mathrm{p}}_{ij}$	total, elastic, and plastic deviatoric strain increment
$\mathrm{d}\varepsilon_{\mathrm{v}}$, $\mathrm{d}\varepsilon^{\mathrm{e}}_{\mathrm{v}}$, $\mathrm{d}\varepsilon^{\mathrm{p}}_{\mathrm{v}}$	total, elastic, and plastic volumetric strain increment
$\mathrm{d}\varepsilon_{\mathrm{vd}}$, $\mathrm{d}\varepsilon^{\mathrm{p}}_{\mathrm{d}}$	shear-induced volumetric strain and plastic strain increment
$\mathrm{d}p$	increament of mean stress
$\mathrm{d}r_{kl}$	increament of deviatoric stress ratio tensor
$\mathrm{d}s_{ij}$	increament of deviatoric stress tensor
e, e_{c}	void ratio, critical void ratio
e_{ij}, e^{e}_{ij}, e^{p}_{ij}	deviatoric strain, elastic and plastic deviatoric strains, respectively
g	gravity
$g(\theta)$	shape function on $p=$const plane
$G_{\max}$	elastic shear modulus
G_o	model parameter
G	secant modulus
h_{r}	model parameter
$h(x)$	heavyside step function
H_{r}, H_{p}	plastic shear modulus for $\mathrm{d}r_{ij}$ and $\mathrm{d}p$ mechanisms, respectively
I_{p}	state pressure index
J	second deviatoric stress invariant
k_{r}	model parameter
K	elastic bulk modulus
K_0	coefficient of lateral earth pressure at rest
K_{r}, K_{p}	plastic bulk modulus for $\mathrm{d}r_{ij}$ and $\mathrm{d}p$ mechanisms, respectively
m	state-dependent index
M	critical stress ratio in $p-q$ space
M_{p}	phase transformation stress ratio in $p-q$ space
$(n_{\mathrm{D}})_{ij}$, $(n_{\mathrm{N}})_{ij}$	unit tensor indicating the direction of the deviatoric plastic strain increment, and deviatoric unit loading, respectively
p	mean normal stress
p_{c}	mean normal stress at critical state
p_{m}	maximum mean normal stress
p_{a}	atmospheric pressure
q	deviatoric stress in triaxial space
r_{ij}, $\bar{r}_{ij}$	stress ratio and image stress ratio, respectively
R, R_{f}, R_{p}, R_{m}	stress ratio invariants for loading, failure, phase transformation, and maximum, respectively
R_{p}	stress ratio invariants for dilatancy
s_{ij}	deviatoric stress tensor
$V(e)$	a function of void ratio
w	a function controls shear-induced volume changes [1,2]
α	model parameter
α_{ij}	projection center for $\bar{r}_{ij}$
δ_{ij}	Kronecker delta
ε_{v}, $\varepsilon_{\mathrm{vd}}$	total and shear-induced volumetric strain
γ	engineering shear strain
γ_{a}	shear strain amplitude
κ	model parameter
ρ, $\bar{\rho}$	distances from projection center
σ_{vo}	overburden pressure
τ	shear stress
τ_{m}	maximum shear stress
η	stress ratio in triaxial space
ξ	accumulated plastic deviatoric strain

In cases where an earth structure is subjected to severe ground motions, and where liquefaction may occur soon during shaking, an alternative approach to account for the effects of buildup of pore pressure and the potential for liquefaction during earthquake shaking is to use a nonlinear effective-stress analysis. This paper describes a nonlinear, fully coupled dynamic analysis procedure for estimating the potential for buildup of pore pressure, the potential for liquefaction, and the resulting permanent deformation of earth structures. The basic elements for such analyses are: (1) an estimated site ground motion; (2) a constitutive model to simulate soil behavior under conditions of cyclic loading and liquefaction; (3) a computer program capable of performing dynamic analyses that are fully coupled (that include mechanical aspects and groundwater flow); and (4) relevant laboratory and in situ measurements of soil properties.

The procedure uses a nonlinear, bounding surface plasticity constitutive model for sand [1,2], incorporated into the finite-difference computer program FLAC [4]. Because the basis for such an analysis is a cyclic plasticity soil model, we will briefly introduce this model before shifting our focus to applications. Recent improvements to the model include: (1) a newly proposed state parameter, the state pressure index, and its use in defining a dilatancy curve; (2) simulation of the critical-state behavior of sands; and (3) simulation of post-liquefaction deformation of sands. These new formulations are verified by comparing model simulations to laboratory test results.

This paper also introduces our current practice of using this bounding surface plasticity model, as incorporated into the computer program FLAC, to perform nonlinear, fully coupled dynamic analyses. The procedures for using and calibrating the model also are explained. The soil tests to