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Site effects on nonlinear seismic response analysis of layered grounds

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Abstract

This study aims to numerically investigate the nonlinear dynamic characteristics of 2D composite grounds of dried soil layers and water saturated porous layers which are in the possibility of liquefaction, using an adaptive absorbing boundary condition, and to show the local site effects on the time-dependent energy concentration at the ground surface during earthquake. At first to verify the reliability of proposed method for nonlinear problems, a ground model with proposed absorbing boundaries is investigated for liquefaction briefly by comparing with reference solutions. Then, using a typical model of Kobe ground and Kobe earthquake, local site effects due to the topographical irregularity are analyzed in terms of key parameters regarding earthquake and liquefaction, and reviewed in association with the actual spread of damages.

1 Introduction

Severe damages of engineering structures in 1995 Kobe earthquake (1995 Hyogo-ken Nanbu earthquake) are characterized by the superstructure damage area on the hard ground and the underground structure damage area on the soft reclaimed ground that is mostly liquefied. Therefore, great attention should be paid to the issue of the local site effects due to the topographical irregularity and liquefaction for the water saturated porous media in seismic response analysis.

In general, the aforementioned problems are investigated by finite element model which is considered as an effective technique in seismic analysis. However, such efforts are usually restricted to a finite domain. An artificial boundary, consequently, is needed to be devised to incorporate the radiation condition of the truncated unbounded region into the finite computational domain.

In the dynamic analysis, the theory of propagation of elastic waves in saturated porous media was firstly presented by Biot [1, 2]. Since then, many finite element models have been developed for this problem. Especially, regarding the absorbing boundary conditions for this problem, Modaressi and Benzenati [3] presented a closed form solution due to *u-p* formulation, and Degrande and De Roeck [4] investigated in detail in frequency domain. Akiyoshi *et al* [5, 6] presented an absorbing boundary condition for *u-w*, *u-U*, and *u-p* formulations in time domain and showed the application to nonlinear problem (liquefaction), the effectiveness of which was verified for the simple or complicated layered grounds in corresponding works [7]. For the composite media with topographical irregularity, this effectiveness, however, is still needed to be further investigated.

In advance of the nonlinear seismic response analysis of complicated layered grounds, the absorbing boundary condition which is developed and incorporated into the existing two-dimensional finite element program for dynamic effective stress (liquefaction) analysis based on the two phase mixture theory and associated constitutive equations is tested for the effectiveness and accuracy. Finally, nonlinear local site effects due to the topographical irregularity and liquefaction are investigated in terms of key parameters regarding earthquake and material properties of soils, and reviewed in association with the actual spread of damages.

2 Finite element equation with absorbing boundary

Based on Biot's two-phase mixture theory [1, 2], the two-dimensional dynamic equilibrium equations for the soil-water phase and generalized Darcy law for the pore water may be expressed as:

$$L^T\sigma + \rho b = \rho\ddot{u} + \rho_f\ddot{w}$$

$$-\nabla p + \rho_f b = \rho_f \ddot{u} + \frac{\rho_f}{n}\ddot{w} + \frac{1}{k}\dot{w} \qquad (1)$$

where a superposed dot indicates a time derivative and a vector matrix notation is used to represent tensors; i.e. $u^T = \{u_x, u_z\}$; $\sigma^T = \{\sigma_x, \sigma_z, \tau_{zx}\}$; $w^T = \{w_x, w_z\}$; $b^T = \{b_x, b_z\}$; $\nabla^T = \{\partial/\partial x, \partial/\partial z\}$ and

$$L^T = \begin{pmatrix} \partial/\partial x & 0 & \partial/\partial z \\ 0 & \partial/\partial z & \partial/\partial x \end{pmatrix} \qquad (2)$$

where u and w are the soil skeleton displacement and the relative pore water displacement, respectively; σ is the total stress; b is body force per unit mass; p is pore water pressure; ρ and ρ_f are the density of the bulk soil-water mixture and the density of pore water, so that $\rho = (1-n)\rho_s + n\rho_f$, where ρ_s is the density of the soil skeleton; k is the permeability coefficient and n is the porosity of the soil.

For the compressible water, the stress-strain relationship may be given as:

$$\begin{aligned} d\sigma &= d\sigma' - \alpha m dp = Dd\varepsilon - \alpha m dp \\ p &= -\alpha Q m^T \varepsilon - Q\varsigma \end{aligned} \qquad (3)$$

where $m^T = \{1,1,0\}$ is equivalent to the Kronecker's delta; σ' and ε are the effective stress and strain vectors in the soil media, respectively, given by $\sigma'^T = \{\sigma'_x, \sigma'_z, \tau_{zx}\}$; $\varepsilon^T = \{\varepsilon_x, \varepsilon_z, \gamma_{zx}\}$; D is the stiffness matrix; α and Q are the constants, defined as $\alpha = 1$ and $Q = K_f/n$ for the saturated soil approximately; ς is the volumetric strain in the pore water.

2.1 Constitutive equations for liquefaction

To treat non-linearity (liquefaction) of the soil, the constitutive model for the plain condition is constructed based on the 2-D strain-space multimechanism model for cyclic mobility of sandy soil first proposed by Iai *et al* [8, 9]. The efficiency of the model characterized by some specific parameters has been shown in the references [10, 11].

2.2 Absorbing boundary condition for liquefaction analysis

In the seismic response analysis, the finite element model, generally, is restricted to a finite domain, which implies that an artificial boundary conditions are required to eliminate the reflected waves from the boundaries of the computational region.

Figure 1 shows a typical model of seismic analysis of ground responses. In

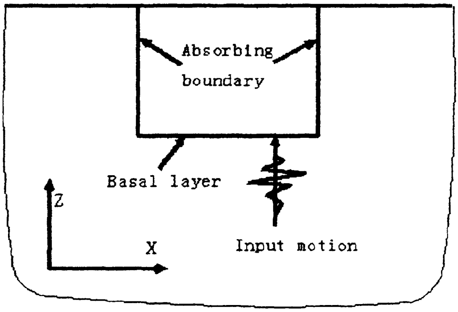

Figure 1. A typical ground model

this study, an absorbing boundary condition in time domain [5] is used to simulate the dynamic effect of infinite domain.

For a two-dimensional model, we use the following absorbing boundary conditions for *u-w* formulation in a local Cartesian coordinate system $(\tilde{x},\tilde{z})$ which are equivalent to the viscous damper's characteristics like Lysmer's viscous damper for one phase media [12];

$$\{\tilde{\tau}_{zx},\tilde{\sigma}_z,0,-\tilde{p}\} = -\begin{pmatrix} A_{uu} & A_{uw} \\ A_{uw}^T & A_{ww} \end{pmatrix}\begin{Bmatrix} \dot{\tilde{u}} \\ \dot{\tilde{w}} \end{Bmatrix} \tag{4}$$

with

$$A_{uu} = \begin{pmatrix} \rho V_S & 0 \\ 0 & \rho V_P \end{pmatrix}; \quad A_{uw} = \begin{pmatrix} 0 & 0 \\ 0 & \alpha Q/V_P \end{pmatrix}$$

$$A_{ww} = \begin{pmatrix} 0 & 0 \\ 0 & Q/V_P \end{pmatrix} \tag{5}$$

$$V_P = \sqrt{\left(\lambda + 2G + \alpha^2 Q\right)/\rho}\,; \quad V_S = \sqrt{G/\rho}$$

where λ and G are Lame's constant.

To generate the absorbing boundary conditions in global Cartesian coordinate system, a projection matrix P is used to transform the vectors in local Cartesian coordinate system to the global Cartesian coordinate system. In addition, if the motion of the free field is taken into account, the absorbing

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boundary condition may be rewritten in terms of traction as:

$$\begin{Bmatrix} \hat{t} \\ -\hat{p}n \end{Bmatrix} = \begin{Bmatrix} \hat{t}^f \\ -\hat{p}^f n \end{Bmatrix} - \begin{pmatrix} P^T A_{uu} P & P^T A_{uw} P \\ P^T A_{uw}^T P & P^T A_{ww} P \end{pmatrix} \begin{Bmatrix} \dot{u} - \dot{u}^f \\ \dot{w} - \dot{w}^f \end{Bmatrix} \qquad (6)$$

where a superscript f on the variable represents the contribution from the motion of the free field.

For nonlinear cases such as liquefaction, the current shear modulus G in eqn. (5) follows the current mean effective stress of soil which varies in time and therefore G is dependent of time [12]. Hence to decide G independently, in this study, the known value of G for the preceding time is used and the efficiency of the procedure for the nonlinear problem will appear in the reference [7].

3 Numerical evaluation of absorbing boundary condition for nonlinear problems

To investigate the effectiveness of proposed absorbing boundary conditions in seismic response analysis of the composite grounds of linear and non-linear media, a two-dimensional finite element model (2-D FE model) is presented in the Figure 2, in which the absorbing boundary (AB) condition is used at

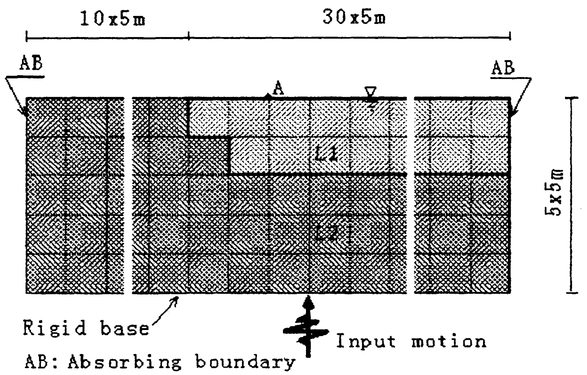

Figure 2. 2-D FE model

both side boundaries and the motion of the 1995 Kobe earthquake with the maximum acceleration of 0.55g acts horizontally on the bottom. As the reference solution, a much wider model with the range of 25m(in depth)×2.2km(in width) is used for the lack of appropriate numerical examples for this ground model. The view point A, as shown in Figure 2, is chosen in the nonlinear (upper layer) domain to represent the efficiency of the proposed technique. In numerical analysis, the ground model is divided by the upper layer and lower layer which are assumed to be non-linear and linear, respectively. Their corresponding SPT N-values are 10 and 50, respectively. The other basic parameters are given as: $\nu = 0.33$; $n = 0.4$; $\rho = 1.9 \times 10^3 \, kg/m^3$; $k = 1 \times 10^{-5} \, m/s$; $K_f = 2 \times 10^6 \, kPa$; $\alpha = 1.0$. In addition, soil parameters for the upper layer is shown in Table 1.

Table 1. Soil parameters for upper layer of a two-layered ground model

Parameter	p_1	p_2	w_1	S_1	c_1	ϕ'_f	ϕ'_P	H_m
L1	0.5	0.85	21.3	0.005	1.0	31°	28°	0.3

Figure 3 show the comparison of proposed absorbing boundary (AB) and the reference solution (RS) at the view point A. The perfect agreement can be seen in this figure, which further demonstrates that the proposed absorbing boundary technique can surely meet the demands of effectiveness and accuracy in seismic response analysis.

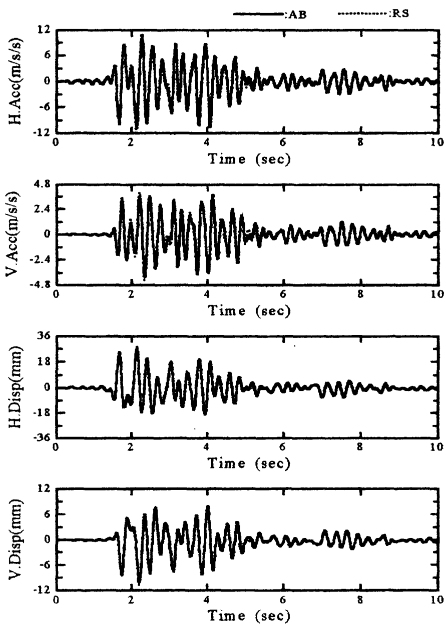

Figure 3. Nonlinear seismic responses at point A

4 Local site effect analysis of a Kobe ground model

Now to investigate the local site effects on layered ground responses,

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aforementioned technique is used to analyze a typical ground model for Kobe area and the 1995 Kobe earthquake as shown in Figure 4. This sedimentary layered ground are divided by five fields, according to [13]. The four layers in the right side which is adjacent to the sea are numbered by *L1* to *L4* from the top to the base, the SPT N-values of which are 10, 3, 50, 10, respectively. The SPT N-value of fifth media *L5* in the middle of the model is 30. The basic parameters are commonly used as in the previous section except for the density, and soil parameters for *L1* and *L2* in the Kobe ground model are shown in Table 2, in which the density of soil is $10^3 kg/m^3$. The densities of *L3*, *L4* and *L5* are assumed as 1.9, 1.8 and 1.9 ($10^3 kg/m^3$), respectively. In addition, the Kobe ground, in fact, is combined by the inclined layers which leads to the variation of dynamic features for different depth of the layer. Therefore, the part of basal layer *L4* within 350m from left side boundary should be considered as a non-linear media, the soil parameters of which are same as *L1* shown in Table 2 except p_2, w_1 and c_1 which may be assumed as 0.98, 8.62 and 1.6, respectively. The motion of the Kobe earthquake impinges normally the bottom surface of the model as shown in Figure 4, in which *Fl, Ac, Asg, Dc* and *Dsg* represent the reclaimed sand and gravel, alluvial clay, alluvial sand and gravel, diluvial clay, and diluvial sand and gravel, respectively.

Table 2. Soil parameters for L1 and L2 in the Kobe ground model

Parameter	ρ	p_1	p_2	w_1	S_1	c_1	ϕ'_f	ϕ'_P	H_m
L1 (Fl)	1.8	0.5	0.85	16.4	0.005	1.0	31°	28°	0.3
L2 (Ac)	1.7	0.5	1.03	5.9	0.005	1.6	30°	28°	0.3

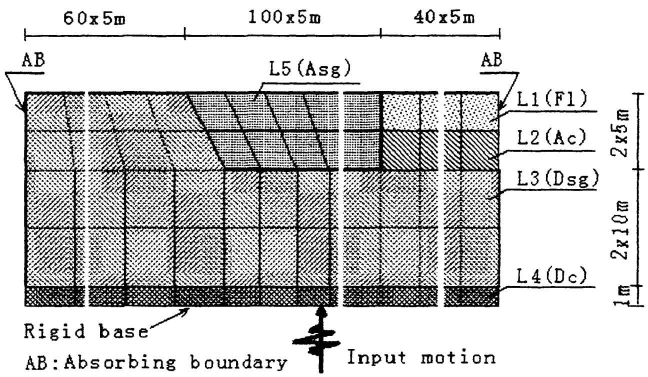

Figure 4. A FE model of Kobe ground

Figure 5 shows the distributions of horizontal acceleration at the ground surface and the shear strain at the depth of 2.5m at each time step, respectively. Figure 6 presents the distributions of maximum acceleration at the ground surface and the shear strain at the depth of 2.5m versus lateral distance from left side boundary.

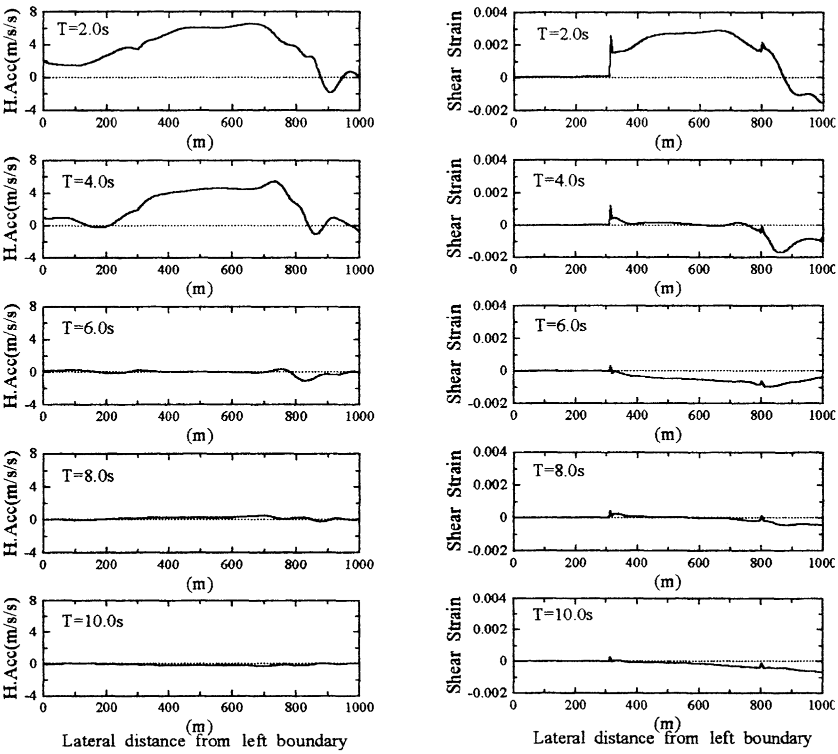

Figure 5. The distribution of horizontal acceleration at ground surface and shear strain at the depth of 2.5m at each time step

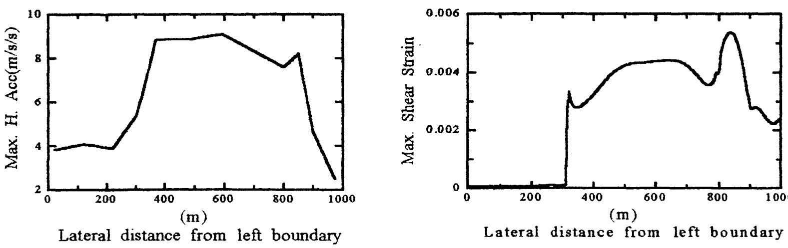

Figure 6. Maximum acceleration at ground surface and shear strain at the depth of 2.5m

In Figure 5, a large acceleration-dominated area appears in the short period of the main shock of input. This seismic intensity dominated area corresponds to the isolated alluvial layer zone (*Asg* in Figure 4) which would be independent of liquefaction. This high seismic intensity zone also agrees with the observation of most severe structural disaster zone in Kobe area, which has been called "damage band area" along the coastal line. Also the distribution of maximum acceleration at the ground surface shown in Figure 6 shares the similar feature that high seismic intensity zone places from 300m to 900m from the left boundary of the ground model.

In Figure 6, it can be seen that bigger shear strain responses appear not only within 200m from the right side boundary of the ground model which corresponds to the extremely soft ground of the layers L_1 and L_2 (*Fl* and *Ac* area), but also the hard ground (*Asg* area), depending on the irregularity of the layer boundaries. Furthermore, the soil liquefaction leads to the residual deformation which can be detected in these diagrams. These analytical results of instantaneous and residual large shear strain of ground surface agree with the observation of the severe damaged area of underground structures.

Referring to the actual damage records for the 1995 Kobe earthquake, large shear strain area (*Asg* and L_1 and L_2 zone) coincide with the lifeline-damaged area, and the poor bearing capacity area due to liquefaction (L_1 and L_2 zone) corresponds to pile foundation damaged area.

5 Conclusions

An absorbing boundary condition for the dynamic analysis of ground model is presented, which is adaptable to both the linear and non-linear water saturated grounds. Due to the implementation of the proposed absorbing boundary condition in the existing FE program for effective stress analysis, the numerical results show that the proposed technique can meet the demands of effectiveness and accuracy in seismic response analysis of actual non-linear grounds. Furthermore, the non-linear analysis of the Kobe ground model with the absorbing boundary reveals the dynamic local site effects due to the topographical irregularity and liquefaction that the thin unsaturated layer of the alluvial sand and gravel layer concentrates not only the high seismic intensity but also large shear strain at the surface of irregularly layered grounds, and the saturated soft grounds like the reclaimed sand and alluvial clay soils produce the instantaneous and permanent large shear strain near ground surface, and results in the well explanation of the damage distribution in the Kobe earthquake.

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