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SITE EFFECTSON SIESMIC RESPONSE OF NON LINEAR LAYERED GROUND

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SUMMARY

This study aims to numerically investigate the nonlinear dynamic characteristics of 2D composite grounds of single-phase soil layers and water saturated porous layers which are possible to be liquefied, and to show the site effects on the time-dependent energy concentration at the ground surface for the 1995 Kobe earthquake. Using the FE program for effective stress analysis, numerical computations are performed for the model of a typical Kobe ground which is basically the irregular composite layers of saturated or unsaturated soil with absorbing boundary dampers at both side boundaries. One of important conclusions of this study is that site effects due to the irregular layering or reclamation of nonlinear soil deposits induce the concentration of acceleration and strain on the ground surface.

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.

The key point of this problem is how to model reasonably the saturated and infinite soil. Usually in order to reduce the cost of analysis, the computational model is restricted to finite domain with an artificial boundary. For the saturated porous media, Biot's two phase mixture theory [Biot, 1956a and b] is frequently used for linear and nonlinear. dynamic analysis. The dynamic analysis is usually implemented via numerical methods involving discretization of both spatial and temporal domains. The typical finite element models developed for the dynamic analysis of solid-fluid problems have accounted for a complex geometry and nonlinear behavior.

In the near field, the non-linear response of soil is influenced generally by various factors such as state of stress, stress path, inelasticity, volume change, and type and rate of loading. Up to now, a number of constitutive models describing the cyclic behaviour of soil have been developed. Of these, the strain-space plasticity model for the cyclic mobility of

sandy soil proposed by Iai et al [Iai, Matsunaga and Kameoka, 1992] appears to be practical, rational and promising. The constitutive properties are devised to be characterized by a volumetric mechanism and a number of microscopic simple shear mechanisms, which can take into account the effect of principal stress axis rotation [Akiyoshi, Matsumoto, Fuchida and Fang, 1994].

In order to simulate the effect of the far field, it is necessary to devise special boundary techniques to incorporate the radiation condition of the truncated unbounded domain into the finite computational model. In the dynamic analysis of dry media, several techniques have been proposed. However, the work on how to model reasonably an unbounded domain in the non-linear seismic analysis of a saturated soil-structure system seems far from adequate.

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In this paper, using an absorbing boundary condition which is formulated as a viscous damper in terms of solid velocity and relative fluid velocity [Akiyoshi, Fuchida and Fang, 1994] and proved to be effective even for liquefaction of water saturated grounds [Akiyoshi, Sun and Fuchida, 1999], a non-linear seismic response analysis method for a 2-D saturated soil is presented. In order to analyze heavily damaged area (band) for Kobe earthquake in 1995, the dynamic site effects of topographical irregularity and nonlinearity of the Kobe ground on the time-dependent stiffness of soil and amplification characteristics of the surface layers are investigated in terms of maximum peak acceleration of the input. Consideration is made for the comparison between the heavily damaged area of structures and lifelines in Kobe earthquake and the computational distribution of maximum acceleration and strain at the ground surface.

FINITE ELEMENT EQUATION WITH ABSORBING BOUNDARY

Based on Biot's two-phase mixture theory [Biot, 1956a and b], the two-dimensional dynamic equilibrium equations for the soil-water phase and generalized Darcy law for the pore water may be expressed as:

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

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

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

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

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.

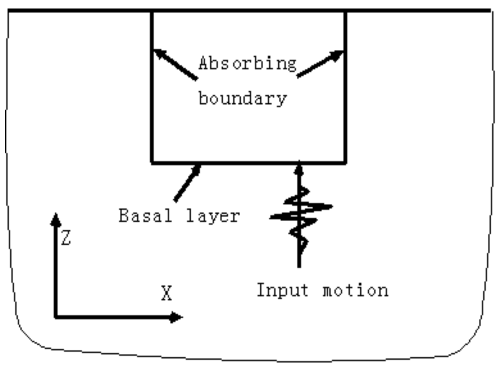


Figure 1: A typical ground model

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

$$d\sigma = d\sigma' - \alpha m dp = D d\varepsilon - \alpha m dp$$

$$p = -\alpha Q m^T \varepsilon - Q\varsigma \tag{3}$$

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.

In the seismic response analysis, the finite element model is generally 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. As Figure 1 shows a typical model of seismic analysis of ground responses, in this study, an absorbing boundary condition in time domain 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 [Lysmer and Waas, 1972] ;

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

with

$$A_{uu} = \begin{pmatrix} \rho V_S & 0 \\ 0 & \rho V_P \end{pmatrix}; \quad A_{uw} = \begin{pmatrix} 0 & 0 \\ 0 & \alpha Q / V_P \end{pmatrix}; \quad A_{ww} = \begin{pmatrix} 0 & 0 \\ 0 & Q / V_P \end{pmatrix} \tag{5}$$

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

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 boundary condition may be rewritten in terms of traction as:

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

where a superscript f on the variable represents the contribution from the motion of the free field. For nonlinear cases such as liquefaction, the viscous coefficient Asr (s,r=u,w) in eqn. (4) are not constant, because the wave velocities Vp, Vs are dependent of time-varying elastic coefficient λ and G due to the change of the effective stress of soil elements.

By considering the irreducible weak Galerkin formulation, the matrix form of finite element equation for a saturated porous medium with compressible pore water including the absorbing boundary condition may be written as:

$$\begin{pmatrix} m_{uu} & m_{uw} \\ m_{uw}^T & m_{ww} \end{pmatrix} \begin{Bmatrix} \ddot{\bar{u}} \\ \ddot{\bar{w}} \end{Bmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & c_{ww} \end{pmatrix} \begin{Bmatrix} \dot{\bar{u}} \\ \dot{\bar{w}} \end{Bmatrix} + \begin{pmatrix} K_{uu} & K_{uw} \\ K_{uw}^T & K_{ww} \end{pmatrix} \begin{Bmatrix} \bar{u} \\ \bar{w} \end{Bmatrix} + \begin{Bmatrix} \int_\Omega B_u^T \sigma' d\Omega \\ 0 \end{Bmatrix}$$
$$= \begin{Bmatrix} \bar{f}_u + \bar{f}_u^f \\ \bar{f}_w + \bar{f}_w^f \end{Bmatrix} - \begin{pmatrix} c'_{uu} & c'_{uw} \\ c'^T_{uw} & c'_{ww} \end{pmatrix} \begin{Bmatrix} \dot{\bar{u}} - \dot{\bar{u}}^f \\ \dot{\bar{w}} - \dot{\bar{w}}^f \end{Bmatrix} \tag{7}$$

where $\bar{u}$ and $\bar{w}$ are the nodal displacement vectors and other notations can be seen in the reference [Akiyoshi, Fang, Fuchida and Matsumoto, 1996].

LOCAL SITE EFFECT ANALYSIS OF A KOBE GROUND MODEL

Now to investigate the local site effects on layered ground responses, aforementioned technique is used to

analyze a typical ground near Sanno-Miya district in Kobe as shown in Figure 2. The surface layer may be characterized by the layering of thin diluvial clay (Dc), thick diluvial sand and gravel (Dsg), alluvial sand and

gravel (Asg) or alluvial clay (Ac), and finally reclaimed sand and gravel (Fl), resting on the base rock (Osaka group layers). Heavily damaged belt is located in 700 – 1600m from the sea side (coastal line). The Kobe ground in Figure 2 is replaced by the ground model of 1000m in width × 31m in depth as Figure 3 for

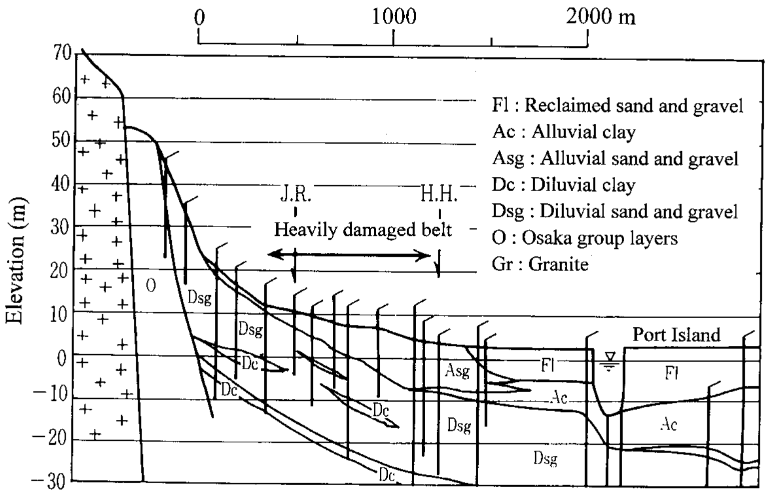


Figure 2: A typical geological cross section near Sanno-Miya district in Kobe

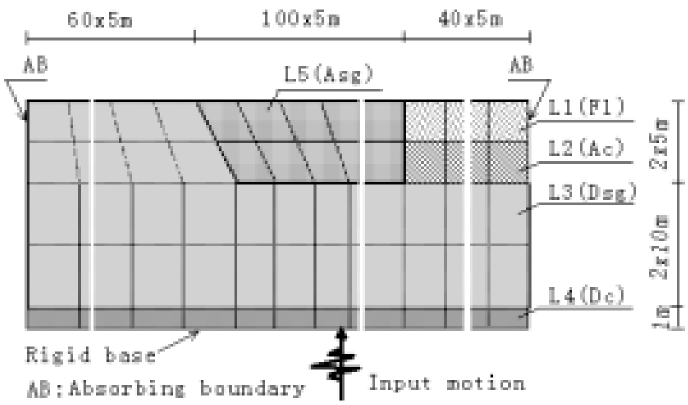


Figure 3: A FE model of Kobe ground

Table 1: Soil parameters for L1 to L5 in the Kobe ground model

Parameters	•	p1	p2	w1	S1	c1	•'f	•'P	Hm	N
L1(Fl)	1.8	0.5	0.85	16.4	0.005	1.0	31°	28°	0.3	10
L2(Ac)	1.7	0.5	1.03	5.9	0.005	1.6	30°	28°	0.3	3
L3(Dsg)	1.9	-	-	-	-	-	-	-	-	50
L4(Dc)	1.8	0.5	0.98	8.62	1.6	1.0	31°	28°	0.3	10
L5(Asg)	1.9	0.5	0.85	21.3	0.005	1.0	31°	28°	0.3	30

•••• is the density of soil (×103 kg/m3), and N is the SPT N-value of soil.

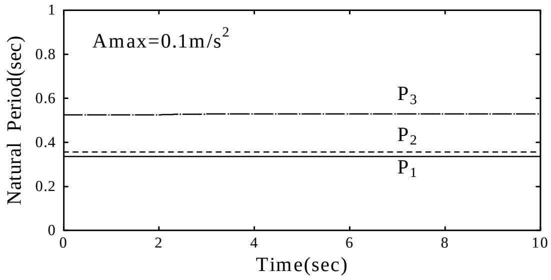
computation in which each layer is named as L1(Fl), L2(Ac), L3(Dsg), L4(Dc) and L5(Asg) . Soil parameters of nonlinear layers except for L3 of linear ground are listed in Table 1.

This sedimentary layered ground are divided by five fields, according to the reference [Ohya, 1996]. 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 for the Kobe ground model are shown in Table 1. The other basic parameters are given as: •=0.33; n=0.4; k=1×10-5m/s; Kf=2×106kPa; •=1.0. 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 1 except p2, w1 and c1 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 3.

Liquefaction will occur depending mostly on the soil profiles and the magnitude of earthquakes, and therefore induces the local degrading of the shear modulus G of soil which results in the extension of the natural period TG of the surface layer during the shaking, in which TG is defined here as

$$T_G = 4\left(H_1 \sqrt{\frac{\rho_1}{G_1}} + \bullet \bullet \bullet + H_n \sqrt{\frac{\rho_n}{G_n}} \right) \tag{8}$$

So, in Figure 4, the time-dependent natural period is shown for three different maximum acceleration amplitudes, Amax, of Kobe earthquake and for three observation points P1, P2 and P3 which locates at the center of each surface points of the typical three layers L3(Dsg), L5(Asg) and L1(Fl), respectively. Large input acceleration induces the drastic shift of natural periods TG at P3 due to liquefaction and gives the slight effect on TG at the adjacent P2.



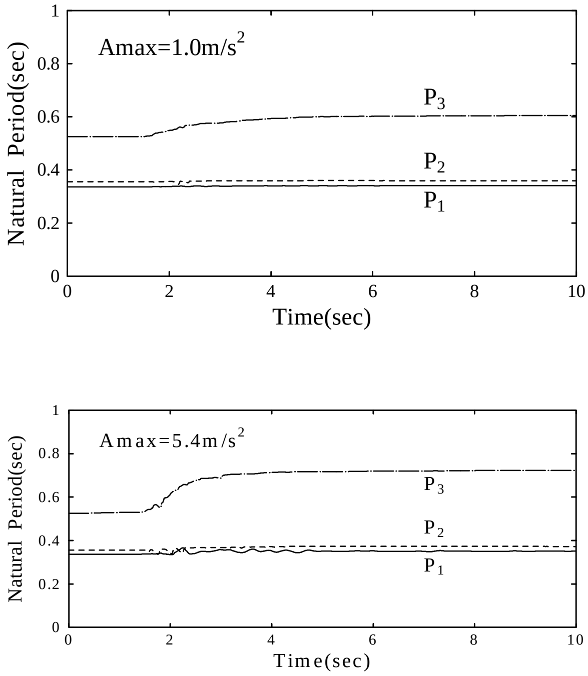
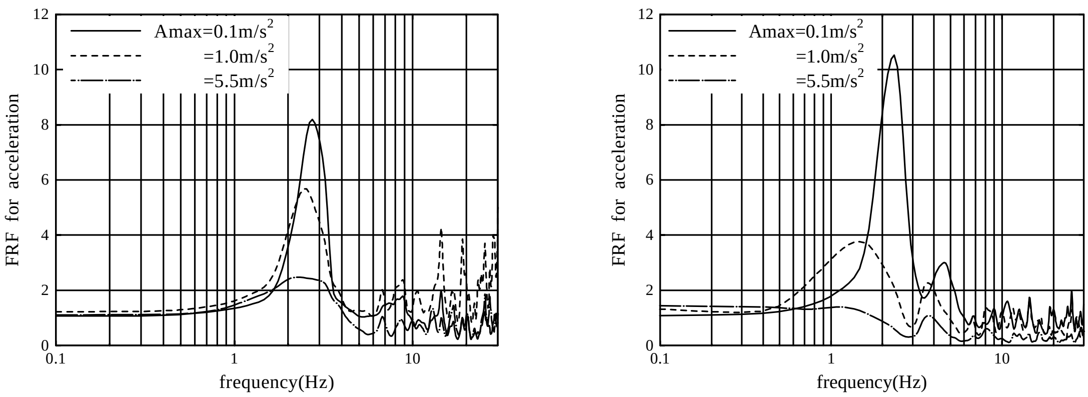


Figure 4: Natural periods of grounds

Site effect due to irregular layering and distribution of nonlinear materials can be seen on the variation of dynamic amplification of the surface layer according to earthquakes of different acceleration intensity Amax. Figure 5 shows the frequency response functions at the points P2 and P3 in the diagrams (a) and (b), respectively, which are obtained by the ratio of accelerational Fourier spectra at the ground surface to that of the



(a) FRF at P_2 (b) FRF at P_3

Figure 5: Frequency response function of ground surface at P2 and P3

input at the basal surface, for three deformed Kobe earthquakes of the maximum acceleration amplitude Amax of

0.1, 1.0 and 5.5 m/s2. With the increment of the maximum acceleration amplitude Amax, the frequency response function (FRF) at P3 heavily reduces the amplification characteristics due to liquefaction in the reclaimed layer L1(Fl) and shortens the resonance frequency. For the input of Amax=5.5 m/s2, the peak amplification factor of the FRF at the point P2 falls to 2.5 and the resonance frequency slightly moves to lower range of frequency, which is expected to be affected by the liquefaction at the sea side layer L1.

Figure 6 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 7 presents the distributions of maximum acceleration at the ground surface and the shear strain at the depth of 2.5m versus lateral distance from the left side boundary.

In Figure 6, a large acceleration-dominated area appears soon after the main shock of input. This seismic intensity dominated area corresponds to the isolated alluvial layer zone (Asg in Figure 3) 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 "heavily damaged belt" along the coastal line. Also the distribution of maximum acceleration at the ground surface shown in Figure 7 shares the similar feature that high seismic intensity zone places from 300m to 900m from the left boundary of the ground model.

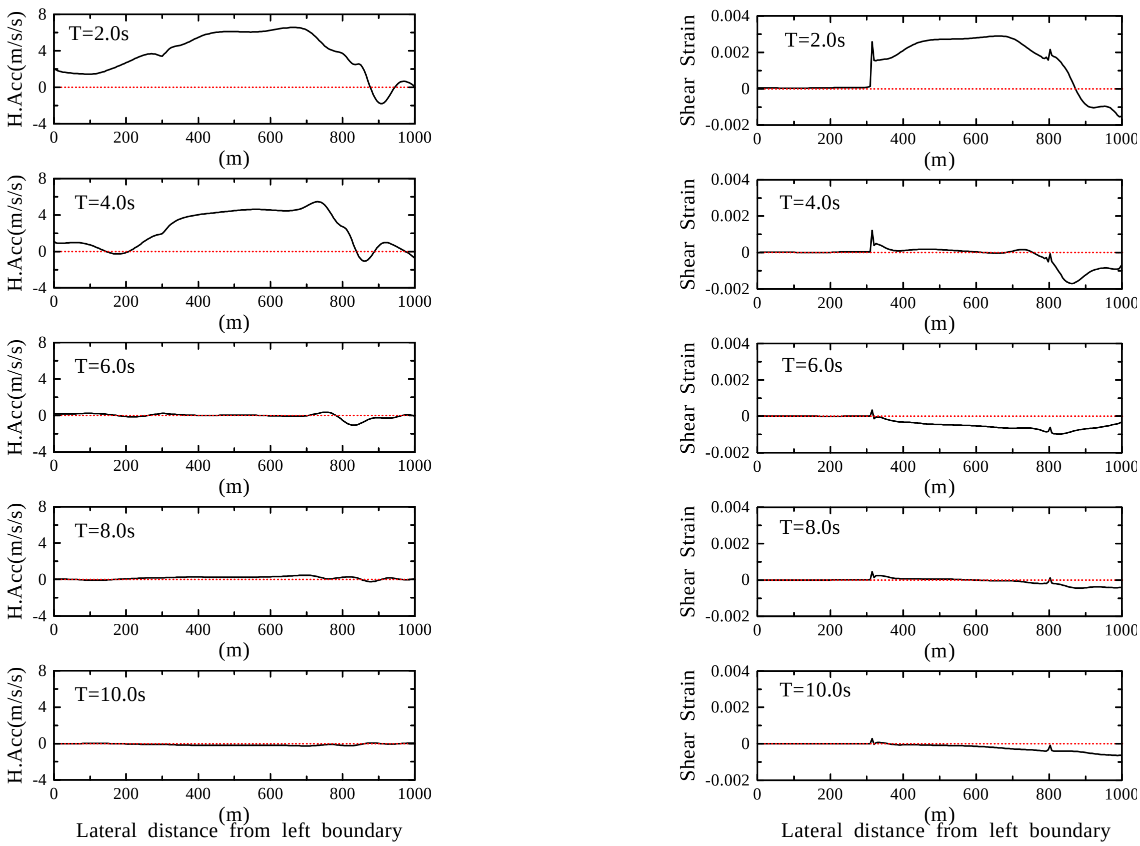


Figure 6: The distribution of horizontal acceleration at ground surface and shear strain at the depth of 2.5m at each time step

In Figure 7, 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 L1 and L2 (Fl and

Ac area), but also the hard ground (Asg area), depending on the irregularity of the layer boundaries.

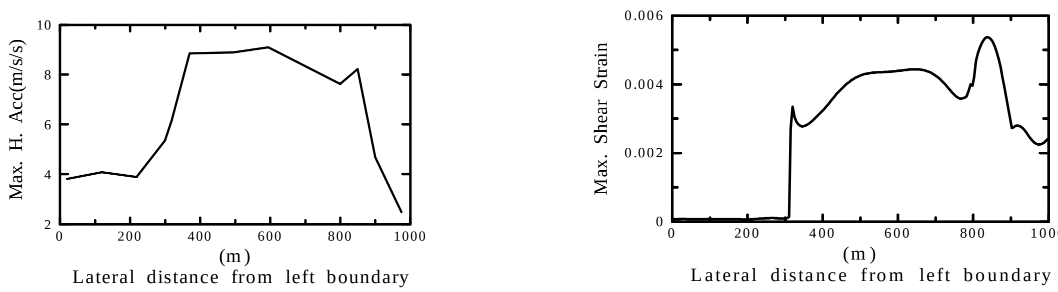


Figure 7 Maximum acceleration at ground surface and shear strain at the depth of 2.5m

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 heavily damaged area of underground structures

Referring to the actual damage records for the 1995 Kobe earthquake, large shear strain area (Asg and L1 and L2 zone) coincide with the lifeline-damaged area, and the poor bearing capacity area due to liquefaction (L1 and L2 zone) corresponds to pile foundation damaged area.

CONCLUSIONS

An absorbing boundary condition for the dynamic analysis of ground model is presented, which is adaptable to both the linear and nonlinear 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. This results in the well explanation of the damage distribution in the Kobe earthquake.

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