13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 3380

# ESTIMATION METHOD OF SEISMIC STRUCTURAL DAMAGES BASED ON THE SITE EFFECT ANALYSIS

**Kunihiko FUCHIDA[1] Takashi AKIYOSHI[2] Hidetoshi MATSUMOTO[3]**

## SUMMARY

An estimation method of the structural damage distributions, which is based on the site effects analysis of the Kobe ground for the 1995 Hyogoken nanbu earthquake, is presented. The two dimensional finite element effective-stress analysis program, which includes the absorbing boundary conditions to satisfy the far field dynamics for the earthquake, is used. For the analysis of the site effects during the earthquake, four different levels of earthquakes are inputted at the base rock surface, and eight actual cross sections of Kobe ground are chosen as the surface layers models. Results show that the site effects are characterized mainly as the nonlinear coupling of the concentration of acceleration response due to the non-uniform layering in space and the increased ground strain response with degrading stiffness in time due to liquefaction, depending on the intensity of the earthquake. The spreads of response acceleration and strain near ground surface mostly agree well with the actual damage distributions of buildings and the damage ratio distributions of buried pipelines, respectively. Estimation in advance of structural damage distributions for great earthquakes will be possible from computational acceleration and strain of ground in consideration of nonlinear wave propagation in surface layers.

## INTRODUCTION

Severe damages of engineering structures in the Kobe earthquake (1995 Hyogoken nanbu earthquake) are characterized by the superstructure damage area on the hard ground and the underground structure damage area on the soft reclaimed ground which was mostly liquefied. So far these damages are tried to be explained by some of analyses which have been made for energy concentration at specific local sites due to the edge effect of soil layers. However success of such attempts has depended on the existence of proper computational programs considering nonlinearity of soft soil with the far field conditions and fitness evaluation of analyses comparing with detailed data base of damages.

An analytical procedure of this problem is how to model reasonably the saturated and infinite soil. The computational model is usually restricted to finite domain with an artificial boundary in order to reduce

[1] Yatsushiro College of Technology
[2] Kumamoto University
[3] Kumamoto University

the cost of analysis. For the saturated porous media, Biot's two phase mixture theory [1, 2] 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.

Additionally, in the near field, the non-linear response of soil is influenced 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 behavior of soil have been developed. Among these, the strain-space plasticity model for the cyclic mobility of sandy soil proposed by Iai *et al* [3] appears to be practical, rational and promising. The constitutive properties of this model 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 [4].

Furthermore, 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. Several techniques have been proposed in the dynamic analysis of dry media. 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. In the meantime, the absorbing boundary conditions of the paraxial approximation seems to be effective and practical since the error estimation has been made for 2D-FE nonlinear saturated soils [5, 6, 7].

## FINITE ELEMENT EQUATION WITH ABSORBING BOUNDARY CONDITION

The analytical method used in this study is briefly described. This method adopts the two-dimensional dynamic equilibrium equations for the soil-water phase and generalized Darcy law for the pore water based on Biot's two-phase mixture theory as in the references [1, 2]. To treat non-linearity (liquefaction) of the soil in the near field, the constitutive model for the plain condition is introduced. This constitutive model is constructed based on the 2-D strain-space multimechanism model for cyclic mobility of sandy soil first proposed by Iai et al [3]. For the far field condition, the absorbing boundary condition is prepared [5].

Above dynamic equilibrium equations are formulated to the finite element equation 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:

$$\begin{pmatrix} m_{uu} & m_{uw} \\ m_{uw}^T & m_{ww} \end{pmatrix} \begin{Bmatrix} \ddot{\bar{u}} \\ \ddot{\bar{w}} \end{Bmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & c_{ww} \end{pmatrix} \begin{Bmatrix} \dot{\bar{u}} \\ \dot{\bar{w}} \end{Bmatrix} + \begin{pmatrix} K_{uu} & K_{uw} \\ K_{uw}^T & K_{ww} \end{pmatrix} \begin{Bmatrix} \bar{u} \\ \bar{w} \end{Bmatrix} + \begin{Bmatrix} \int_\Omega B_u^T \sigma' d\Omega \\ 0 \end{Bmatrix}$$
$$= \begin{Bmatrix} \bar{f}_u + \bar{f}_u^f \\ \bar{f}_w + \bar{f}_w^f \end{Bmatrix} - \begin{pmatrix} c'_{uu} & c'_{uw} \\ c'^T_{uw} & c'_{ww} \end{pmatrix} \begin{Bmatrix} \dot{\bar{u}} - \dot{\bar{u}}^f \\ \dot{\bar{w}} - \dot{\bar{w}}^f \end{Bmatrix} \tag{1}$$

where u and w are the nodal displacement vectors and other notations can be seen in the reference [7]. Equation (1) is coded as the 2D-FE effective stress analysis program of the name "NUW2".

## RECORDS OF SEISMIC DAMAGED AND MODELING OF SURFACE LAYERS

Figure 1 shows the banded areas of severe seismic intensity around Kobe city [8]. These areas are decided by the Japan Meteorological Association (JMA) based on the conventional conversion codes and semi-empirical formula of damage to seismic intensity which is basically equivalent to acceleration. In the diagram the selected eight cross sections from A-A' to F-F' are also plotted for later analysis.

Figure 2 shows the damage rates of water distribution pipes around Kobe city. This diagram of the pipe damage rates (P.D.R.) is referred to investigate damages mainly due to large deformation of soil later.

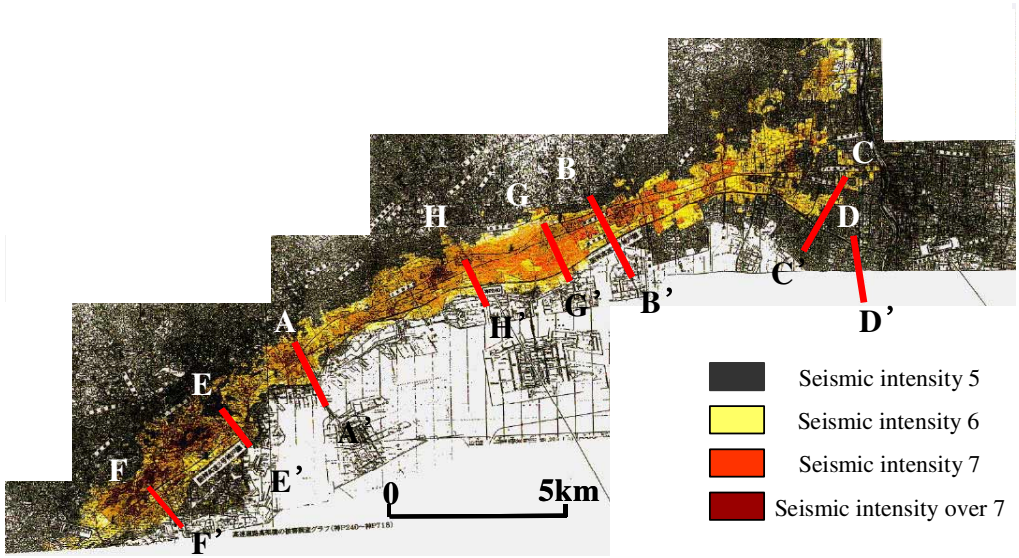


**Fig.1 Seismic intensity distribution around Kobe city**

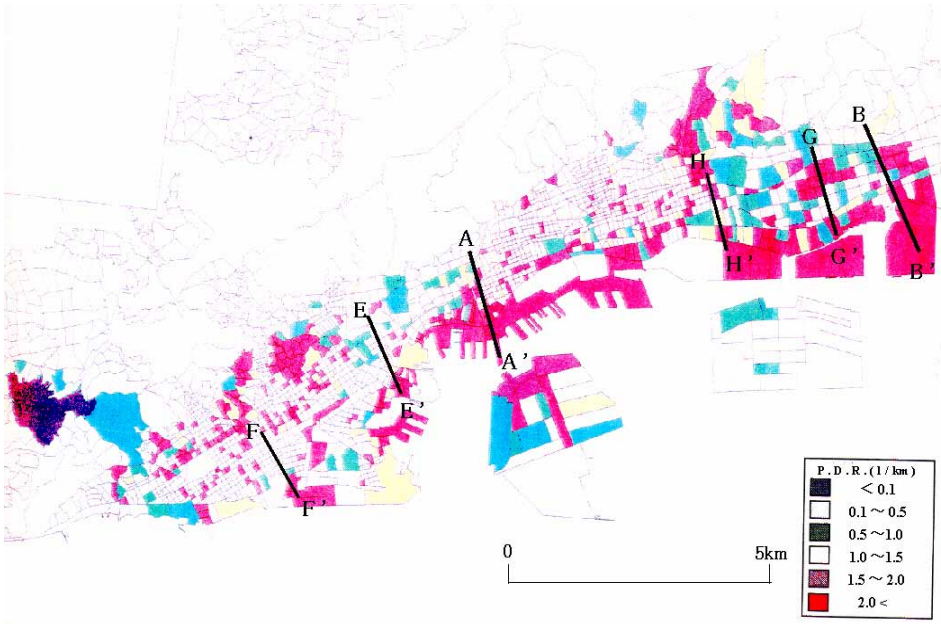


**Fig.2 Damage rate view of water distribution pipes around Kobe city**

The surface layers of Kobe ground are modeled by 2D-FE for the cross sections of A-A' to F-F' based on the reference [10] as shown in Figure 3. These eight cross sections of the width of 1,475m to 2,880m and the depth of 20m to 40m are divided into 100 and 6 to 8 finite elements, respectively. In the later presentation the width of ground models will be described as 1,000m. The ground models rest on the rigid base rock surface and have absorbing (viscous) boundaries (A. B.) at both sides. The left and right sides of the diagrams are toward mountain and sea sides, respectively. In the diagrams N denotes the standard penetration test N-value which is converted to the initial soil stiffness (shear modulus) in the analysis. The geological parameters in the cross sections in Figure 3 are given as; A1, B1, C2, D1, E1, F1, G1, H1 denote the diluvial sandy gravel, A2, B2, C2, D2, H2 the alluvial sandy gravel, A3, B3, E3, F3, G3, H3 the reclaimed soft soil, C4, E4, F4 the diluvial clay, A5, B5, C5, D5, E5, F5 the alluvial clay, and B6, E6, F6, G6, H6 the composite of alluvial sandy gravel and alluvial clay.

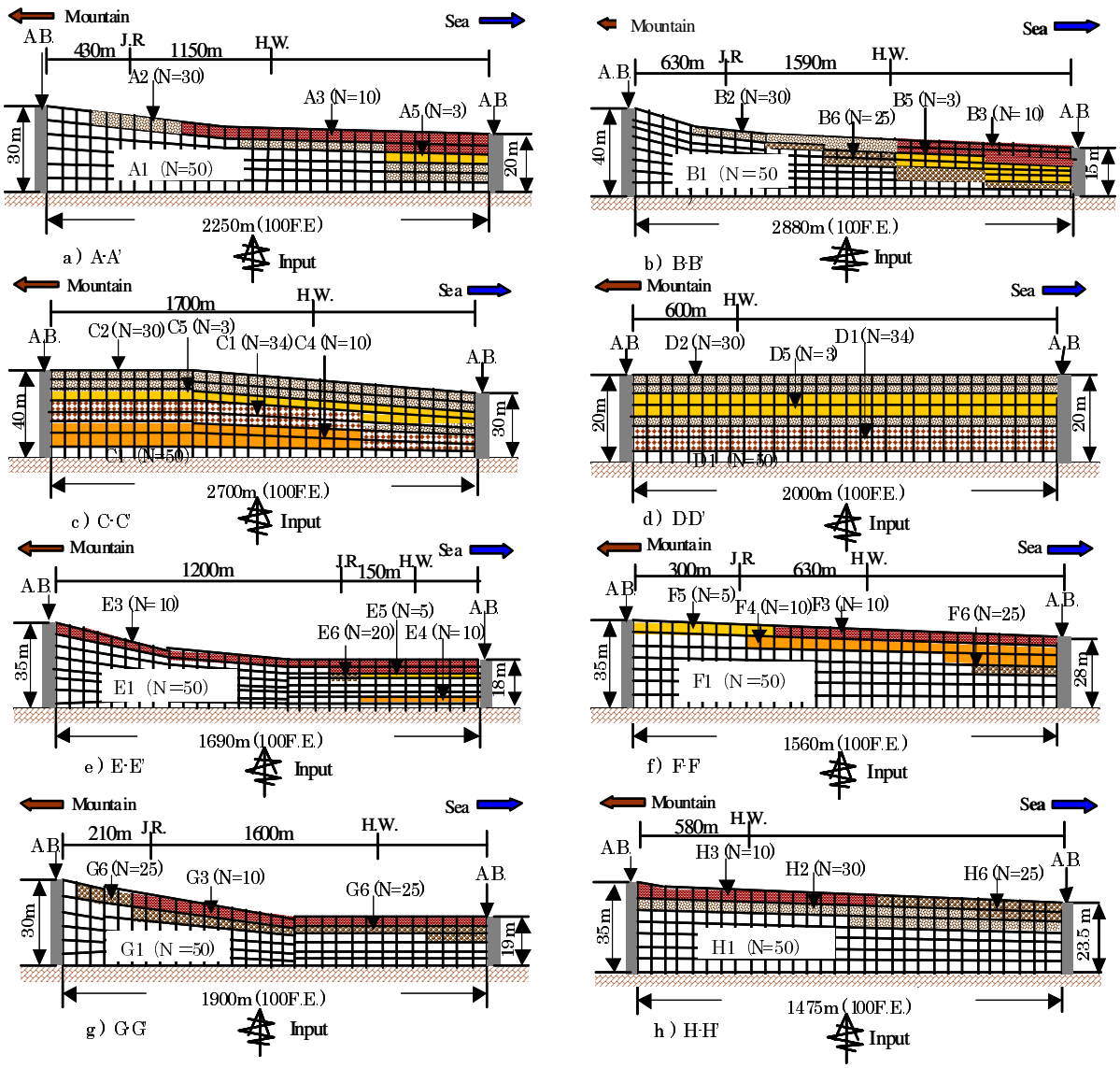


**Fig.3 Cross sections of Kobe ground**

The constitutive equation of cyclic mobility by Iai *et al* [3] needs several parameters. The six parameters ($S_1$, $w_1$, $p_1$, $p_2$, $c_1$, $\phi_p$) for representing dilatancy and four parameters ($\rho$, $G_{mo}$, $\phi_f$, $H_m$) for dynamic deformation characteristics in the stress-strain relation for sandy soil are allocated for each soil element. The standard values of these ten parameters for the program NUW2 can be seen in the reference [11]. The other parameters are given as: poisson's ratio $\nu$=0.33, porosity $n$=0.4, permeability coefficient $k$=1*10$^{-5}$m/s, and bulk modulus $K_f$=2*10$^6$kPa.

## ANALYSIS OF RESPONSE CHARACTERISTICS OF SURFACE LAYERS

Kobe earthquake recorded at GL-32m in Port Island is used as input seismic acceleration waves. The NS and UD components of this input waves are impinged simultaneously upward from horizontal base surface of the ground models with the maximum acceleration amplitude $A_{max}$ of 0.1, 1.0, 5.4 and 10.0m/s$^2$.

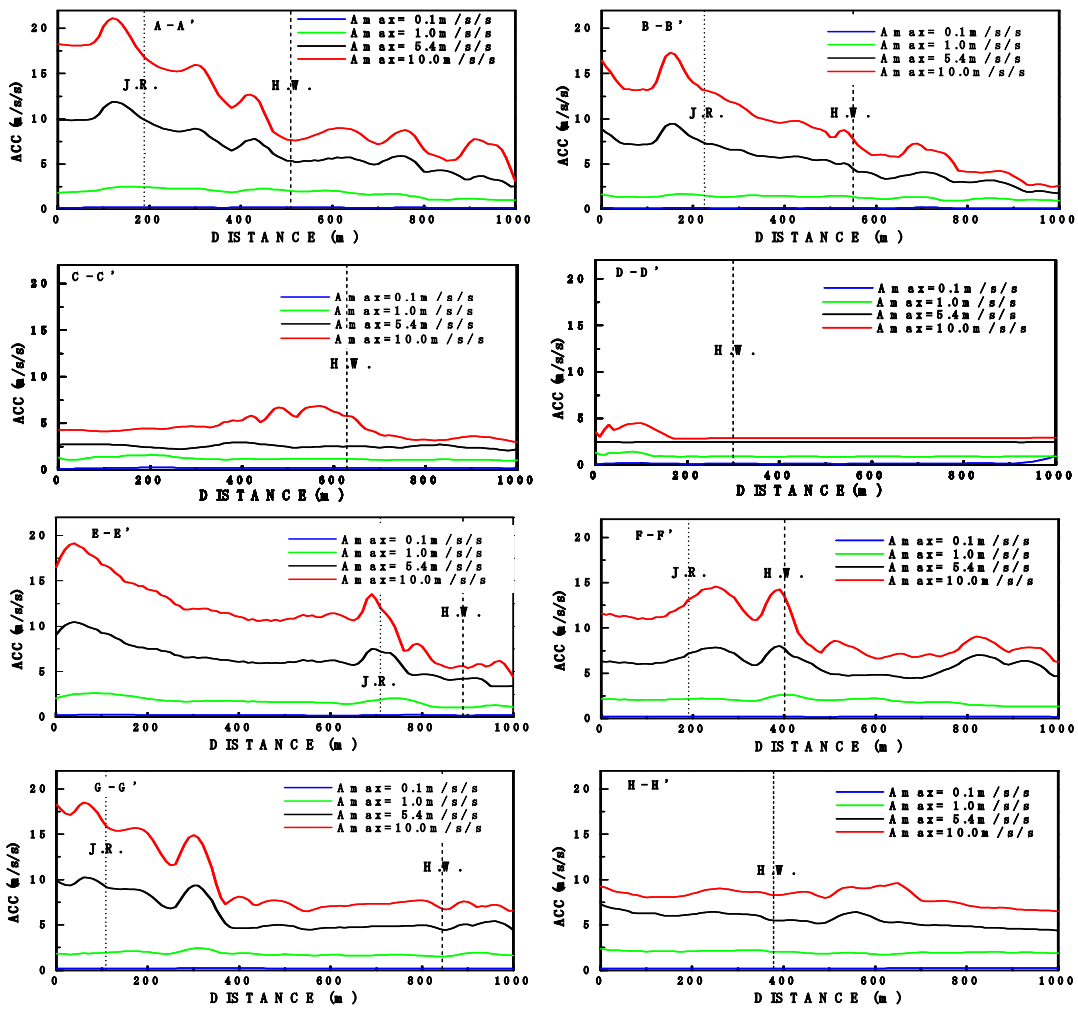


**Fig.4 Maximum response acceleration of the ground surface**

The site effects of nonlinear acceleration transfer characteristics of surface layers due to input intensities $A_{max}$ are shown in Figure 4. In Figure 4, both concentration of acceleration and considerable deterioration of the transfer characteristics appear typically at the mountain sides and sea sides of cross section A-A' (most upper left diagram), respectively, and uniform non-relational characteristics of surface layers to $A_{max}$ exists at the coastal sides of the cross section C-C' and D-D'. For low levels of intensities $A_{max} < 1.0\text{m/s}^2$, t

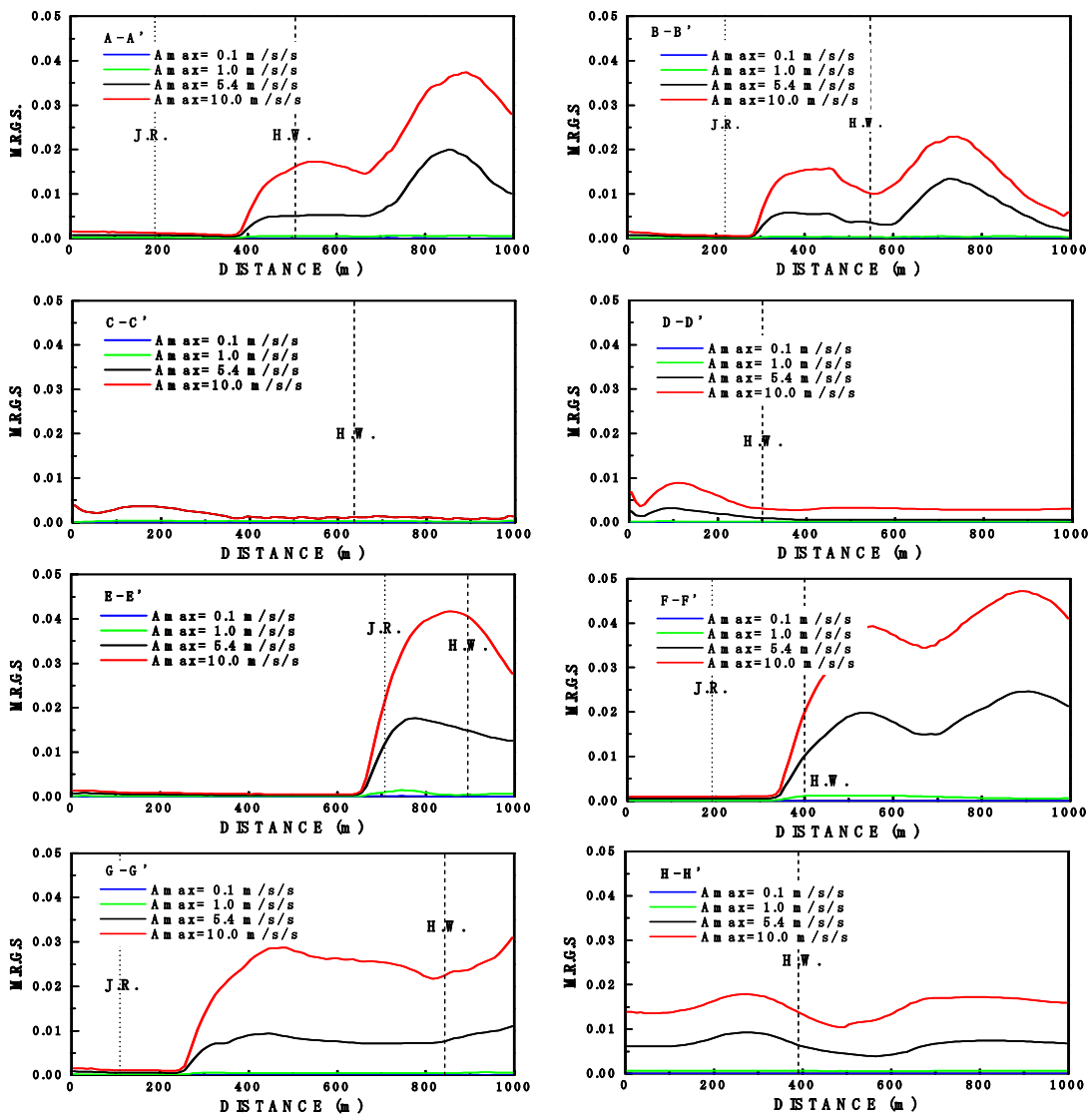


**Fig.5 Maximum response ground strain near the surface (G.L.-2m)**

he stiffness of soils or local stiffness of surface layers are kept linear, but the high levels of the intensity lead to nonlinear dynamic characteristics which result in the long natural period of surface layers. Most

strong seismic intensity areas are identified around J.R. in the diagram which almost coincide with the so called "belt area of disastrous structural damages" in Kobe earthquake. This means that surface layers without deep rock layers are enough for the analysis of the seismic response by NUW2.

Figure 5 shows the distribution of maximum ground strain along each cross section for four cases of the maximum acceleration amplitude $A_{max}$. Large ground strain appears near the coastal areas where may refer to heavily damaged areas of underground structures such as pipelines and pile foundations.

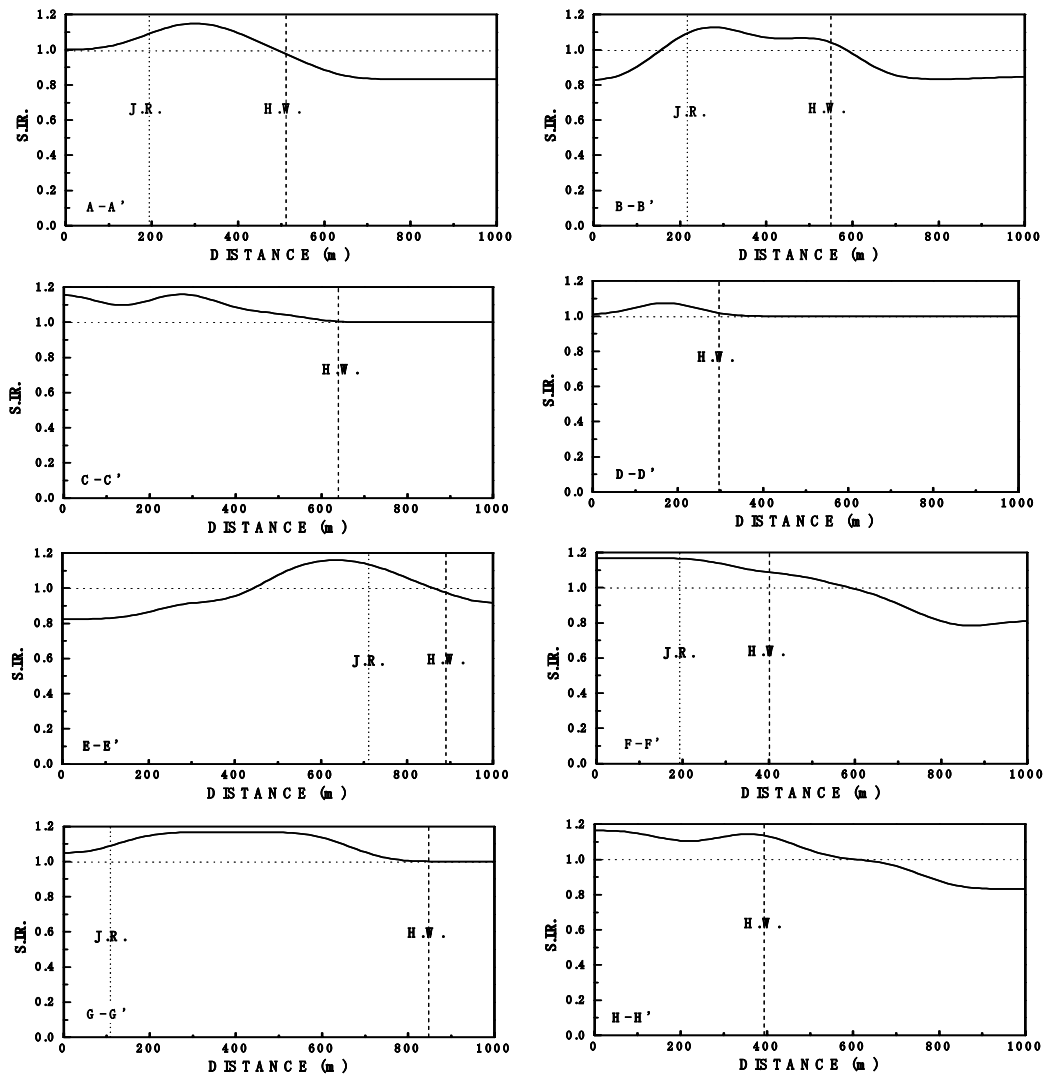


**Fig.6 Seismic intensity ratio (S.I.R.) at ground level**

Then the distributions of response acceleration and strain for $A_{max}$ =5.4m/s$^2$ are compared with the old seismic intensity (S.I.) (Figure 1) and damage ratio (P.D.R.) of water distribution pipes in the actual

damaged area (Figure 2), respectively. For direct comparison the response acceleration in Figure 6 is converted to the new seismic intensity (S.I.) defined by JMA in 1996. Here the seismic intensity ratio is defined as follows:

S.I.R.=(the old S.I. by actual damages)/(the new S.I. by analysis)

This S.I.R., as shown for eight cross sections in Figure 6, includes the relative error (difference) of 20% between damage based S.I. and analytical one. To estimate the difference, accuracy is defined as:

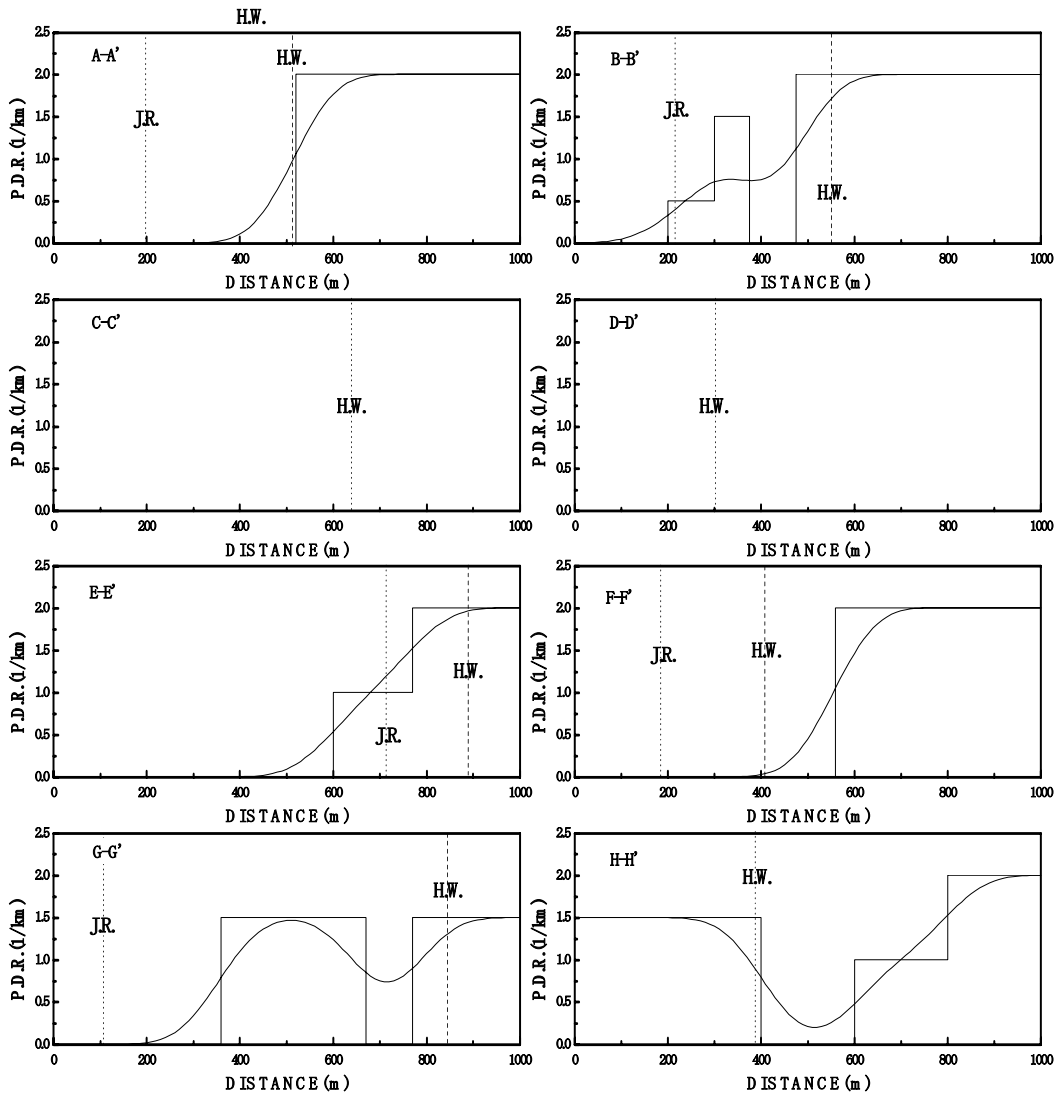


**Fig.7 Smoothing damage rate (P.D.R.) of water distribution pipes**

Accuracy = (r.m.s. of the difference)/(average of the damage based S.I.)

Results of error estimation for S.I.R., which are shown in Table 1, give good agreement of the damage based S.I. with the analytical S.I. with the accuracy of 15%.

On the other hand, original damage ratios (P.D.R.) of water distribution pipes due to the reference [9] and the smoothed ratios are plotted in Figure 7. Both curves of the ground strain distribution (Figure 5) and the smoothed ratios (Figure7) are almost similar. Then taking numerical evaluation of both curves leads to Table 2. Correlation coefficients is almost greater than 0.7 which would mean good agreement except for the cross section of C-C' and D-D' and totally lead to the statistical inference equation $y$=96.5$x$ (1/km) of P.D.R. with the correlation coefficient of 0.820 where $x$ is the ground strain.

**Table 1 Accuracy of seismic intensity ratio**

| Cross section | Accuracy |
|---|---|
| A-A' | 0.116 |
| B-B' | 0.114 |
| C-C' | 0.065 |
| D-D' | 0.023 |
| E-E' | 0.114 |
| F-F' | 0.146 |
| G-G' | 0.063 |
| H-H' | 0.115 |

**Table 2 Correlation Between P.D.R. and Maximum ground strain**

| Cross section | Correlation Coefficients |
|---|---|
| A-A' | 0.820 |
| B-B' | 0.697 |
| C-C' | * |
| D-D' | * |
| E-E' | 0.787 |
| F-F' | 0.842 |
| G-G' | 0.935 |
| H-H' | 0.722 |

## CONCLUSIONS

To represent the energy concentration at the specific sited including the nonlinear water saturated soil, the 2D-FE effective stress analysis program (NUW2) with absorbing boundary condition is devised and used for the response analysis of Kobe ground for the input of the 1995 Hyogoken nanbu earthquake. Results show that site effects based on the analysis due to the program NUW2 have strong correlation with horizontal spread of actual structural damages. Hence the analysis using effective stress analysis program for proper data of soils and structures with expected input would lead to an effective estimation of structural damages.

## REFERENCES


1. Biot, M.A., "Theory of propagation of elastic waves in a water-saturated porous solid", J. Acoust. Soc. America, 1956; **28**, 168-178.
2. Biot, M.A., "Theory of propagation of elastic waves in a water-saturated porous solid", J. Acoust. Soc. America, 1956, **28**, 179-191.
3. Iai, S., Matsunaga, Y. & Kameoka, T., "Strain space plasticity model for cyclic mobility", Soils and Foundations, 1992, **32(2)**, 1-15.

4. Akiyoshi, T., Matsumoto, H., Fuchida, K. & Fang, H. L., "Cyclic mobility behavior of sand by the three dimensional strain space multimechanism model", Int. J. Num. Anal. Meth. Geomech., 1994, **18(6)**, 397-415.
5. Akiyoshi, T., Fuchida, K. & Fang, H. L., "Absorbing boundary conditions for dynamic analysis of fluid-saturated porous media", Soil Dynamics and Earthquake Engineering, 1994, **13(4)**, 387-397.
6. Akiyoshi, Sun, X. & Fuchida, K., "Error estimation of absorbing boundary condition for two-phase ground", J. Structural and Earthquake Engineering, JSCE, 1999, **16(2)**, 133s-142s.
7. Akiyoshi, T., Fang, H. L., Fuchida, K. & Matsumoto, H., "A nonlinear seismic response analysis method for saturated soil-structure system with absorbing boundary", Int. J. Num. Anl. Meth. Geomech. 1996, **20(5)**, 307-329.
8. Tamura, C., "Characteristics of the Great Hanshin-Awaji Earthquake", Doboku-Sekou, 1995 (in Japanese).
9. Matsumoto, F., Study on seismic risk estimation of water distribution pipes damage and characteristics of regional water supply ability using GIS, Graduation thesis, Faculty of Engineering, Kobe University, 1996 (in Japanese).
10. The Committee of the great earthquake reconnaissance, Reconnaissance report for the great Hanshin-Awaji Earthquake (commentary), the Japanese Geotechnical Society, 1996, 222-224 (in Japanese).
11. Akiyoshi, T., Fuchida, K. & Shirinashihama, S., Local site effects of transient dynamic characteristics of irregularly layered grounds, Proc. Fourth Int. Conf. on Recent Advances in Geotech. Earthq. Eng. And Soil Dynamics, Paper No.3.11, 2001.