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IDENTIFICATION OF DYNAMIC CHARACTERISTICS OF SURFACE GROUND USING EARTHQUAKE OBSERVATION RECORDS AND ITS APPLICATION
－ SURFACE GROUND CHARACTERISTICS OF ZUSHI CITY －

Koji ANDO[1] **Takahiro IWATATE**[2] **and Yoshiya ODA**[3]

[1] *Self-employed, Tokyo, Japan.*
[2] *Professor, Tokyo Metropolitan University, Tokyo, Japan.*
[3] *Assistant professor, Tokyo Metropolitan University, Tokyo, Japan.*

ABSTRACT :

When aseismic design and assessment of damage of the structure of civil engineering and architecture are performed, it is important to grasp characteristics of surface ground which has a great influence on the behaviors of those structures during earthquake. According to the past seismic damage cases, it is in particular clear that the structure on the complicated irregular ground suffered great damage in earthquake. The purpose of this study is to identify the ground structure and the dynamic characteristics of the surface ground by the vertical array earthquake observation records. Earthquake observation has been carried out from 1994 by Tokyo Metropolitan University to acquire the fundamental earthquake data that were necessary for the seismic damage assumption as a part of the disaster prevention planning of Zushi city. In this study, using the earthquake observation records, the surface ground around the observation stations having the inclined bedrock modeled by two-dimensional FEM was identified, and the dynamic characteristics of the ground was investigated. And the dynamic response characteristic of the general irregular ground was considered based on the consequence.

KEYWORDS: Earthquake Observation, Irregular ground, Modal Analysis, FEM Identification Analysis, Dynamic characteristic of ground, Zushi.

1. Introduction

The city of Zushi is located in Kanagawa Prefecture, in the southern part of the Tokyo metropolitan area, an area that is particularly high seism city. The city suffered severe damages during the 1923 Great Kanto Earthquake (M=7.9).Two major rivers run through the city,the Tagoe River and the Ikego River. Geographically, the city can be divided into three zones based on the ground characteristics; the Holocene lowland zones along the banks and mouths of the main rivers; a zone consisting of reclaimed land near the coastline, and a hill zone (Figure 1-a). The Geological sections of the site along and across the Tagoe River are shown in Figures1-b and 1-c.

It is a most important item contributing the seismic disaster mitigation of this area. Therefore, Tokyo Metropolitan University has started the research of the local seismic vulnerability of Zushi-site area together with Zushi city government.

The objective of this study is to clarify the dynamic characteristics of the ground of Zushi-site during earthquake and to obtain the basic data for seismic disaster mitigation of this area.

The contents of this paper presents as follows.

① Firstly, the outline of the earthquake observations conducted at Zushi- site.

② Secondly, the modal analysis method to grasp the dynamic characteristics of the ground using the observed earthquake data

③Thirdly, the model identification analysis method to carry out based on the results of the modal analysis.

④Finally, the application examples for the observed earthquake records of Zushi- site.

2. Earthquake observations 1),2)

Seismic array observation has commenced in June, 1994, at five ground surface stations (designated by K1～K5) in Zushi-site. In 1998, one station in borehole point K6 (bedrock-30m) was added. Stations, K1, K2, K4 and K5 has located on the surface of Holocene low- land along the two rivers (Tagoe and Ikego), K3 was located on a rock outcrop, and K6 (-29m depth) was located in base rock below K1 (Figure 1). Bedrock with velocity *Vs* greater than 400m/s occurs at a depth of -26 m at K1, -12 m at K2, -15 m at K4, and –7 m at K5, respectively.

More than 150 earthquakes were recorded between 1994 and 2005, including, the 1995 Chibaken-Nanbu earthquake (M=5.2), the 1995 Hyogoken-Nanbu earthquake (M=7.2), the 1995 Sagami-Bay earthquake (M=5.6), the 2005 Chibaken-Hokuseibu earthquake (M=6.0), the 2005 Ibarakiken-Nanbu earthquake (M=5.1), and etc. In these earthquakes, the recorded maximum acceleration were 75 gal in horizontal component and 13 gal in vertical one, respectively, during the Sagami-Bay Earthquake.

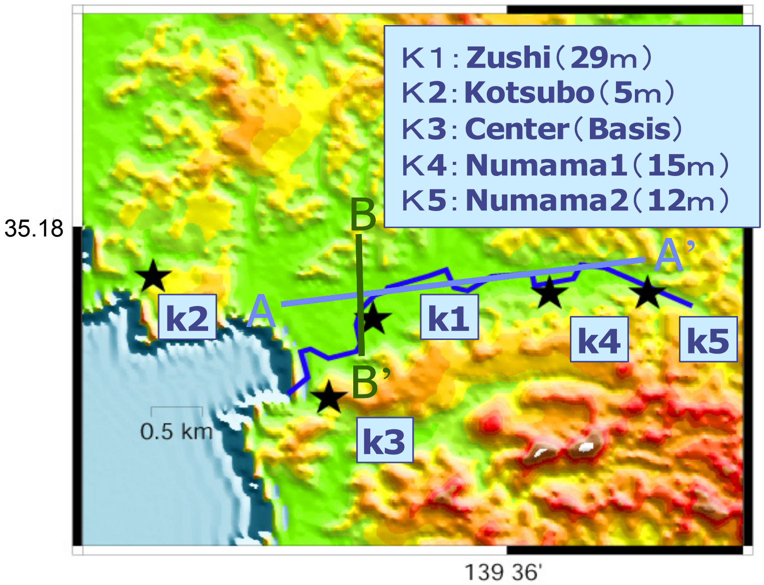

Figure 1-a Geographical feature and location of observation station at Zushi site (K1～K6)

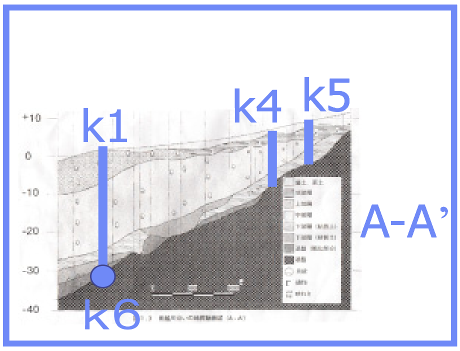

Figure 1-b A-A section

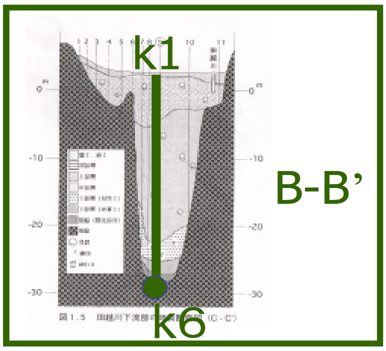

Figure 1-c B-B section

2. Modal analysis method 3)

The purpose of the modal analysis is to clarify the dynamic characteristics of the vibration system by mode constants (eigenvalue and eigenvector) obtained from observed records by Least squares method. The equation of motion of the vibration system having a viscous damping is expressed in the following equation.The system to treat in this analysis is assumed to behave according to this equation.

$$\boldsymbol{M}\ddot{\boldsymbol{x}}(t)+\boldsymbol{C}\dot{\boldsymbol{x}}(t)+\boldsymbol{K}\boldsymbol{x}(t)=\boldsymbol{f}(t) \tag{1}$$

where, $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are mass, damping and rigidity matrix, respectively. Also, $\boldsymbol{x}(t)$ and $\boldsymbol{f}(t)$ are relative displacement and external force vector, respectively.

The mode constant can be obtained by evaluating the residuals between the solutions of Eqn.(1) expressed to its explicit function and the observed records. As the solution of Eqn.(1), the following relative acceleration $\ddot{\boldsymbol{x}}(t)$ corresponding to the acceleration record to treat for the observed record is used.

$$\ddot{\boldsymbol{x}}(t)=2Real\left[\sum_{r=1}^{N}\left\{\lambda_r\alpha_r e^{\lambda_r t}+\boldsymbol{u}_r^{T}\beta_r(t)\right\}\lambda_r\boldsymbol{u}_r\right] \tag{2}$$

where, λ_r and $\boldsymbol{u}_r$ are the r^{th} eigenvalue and eigenvector, respectively. The first term of the right-hand side of the upper expression is a general solution in the case of $\boldsymbol{f}(t)=\boldsymbol{0}$, and the secondary term is a particular solution. Vector $\beta_r(t)$ satisfies the differential equation $\dot{\beta}_r(t)=\lambda_r\beta_r(t)+\boldsymbol{f}(t)$.

Because λ_r is a nonlinear parameter for $\ddot{\boldsymbol{x}}(t)$, it is calculated separately from a linear parameter $\boldsymbol{u}_r$. Firstly, as for $\ddot{\boldsymbol{x}}(t)$, it is linearized with respect to the adjustment quantity $\Delta\lambda_r$ of λ_r using Taylor's theorem, and the most probable value $\delta\lambda_r$ is obtained by minimizing the squared sum of the residuals between the analysis values (Eqn.(2)) and the observed records, and the eigenvalue is improved in $\lambda_r^{new}=\lambda_r+\delta\lambda_r$. Subsequently $\boldsymbol{u}_r$ is calculated based on that result. The calculations of $\delta\lambda_r$ and $\boldsymbol{u}_r$ are iterated until the rate of change of the squared residuals or $\delta\lambda_r$ converges in the predetermined value.

The transfer function of the system is expressed using the mode constants λ_r and $\boldsymbol{u}_r$ obtained from the modal analysis as follows.

$$\boldsymbol{T}(\omega)=\sum_{r}\frac{\omega^2\boldsymbol{u}_r^{T}\boldsymbol{M}\boldsymbol{e}}{i\omega-\lambda_r}\boldsymbol{u}_r+\boldsymbol{e} \tag{3}$$

where, the modal participation function $\boldsymbol{u}_r^{T}\boldsymbol{M}\boldsymbol{e}\boldsymbol{u}_r$ is a constant independent of $\boldsymbol{M}$. $\boldsymbol{e}$ is the unit vector.

3. Numerical model identification analysis method 3)

The purpose of the identification analysis is to grasp dynamic characteristics of the object system depending on the equation of motion(1) adjusted by evaluating the squared residuals between the solutions of Eqn.(1) and the observed records. Where, as the observed record, the transfer function (Eqn.(3)) obtained from the modal analysis is used.

By the way, because the transfer function is nonlinear with respect to the material property value, the function linearized with respect to that adjustment quantity by Taylor's theorem is used, and that most probable value is calculated in conditions of the residual minimization. However, that quantity is calculated indirectly as follows.

The linearized transfer function is expressed as follows by using the perturbation theory.

$$\boldsymbol{T}(\omega,\boldsymbol{p})\approx\boldsymbol{T}(\omega,\boldsymbol{p}_0)+\sum_{n=1}^{N}a_n\frac{\partial\boldsymbol{T}(\omega,\boldsymbol{p}_0)}{\partial p_n}\Delta p_n \tag{4}$$

where, $\partial\boldsymbol{T}/\partial p_n\cdot\Delta p_n$ is a function of the first order shift of λ_r and $\boldsymbol{u}_r$ for the perturbation Δp_n, and it is a known quantity. $\boldsymbol{p}$ is the vector quantity denoting the material property value, and $\boldsymbol{p}_0$ is the initial value. N is number of the material properties. The expansion coefficient a_n is obtained from the residual minimization, and the most probable value of the adjustment quantity $\delta p_n = a_n \Delta p_n$ is calculated.

The above-mentioned calculations are iterated until the rate of change of the squared residuals or the adjustment quantity δp_n becomes lower than the predetermined value.

4. Application example – Surface ground characteristics of Zushi city

4.1.Application of modal analysis

In the analysis, the surface ground of K1 in Zusi-site having the inclined base was aimed at doing the calculations. The section of that soil is shown in Figure2 (the representative fractions of the length and breadth are different). The earthquake observation records used in the modal analysis are the absolute accelerations of horizontal (EW) and vertical (UD) directions observed at two points of the ground surface observation station K1 and the observation station K6 (G.L .-30m) in the bedrock shown in the same figure. On the equation of motion(1), the record of K6 is an input acceleration for the surface ground, and the record of K1 is one of that response. The specifications of earthquakes used for the analysis are shown in Table1. In the analysis, it was applied for these two records at the same time, and the average mode constants were calculated.

The number of modes obtained by the analysis is two in the object frequency range 0.0～10.0Hz. The eigenvalue of each mode is shown in Table2 with the eigenfrequency (f(Hz)) and the damping factor (h(%)). In the modal participation function of EW direction shown in the same table, the primary mode is about 8 times as large as the secondary, and that the response by the primary mode takes the large percentage for the response is understood. The comparison figures of the response at K1 are shown in Figure 3-1,2. As to the accelerograms by the Eqn.(2), UD has some residuals for the observed record, but EW is reproduced about the maximum and the periodicity well. The transfer function by Eqn.(3) is shown in Figure4 with the dotted line. In this way, it is understood that the analysis result was able to catch the predominant frequencies of the earthquake records well.

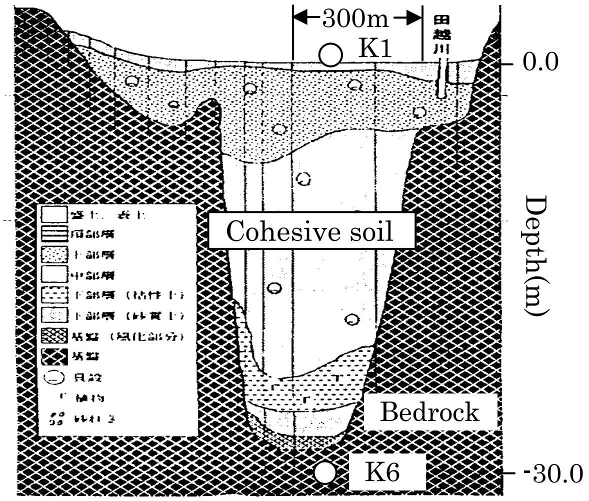

Figure 2 Geological section of Zushi city

4.2. Application of model identification analysis

In the analysis, the right side half of the valley part of Figure2 was aimed at. That model is shown in Figure 6. The size of the model is 30m in depth and 300m in width. The soil was represented with the isoparametric element of eight nodal points. This model has the viscous boundary for the side and the

Table 1 Specifications of earthquakes used by modal analysis

Number	Origin time	Name	Depth(km)	Magnitude
1	1998.08.29 8:46	Tokyo bay region	70.0	5.4
2	1999.09.13 7:56	NW Chiba pref	80.0	5.1

Table 2 Modal parameters estimated by modal analysis

Mode		Eigenfrequency (Hz)	Damping factor (%)	Participation
EW	1	2.16	11.0	0.055
	2	6.27	6.9	0.007
UD	1	3.90	25.2	0.023

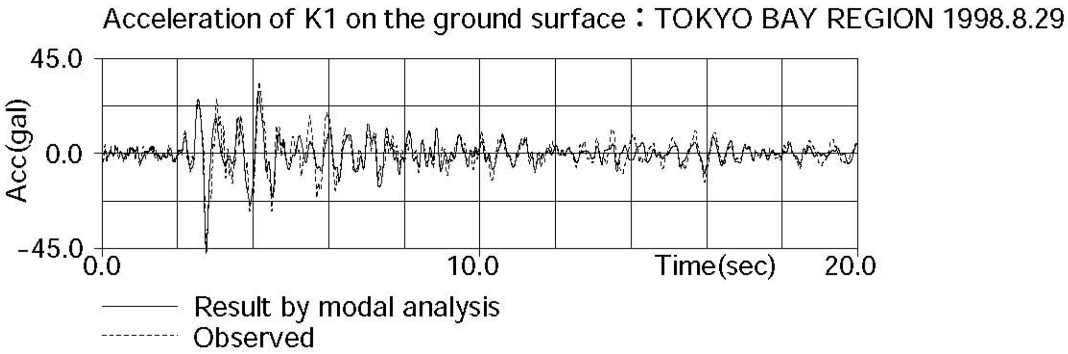

Figure 3-1 Comparison between analyzed and observed acceleration : Tokyo Bay region(EW)

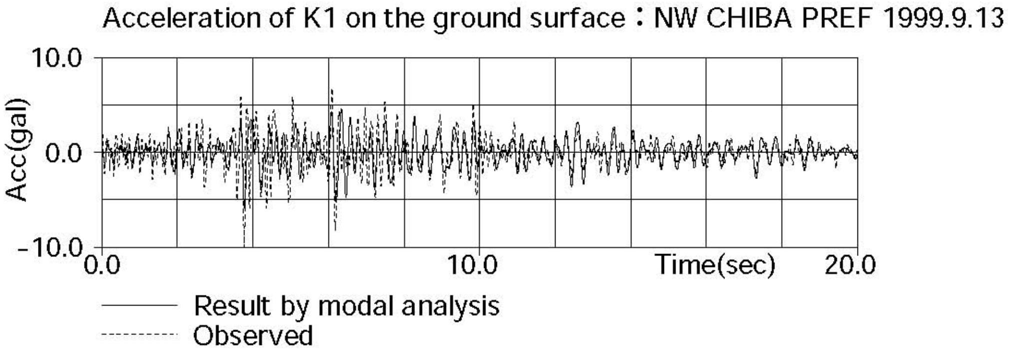

Figure 3-2 Comparison between analyzed and observed acceleration : NW Chiba pref(UD)

fixed boundary for the bottom. The initial material property value given the model is the result by the subsurface exploration. In the identification analysis carried out under the above-mentioned conditions, the density and the thickness estimated with comparatively high accuracy by the subsurface exploration were fixed, and Young's modulus and the damping coefficient were set in parameters.

By the analysis, Young's modulus of the cohesive soil layer (cf. Figure 2) changes most greatly, and that rate of change is +0.85 in terms of the shear wave velocity. The other parameters are around 0.1s. Figure4 and 5 are the comparison figures of the transfer function and the accelerograms. The modal analysis results (dotted line) aimed for in the analysis are reproduced well by the identified model. The accelerograms shown in Figure5 are also good. The eigenvalues of the mode with the large modal participation function are shown in Table 3.

Figure6 is the distribution map of the shearing strain for the input of the horizontal and vertical records of the 1998 Tokyo Bay region earthquake given at the bedrock. As the feature of the distribution, by comparing the central part of the valley having the predominant shearing mode and the vicinity of the inclined rock surface and base, it may be said that the strain region of the level of the latter is larger.

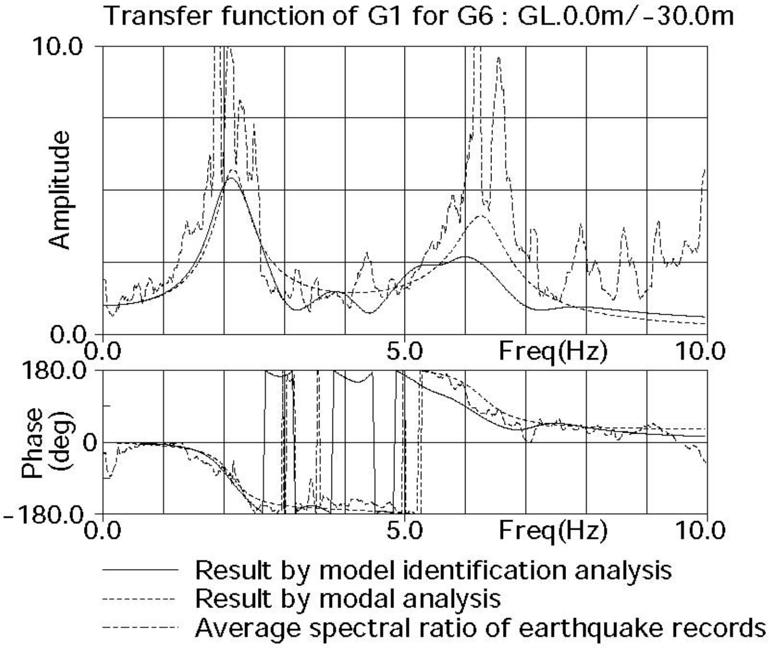

Figure 4-1 Comparison of transfer function between model identification analysis method , modal analysis method and average spectral ratio of earthquake records (EW)

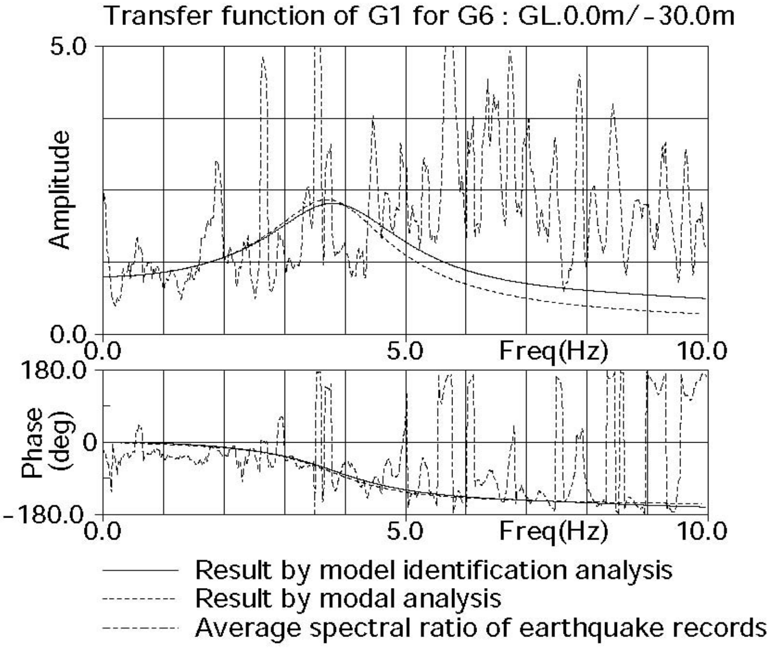

Figure 4-2 Comparison of transfer function between model identification analysis method , modal analysis method and average spectral ratio of earthquake records (UD)

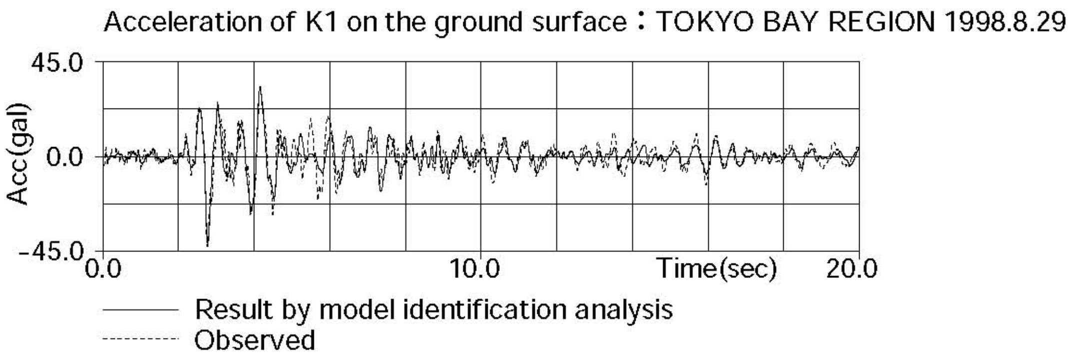

Figure 5-1 Comparison of acceleration between model identification analysis method and observation : Tokyo Bay region (EW)

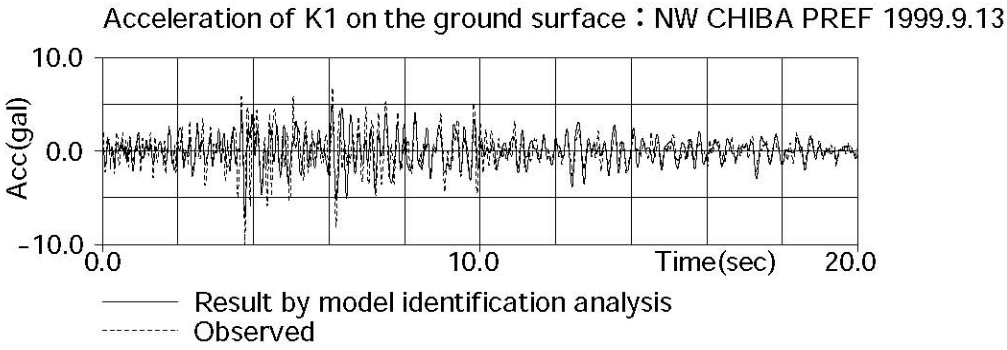

Figure 5-2 Comparison of acceleration between model identification analysis method and observation : NW Chiba pref (UD)

Table 3 Modal constant of identified model

Mode		Eigenfrequency (Hz)	Damping factor (%)	Participation
EW	1	2.03	16.9	0.013
	2	2.28	15.6	0.011
	3	2.69	14.2	0.011
	4	5.37	10.5	0.007
	5	5.67	10.2	0.007
	6	5.92	11.1	0.009
UD	1	3.93	28.7	0.014

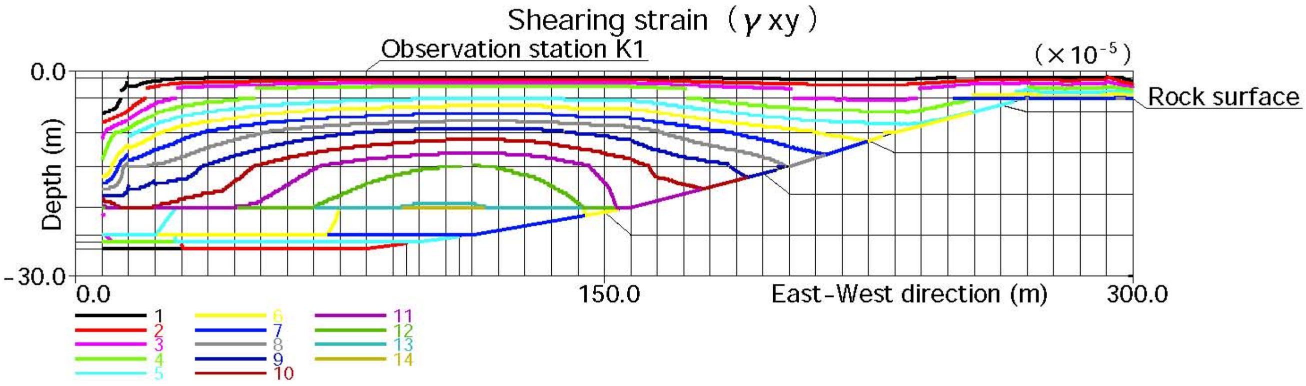

Figure 6 Shearing strain distribution by the Tokyo Bay region earthquake

5. Conclusion

As a result of having carried out FEM model identification analysis for the ground having an inclined base aimed at in this study, the several predominant modes that were not confirmed in the horizontal stratification ground model appeared. In addition, in the vicinity of the rock surface and base having the impedance different greatly(ratio 0.2～0.5 for base), it became clear that the strain of the level occurred over the large region.

The seismic damages were seen in the soil such as the object example of this study well geometrically, and it may be said that the damage factors were inspected by the mode constitution and the shearing strain distribution obtained from the identification analysis. In the case of the seismic design, it is necessary to pay attention to the ground structure to have a great influence for the earthquake damage.

As above, it is thought that the FEM model identification analysis is meaningful in improvement of the precision of the quake resistance evaluation and the damage prediction of ground / structure in the complicated irregular ground.

These results are useful for seismic disaster mitigation and seismic design of structure in Zushi-site.

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