研　究　速　報

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A QUASI-THREE-DIMENTIONAL GROUND MODEL FOR EARTHQUAKE RESPONSE ANALYSIS OF UNDERGROUND STRUCTURES
——Verification of the Model by Vibration Tests——
地下構造物の地震応答解析のための擬似3次元地盤モデルの提案
——模型振動実験による地盤モデルの検証——

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1. Introduction

In the latest issue of this journal[1], the authors introduced a quasi-three-dimensional ground model for earthquake response analysis, centering on how to model alluvial ground and how to form matrices for the equation of motion.

In this paper, the results of vibration tests using a model ground put on a shaking table and the comparison of the results between the analysis and the experiment are reported for the verification of the ground model.

2. Model and Vibration Tests

In order to verify the adequacy of the ground model and to show its effectiveness, a complicated ground condition is selected delibverately for the model ground. Photo.1 shows the diluvial ground model. A drowned valley is formed with plaster in a wooden box. The alluvial layer composed of acrylic amid gel is formed covering over diluvium.

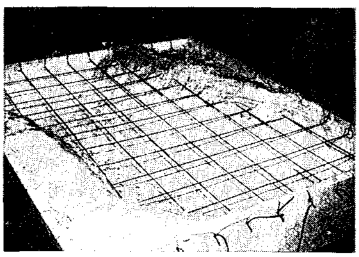

Photo.1　A Photograph of the Test Ground Model (The valley shape is formed by plaster)

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Fig.1 is the plan of the alluvial layer of the model ground. The contour lines show thickness of the layer. Near the upper free boundary, the valley slopes on both sides are steep and the maximum depth is 20 cm. While in the lower valley, the slopes on both sides are gentle and the maximum depth reaches to 18 cm.

Shear wave velocity of the gel is about 240 cm／sec ; therefore, the diluvial formation is considered to be rigid in comparison with the alluvial layer. Since the rigidity of gel is very low, the amplitude of vibration of the ground surface becomes fairly

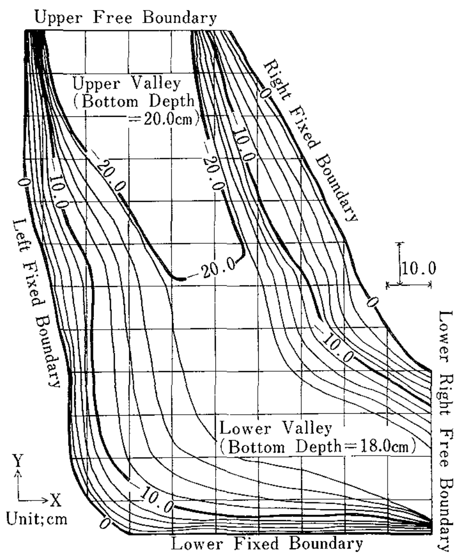

Fig.1　A Plan of Alluvial Layer of a Experimental Ground Model

large. Many target marks are sticked on the model surface at intersections of the grid of fine rubber strings set at depth of 3 cm under the surface, in order to investigate the movements and the modes of the surface layer during excitation. In addition, small-sized accelerometers are also installed in the ground and on the shaking table.

The model was set on the shaking table and rocked in one horizonal direction, which was performed in every direction at 15 degree intervals. By resonance tests, the periods and the modes of predominant vibrations were obtained, using oscillograms and photographs.

3. Comparison Between the Analysis and the Experiment

In order to verify the proposed mathematical model, modal analysis on the test ground model was performed. The following equation was used to determine the natural periods and vibration modes :

$$[K]\cdot\begin{bmatrix}X\\Y\end{bmatrix}=\omega^2\cdot[M]\cdot\begin{bmatrix}X\\Y\end{bmatrix} \qquad (1)$$

where, $[K]$; Rigidity matrix which is the sum of $[K_2]$ and $[K_3]$ (See Reference 1)

ω ; Circular frequency

$[M]$; Mass matrix

$\begin{bmatrix}X\\Y\end{bmatrix}$; Modal vector matrix

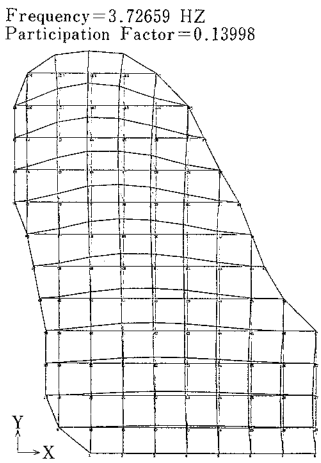

Fig.2 Fundamental Natural Mode of the Analysis

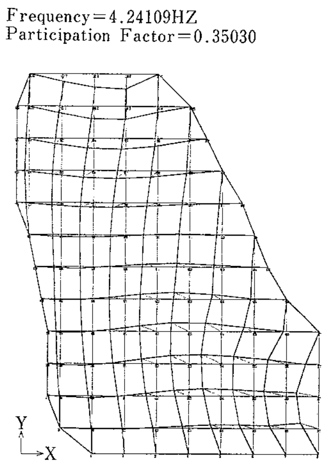

Fig.3 Second Natural Mode of the Analysis

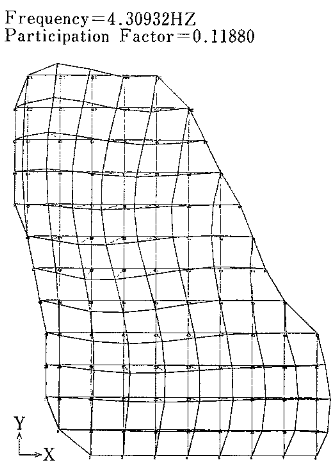

Fig.4 Third Natural Mode of the Analysis

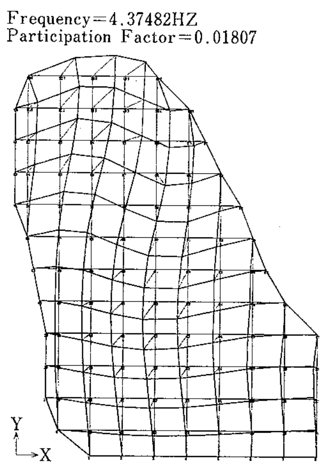

Fig.5 Fourth Natural Mode of the Analysis

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The number of nodal points used in the analysis is 110 and that of freedom is 176. The 10 natural vibration modes in low order were calculated by Subspace Iteration Method. The consecutive 5 from the lowest are shown in Fig.2 through 6. The sum of the participation factors (effective mass rations) of the above 5 modes reaches to 0.84.

Fig.7 shows the sketch of the fundamental mode of the experiment. The displacement amplitudes of the target marks were measured using enlarged phtographs. The frequency of the fundamental vibration is 3.64 HZ and the vibration of the upper valley in Y derection is predominant. This mode appears even when the excitation is carried out in the direction perpendicular to the axis of the upper valley.

Fig.8 shows the second order vibration mode of the experiment. The vibration of the lower valley is predominant in both X and Y directions. The frequency of this mode is 4.40 HZ.

The third mode of the experiment is illustrated in Fig.9. In this mode, vibration can be seen on the entire ground surface, and its frequency is 4.94 HZ.

The comparison between Fig.2 and Fig.7 proves that the fundamental modes of the numerical analysis and the experiment coincide with each other. The difference in frequency of the above two fundamental modes is only 2% as shown in Table 1. These two modal shapes show little discordance.

Taking a look at Fig.3 and Fig.4, one can notice

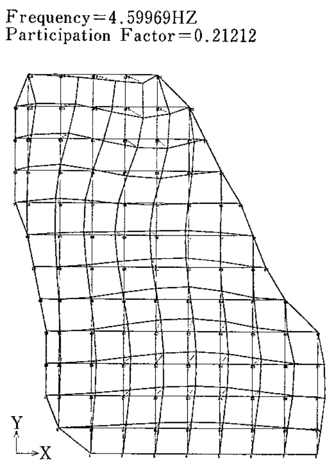

Fig.6 Fifth Natural Mode of the Analysis

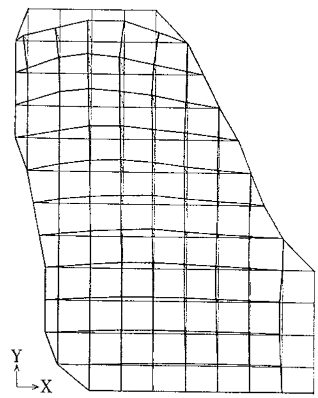

Fig.7 Fundamental Predominant Mode of the Experiment

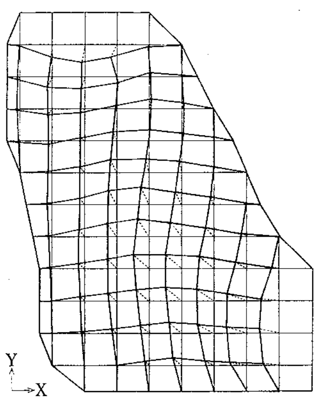

Fig.8 Second Predominant Mode of the Experiment

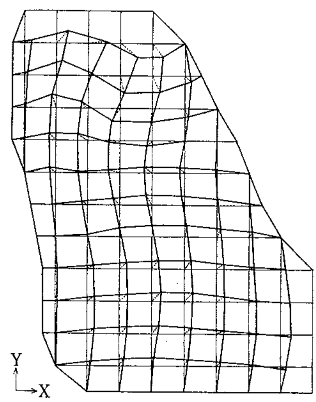

Fig.9 Third Predominant Mode of the Experiment

Table 1 Comparison between the Analysis and the Experiment

Mode No.	Experiment (HZ)	Analysis (HZ)	Error (%)
1	3.64	3.72	2.2
2	4.40	4.24	3.8
3	4.94	4.60	6.9

that the shapes of the second and third modes of the analysis resemble each other. Their frequencies are also close ; 4.24 and 4.31 HZ. A further comparison between these two modes and the second mode of the experiment suggests that the characteristics of the latter can be located in the middle of those of the former. Since the participation factors of the second and the third modes of the analysis are 0.118 and 0.350 respectively, they are, as a matter of course, expected to appear predominantly in the experiment.

The fourth natural vibration of the analysis was not observed in the experiment. This is attributed to the fact that the participation factor of this mode is so small as to 0.018.

The third predominant vibration of the experiment has a resemblance to the fifth natural vibration of the analysis. Their frequencies are 4.94 HZ and 4.60 HZ respectively. This mode appears in the experiment because its participation factor is 0.212, which is relatively large.

Considerations on the differences in mode and frequency are as follows :

(1) The differences in the fundamental vibration mode at the left corner near the upper free boundary of the ground model may result from the difficulty in simulating the free boundary condition by the numerical analysis.

(2) Within the frequency domain of lower order vibrations, the state of vibrations of the model ground varies gradually corresponding to the excitation frequencies. This is caused because three dimensional structure of the alluvial ground is constituted by the complicated plane geometry and the thickness which gradually varies from place to place. Then in some cases, it is not so easy to define the natural vibrations strictly in resonance tests.

(3) The mesh of the numerical analysis is not so fine as to be enough to represent the shape and the fixed condition of the valley. However, the simulations by the numerical analysis showed satisfactory agreements with the results of the experiment.

4. Conclusions

In this paper, the verification of the method proposed by the authors to model alluvial ground for earthquake response analysis was carried out, comparing the modes of the analysis with those of the vibration test. The results of the comparison are summarized as follows :

(1) The vibration test on the complicated alluvial ground model was carried out.

(2) The modes and frequencies of lower order natural vibrations of the test model were analyzed, using the mathematical model proposed by the authors.

(3) Even when the mesh is relatively rough, the results of the experiment were able to be simulated by the proposed method.

(4) The method proposed by the authors is applicable for practical use in simulating dynamic behavior of alluvial ground for earthquake response analysis of underground structures.

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References

1) Tamura, C. and T. Suzuki : A Quasi-Three-Dimensional Ground Model for Earthquake Response Analysis of Underground Structures——Construction of Ground Model——, "SEISAN－KENKYU" (Monthly Journal of Institute of Industrial Science, University of Tokyo) , Vol.39, No.1, January 1987