Three-Dimensional Predictive Analysis of Ground Vibrations Produced by Machines,Traffics and Construction Operations

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ABSTRACT: Construction of high-tech facilities that must be protected against vibrations caused by machine, traffics and construction vibrations has been in great demand. In order to satisfy the requirement of performance of these facilities, it is needed to control the vibrations within the allowable limit being strict for precision instruments in buildings. This implies necessity for development of 3-dimensional dynamic soil-structure analysis that makes it possible to accurately predict the vibrations transmitting from sources to structures via soils, as well as, to employ it to develop the most suitable measures for reduction of vibrations. Therefore, we have developed the analysis technique that combines 3-D FEM with thin layer method to predict the ground vibrations produced by traffics, machines and construction operations. In the present technique, 3-D finite element and thin layer models represent near-field including structures and far-field, respectively.

1. INTRODUCTION

Construction of high-tech facilities that must be protected against vibrations caused by machines, traffics and construction operations has been in great demand. In order to satisfy the requirement of performance of these facilities, it is necessary to control the vibrations within the allowable limit being strict for precision instruments in buildings. This implies necessity for development of 3-dimensional dynamic soil-structure analysis that makes it possible to accurately predict the vibrations transmitting from sources to structures via soils, and to apply it to the most suitable measures for reduction of vibrations. However, there is a problem in the capacity and computing speed of the computer to model the whole soil-structure with 3-D FEM. Therefore, we have developed the analysis technique, shown in Figure.1, which combines 3-D FEM with thin layer method to predict the ground vibrations produced by traffics, machines and construction operations. Hence, 3-D finite element and thin layer models represent near-field including structures and far-field, respectively.

This paper outlines the analysis system developed together with its application to the analysis of the ground vibrations produced by pile driving test.

2. CONCEPT OF ANALYSIS

The analysis system developed in the present research consists of the post processor that displays the analysis results, the solver that performs the analysis and the pre processor that makes the analysis model.

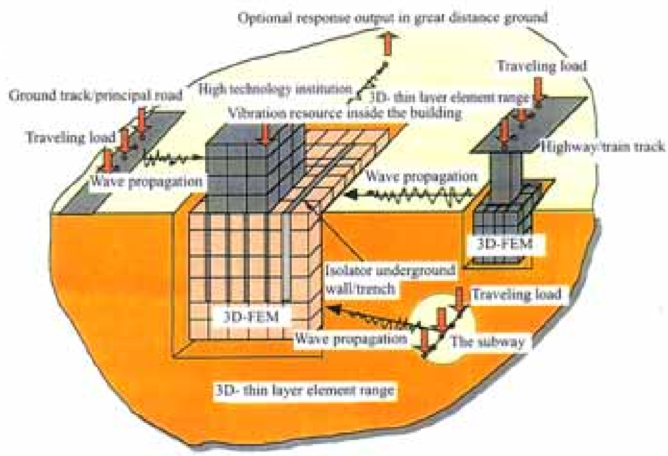


Figure 1. Concept of Modeling

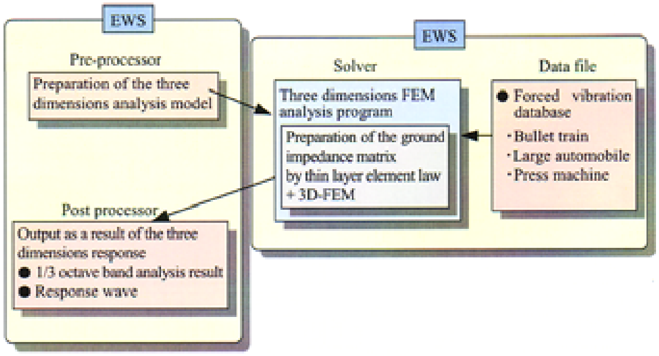


Figure 2. Outline of System

The constitution of the present system is shown in Figure 2. The analysis procedure is explained as;

STEP1 (Modeling) : Foundations of buildings and their near-fields (surrounding soils) are modeled with 3 dimensional finite elements in the pre-processor. On the other hand, free field is represented by thin layered semi-infinite region. Furthermore, the points for calculation of response and for exciting force are given in the finite element region or/and in the thin-layered region.

STEP2 (Analysis);
Impedance matrix of a semi-infinite region of soils is calculated by using the thin layer technique in the solver. This matrix is combined with the stiffness matrix of the finite element region. Next, response analysis is carried out.

STEP3 (Display of results); Numerical results are displayed by using the post processor. Here, the wave propagation in the field can be simulated. Furthermore, the 1/3 octave band filtered spectra can be displayed for the evaluation of vibration.

3. ANALYSIS METHODOLOGY

3.1 *Combination method of 3 dimensional finite element and thin layered region*

Fig. 3 shows the procedure for calculation of impedance. Excavated parts (foundations with their surrounding soils of structures on which source and receipt are) are discretized into finite elements. The stiffness and inertia clause of excavated part are formed from finite element technique. The impedance $[X_{bb}^{E}]$ of the excavated part is defined on the outer boundary of the excavated part. On the other-hand, the impedance $[X_{bb}^{F}]$ on the boundary of excavated part of a free field system is calculated by using the 3-dimensional point exciting thin-layer method. These two impedances $[X_{bb}^{E}]$, $[X_{bb}^{F}]$ and the dynamic stiffness matrix $[S_{aa}\sim S_{bb}]$ of structures are combined. The equilibrium equation in frequency domain is derived on the basis of flexible volume method.

$$[S]\{U\}=\{P\} \quad \text{--------} \quad (1)$$

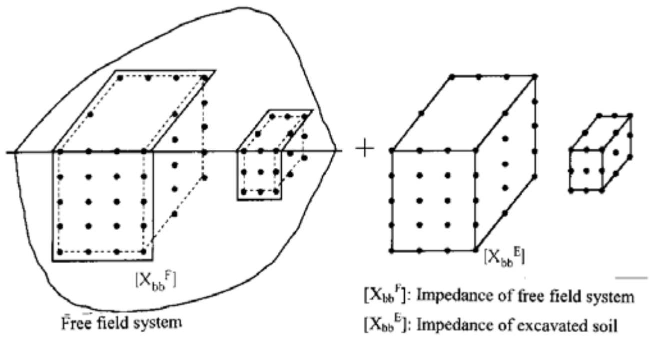


Figure 3. Concept of Calculating The Impedance

3.2 *Response in far field*

Response {Ur}at far field idealized by thin-layered region can be derived as;

$$\{Ur\}=[A_{bb}^{F}]\ \{Ps\} \text{---------------} (2)$$

, where

{Ur} : displacement vector at far field
$[A_{bb}^{F}]$: flexible matrix defined between points at the boundary and those in the far field
{Ps} : force vector induced on the boundary

3.3 *Response to exciting force produced in thin layer region*

The sub-equation in the thin layer region and the sub-equation in the finite element regions are formulated as,.

$$\{P_b\}=[X_{bb}^{G}]\ \{U_b\} \text{------------} (3)$$
$$\{P_F\}=[K_F]\ \{U_F\} \text{--------------} (4)$$

where,

$\{P_b\}$: force vector of soil
$\{U_b\}$: displacement vector of soil
$[X_{bb}^{G}]= [X_{bb}^{F}]-[X_{bb}^{E}]$: impedance of excavated part of soil
$\{P_F\}$: force vector of FE region.
$\{U_F\}$: displacement vector of FE region.
$[K_F]$: impedance of FE region

The equation (5) of the whole system are derived from formula (3), (4).

$$\{P_T\}=([K_F]+[X_{bb}^{G}])\ \{U_T\} \text{-----------------------} (5)$$

Suppose that the external force act as a series of forces {Pa}, response of the combined model can be calculated by the external force $\{P_T\}$.

$$\{P_T\}=[\{0\},\{0\},\{Pa\}]$$
$$\{U_T\}=([K_F]+[X_{bb}^G])^{-1}\{P_T\} \quad \text{-----------------------(6)}$$

The responses can be calculated from equation (6) in the finite element region, on the boundary and in the far field of thin layered region.

3.4 *1/3 octave band analysis functions*
Since the permissible limit of vibrations both for human bodies and for high-tech equipment are usually given by the amplitude in the center frequency of 1/3 octave bands, 1/3 octave analysis functions is installed in the present tool of analysis.

4. ANALYSIS OF VIBRATIONS PRODUCED BY PILE DRIVING

4.1 *Outline of field test*

Rapid load tests of piles were conducted to evaluate the baring capacity of existing cast-incase concrete piles. In the rapid load test, when the pile head was hit by a hammer, the dynamic displacement of the pile head was recorded to obtain the ultimate baring capacity of the pile toe. Since ground vibrations were produced during this integrity test, we measured them not only to assess the vibrations produced by the rapid load test but also to analyze them by employing the analysis technique introduced in the present paper. Figure.4 shows the schematic drawing of the rapid load test using the cushion of forming urethane. A drop hammer pile driver was utilized with a hammer of 39.2kN.

The piles were cast-in-case ones constructed about 20 yeas ago, of which overall diameter and length were 750mm and 8m, respectively. Ground vibrations were measured at a distance of 25, 45 and 65m from the pile.

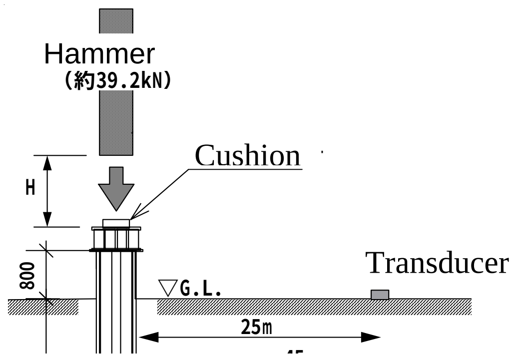


Figure 4 Rapid load test

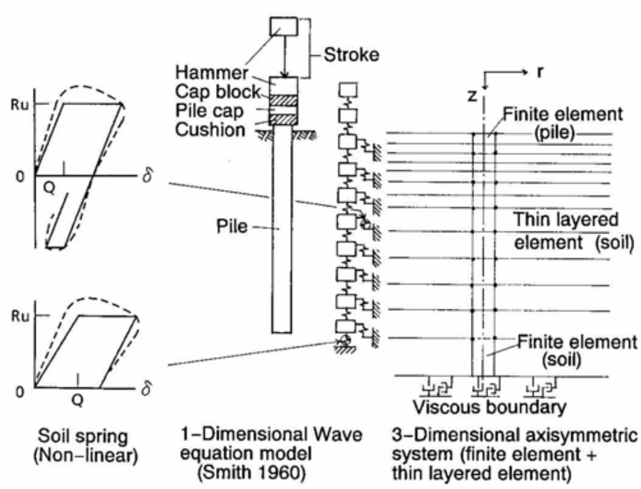
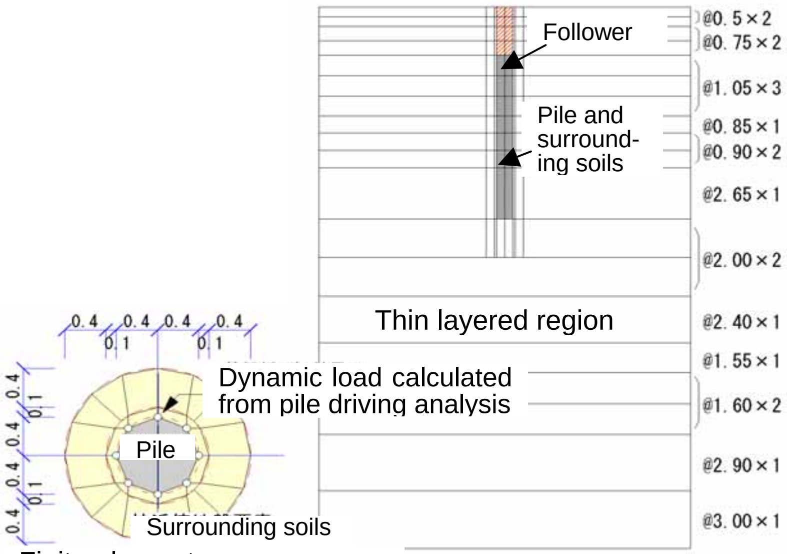


Figure 5 Analysis model of pile driving



Finite elements
of pile and surrounding soils

Figure 6 Analysis model of ground vibration using proposed method

GL- (m)	地質	N (杭用)	Vs (m/s)	ρ	E (kN/m²)	G (kN/m²)	h
-1.00	埋土		120	2.10	88500	30200	0.04
-2.50	埋土		170	2.10	176100	60700	0.04
-5.65	砂質粘土	9	260	1.60	321100	108200	0.04
-8.30	砂質粘土	3	170	1.60	138100	46200	0.04
-10.95	砂礫	24	470	2.10	1356000	463900	0.04
-14.95	砂		410	1.90	937700	319400	0.04
-17.35	細砂		430	1.95	1056000	360600	0.04
-22.10	粘土		340	1.75	596100	202300	0.04
-28.00	細砂		490	1.95	1332000	465200	0.04

Fig. 7 Soil model

4.2 *Analysis Procedure*

For impact pile driving operations utilizing a drop hammer under horizontally deposited soil conditions, the dynamic analysis method combines the non-linear pile driving analysis of a hammer-pile-soil model (See Figure 5) with the linear analysis of three-dimensionally propagating waves in multi-layered media. Although such analysis procedure was introduced by us in ISEV2003 (T. Hanazato), the analysis technique proposed in the present paper was employed to conduct the latter analysis. The pile and the surrounding soils were represented by the 3-dimensional finite elements, shown in Figure 6. The dynamic loads acting on the interface between the finite element region including the pile and the thin-layered model was calculated by the former pile driving analysis. Figure 7 shows the soil model used in the present analysis.

4.3 *Analysis results*

Figures 8 and 9 compare the analysis results with the measurements. In these figures, X and Z denote horizontal (Radial) and vertical components, respectively. The calculated attenuation with distance of the acceleration vibration level was in good agreement with the measurements, shown in Fig.8. The simulated waveforms also show good correlation between the analysis and the measurements, shown in Figure 9. It should be noticed that not only the vertical component but also the horizontal components show good comparison. Furthermore, the Fourier Spectra of the numerical results were in excellent agreement with the measurements. Those results demonstrate that the analysis method presented in this paper is useful in predicting ground vibrations produced by pile driving, indicating that it can be employed for predicting ground vibrations produced by machines, traffics and construction operations.

5. CONCLUSIONS

The analysis method presented in this paper can be employed for predicting ground vibrations produced by machines, traffics and construction operations. In order to predict ground vibrations produced those sources, it is essential to evaluate exciting forces as acculately as possible.

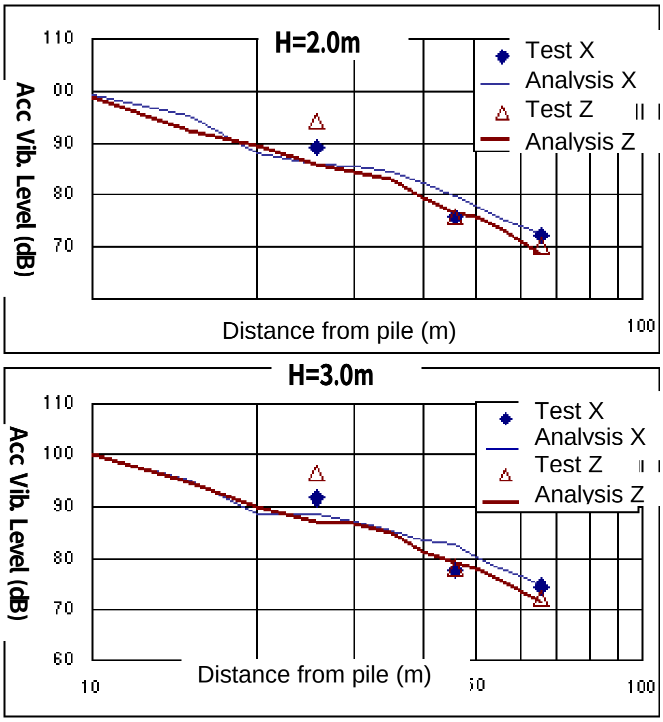


Figure 8 Calculated attenuation with distance of acceleration vibration level, compared with measurements

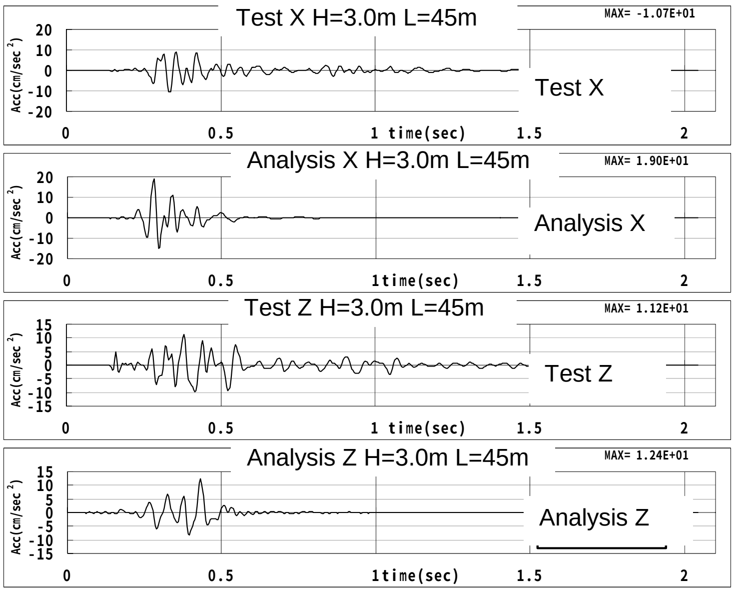


Figure 9 Calculated waveforms of acceleration, compared with measurements

REFERENCES

H. Tajimi “ A Contribution to theoretical prediction of dynamic stiffness of surface foundations”, 7WCEE, Vol.5, pp105-112,1980

T. Hanazato “ Ground vibrations produced during construction of pile foundations”, Proc. of ISEV2003, pp186-201,2003