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3D SOIL-BUILDING INTERACTION METHOD BASED ON AN INPUT SEISMIC WAVE FIELD

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SUMMARY

A 3D soil-building interaction method based on an input seismic wave field is proposed. A new concept of an input wave field is introduced to treat surface waves excited by a deep structure. An S-wave field, a surface-wave field, and a whole-wave field are estimated for a large earthquake, and building responses excited by the whole-wave field are calculated. As an application, a linear interaction analysis based on an input wave field successfully estimates seismic responses of low- to high-rise buildings in the lakebed zone of Mexico City.

1. PURPOSES

A 3D soil-building interaction method based on an input seismic wave field is proposed. A seismic wave field means a 3D space in which seismic waves propagate. A new concept of an input wave field is introduced instead of an input motion, in order to treat seismic surface waves excited by a deep structure in a small soil-building interaction system. The method is applied to estimate linear building responses during a large earthquake at a soft-soil site where surface waves are very dominant.

Observed seismic motions may include considerable surface waves. Whereas the predominant periods of S waves and surface waves are often very close to each other, the amplifications of these waves can be quite different. Therefore, we need to identify S waves and surface waves, and to treat them separately. Certainly, body-wave and surface-wave incidences into a soil-building interaction system are available for body waves and local surface waves. However, the surface-wave incidences are not applicable to seismic surface waves that are usually excited by a deep structure. Since horizontally-propagating surface waves are influenced by not only a shallow underground structure but also a deep structure, the amplification of surface waves in a surficial deposit cannot be reproduced by a surface-wave incidence into an interaction system. This surface-wave problem is serious at a soft-soil site.

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In order to overcome this problem, we recently proposed a 3D soil-building interaction method based on an input wave field in two studies (Iida [1]). Since the two studies were a first step to develop the method, we performed a linear interaction analysis in a multi-layered underground structure subject to only horizontal seismic motions, in order to demonstrate the validity of the method. In the former stage of the method, an S-, surface-, and whole-wave fields were estimated for a large earthquake. In the latter stage, a 3D soil-building interaction analysis was performed in the estimated whole-wave field.

As an application, we estimated linear seismic responses of low- to high-rise RC buildings during a large earthquake in the lakebed zone of Mexico City where surface waves were heavily excited by a deep structure, and tried to explain a typical building damage pattern observed in Mexico City. For comparison, a conventional interaction analysis based on an input motion was performed. In the present study, essential contents of the two studies are explained briefly.

2. NATURE OF SEISMIC MOTIONS

Prior to the main subject, we investigate the nature of seismic motions observed in the lakebed zone of Mexico City. The nature of seismic motions was analyzed systematically in a seismological study (Iida [2]). In order to interpret the amplification observed at the Roma-C borehole station of the lakebed zone, we calculated theoretical amplification for S waves and fundamental-mode Love and Rayleigh waves by elastic wave theory. The large amplification observed at the predominant period of ground (2.5 s) could not be explained by theoretical S waves, even if no attenuation of ground was assumed. The observed amplification could be interpreted by surface waves excited by a deep structure, and Love waves were suitable rather than Rayleigh waves. In conclusion, the observed seismic motions were mainly Love waves, while they included Rayleigh waves and S waves.

Next, we separated surface accelerograms recorded at the station into S-wave and surface-wave accelerograms, by an improved version of Kinoshita's method (Kinoshita [3]). The method was a kind of cross-correlation analysis available for a pair of a surface recording and a downhole recording. In the late time section of the recordings and in the period range longer than 2.0 s, most seismic motions were surface waves. This result was quite consistent with the results of the above-mentioned amplification analysis.

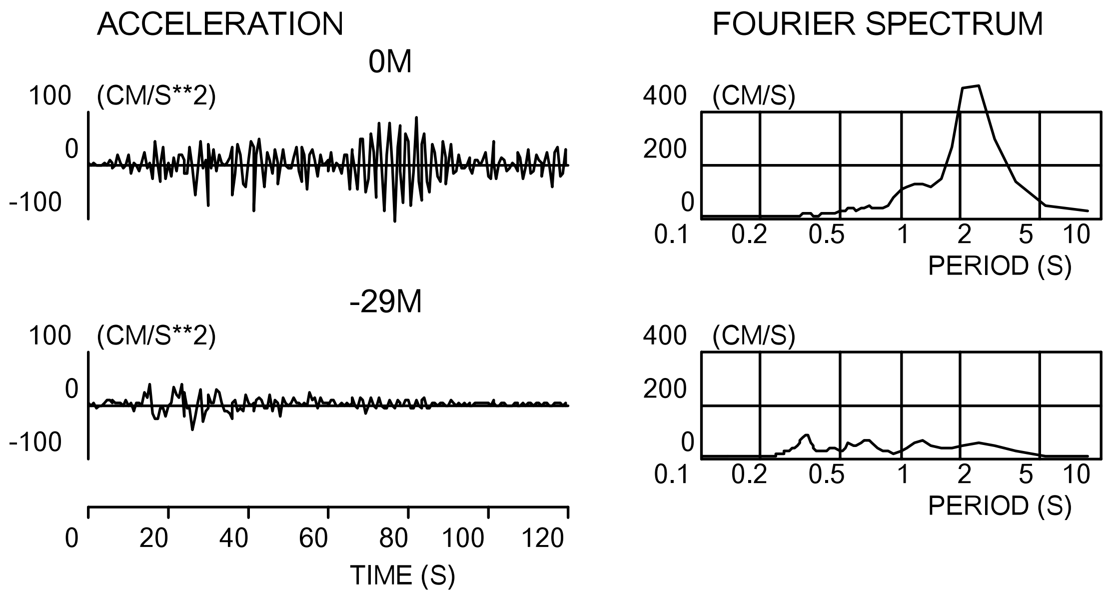

FIG. 1. Synthesized whole-wave accelerograms (whole-wave field).

3. WAVE FIELDS

An S-wave field and a surface-wave field were estimated for a large earthquake (Iida [1]). First, surface S- and surface-wave accelerograms were separately synthesized for a hypothetical Guerrero earthquake (M = 8.1), using an empirical Green's function summation method developed by Iida (Iida [4]). The Guerrero earthquake was equivalent to the 1985 Michoacan earthquake (M = 8.1) in earthquake magnitude and mechanism, so similar damage patterns were anticipated for the both earthquakes. The fault geometry and the fault parameters of the Guerrero earthquake were exhibited in Fig. 1 of the above-mentioned previous study (Iida [4]).

Second, an S-wave field and a surface-wave field were separately estimated, by elastic wave theory. In advance of this estimation, the kinds of surface waves needed to be identified. We roughly assumed that all surface waves were fundamental-mode Love waves excited by a deep structure. A whole-wave field was obtained as the sum of the S- and surface-wave fields, and is displayed in Fig. 1. Only the east-west component is displayed throughout this study. Considerable surface seismic motions were surface waves, which were heavily amplified in the soft surficial deposit.

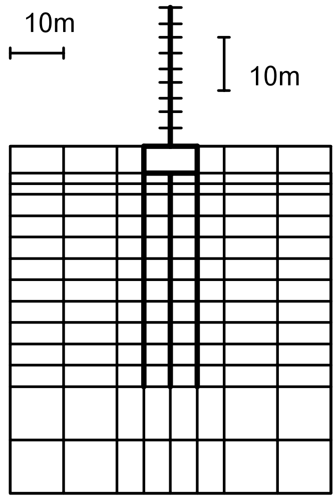

FIG. 2. 3D building-foundation-pile-soil system.

4. INTERACTION METHOD

A 3D finite element soil-building interaction analysis based on the input whole-wave field was performed. A comparative interaction analysis based on an input motion was also performed. Fig. 2 illustrates the 3D building-foundation-pile-soil system used, which is identical about the two horizontal directions. The system was basically the same as that employed in the above-mentioned previous study (Iida [4]). The lumped-mass stick building superstructure rests on the rigid box foundation supported on the frictional piles. Each pile is modeled by beam elements, and the soil volume by 3D rectangular prism elements.

The linear equation of motion which connects the building superstructure, the rigid foundation, the frictional piles, and the soil is represented by the following equation:

$$[M]\cdot\{\ddot{\delta}_a\ \ddot{\delta}_b\ \ddot{\delta}_c\ \ddot{\delta}_d\ \ddot{\delta}_e\}^T + [C]\cdot\{\dot{\delta}_a\ \dot{\delta}_b\ \dot{\delta}_c\ \dot{\delta}_d\ \dot{\delta}_e\}^T + [K]\cdot\{\delta_a\ \delta_b\ \delta_c\ \delta_d\ \delta_e\}^T = \{F_a\ F_b\ F_c\ F_d\ F_e\}^T$$

where [M] is the mass matrix, [C] is the damping matrix, [K] is the stiffness matrix, $\{\delta\}$ is the displacement vector, {F} is the external force vector, and superscript T means the transposed vector. Subscripts a, b, c, d, and e correspond to the building superstructure, the rigid foundation, the frictional piles or the soil, the side boundaries of the 3D (x, y, z-coordinate) system, and the bottom boundary of the system, respectively.

In the case of the input motion, we assume the following external force vector:

$$\{F_a\ F_b\ F_c\ F_d\ F_e\}^T = [M]\cdot\{\ddot{\alpha}_e\ \ddot{\alpha}_e\ \ddot{\alpha}_e\ \ddot{\alpha}_e\ \ddot{\alpha}_e\}^T$$

where α is the external displacement on the bottom boundary of the system. When the input whole-wave field is employed, the external force vector is expressed by

$$\{F_a\ F_b\ F_c\ F_d\ F_e\}^T = [M]\cdot\{0\ \ddot{p}_b+\ddot{q}_b\ \ddot{p}_c(z)+\ddot{q}_c(x,y,z)\ \ddot{p}_d(z)+\ddot{q}_d(x,y,z)\ \ddot{p}_e+\ddot{q}_e(x,y)\}^T$$

where p and q are the external displacements contributed by S waves and surface waves in the soil volume, respectively.

The 3D soil volume had a building-depensent horizontal extension, and a vertical extension down to a depth of 65 m. Prior to dynamic calculation, initial soil and pile stresses produced by gravity were evaluated by a static analysis. We assumed spatially-constant Rayleigh-type damping for the whole system of h = h1 = h2, where h1 and h2 were the damping coefficients at the primary and secondary predominant periods of the soil model, respectively.

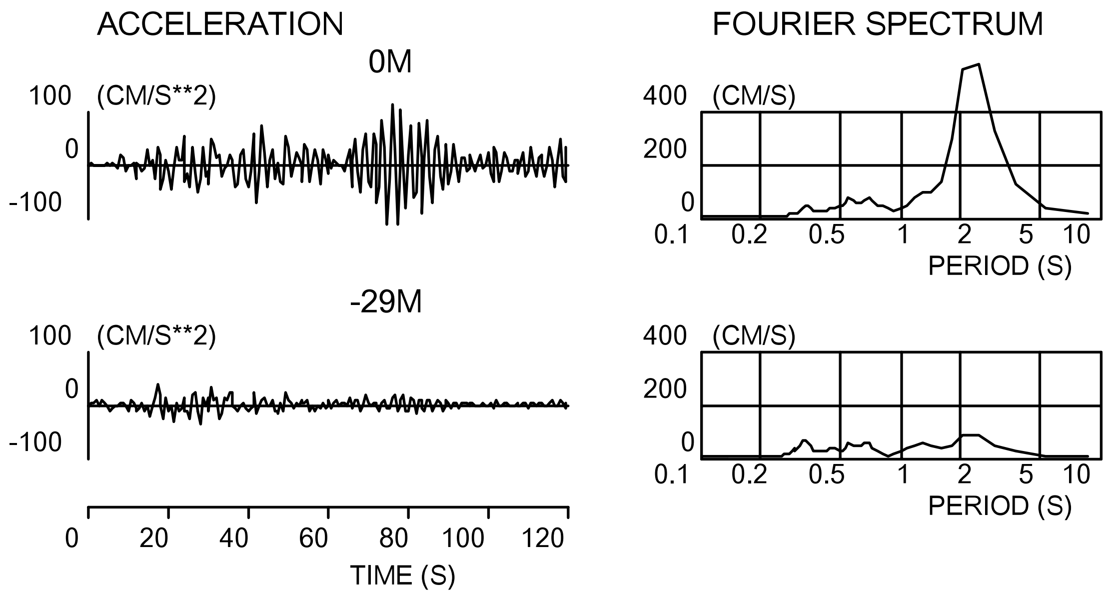

FIG. 3. FE simulated accelerograms due to the input whole-wave field.

We used five kinds of average RC buildings designed before 1985 in the lakebed zone of Mexico City. The five kinds of buildings were one low-rise (3-story), two mid-rise (9- and 15-story), and two high-rise (25- and 40-story) buildings. The natural periods indicated that these buildings were very flexible. Regarding the piles, we fixed the number of the piles of each building used in the analysis (analytical piles) at 9 (Fig. 2), owing to computer limitations. This modeling meant that one analytical pile represented many real piles. The 3-story building has no piles.

5. SOIL RESPONSES

Prior to a building response analysis, a 3D linear FE soil response analysis excited by the input wave field was conducted by removing the building from the interaction system, in order to confirm the reproduction of the wave field. The soil response calculation was valid in the period range of more than about 0.5 s, which was roughly equal to the fundamental period of the 3-story building. Dynamic calculation for 120 s with a time interval of 0.01 s was performed by using an input wave field and an input motion. The damping coefficient h was estimated to be 0.30 experimentally for the input whole-wave field of Fig. 1. A damping coefficient of h = 0.05 was assumed in the case of an input motion. Probably, this assumed value was underestimated (too small damping) for the soft deposit.

The FE simulated accelerograms due to the input whole-wave field are displayed in Fig. 3. The whole-wave field of Fig. 1 is retrieved fairly well by the simulated accelerograms. For comparison, FE simulated accelerograms due to the input motion are illustrated in Fig. 4. In spite of the very small soil damping, the simulated accelerograms cannot retrieve the late large-amplitude surface-wave phases of Fig. 1. The large differences in the Fourier spectra between Fig. 3 and Fig. 4 are expected by elastic wave theory.

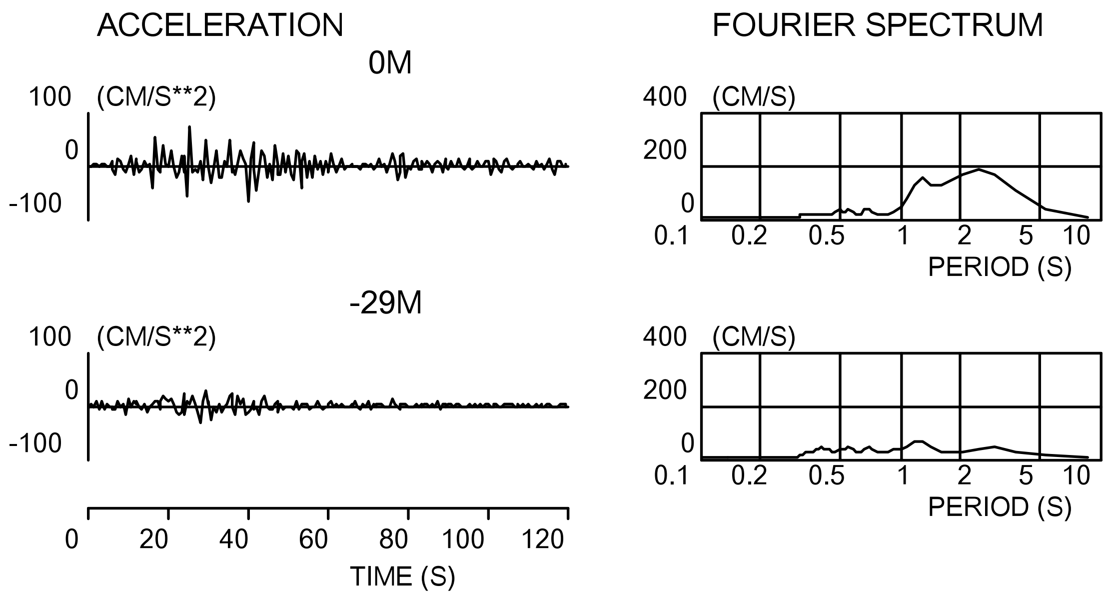

FIG. 4. FE simulated accelerograms due to the input motion.

6. BUILDING RESPONSES

A 3D linear soil-building interaction analysis was conducted, using the same calculation condition and the same damping as those used in the soil response analysis. Tables 1 and 2 summarize the maximum response values of the superstructures of the five kinds of buildings excited by the same input whole-wave field and the same input motion, respectively. The maximum top-story accelerations of the 9- and 15-story buildings excited by the input wave field are considerably large. In the case of the input motion, whereas the ground motion was underestimated, the maximum accelerations of the tall buildings are considerably overestimated. It is attributed to the false seismic external force that does not work physically towards the building superstructure.

Table 1. Maximum response values of the superstructures of the five kinds of buildings excited by the input whole-wave field.

Building	3-story	9-story	15-story	25-story	40-story
Top-story acceleration (cm/s^2)	240	408	551	270	142
Inter-story drift (cm)	1.1	5.3	12.8	15.0	9.8
Ratio of the shear force to the yield strength in the first story (%)	101	131	106	63	39

Table 2. Maximum response values of the superstructures of the five kinds of buildings excited by the input motion.

Building	3-story	9-story	15-story	25-story	40-story
Top-story acceleration (cm/s^2)	268	443	954	473	330
Inter-story drift (cm)	0.9	4.7	23.9	24.9	35.9
Ratio of the shear force to the yield strength in the first story (%)	72	79	209	42	28

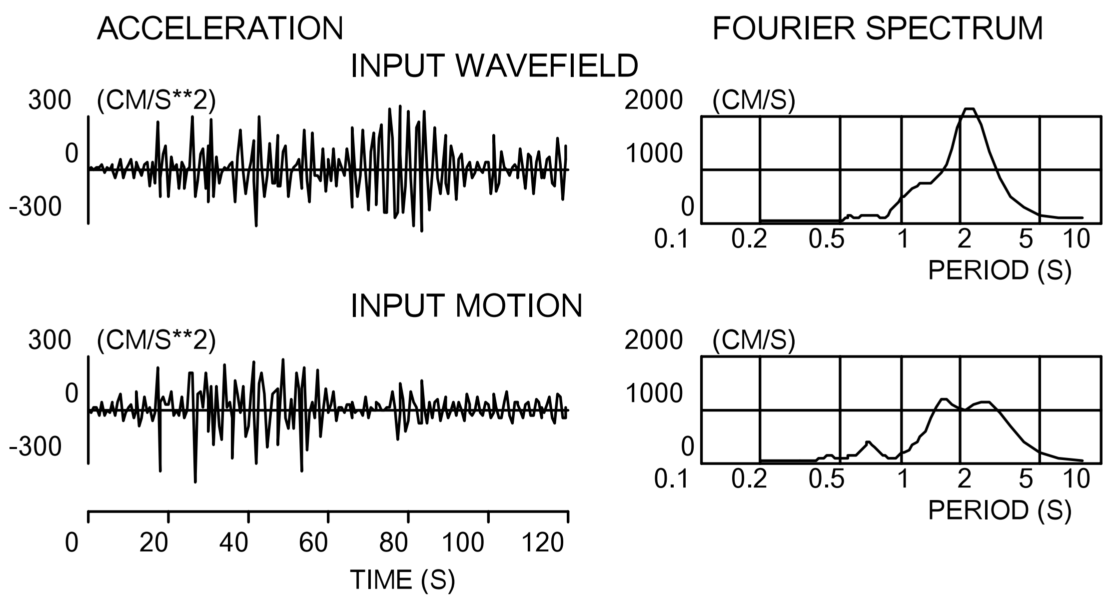

FIG. 5. Top-story accelerograms of the 9-story building excited by the input whole-wave field and the input motion.

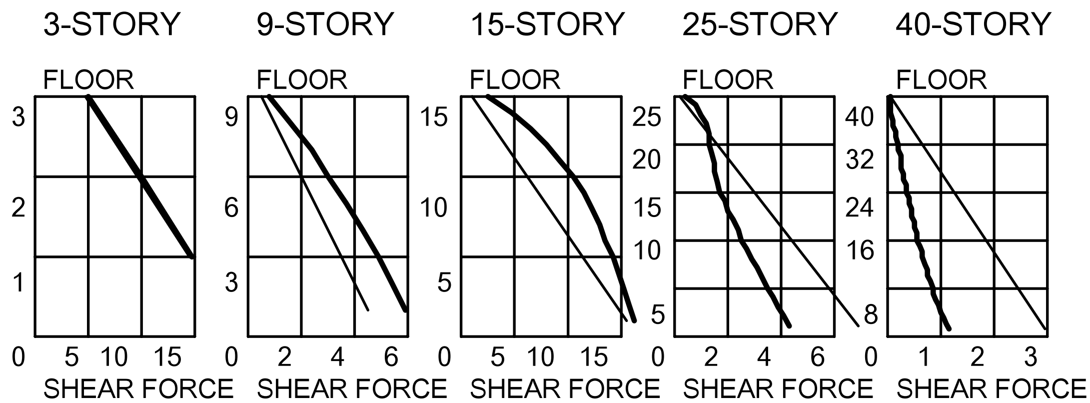

FIG. 6. Vertical distributions of the maximum shear force of the five kinds of buildings excited by the input whole-wave field. The straight thin lines mean the yield strength.

We also calculated the maximum inter-story drift and the maximum ratio of the shear force to the yield shear strength in the first story. The story drift of the 3-story building excited by the wave field is very small, while the shear force/strength ratios of the 25- and 40-story buildings are low. In the case of the input motion, the story drifts of the tall buildings are extremely large. Only the 15-story building does not have enough shear strength to resist the excessive soil-building resonance with a predominant period (about 2.5 s) of the ground motion, which is due to the above-mentioned false external force. The other buildings sustain less shear force because of the underestimated ground motion.

The top-story accelerograms of the 9-story building excited by the input whole-wave field and the input motion are compared in Fig. 5. When the wave field is used, the 9-story building resonates with the predominant period of the ground motion rather than the fundamental period (about 1.3 s) of the building. In the case of the input motion, the large responses of the late time section excited by the wave field cannot be reproduced. Fig. 6 shows the vertical distributions of the maximum shear force of the five kinds of buildings excited by the input whole-wave field. The shear force of the 9- and 15-story buildings gets larger than the yield strength, which are very consistent with a real damage pattern.

7. CONCLUSIONS

A 3D soil-building interaction method based on an input seismic wave field was proposed, and was applied to estimate linear seismic responses of low- to high-rise RC buildings during a large earthquake in the lakebed zone of Mexico City. The conclusions are summarized as follows. (1) An interaction method based on an input wave field gave a result that a mid-rise building shook more heavily than a low- and a high-rise building, which was in good agreement with a real building damage pattern. (2) A conventional method based on an input motion was not able to calculate appropriate building responses, because high amplification of surface waves was not reproduced.

ACKNOWLEGMENTS

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