KINEMATIC INTERACTION OF SOIL-STRUCTURE SYSTEM BASED ON OBSERVED DATA

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SUMMARY

Using both of the finite element method and regression analysis method, the kinematic interaction of soil-structure system is investigated quantitatively based on observed data of large-scale LNG inground tanks. The inground tank would be treated as a massless rigid foundation which has only effect of the kinematic interaction and little of the dynamic interaction, since the inground tank is a stiff structure with a small unit weight of 0.85 t/m^3.

The numerical low-pass filter is proposed to represent the effect of kinematic interaction and effectiveness of this filter is confirmed by earthquake records of four structures : a large-scale LNG inground tank, a foundation of a blast furnace of iron work, a reinforced concrete 14-story building and a reactor building of nuclear power plant.

INTRODUCTION

Generally stiffness of foundation slab is much stronger than that of soil, it works to constrain the input ground motion which has spatial variation in both phase and amplitude around the foundation during earthquake. Components of the ground motion, whose wave lengths are relatively short compared with dimension of the slab, will be weakened. Thus the foundation behaves as a kind of low pass filter which works on the ground motion, and this effect is called " Kinematic Interaction " (Ref. 1).

In the past, many studies have been made on the kinematic iteraction both theoretically and experimentally, and characteristics of the kinematic interaction have become clearer (Refs. 2~9). Development of a rational design method which evaluates the kinematic interaction effectively have been expected for a long time, especially in nuclear power industries.

A useful numerical tool which serves as a low-pass filter, H(f), to represent the effect of kinematic interaction is proposed based on observed data. Earthquake response analysis of soil-structure system considering the kinematic interaction consists of following two steps : (1) an estimation of the foundation input motion from a free-field motion using the proposed numerical low-pass filter, (2) the earthquake response analysis of a spring-mass-dashpot system by the estimated foundation input motion.

In this paper, first, the kinematic interaction is investigated quantitatively based on observed data of large-scale LNG inground tanks. The inground tank would be treated as a massless rigid foundation which has only effect of the kinematic interaction and little of the dynamic interaction, since the inground tank is a stiff structure with a small unit weight of 0.85 t/m^3. Next, refered to results of these investigations the numerical low-pass filter is proposed and effectiveness of this filter is confirmed by earthquake records of four different structures : a large-scale LNG inground tank, a foundation of a blast furnace of iron work, a reinforced concrete 14-story building and a reactor building of nuclear power plant.

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KINEMATIC INTERACTION OF LARGE-SCALE INGROUND TANKS

In this section, using the finite element method (FEM) the kinematic interaction is investigated based on earthquake records of a large-scale LNG inground tank. Then, statistical characteristics of the kinematic interaction of the inground tank are examined based on microtremor records of eighteen large-scale LNG inground tanks.

Verification of Kinematic Interaction (Ref. 10)

Earthquake accelerograms have been recorded for a large-scale inground cylindrical tank of reinforced concrete. A diameter and a height are 67.9 m wide and 26.2 m deep respectively, a thickness of side wall and a bottom slab are 1.8 m and 5.5 m respectively, and an embedded depth is 24.5 m as shown in Fig. 1 . Soil properties are following : the upper part above GL -14 m consists of reclamation soil and alluvium, and the lower part below GL -14 m of diluvium. The average shear wave velocities of each layer are 150 m/s at GL ±0 m ~ -14 m, 380 m/s at GL -14 m ~ -40 m and faster than 450 m/s under GL -40 m.

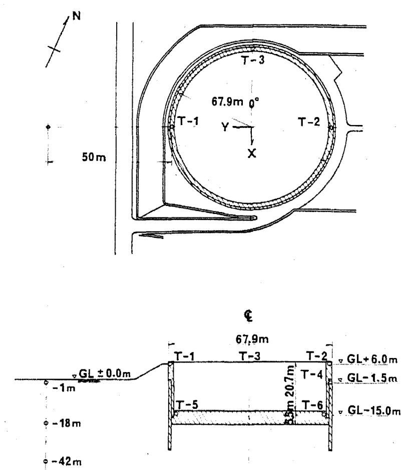

Fig. 1 Large-Scale Inground Tank

As pointed out previously, the kinematic interaction is regarded as an effect of input energy loss of massless rigid foundation. It would be possible to model the inground tank as a massless rigid foundation, since the inground tank has small unit weight of about 0.85 t/m^3.

Figure 2 shows the analytical result of the transfer function between a ground and a foundation with the observation result.

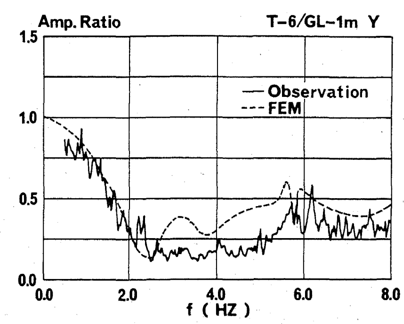

Fig. 2 Transfer Function
(Large-Scale LNG Inground Tank)

In Fig.2, the heavy line is the observation result, which is the average of transfer functions of thirteen earthquakes, and the dotted line is the analytical result. The observation result shows typical of the filtering effect of kinematic interaction such as the amplitude ratio decreases with the increase of the frequency in the frequency domain of 0.0 ~ 2.5 Hz and it staies on about 0.35 in the frequency domain of 2.5 ~ 8.0 Hz.

The analytical result is evaluated using an axi-symmetrical finite element method. The model applied to the analysis is used in design practice except that the unit weight of the tank concrete is reduced to one-tenth of an usual 2.45 t/m^3 to discuss only the kinematic interaction. It is observed from Fig. 2 that the analytical result agrees approximately well with the observation result.

Statistical Characteristics of Kinematic Interaction (Ref. 11)

Using the earthquake observation system of the inground tank investigated above, the microtremors were also recorded and analyzed to verify their ability to discuss the kinematic interaction.

In Fig. 3, the dotted line shows the transfer function based on microtremor records and the solid line on a strong earthquake record whose maximum acceleration of 194 Gal is about 8000-times large as that of microtremor.

Two curves almost coincide in the frequency of 0.0 ~ 2.5 Hz and the result on microtremor is smaller than that of the earthquake record in the frequency of 2.5 ~ 10.0 Hz. Thus, the transfer function in the low frequency domain based on microtremor records can be applied to investigate the effect of kinematic interaction.

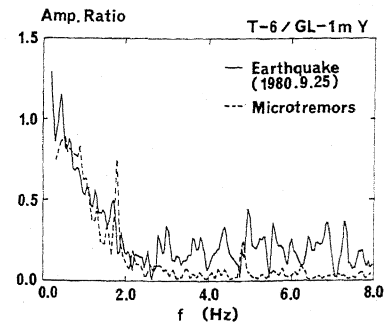

Fig. 3 Transfer Function
(Large-Scale LNG Inground Tank)

Microtremor observations of eighteen large-scale LNG inground tanks are carried out. The diameters and depths of inground tanks are 32.3 ~ 73.5 m wide and 19.8 ~ 42.6 m deep respectively and they are in the same type of the inground tank as shown in Fig. 1. Microtremors observed both on the top of side walls and on the ground at the distance of 20 ~ 30 m from an inground tank are used to analysis.

As the results of microtremor observation, transfer functions, which relate the translation of the ground motions to the motion of the inground tank, of two adjacent inground tanks are as shown in Figs. 4 and 5. The diameter and the height of small tank are 68 m wide and 24.5 m deep in Fig. 4, and 32 m wide and 20 m deep in Fig. 5. These figures show the significant differences between the transfer functions due to the scale effect.

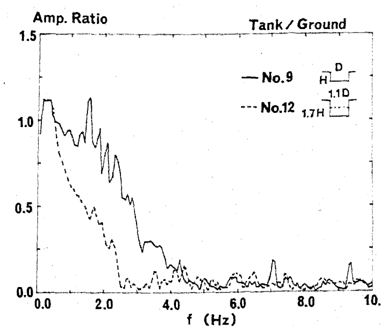

Fig. 4 Transfer Function
(Microtremor Observation)

By regression analysis, the statistical characteristics of the scale effect for kinematic interaction are investigated based on the transfer functions of eighteen inground tanks.

In the analysis, the objective variable is defined with the period $\tau_{0.5}$ where the amplitude ratio of the transfer function becomes 0.5 first with increase of the frequency. This variable varies proportionally with the intensity of filtering effect. Design variables are defined by (H/V_s) and (D/V_s) where H and D are the depth and the diameter of inground tank respectively and V_s is the average shear wave velocity of a surrounding soil of inground tank.

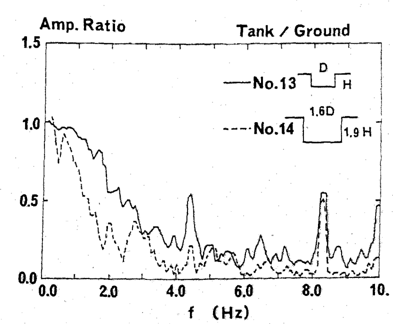

Fig. 5 Transfer Function
(Microtremor Observation)

The variables (H/V_s) and (D/V_s) indicate the time durations when the shear wave with velocity V_s propagates distances of width and depth of a foundation, respectively and (H/V_s) is used as the parameter of numerical low-pass filters proposed for design analyses (Refs. 2 and 8).

The result of regression analysis is given by the following equations:

$$\tau_{0.5} = 3.62\ (H/V_s) - 0.178 \quad \cdots\cdots\cdots\cdots\cdots (1)$$

$$\tau_{0.5} = 4.42\ (H/V_s) - 1.02\ (D/V_s) + 0.084 \quad \cdots\cdots\cdots (2)$$

The correlation coefficient of Eq. (1) and the multiple correlation coefficient of Eq. (2) are 0.78 and 0.95 respectively.

In Eqs. (1) and (2), $\tau_{0.5}$ varies proportionally with the increase of (H/Vs). However, in Eq. (2), $\tau_{0.5}$ varies inversely with increase of (D/V_s). This property is difficult to understand since that the intensity of filtering effect of kinematic interaction varies proportionally with the increase of scale of a foundation.

These tendencies of kinematic interaction of embedded foundations are based on parametrical studied of various depth and width of foundations using a plane strain finite element method, i.e., the FLUSH program. A standard model of a massless rigid foundation with 20 m in depth and 80 m in width is embedded in a soil whose shear wave velocity is 500 m/s. The results are shown in Figs. 6 and 7.

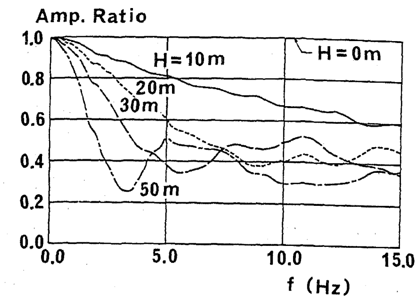

Fig. 6 Transfer Function (FEM Analysis)

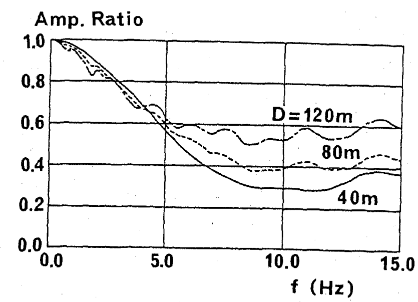

Fig. 7 Transfer Function (FEM Analysis)

Figure 6 indicates that the filtering effect of kinematic interaction is proportional to the increase of depth of a foundation.

Figure 7 shows that the variation of width of a foundation has little influences on the kinematic interaction of embedded foundation. However, in the frequency domain of 5.0 ~ 15.0 Hz, the amplitude ratio of transfer functions varies inversely with the increase of width of a foundation. This result shows the similar tendency as Eq. (2). It would be explained as follows : since the seismic input is assumed as the shear wave which propagates vertically right under a foundation in the FEM analysis, the ground motions beneath the bottom slab of a foundation have less spatial variation both in amplitude and phase than in a lateral soil of a foundation. Thus the kinematic interaction of an embedded foundation is produced more on the side wall than on the bottom of a foundation and the filtering effect is weakened as the width of an embedded foundation increases.

THE LOW-PASS FILTER WHICH REPRESENTS OF FILTERING EFFECT

Proposed Low-Pass Filter

The low-pass filters to represent the effect of kinematic interaction were proposed for design analyses in past studies (Refs. 1, 2 and 8). These filters were made after considering following items : (1) conservative estimation of the effect of kinematic interaction, (2) the simple function which has a physical meaning, (3) number of arguments used in the equation and (4) simple calculation to estimate a foundation input motion. However, it is very difficult to satisfy these conditions, because the effect of kinematic interaction is so complicated to depend totally on a geometrical cofiguration of a foundation slab, inground characteristics and input excitation (Ref. 12).

In this study, since the effect of the kinematic interaction is influenced much by the parameter (H/V_S) as investigated above, the very simple low-pass filter with the variable (H/V_S) is proposed to represent the effect of kinematic interaction for design analyses based on the observed data (Ref. 13).

The proposed filter is given by the following equation :

$$|H(f)| = \tilde{f} / (\pi f) \sin \{ (\pi f) / \tilde{f} \} \quad \text{for } 0 \le f \le 0.71 \tilde{f}$$
$$= 0.35 \quad 0.71 \tilde{f} \le f \cdots\cdots (3)$$

where

$$\tilde{f} = 1.408 / \tau^*$$
$$= 1.408 / \{ 2.19 (H/V_S) + 0.117 \} \cdots (4)$$

and H is a depth of a foundation and V_S is the average shear wave velocity of a lateral soil of a foundation. The first equation in Eq. (3) indicates that the motion of a foundation is estimated from the average of shear wave motions on the side wall of a foundation, under the assumption that the effect of kinematic interaction on the bottom of a foundation can be ignored. The second equation of Eq. (3) is the under limit of amplitude ratio.

The proposed filter agrees approximetely well with the transfer function of a large-scale LNG inground tank as shown in Fig. 8 and it is not conservative compared with other filters proposed from the FEM analyses (Refs. 2 and 8).

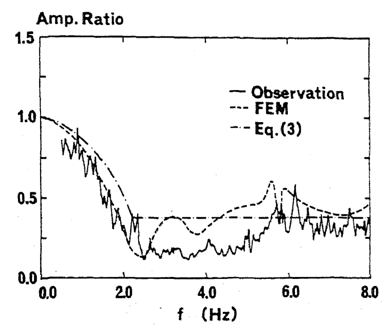

Fig. 8 Proposed Low-Pass Filter (Eq. (3))

In Eq. (4), the period τ^*, where the amplitude ratio of the filter becomes 0.35 first with the increase of the frequency, is given by the regression analysis with correlation coefficient of 0.97 based on the earthquake records of thirteen structures as shown with a solid line in Fig. 9. In the regression analysis, structures which have a little dynamic interaction are chosen as the subject of the study and some of them are used to confirm the applications of the proposed low-pass filter in a next section.

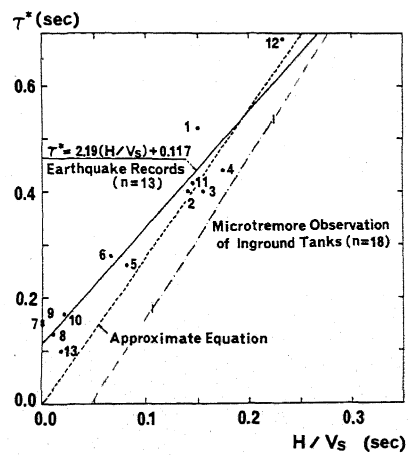

Fig. 9 Relation between τ^* and (H / V_S)

In Fig. 9, the dotted line is calculated from the approximate equation described above and the dot-dash line is from Eq. (2) modified by considering the difference between the parameters $\tau_{0.5}$ and τ^* using the first equation of Eq. (3). In Fig. 9, τ^* based on the earthquake recrds varies proportionally with the increase of (H/Vs) and when (H/Vs) = 0 , it does not become zero by both effects of kinematic interaction on the bottom slab of a foundation and foundation piles. τ^* based on the microtremor records of inground tanks as shown with dot-dash line is smaller than that based on earthquake records because of following differences : observation points on a foundation, distance between a structure and a measured point on the ground and characteristics of input excitations.

Applications of the Proposed Low-Pass Filter on Field Data

In this section, applications of the proposed low-pass filter are investigated by comparing calculated input foundation motion from a free-field motion using the proposed low-pass filter with the observed motion of a foundation in the response spectrum for a value of 5 percent of critical damping.

Large-Scale LNG Inground Tank

The large-scale LNG inground tank as shown in Fig. 1 is investigated again as an example of a deep embedded foundation. The filtering effect of kinematic interaction is estimated by the proposed low-pass filer given by Eq. (3) where f is estimated by Eq. (4) with the average shear wave velocity of 163 m/s of a lateral soil and 24.5m of a foundation depth .

Figure 10 shows the response spectrums for the ground motion at GL -1 m , the estimated input foundation motion and the motion at bottom slab of a inground tank. The response spectrum for the estimated input foundation motion almost agrees with that of the foundation motion.

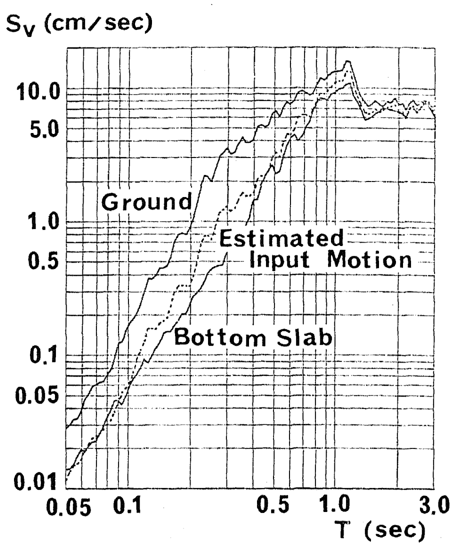

Fig. 10 Response Spectrum (Large-Scale LNG Inground Tank)

Foundation of a Blast Furnace of Iron Work

A foundation of a blast furnace of iron works is investigated as an example of a deep embedded structure. The foundation is a cellular foundation with steel pipe piles whose diameter and depth are 35.4 m wide and 19.4 m deep, respectively and they are embedded in the soil of the shear wave velocity of 138 m/s.

Figure 11 shows the response spectrums for the free-field motion, the estimated input foundation motion and the observed foundation foundation.

The response spectrum for the estimated input foundation motion agrees relatively well with that of the motion of a foundation, although the response spectrum for the estimated input foundation motion is smaller than that of the motion of a foundation in longer periods than 0.5 second.

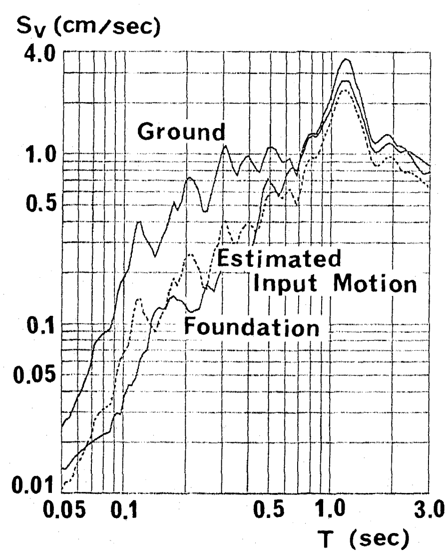

Fig. 11 Response Spectrum (Foundation of a Blast Furnace of Iron Work)

Hollywood Storage Building

Hollywood Storage Building, which is a reinforced concrete frame of 14-story building, is investigated as a more general structures. its dimension is are 66.3 m long, 15.5 m wide and 45.7 m high, respectively, and it is supported on piles (Refs. 4 and 14). Longitudinal components of accelerographs during San Fernando earthquake in 1971 both on the basement and on the free-field 34 m away from the building are used.

Figure 12 shows the response spectrums for the free-field motion, the estimated input foundation motion and the observed motion at the basement.

The response spectrum of the estimated input foundation motion shows a fairly good approximation with that of the motion at the basement.

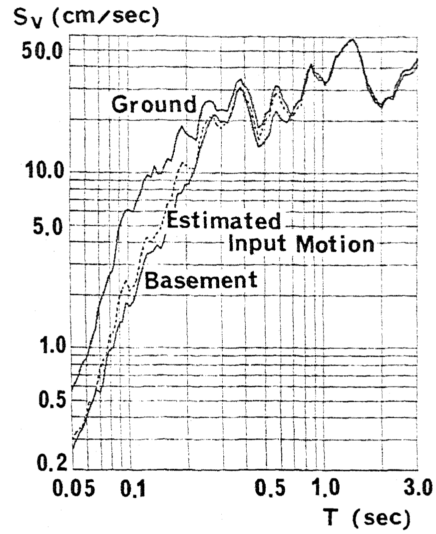

Fig. 12 Response Spectrum (Hollywood Storage Building)

Reactor Building of Nuclear Power Plant

Finally, a reactor building of a nuclear power plant is investigated (Ref. 15). The reactor building is the reinforced concrete structure with 67.0 m wide and 73.0 m high. The filtering parameter τ^* is estimated by Eq. (4) with the shear wave velocity of 298 m/s of a surrounding soil and the embedded depth of 23.5 m.

Figure 13 shows the response spectrums for the free-field motion, the estimated input foundation motion and the motion at the base mat. The response spectrum of the estimated input foundation motion is relatively larger than that of the motion at the base mat in high frequency.

Though the natural period of the building is about 0.3 second, there are practically no change in the response spectrum of the motion at base-mat.

Futhermore, in order to confirm that the reactor building has a little dynamic interaction, the transfer function between a ground and a foun- dation using the mass-spring-dashpot system of nine-degrees of freedom are calculated. The amplitude ratio of the transfer function varies between the narrow bounds of 0.85 ~ 1.25 in the longer period than 0.14 second.

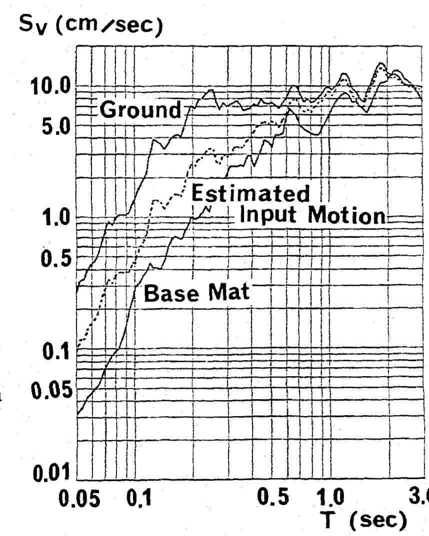

Fig. 13 Response Spectrum (Reactor Building of Nuclear Power Plant)

CONCLUSIONS

Using the finite element method the kinematic interaction is verified based on earthquake records of large-scale LNG inground tank. The inground tank is modeled as a massless rigid foundation which has only effect of the kinematic interaction and little of the dynamic interaction, since the inground tank is a stiff structure and a small unit weight of 0.85 t/m^3.

Next, the effect of kinematic interaction is investigated based on microtremor records of eighteen large-scale inground tanks. As both results of regression analysis and the FEM analysis, the filtering effect of kinematic interaction is influenced much with the variation of depth than that of width of an embedded foundation.

Refered to these results, the numerical low-pass filter is proposed to represent the effect of kinematic interaction based on the observed data. The effectiveness of this filter is confirmed by earthquake records of four different structures. Applications of the proposed low-pass filter are investigated by comparing the calculated input foundation motion from a free-field motion using the proposed low-pass filter with the observed motion of a foundation in the response spectrum. The response spectrum of the estimated input foundation motion agrees well with that of the observed motion of a foundation.

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