Effects of Contact Condition of Side Walls of Embedded Foundation on Dynamic Response of Structures

Kazuhiro Yoshida[a] and Tetsuya Hagiwara[b]

In the present study, dynamic response characteristics of a massive structure with a rigid foundation partially embedded in an elastic half space were examined by using the 3-dimensional boundary element method. Analyses were carried out for various contact conditions of the side walls of the embedded foundation. Results obtained in this study indicate that when 3 side walls of the embedded foundation are welded to the surrounding soil, dynamic response of the foundation is almost similar to that of the fully contacted foundation. It is also true when the embedment depth of the foundation is smaller, effects of contact condition of side walls become relatively small.

INTRODUCTION

In the asesimic design of massive and rigid structures typically seen in the nuclear power plants, it is very important to evaluate effects of dynamic soil-structure interaction properly. A lot of actual structures have embedded foundations. The dynamic analyses become greatly difficult for embedded foundations compared with surface foundations. Three-dimensional analyses of the embedded foundations have been carried out widely by using the boundary element method or the thin layer element method, recently (AIJ,1996). Some of the analyses were performed to calculate dynamic response of non-uniformly embedded foundations (Matsumoto et al., 1984, Koyakagi et al., 1989, Omote et al., 1991) In those analyses, the ground surface is assumed to have some step or slope. When we consider the ground condition in the vicinity of large scaled structures like reactor buildings, it seems to be more realistic to assume that the backfill soil does not exist between the adjacent structures than to assume that the ground surface has steep step or slope.

a) Shimizu Corporation, 4-17 Etchujima, 3-Chome, Koto-ku, Tokyo 135-8530, JAPAN
b) Shimizu Corporation, 2-3 Sibaura, 1-Chome, Minato-ku, Tokyo 105-8007, JAPAN

The purpose of the present study is to evaluate dynamic impedance functions and foundation input motions of rigid embedded foundation under various boundary conditions by using the three-dimensional boundary element method (Yoshida and Kawase, 1986). By applying those impedance functions and foundation input motions to a simple lumped mass model, another purpose of the present study is to evaluate the influence of the contact conditions of the embedded foundation on the dynamic characteristics of the large scaled structures.

ANALYSIS METHOD AND MODELS

The ground is assumed to be a homogeneous, isotropic elastic half space. The shear wave velocity of the half-space is assumed to be 500m/s and the density is supposed to be 1.8ton/m^3, the Poisson ratio is 0.40, and the material damping is set to be 3 %. The foundation with a square section of 80 x 80 m is embedded to the depth of 40m under the ground surface. Three-dimensional boundary element method is mainly used for the present analyses. Because the dynamic Mindlin's solution that satisfies the boundary condition at the ground surface is used as a Green's function in the present boundary element method, only the surface of the embedded foundation to the surrounding soil is discretized by boundary elements. The number of boundary elements used at the bottom of the foundation is 12 x 12, and the foundation is covered by 6 elements in the vertical direction as shown in Fig. 1. The contact boundary condition of the rigid embedded foundation touching the surrounding soil is given as the displacement boundary, and the part of the side walls not touching the soil is given as the stress free boundary. To verify the present boundary element method to solve the mixed boundary value problem, we consider a foundation that is partially welded to the surrounding soil in the vertical direction. The axi-symmetric finite element method (Hagiwara and Yoshida, 1998) as illustrated in Fig.2 is employed for a verification study. The foundation model used in the axi-symmetric FEM is assumed to have the same bottom area as the 3-D BEM. Comparison is made by impedance functions and foundation input motions. The portion of the side wall separated from the surrounding soil is set to be 0.0 (F-model), and 0.50 (P-model) of the entire side wall as depicted in Fig.3. Results are presented in Fig. 4 for impedance functions and in Fig. 5 for foundation input motions. The impedance functions in the figure are evaluated at the center of the bottom of the rigid foundation and are normalized by the product of the half-width of the foundation (b) and the rigidity of the surrounding soil (G). The foundation input motions are estimated by the ratio of displacements at the bottom of the foundation to those at the ground surface in the free field when the foundation is subjected to vertically incident SH waves. In those figures, results by the boundary element method are indicated by symbols and results by the axi-symmetric finite element method are shown by solid or dotted lines. As for the impedance functions, though small discrepancies can be seen in the rocking components because the radius of the equivalent area circle is used in an axi-symmetric finite element method, results by the present two methods give good correspondence on the whole. The good agreement can also be seen as for the foundation input motions. By judging from the results of this comparison study, the present boundary element method and the employed analysis model may be suitable for solving the mixed boundary value problems.

Next, we consider several types of contact conditions between the side walls of an embedded foundation and the surrounding soil. Six models as depicted in Fig. 6 are employed here; a model welded to the soil over the entire surface (F-model), a model with 3 side walls bonded to the soil (P1 model), two models with 2 side walls touching the soil (P21 and P22 models), a model with only 1 side wall welded to the soil (P3 model), and a model contacting with the surrounding soil only at the bottom (P4 model). In the following analyses, when a side wall of an embedded foundation is touching the surrounding soil, the wall is assumed to be perfectly welded to the soil.

ANALYSIS RESULTS

Impedance functions of rigid embedded foundations calculated by the 3-D boundary element method are compared for the various contact conditions in Fig. 7. As for the impedance functions in the horizontal X direction, when the number of walls bonded to the soil in the orthogonal direction to the X axis becomes larger, real parts of the impedance functions tend to increase in relatively lower frequencies. On the contrary, the real parts show decrease in the relatively higher frequencies because the additional mass becomes bigger. The imaginary parts grow increase as the number of side walls touching the surrounding soil becomes large. In the comparison between P21 and P22 models that are bonded to the soil at two side walls, P21 model gives larger radiation damping than P22 model. This tendency may come from the fact that P22 model mainly generates shearing waves to the soil, however P21 model creates also dilatational waves. Impedance functions in the horizontal Y direction show contrary to those in the X direction. P1 and P3 models indicate relatively larger imaginary parts in the horizontal Y direction than those in the X direction.

Rocking impedance functions around the Y axis show large values in both real and imaginary parts when the number of the side walls contacting the soil in the orthogonal direction to the X axis becomes large. This tendency is also remarkable in rocking impedance functions around the Y axis.

As for the horizontal-rocking coupling terms, it can be seen similar tendency to the rocking impedance functions. P4 model, which is welded to the surrounding soil only at the foundation bottom, gives small values of the horizontal-rocking coupling components. This is similar to surface foundation. P4 model also generates the same imaginary values both in horizontal and rocking impedance functions as the surface foundation. When foundation has some embedment, imaginary parts of the impedance functions are dominant in the higher frequency range. If we compare the results by F and P4 models, considerably parts of the imaginary parts of the impedance functions come from the side wall contributions. If we think about the vibration in the Y direction, P1 model, which is touching the soil at three sides, gives the same tendency as fully contacting F model.

Figure 8 shows the comparison of foundation input motions at the center of the foundation bottom to the ground surface when the embedded foundations are subjected to vertically incident SH waves. When the foundations are embedded in the ground, the horizontal components become small and the rocking components appear in the foundation input motions because the side walls of the rigid foundations restrain the vertical wave distributions. If we look at the foundation input motions in the horizontal X direction, it is recognized that the dip of the input motions shifts to the lower frequency as the number of the contacting side walls becomes small. Rotational input motions around the Y axis can be seen even in P4 model that has no touching side walls. As for the horizontal input motions in the Y direction, except for results by P4 model, which has no side walls, all models give smaller difference with fully contacting F model than those in the X direction. This tendency is similar to the impedance functions that contribution of the side walls existing in the orthogonal to the input direction is remarkable.   The same tendency can be seen in the rocking input motions around the X axis. If we consider the vibration in the Y axis, P1 and P22 models have the same characteristics as those of F model.

Next, In order to evaluate how contact conditions of embedded foundation give the dynamic response characteristics of upper structure, a typical, large-scale structure is dynamically analyzed by using the dynamic impedance functions and the foundation input motions calculated by the three-dimension boundary element method. Two analysis models are employed here, one is a model whose foundation is embedded to the depth of 40m under the ground surface and the other is a model whose foundation embedded to 20m in depth. It is assumed that two models have the same cross section (80 x 80m) and embedded in the same half-space. To clarify the dynamic response, the upper structure is modeled by a rigid beam system that has one mass with 6 degrees of freedom at the center of gravity position. The mass is assumed to be 330,000 ton, the height of the center of gravity is supposed to be 20 m above the ground surface, and the rocking moment of inertia is set to be 2.6×10^8 ton m^2/rad. Responses are evaluated by the transfer functions at the point of 56m in height from the foundation bottom. The point is corresponding to the level of the operating floor at the typical reactor building.

When the embedment depth is half width of the foundation (40m), transfer functions to the ground surface are shown in Fig. 9 for various contact conditions. Three figures above are transfer functions in the X direction and the under three are transfer functions in the Y direction. In the first figure, P model stands for the model whose side walls are not touching the soil to a half of embedment depth in the vertical direction (see Fig.2). In the figures, solid lines indicate results by the fully contact F model, and it shows by comparison with results by F model. As for the transfer functions in the X direction, it is recognized that P22 model gives slightly larger amplitude than F model and that P3 and P4 models generate outstandingly larger amplitude. In the present analyses, as the foundation bottom is assumed to be perfectly welded to the soil, though P4 model has no side walls, P4 has rocking input motions. In P4 model, the imaginary part of impedance functions that shows the radiation damping is smaller than that of other models. It is thought from these two reasons that the transfer functions of P4 model may become large. In the transfer functions in the Y direction, response of P1 model whose three side walls are touching the soil is almost corresponding to the response of the fully contact F model. Moreover, P22 model that two sidewalls are bonded to the soil is almost corresponding to the response of F model. It is recognized that response of P3 model that only one side wall is bonded to the soil is more close to the response of F model than those in the X direction.

The transfer functions when the embedment depth of the foundation is a quarter width of the foundation (20m) are shown in Fig. 10. In the first figure, results by a model with the surface foundation (S model) are shown for comparison. When the embedment depth is small, the transfer function has a peak even in F model. However, the peak is considerably small compared with the case of the surface foundation. It is noted on the whole that the influence of the contact conditions of side walls becomes small on the response when the embedment is shallow.

CONCLUSIONS

In the present study, dynamic response characteristics of a massive structure with a rigid foundation partially embedded in an elastic half space were examined by using the 3-dimensional boundary element method. Analyses were carried out for various contact conditions of the side walls of the embedded foundation. Results obtained in this study indicate that when 3 side walls of the embedded foundation are welded to the surrounding soil, dynamic response of the foundation is almost similar to that of the fully contacted foundation. It is also true when the embedment depth of the foundation is smaller, effects of contact condition of side walls become relatively small.

REFERENCES

Architectural Institute of Japan (AIJ), 1996, An Introduction to Dynamic Soil-Structure Interaction.

Hagiwara, T and Yoshida, K., 1998. Comparison study on Dynamic Response of Rigid Embedded Foundations, in Proceedings of the 10th Japan Earthquake Engineering Symposium, pp.2057–2062, (in Japanese).

Koyanagi, Y. Okamoto, S. Yoshida, K. and Inoue, H., 1989. Effects of Non-uniform Embedment on Earthquake Responses of Nuclear Reactor Buildings, in Transactions of 10th SMiRT, pp. 151̃156

Matsumoto, T, Tomura, H. Hamamoto, T. and Gotoh, T., 1984, Dynamic Soil-structure Interaction Analyses of Nuclear Power Plant by Boundary Element Method – Dynamic Characteristics of Embedded Foundation considering Irregularity of the Ground Surface. in Proceedings of Annual meetings of AIJ Kanto branch, pp.269-272, (in Japanese).

Omote, Y. Kurimoto, O. and Seki, T., 1991, Simple Evaluation Method for Embedded Foundations - Part 2 Dynamic Impedance for Irregularly Embedded Foundation, in Proceedings of Annual Meetings of AIJ, pp.887-888, (in Japanese).

Yoshida, K. and Kawase, H., 1986, Dynamic Interaction Analysis of Rigid Embedded Foundations by Boundary Element Method, in Proceedings of the 7th Japan Earthquake Engineering Symposium, pp.1045–1050, (in Japanese).

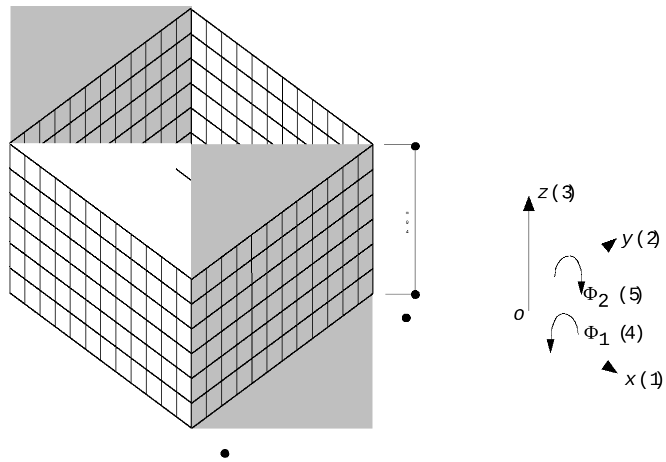

Figure1. Mesh layout used for 3-D BEM

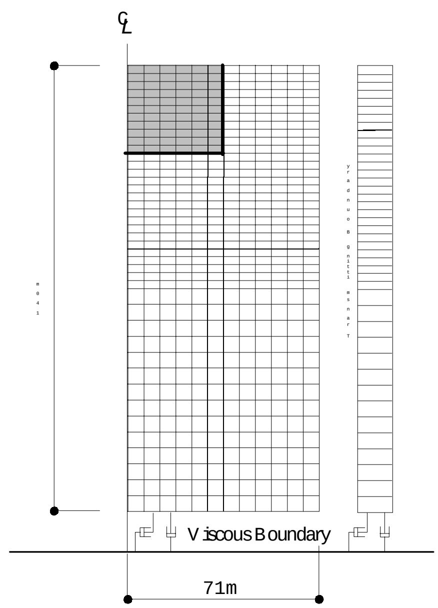

Figure2. Mesh layout used axi-symmetric FEM

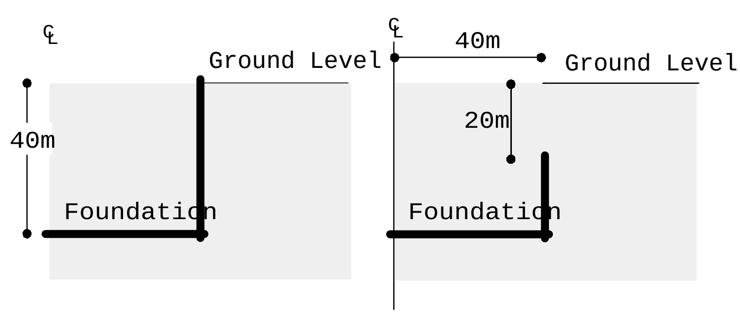

Figure3. Analysis models used for a verification study (a) fully embedded foundation model (F model) and (b) partially embedded model (P model)

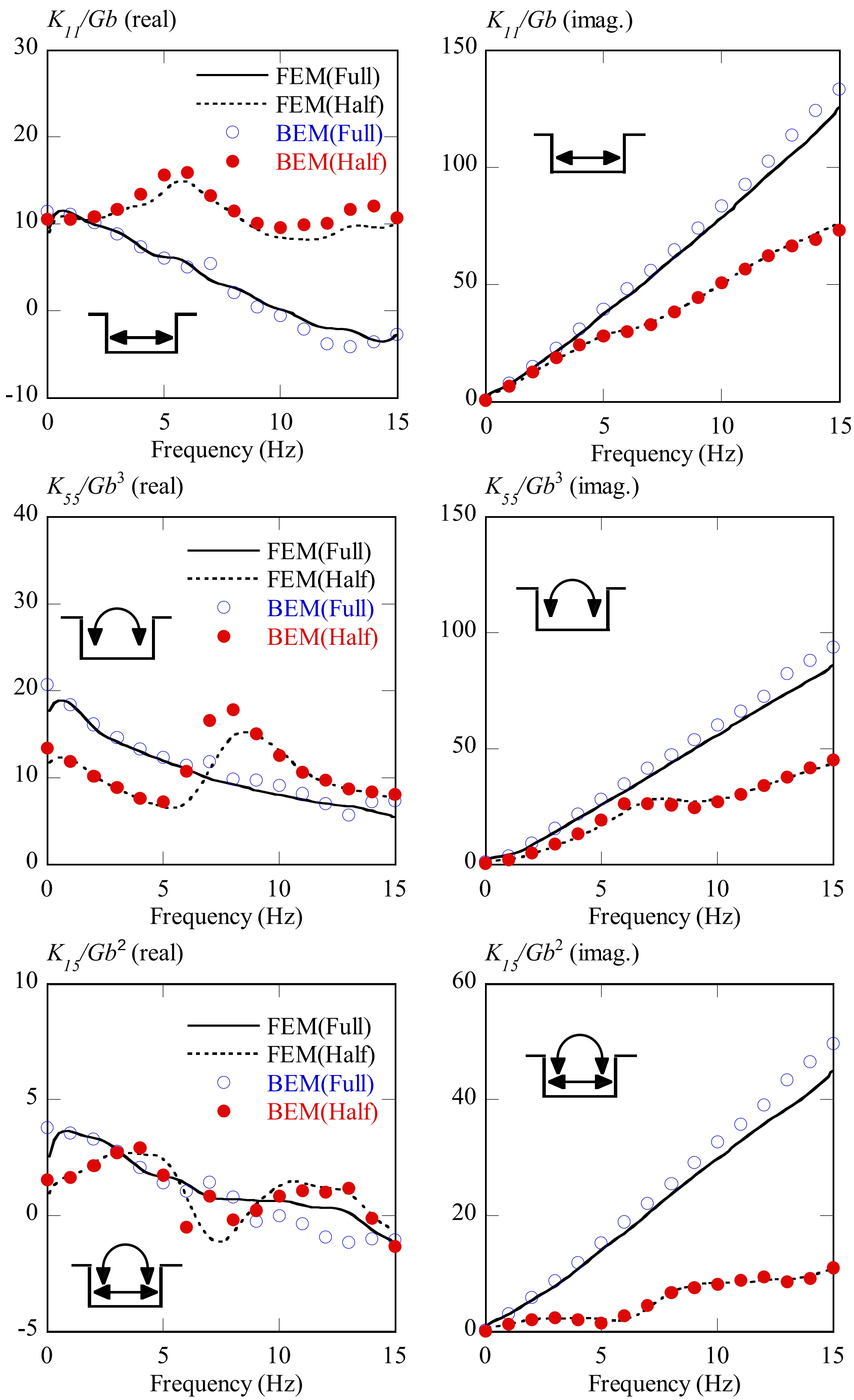

Figure 4. Comparison of impedance functions calculated by 3-D BEM and axi-symmetric FEM

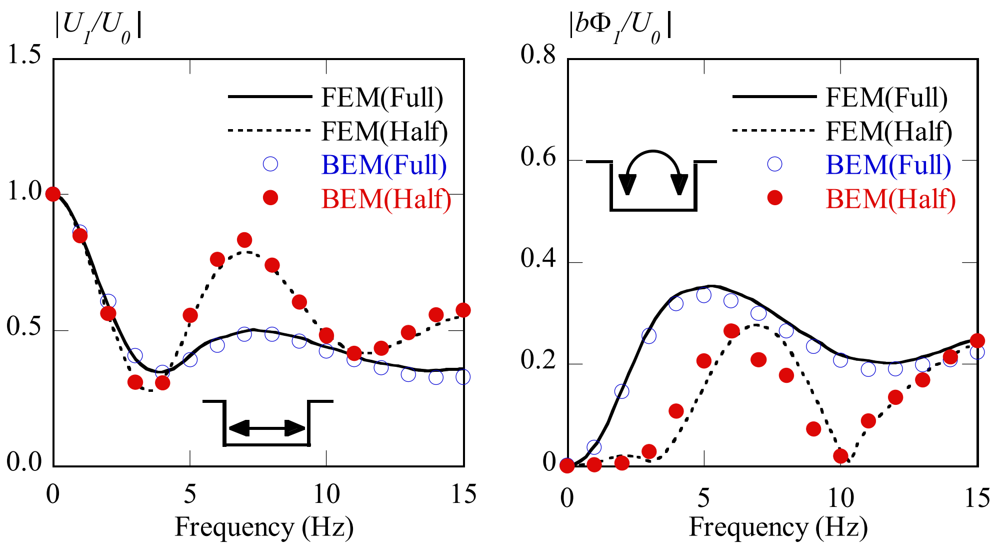

Figure 5. Comparison of foundation input motions calculated by 3-D BEM and axi-symmetric FEM

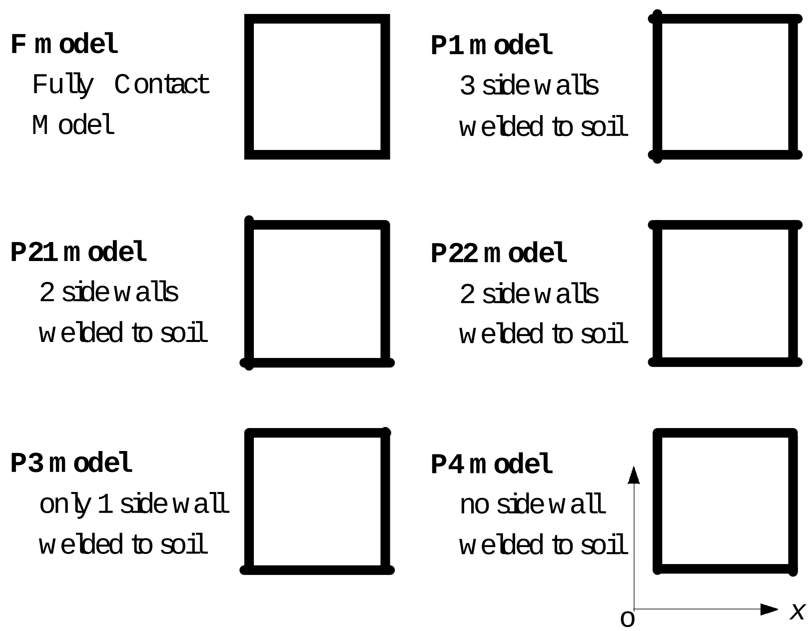

Figure 6. Contact conditions of side walls considered in the present study

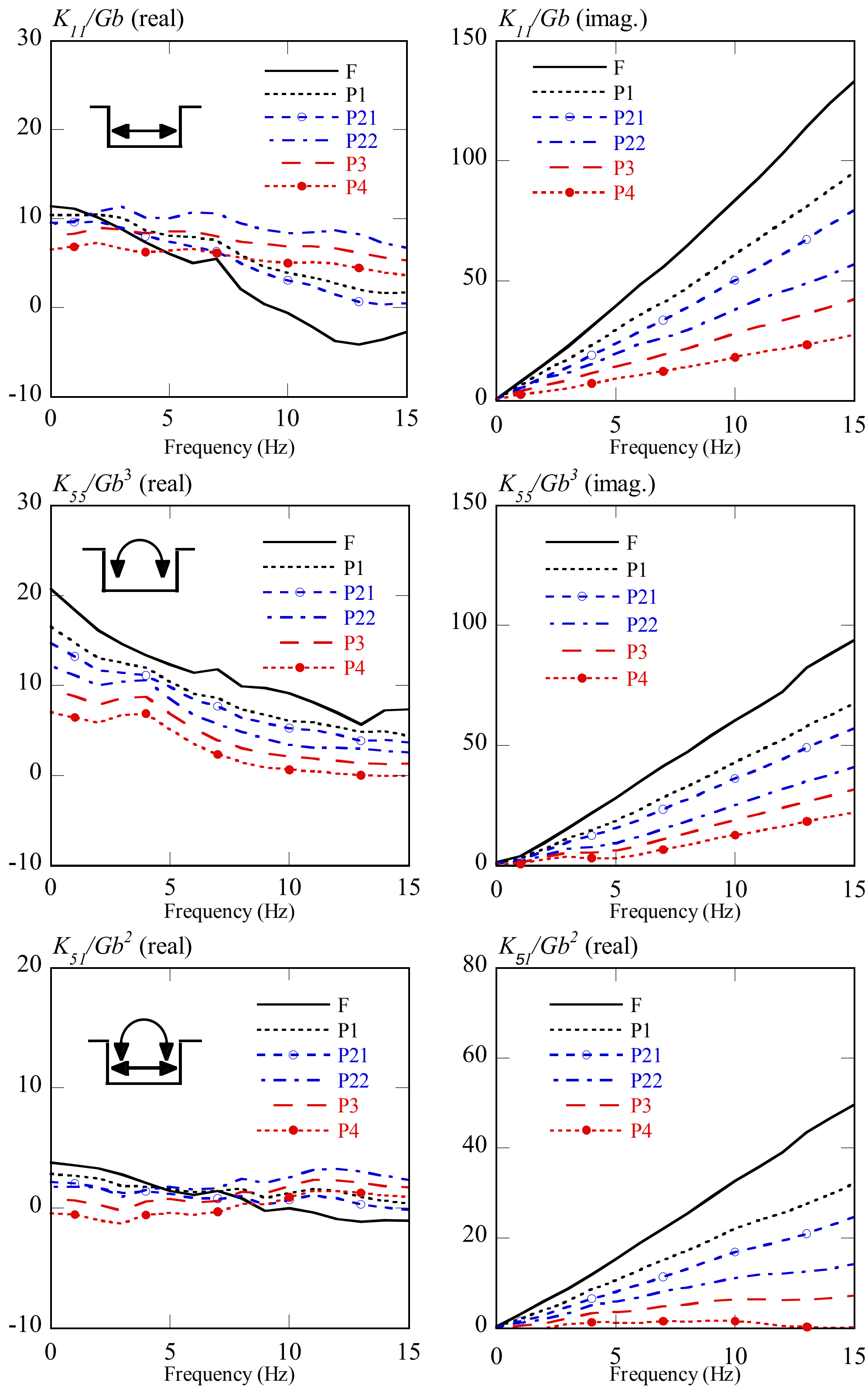

Figure 7(a). Comparison of impedance functions evaluated by 3-D BEM for various contact condition models (in the X direction)

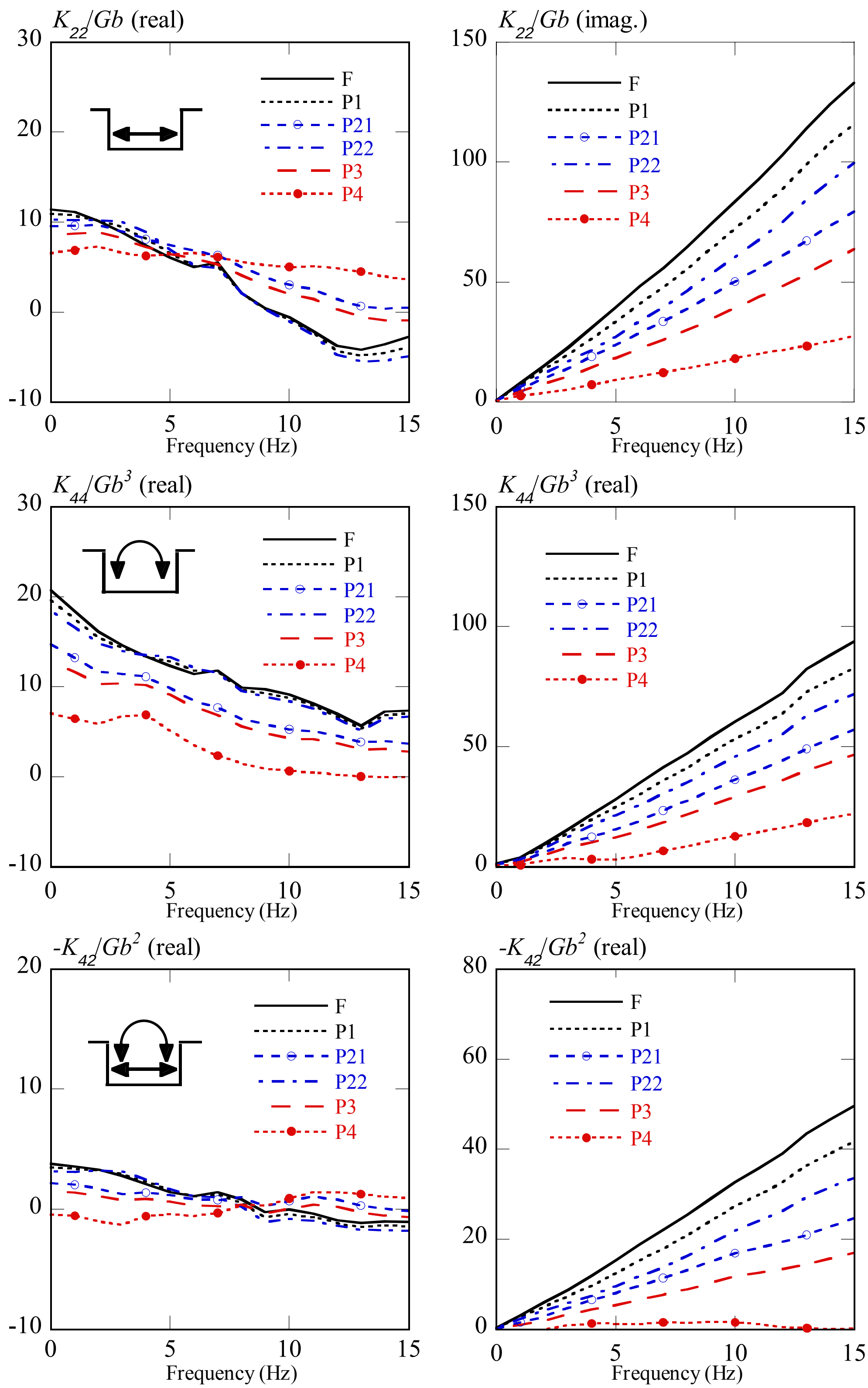

Figure 7(b). Comparison of impedance functions evaluated by 3-D BEM for various contact condition models (in the Y direction)

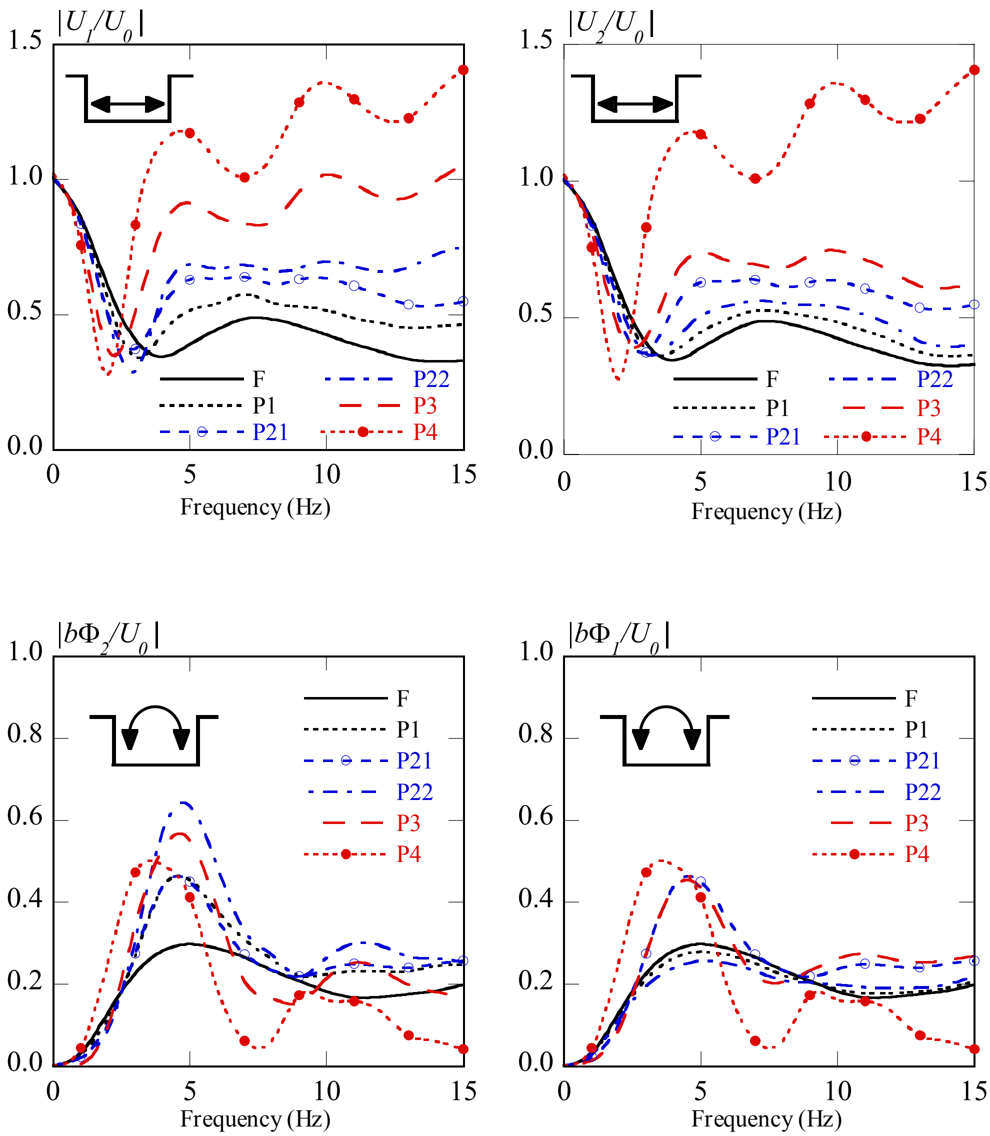

Figure 8. Comparison of foundation input motions evaluated by 3-D BEM for various contact condition models

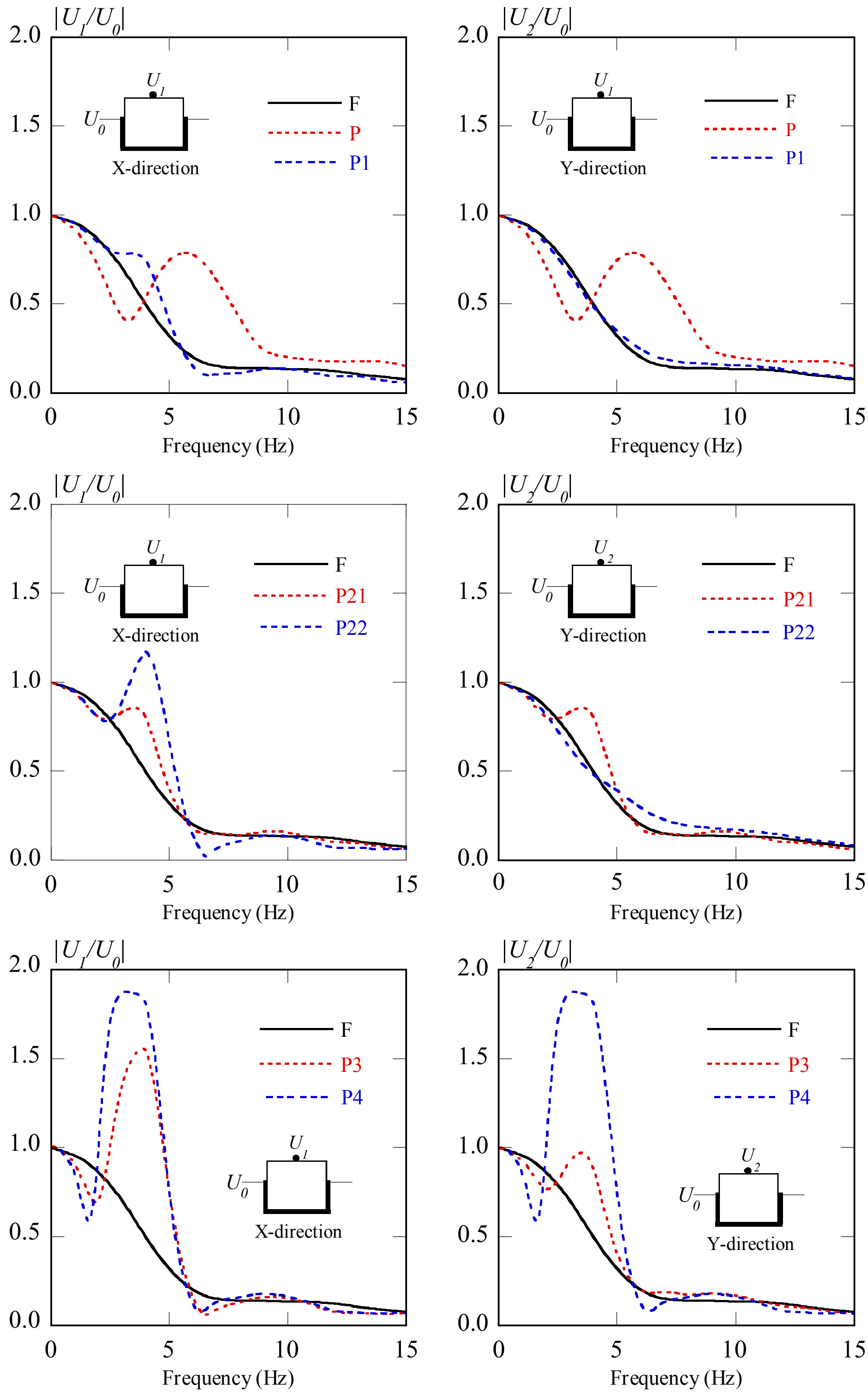

Figure 9. Comparison of transfer functions at EL+56m to the free surface (foundation embedment E=40m)

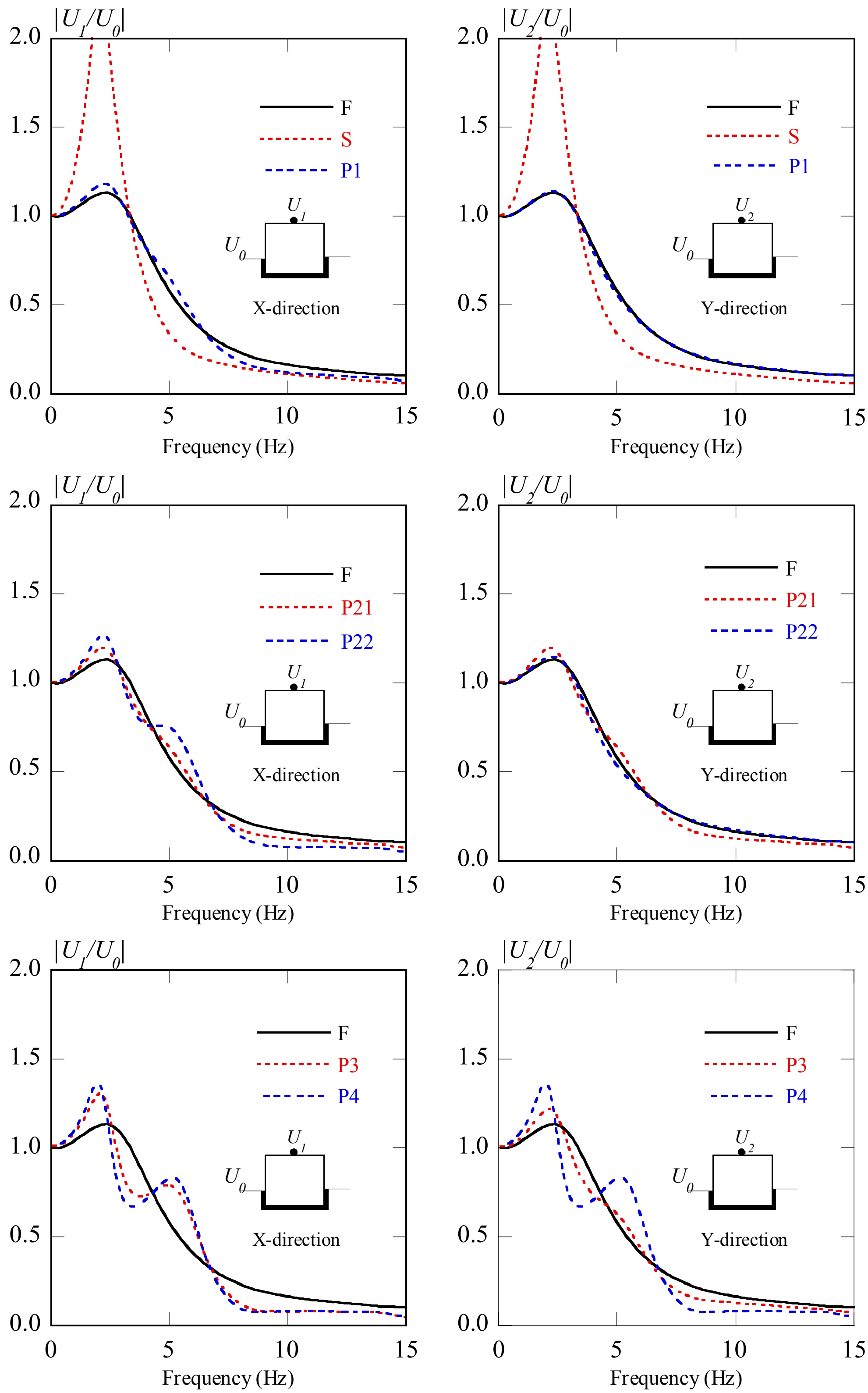

Figure 10. Comparison of transfer functions at EL+56m to the free surface (foundation embedment E=20m)