Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.III)

5-2-10

DYNAMIC STABILITY OF A OFF-SHORE STRUCTURE SURROUNDED BY THICK ICE DURING STRONG EARTHQUAKE MOTIONS

Fusanori MIURA[1], Itsuo NOZAWA[2], Nobuaki SAKAKI[3] and Katsushi HIRANO[4]

[1]Department of Civil Engineering, Yamaguchi University, Ube city, Yamaguchi, Japan
[2]Civil and Construction Department, NKK, Yokohama City, Kanagawa, Japan
[3]Civil Engineering Laboratory, NKK, Kawasaki City, Kanagawa, Japan
[4]Faculty of Graduate Study, Yamaguchi University, Ube City, Yamaguchi, Japan

SUMMARY

The purpose of this study is to investigate the effect of ice on the dynamic response and the stability of a large-scaled off-shore structure which is surrounded by the thick ice during strong earthquake motions. Nonlinear dynamic soil-structure-ice interaction analyses were performed by means of the two-dimensional finite element method, which took into account the possibility of local sliding at the interface between the structural base and the ground. It was found from the analyses that the ice decreased the response of the structure and that increased the stability of the structure against sliding.

INTRODUCTION

The structure analyzed in this study is supposed to be constructed in the Arctic Ocean. The general view of the structure is shown in Fig.1 The cross section of the structure is polygon in shape and the diameter of the bottom is 200m and the height is 96m. The structure is surrounded by ice due to frozen sea in winter. The ice sometimes grows to nearly 10m in thickness. Therefore, the ice may affects significantly on the dynamic response and the stability of the structure against sliding when the structure is subjected to the earthquake motion. Hydrodynamic pressure may also affect the structural response because the depth of the water is about 60m for the present analysis. These effects must be included in the analysis. Since the ground beneath the structure is very soft and the structure is very stiff and heavy, the dynamic soil-structure interaction effect can not be neglected. Besides, the structure may slide when it is attacked by a strong earthquake motion because of the low shearing strength of the soil.

From the consideration above, the dynamic soil-structure-ice interaction analysis including the hydrodynamic pressure and sliding is herein conducted to investigate the effect of constraint of ice on the dynamic response and the dynamic stability of the structure. The hydrodynamic pressure is treated as the virtual mass attached to the structure. Modified joint elements (Ref.1) are arranged along the interface between the structure and the soil in order to express sliding phenomenon. The dynamic stability, i.e., safety against sliding, of the structure was calculated from dynamic stresses of the modified joint elements. Three accelerograms which have different predominant frequencies are used as input motions in this study.

THE MODEL ANALYZED

Although the structure is nearly axisymmetric as shown Fig.1, the soil-structure-ice interaction system was modeled by two-dimensional finite element model (2-D model) as shown in Fig.2. The depth (y-direction) of the 2-D model is 148m. This depth was determined so that the model had the same bottom area of the structure as that of the prototype structure. The material constants which were determined in the following manner are summarized in Table 1.

The unit weight for each segment of the structure was determined so that the total weight of the structure might be the same as those of the prototype segments considering the volume of each segment. In the static analysis to obtain the initial shear stress at the interface between the structure and the ground, the unit weights of the segments beneath the water level were decreased by buoyancy. In determining the stiffness of the structure of 2-D model, the fundamental natural frequency of the axisymmetric structure was calculated first, then, the stiffness was modified so that the structure of 2-D model might have the same natural frequency as that of the axisymmetric structure.

The physical properties of ice have been studied by many researchers and are known as the fact that they exhibit strong dependence on the temperature. Therefore, the temperature dependence should be included in the analysis for rigorous discussion. We adopted the material constants at $-25^{\circ}C$ and assumed to be an elastic material in this study for simplicity. The virtual mass corresponding to the hydrodynamic pressure was allotted to the nodal points on the both sides of the structure. The magnitude of the virtual mass was consistent with the virtual mass which should be allotted to the axisymmetric structure.

The surface layer of 80m in thickness under the structure consists of frozen upper part of the layer and non-frozen lower part of the layer. We introduced the transition layer between the frozen and non-frozen layers, and gave the average material constants of the two layers to the transition layer. The shear strength of the interface between the structure and the surface layer, that is, the shear strength of the modified joint element was assumed to be the same as that of the surface layer in contact with the structure. Since the surface layer is cohesive soil, the shear strength was given only by cohesion, C, in this study, namely, the angle of internal friction was assumed to be zero.

Modified joint elements were arranged at the contact surfaces between the ice and the structure in order to check the possibility of breakage of the ice at the places as well as the interface between the structure and the ground. Here, the shear and tensile strengths of the joint element were those of the ice.

To discuss the effect of the ice on the structural response, a model without the ice part as well as the present proposed model was analyzed for comparison. We denote the model with ice as Model-1 and the model without ice as Model-2. The bottom of the surface layer was fixed in both x and z directions.Namely, a rigid base was assumed beneath the surface layer and it was the source of the ground excitations. The viscous boundary (Ref.2) was introduced in both x and z directions for both sides of the surface layer. At the boundaries of the ice, z directions were fixed and the viscous boundary was introduced in x directions.

EQUATION OF MOTION

The equation of motion of the system can be written as;

$$[M]\{\ddot{x}\}+([C]+[C_b]+[C_L]+[C_R])\{\dot{x}\}+[K]\{x\}$$
$$=\{f\}+([C_L]+[G_{cL}])\{\dot{x}_L\}+([C_R]+[G_{cR}])\{\dot{x}_R\}+[G_L]\{x_L\}+[G_R]\{x_R\}$$

where, $[M],[C],[K]$: the mass, damping and stiffness matrices of the system.
$[C_L]$, $[C_R]$: viscous boundary matrices for the side boundary.
$[G_L]$, $[G_R]$: boundary stiffness matrices associated with the displacements of the free field.
$[G_{CL}]$, $[G_{CR}]$: boundary damping matrices associated with the velocities of the free field.
$\{x_L\}$, $\{x_R\}$: displacement vectors of the free field.

$\{x\}$ is the displacement vector of the system and $\dot{}$ denotes the derivative with respect to time. The subscripts L and R mean the left and right boundaries, respectively. Sliding at the interface between the structure and the soil and breakage of ice at the contact surface with the structure are nonlinear phenomena. The equation of motion, therefore, is nonlinear and should be solved in time domain. Newmark's β method (β=0.25) is employed and the time interval, Δt, is 0.002 sec.

The models explained in the previous section were subjected to three earthquake accelerograms which had different predominant frequencies. They were the El Centro NS component (the 1945 Imperial Valley Earthquake), JPL S82E component (the 1971 San Fernando earthquake) and Hachinohe EW component (the 1968 Tokachi-oki earthquake) and these predominant frequencies were 1.15Hz, 2.8Hz and 0.83Hz, respectively. First, the maximum amplitude of these records were reduced to be 100 gal at the free surface of the ground, and then the accelerograms were converted from the ground surface to the rigid base by the deconvolution procedure. The resultants were the input motions.

RESULTS

Comparison of the structural response The comparison of the response displacement, velocity and acceleration at the top of the structure (point A in Fig.2) are shown in Figs.3, 4 and 5. Figure 3 shows the responses for the El Centro excitation, Fig.4 the JPL excitation and Fig.5 the Hachinohe excitation, respectively. Solid lines are for Model-1 (with ice) and broken lines are for Model-2 (without ice). These figures show that all the responses of Model-1 are lower than those of Model-2. This implies that the existence of ice reduces these responses.

Dynamic stability of the structure against sliding The safety of the structure against sliding is discussed by means of the Total Safety Factor (T.S.F.) which is given by the following equation (Ref.3).

$$T.S.F = \left| \Sigma \tau_{yi} l_i / \Sigma \tau_i l_i \right|_{min.}$$

where l_i is the half length of the modified joint element i and τ_{yi} and τ_i are the shear strength and mobilized shear stress at the half element. The initial stress is included in τ_i. The symbol $| \ |_{min.}$ means the minimum absolute value with respect to duration time of excitation. Figure 6 shows the time histories of the ratio of shear strength to the mobilized shear force of which the minimum value is the T.S.F.. The ratios for Model-1 in all excitation are generally larger than those for Model-2 and T.S.F. are summarized in Table 2. From Fig. 6 and Table 2, it is obvious that the ice increases the safety of the structure against sliding.

Possibility of breakage of ice When the ice is broken, the situation is simillar to that of Model-2 and the response of the structure increases as discussed above. This results in a study on the possibility of breakage of the ice at the interface between the structure. The maximum shearing stress and the maximum tensile stress are summarized in Table 3 for three excitations. The shear strength and tensile strength are 20 kg/cm^2 and 2.5 kg/cm^2, respectively. The maximum values in the present calculation are below these strengths. This implies that the possibility of ice breakage is very low.

CONCLUSION

The effect of ice on the dynamic response and stability of the structure which was surrounded by the ice was investigated by the two-dimensional finite element method. From the analyses performed, the ice decreased the dynamic response and as a result, increased the safety against sliding of the structure.

REFERENCES

1. Toki, K. and Miura, F., "Simulation of a fault rupture mechanism by a two-dimensional finite element method", J. Phys. Earth, 33, 485-511, 1985.
2. Lysmer, J. and Kuhlemeyer, R. L., "Finite dynamic model for infinite media", Proc. ASCE, 95, EM4, 859-877, 1969.
3. Miura, F., "Dynamic stability analyses of rigid structures against sliding and overturning during strong earthquake motions", Proc. 8WCEE, Vol.III, 485-492, 1984.

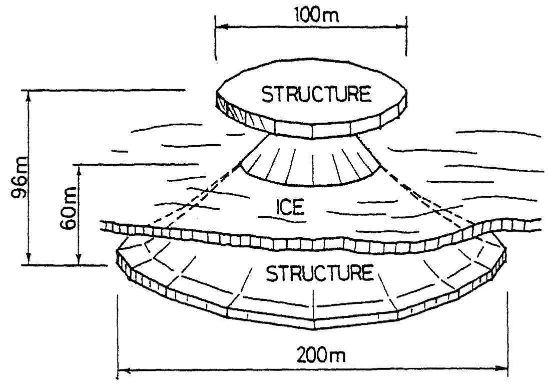

Fig.1 General view of the structure.

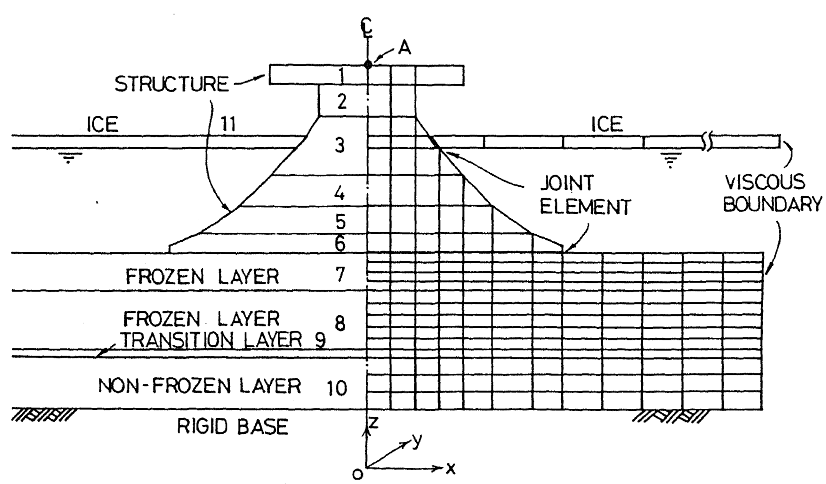

Fig.2 Finite element model of the soil-structure-ice system.

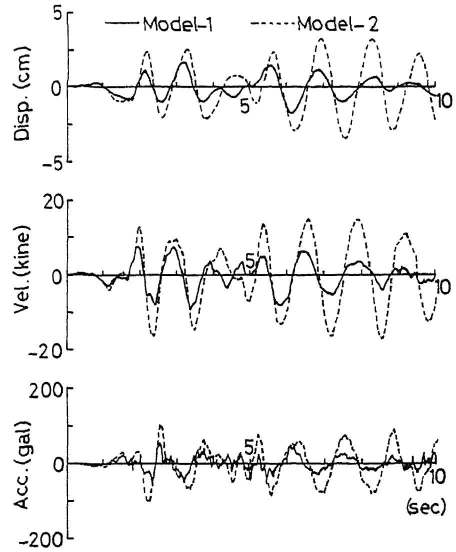

Fig.3 Comparison of the responses (El Centro accelerogram).

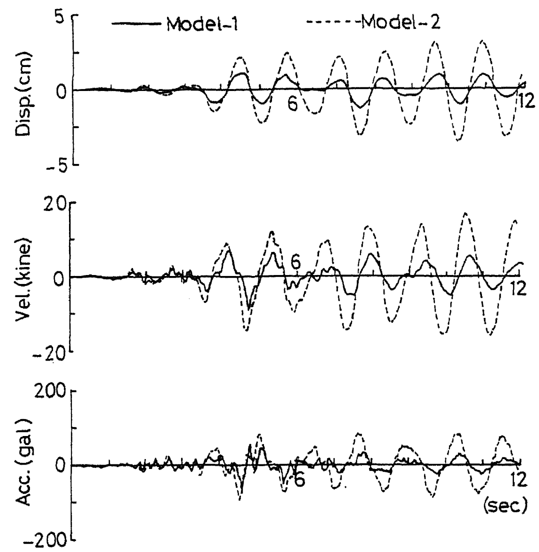

Fig.4 Comparison of the responses (JPL accelerogram).

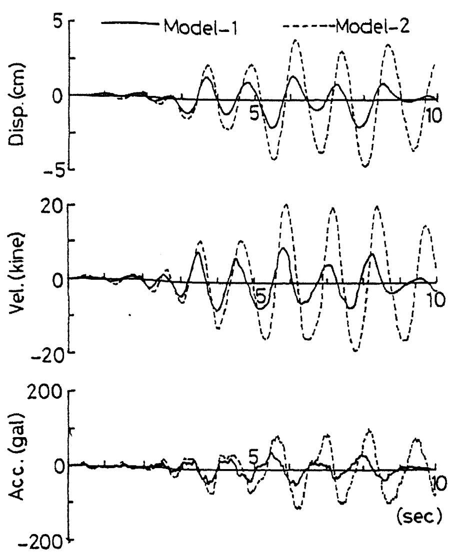

Fig.5 Comparison of the responses (Hachinohe accelerogram).

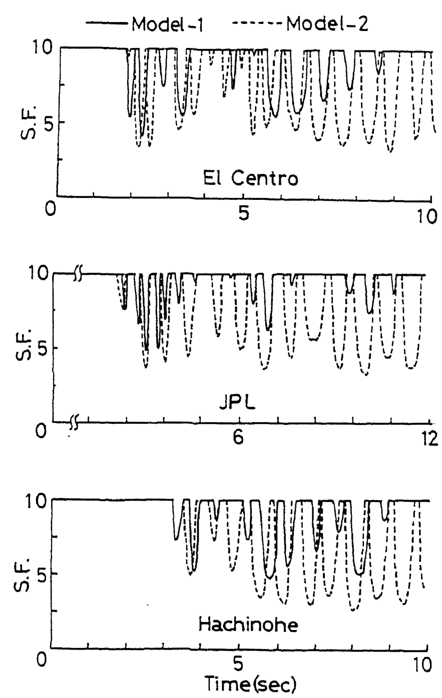

Fig.6 Comparison of safety of the structure against sliding.

Table 1 Material properties of the model.

Material No. in Fig.2		Unit weight (ton/m³)	Shear wave velocity (m/sec)	Poisson's ratio
	1	0.110	2600	0.3
	2	0.056	2600	0.3
Structure	3	0.300	2600	0.3
	4	0.682	2600	0.3
	5	0.877	2600	0.3
	6	1.093	2600	0.3
	7	1.760	119	0.497
Soil	8	1.920	161	0.494
	9	1.920	1020	0.4
	10	1.728	1470	0.3
Ice	11	0.93	1148	0.4

Table 2 Comparison of TSF.

	Model-1 ①	Model-2 ②	① / ②
El Centro	4.15	3.43	1.21
JPL	4.81	3.33	1.44
Hachinohe	4.95	2.66	1.86

Table 3 Comparison of the strengths and the mobilized stresses.
(Unit; kg/cm²)

Input motion	Shear strength	Mobilized shear stress	Tensile strength	Mobilized tensile stress
El Centro		1.07		0.87
JPL	20	0.95	2.5	0.65
Hachinohe		1.12		0.88