Structural Engineering and Mechanics, Vol. 32, No. 3 (2009) 371-382

DOI: http://dx.doi.org/10.12989/sem.2009.32.3.371

A study on the optimal configuration of harbor structure under the combined loads

Kyu-Nam Cho†

Department of Naval Arch. and Ocean Engineering, Hongik University, Chochiwon, Chungnam, Korea

(Received April 29, 2008, Accepted April 17, 2009)

Abstract. Response of harbor structure to environmental loads such as wave load, impact load, ship's contacting load, is a fundamental factor in designing of the structure's optimal configuration. In this paper, typical environmental loads against coastal structures are investigated for designing of the optimal harbor structure. Loads to be considered here are wave load, impact load and contacting load due to ship mooring. Statistical analysis for several harbor structure types under the corresponding loads is carried out, followed by investigation of effect of individual environmental load. Based on these, the optimal configuration for the harbor structure is obtained after considerable engineering process. Estimation of contacting load of the ship is suggested using effective energy concepts for the load, and analysis of structural behavior is done for the optimal designing of the structure in the particular load. A guideline for the design process of the harbor structure is established, and safety of the structure is examined by proposed scheme. For verification of the analytical approach, various steel-piled coastal structures and caissons are chosen and relevant structural analyses are carried out using the Finite Element Methods combined with MIDAS/GTS and ANSYS code. It is found using the Morison equation that impact load cannot be a major load in the typical harbor structure compared with the original wave load, and that configuration shape of the structure may play an important role in consideration of the response criteria.

Keywords: impact load; contacting load; wave load; optimal design; coastal structure; pile boundary condition.

1. Introduction

Environmental loads such as wave loads, including the impact load and ship's contacting load due to the mooring of the ship, are main sources for analysis of harbor structure design. In design of harbor structure, a pier or breakwater, main points of consideration are wave control ability, optimum type selection, and proper cross section design of the structure that withstand wave loads and contacting loads due to ship mooring. The objective of this paper is to evaluate the structure's ability to withstand various kinds of external loads effectively and relevant design of the proper structure. Static and dynamic analyses for several types of harbor structure under the corresponding loads are fundamental in obtaining an optimal configuration of harbor structure.

For evaluation of wave loads, a modified Morison equation that includes impact force due to the breaking wave is introduced, and the relevant theoretical background for estimation of that term is investigated.

† Professor, E-mail: kncho@hongik.ac.kr

Importance of the impact force on the vertical offshore circular structure member in the surf zone due to breaking wave has been taken into consideration.

Three parts of the wave force -- drag force, inertia force, and impact force -- are categorized and identified. Except for the impact force, an equation so called Morison Equation can be applied for common offshore structure design. Drag force and inertia force are represented conventionally for profiling, except for the breaking part.

Impact load is considered to play an important role in several structural response analysis cases (Cho 1996, 2000). In a single-pile response problem (Cho 2000), 59% of the total response was due to impact load participation. In another example of a response problem (Cho 1996), 66% of total response was due to impact load participation.

For a typical coastal structure, effect of an individual load including previously mentioned impact load is investigated with different configuration shapes.

For verification of the analytical approach, various steel-piled coastal structures and caissons are chosen to be objective structures, and structural analyses are carried out using the Finite Element Methods, combined with MIDAS/GTS and ANSYS code. MIDAS/GTS is a structural FEM code developed by Korean company and this program is used for the preliminary analysis (ANSYS 2005, MIDAS 2006).

2. Identification of the environmental loads

2.1 Formulation of the wave loads

Morison Equation was developed for calculation of the surrounding inertia force and the drag force that act on the vertical pile in the water. The equation can be expressed as shown below. However, the Eq. (1) cannot account for the impact force due to breaking wave that is important in designing of offshore structures in the surf zone (Cho 1996, Goda 1991)

$$F = \frac{1}{2}\rho C_D D|u|u + \rho C_I \frac{\pi D^2}{4} a_\chi \quad (1)$$

Where ρ = water density

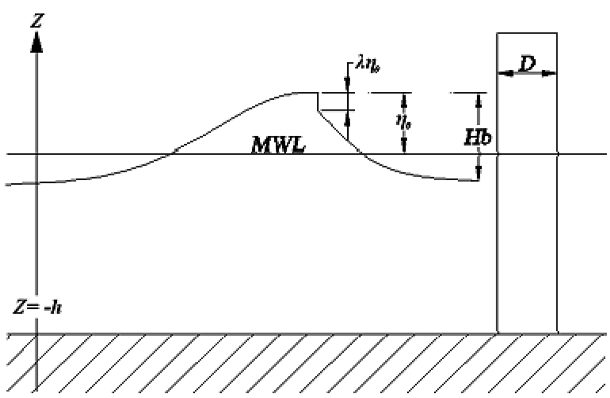


Fig. 1 A typical model of wave loads

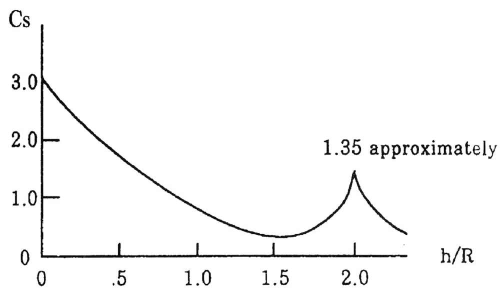


Fig. 2 C_s as a function of relative submergence

C_D = drag coefficient
D = diameter of the pile
u = water particle velocity
C_I = inertia coefficient
$a_x = du/dx$, wave particle velocity

2.2 Morison equation with impact term

The importance of impact force on the vertical offshore circular structure member in the surf zone due to the breaking wave can be included into calculation by modifying Morison Equation, as shown below (Goda 1991, SNAK 2007)

$$F' = F + F_I \tag{2}$$

Impact term can be expressed as shown below.

$$F_I = \frac{1}{2}\rho C_s D u^2 \tag{3}$$

Where C_s = slamming coefficient

The slamming coefficient has a maximum theoretical value of π, which can be used for conservative calculation of the impact force (SNAK 2007). Ratio h/R is the submerged water depth of the circular member into the water divided by the radius of the member.

2.3 Contacting loads of a ship

Effective energy due to the contacting force of a ship can be expressed as shown below (SNAK 2007, Samsung Construction Co. 2006, Park 2001)

$$E = \frac{WV^2}{2g} C_e \times C_m \times C_s \times C_c \tag{4}$$

Where W = weight of the objective ship
C_e = eccentricity coefficient
C_m = virtual mass coefficient
C_s = flexibility coefficient (1.0 for general use)
C_c = shape coefficient of the birth (1.0 for general use)

C_m can be expressed as shown in Eq. (5).

$$C_m = 1 + (\pi/2C_b)(d/B) \tag{5}$$

Where C_b = block coefficient
d = draft of the ship
B = beam of the ship

C_e can be expressed as shown in Eq. (6).

$$C_e = \frac{1}{1 + (l/r)^2} \tag{6}$$

Where l = distance between contacting point and ship's center
r = longitudinal radius of gyration of the water plane of the ship

Environmental loads can be classified as an individual term and/or as the sum of all associated loads classified here (Mansour 2003).

For a reasonable calculation of the wave loads, a fixed point of the pile can be decided as the boundary condition. The middle point between real slope height in the pile and front water depth level can be chosen as the fixed point (Park 2001).

3. Analysis of a harbor structure

3.1 Analysis model

The objective structure to be considered here is a derived steel-piled one, based on the real structure of the concrete caisson structure shown in Fig. 3 (Isobe 2002, Samsung Construction Co. 2006).

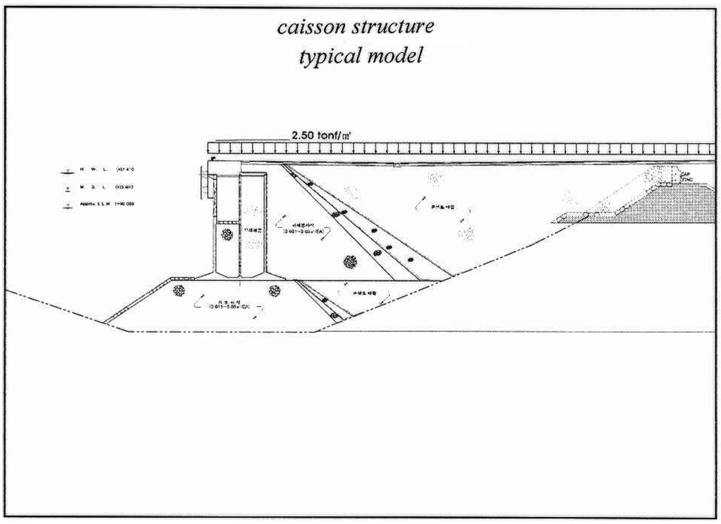


Fig. 3 A real concrete caisson structure

3.2 Modeling of the structure

3.2.1 2-Dimensional modeling of the structure by ANSYS

The objective structure can be modeled by several types of piled structure, as shown in the following figures (ANSYS 2005, MIDAS 2006). As the basic configuration, 3 types of the structures are chosen, i.e., a standard one, an alternative plan 1 and an alternative plan 2. Figs. 4, 5 and 6 show the 2-D objective of the 3 piled structures, respectively. Figs. 7, 8 and 9 show the 3-D objective of the 3 piled structures, respectively.

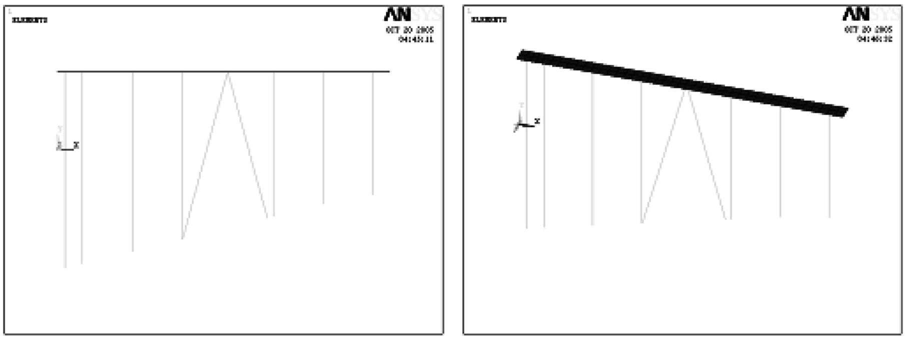


Fig. 4 Standard plan

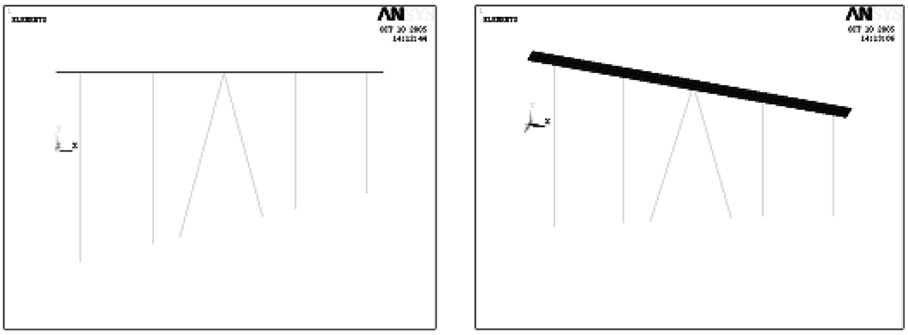


Fig. 5 Alternative plan 1

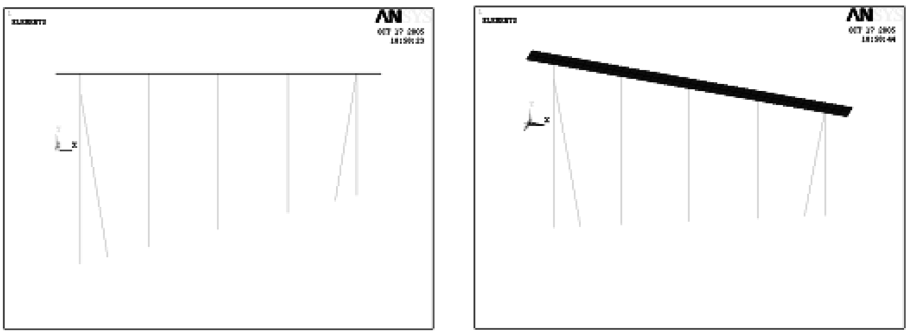


Fig. 6 Alternative plan 2

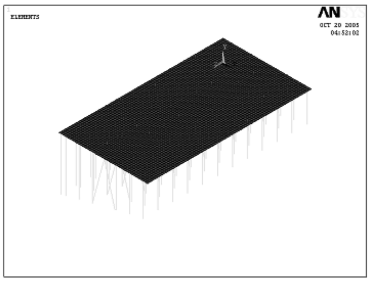


Fig. 7 Standard plan

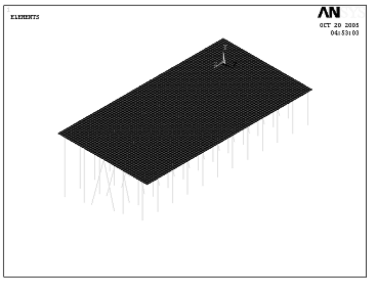


Fig. 8 Alternative plan 1

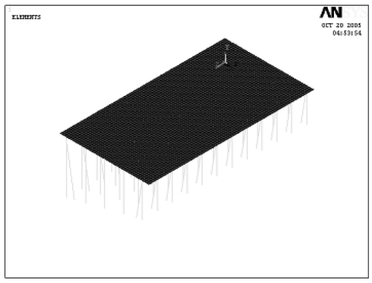


Fig. 9 Alternative plan 2

Standard plan indicates a basic configuration shape that includes inclined structural members located at the middle of the surface plane with the reinforced 2 front piles. Alternative plan 1 indicates a simplified configuration shape that has less piles along the surface plane. This configuration is regarded as an economic shape due to reduction of the pile number. Alternative plan 2 indicates the simplest configuration with inclined pile attached to the front and the aft pile, respectively.

3.2.2 3-Dimensional modeling of the structure by ANSYS

2-Dimensional Modeling can be expanded along the pier, as shown in Fig. 7, Fig. 8 and Fig. 9. These 3-Dimensional models are derived from standard 2-D models, 2-D alternative plan 1, 2-D alternative plan 2, respectively.

3.2.3 Application of boundary condition and loads (2-Dimension model)

Figs. 10, 11, 12, 13, 14 and 15 show the calculated acting environmental loads, based on the procedures in Ch. 2: to the corresponding structures and the relevant boundary conditions in the 2-Dimensional perspective.

The acting environmental loads are simple wave loads, live loads and berthing force, as previously mentioned.

3.2.4 Application of boundary condition and loads (3-Dimension model)

Figs. 10, 11, 12, 13, 14 and 15 show the calculated acting environmental loads, based on the procedures in Ch. 2, to the corresponding structures and the relevant boundary conditions in 2-

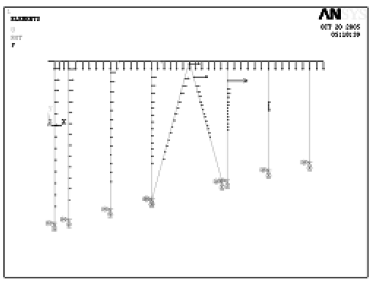


Fig. 10 Standard plan (wave loads +live loads)

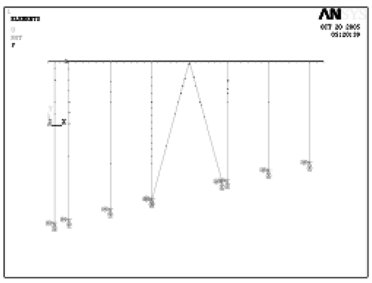


Fig. 11 Standard plan (berthing force)

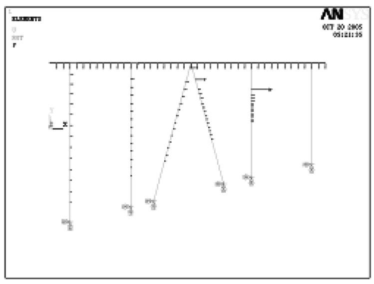


Fig. 12 Alternative plan 1 (wave loads+live loads)

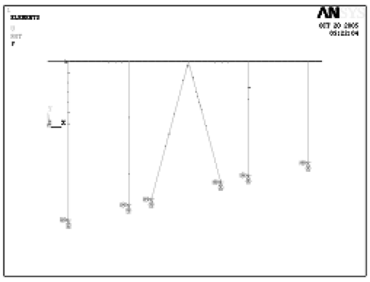


Fig. 13 Alternative plan 1 (berthing force)

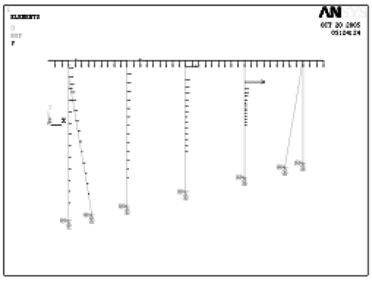


Fig. 14 Alternative plan 2 (wave loads+live loads)

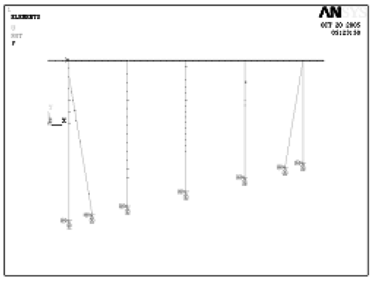


Fig. 15 Alternative plan 2 (berthing force)

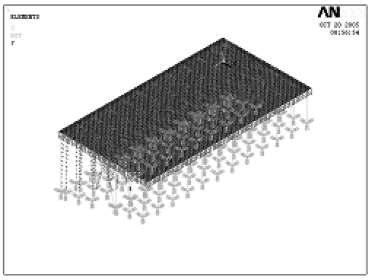


Fig. 16 Standard plan (wave loads +live loads)

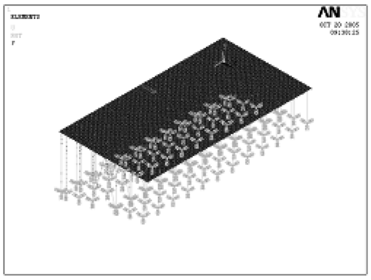


Fig. 17 Standard plan (berthing force)

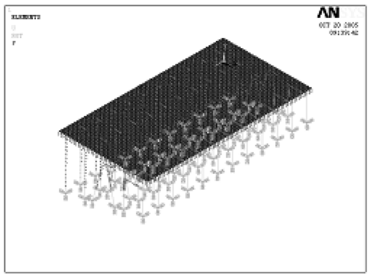


Fig. 18 Alternative plan 1 (wave loads+live loads)

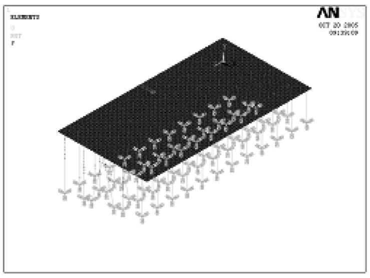


Fig. 19 Alternative plan 1 (berthing force)

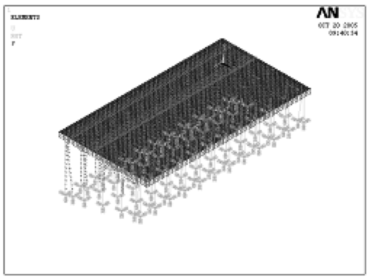


Fig. 20 Alternative plan 2 (wave loads+live loads)

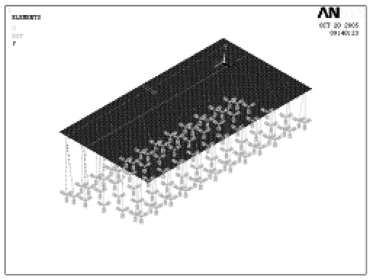


Fig. 21 Alternative plan 2 (berthing force)

dimensional perspective. Figs. 16, 17, 18, 19, 20 and 21 show the acting environmental loads to the corresponding structures, and the relevant boundary conditions in 3-Dimensional perspective.

4. Analysis results and discussions

Several different models are studied and analyzed using Finite Element Method. Table 1 summarizes the analysis results for the previously mentioned models. Considerable engineering procedures are done to obtain sound analysis results that make basic backgrounds in order to choose a safety-wise optimal configuration (Ugural 2000, SNAK 2007).

Based on the analysis results, impact load has a response increase of 30% for the standard plan,

Table 1 Loading conditions

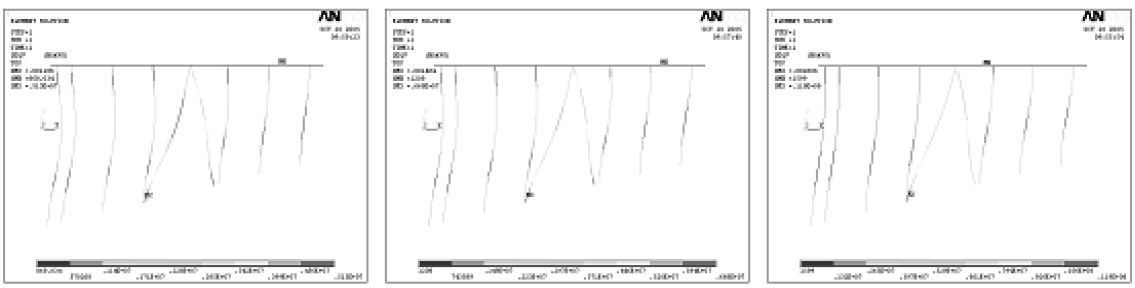
		pile 1	pile 2	pile 3	pile 4	pile 5	pile 6	pile 7	pile 8	pile 9
Pile diameter		0.8128	0.8128	0.8128	0.8128	0.8128	0.8128	0.8128	0.8128	0.8128
Water depth		13.5	12.45	9.45	6.45	5.74	2.14	0.95	−2.95	−4.3
Wave length		82.64	80.99	75.45	68.33	65.96	54.20	48.09	28.89	
Breaking wave		10.62	10.45	9.41	7.86	7.49	4.89	4.12	1.65	
Hight	Drag force(kg)	10.33	10.00	9.30	7.20	6.69	3.79	3.10		
	Inertiaforce(kg)	4.74	4.53	3.82	2.87	2.64	1.39	1.06		
	Impact force(kg)	277.96	314.01	342.32	378.89	380.56	494.87	712.53		
	Total force(N)	2874.7	3223.0	3486.9	3815.8	3824.8	4905.6	7030.8		
Ship's data		GT: 50,000 ton		Dead weight: 61,662 ton			Vvelocity 0.15 m/sec.			
Block coefficient, Energy		Cb: 0.8545			Contacting energy: 3,206.31 N					

and 36% for the alternative plan 1, and 54% for the alternative plan 2 in 2-dimensional modeling. For the 3-dimensional modeling, the response increase values are 25%, 54% for the standard plan and the alternative plan 1.

Compared with the previously mentioned single pile response problems, influences of the impact load are significantly reduced in these structural response problems.

Figs. 22, 23, 24, 25, 26 and 27 show the deformed shapes of the corresponding structures. Table 1 shows loading conditions to the structure. Drag force and inertia force, impact loads are tabulated as well as the ship's data for the calculation of the contacting energy of the ship. Table 2 shows analysis results of 2D and 3D model.

In case of "wave loads+ wave breaking force", 2D results are smaller than 3D results. The reason for this is due to the boundary conditions of each case. For 2D case, boundary is like a plane strain circumstance, thus this condition gives high resistance to the deformations. Characteristics of the berthing force are quite different from other two loads, i.e., wave loads and wave breaking loads. Two loads are applied to the piles directly. However the berthing force is applied to the so called plate, upper part of the structure, instead of the piles. Plate is very strong to the in-plane direction wise load while it is very weak to the vertical direction wise load. The effects of the in-plane

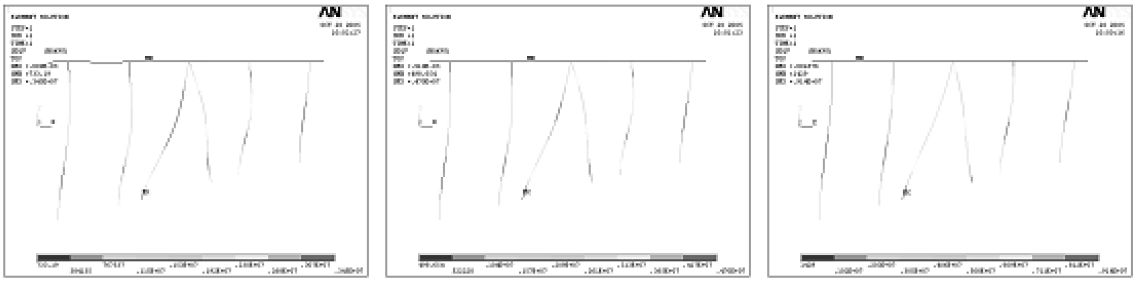


(a) wave loads

(b) wave loads
+ wave breaking force

(c) wave loads
+wave breaking force
+berthing force

Fig. 22 Standard plan (2D Analysis results)

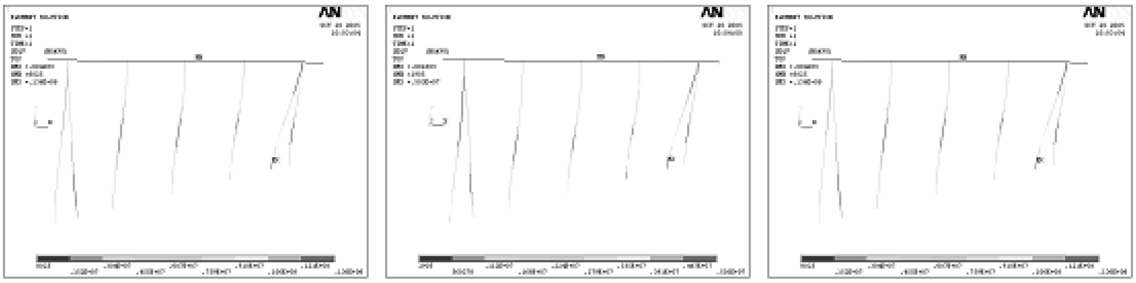


(a) wave loads

(b) wave loads
+ wave breaking force

(c) wave loads
+wave breaking force
+berthing force

Fig. 23 Alternative plan 1 (2D Analysis results)

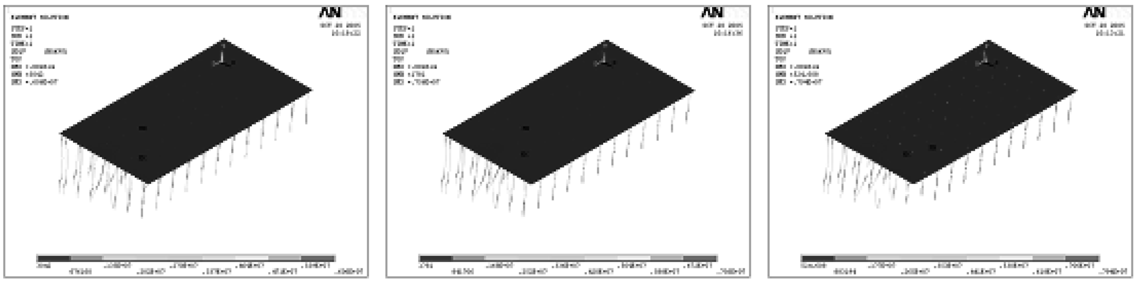


(a) wave loads

(b) wave loads
+ wave breaking force

(c) wave loads
+wave breaking force
+berthing force

Fig. 24 Alternative plan 2 (2D Analysis results)



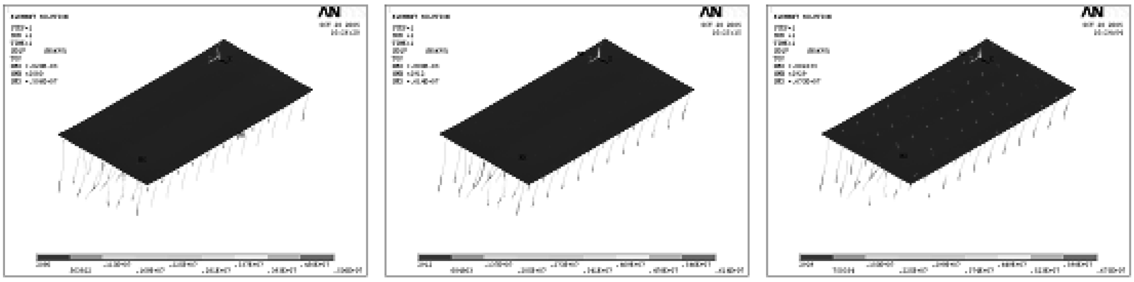
(a) wave loads

(b) wave loads
+ wave breaking force

(c) wave loads
+wave breaking force
+berthing force

Fig. 25 Standard plan (3D Analysis results)

resistance, so called in-plane effects of the plate to the corresponding berthing force play an important role in structural behaviors of the harbor structure. The plate is the member employed in the 3D modeling of the given structure. This is the main reason why the results of 2D modeled deformation results are greater than deformation results of 3D modeling. This fact implies that for

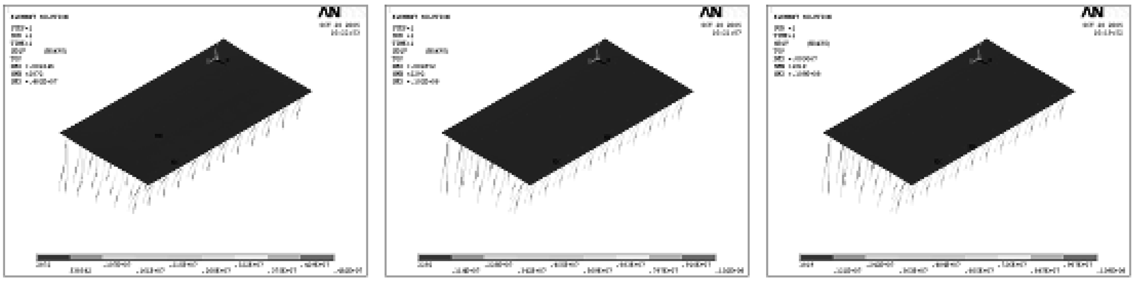


(a) wave loads

(b) wave loads
+ wave breaking force

(c) wave loads
+wave breaking force
+berthing force

Fig. 26 Alternative plan 1 (3D Analysis results)



(a) wave loads

(b) wave loads
+ wave breaking force

(c) wave loads
+wave breaking force
+berthing force

Fig. 27 Alternative plan 2 (3D Analysis results)

Table 2 Analysis results

		Analysis Result (2D)			Analysis Result (3D)		
		standard	alt-1	alt-2	standard	alt-1	alt-2
wave loads	Stress (N/m^2)	5.13×10^6	3.45×10^6	3.26×10^6	6.06×10^6	5.06×10^6	4.82×10^6
	Def. (mm)	1.186	0.609	1.04	2.614	0.62	1.046
wave loads +wave breaking force	Stress (N/m^2)	6.68×10^6	4.70×10^6	5.03×10^6	7.56×10^6	6.14×10^6	10.2×10^6
	Def. (mm)	1.48	0.910	1.603	2.614	0.89	2.852
wave loads +wave breaking force +berthing force	Stress (N/m^2)	11.9×10^6	9.14×10^6	13.6×10^6	7.94×10^6	6.73×10^6	10.9×10^6
	Def. (mm)	2.666	1.876	4.283	2.614	1.033	3.067

the precise analysis of this kind of harbor structure, 3D modeling is highly recommended.

Criteria for choosing the optimal configuration are stress and deformation of the structure. Conventional type of the alternative 1 structure has better behavior with regards to stress and deformations, and therefore is the optimal structure. For the effects of impact load, analysis results show that size of the pile is the main factor to be considered, thus this effect is not significant in this case. Contacting load can be incorporated more precisely with the 3-D model than with the 2-D model, since the in-plane effect of the flat plate of the harbor structure may be more realistically considered in 3-D modeling.

5. Conclusions

Investigation on the effect of typical environmental load against coastal structures shows that individual load effects are incorporated with the shape and size of the relevant piles adopted in the structure. A harbor structure with several piles of small diameters is not significantly influenced by the impact load due to breaking wave in the surf zone. The lesser effect is mainly due to the pile diameters that are relatively small compared with the wave characteristics.

Effects of the configuration shape changes are incorporated into the response criteria, however, these are not significant. For the configuration itself, conventional type of the alternative 1 structure has better behavior with regards to stress and deformation criteria. Effects of the contacting loads can be more precisely incorporated in 3-Dimensional analysis process than with 2-Dimensional analysis. Contacting loads, e.g. berthing force, play a more important role in the response analysis than impact load does, which has generally been regarded as the primarily important load. Quantitatively, the three harbor structure types are all safe, thus the configuration difference is not significant, provided that the structures are not drastically modified.

Acknowledgements

This work was supported by 2007 Hongik University Research Fund.

References

Cho, K.N. (2000), "A study on the determination of wave load acting on offshore structures", *J. Ocean Eng. Technol.*, **10**(1).

Cho, K.N. (1996), "A study on the determination impact wave forces for design of offshore structures", *J. Ocean Eng. Technol.,* **14**(1).

Goda, Y. (1991), *Randon Waves and Coastal Structures*, Chungmungak.

Isobe, E. (2002), "Outline of a VLFS research project in Japan", *Proceeding of Role of Large Floating Structures in the Future*.

Ugural (2000), *Advanced Strength and Applied Elasticity*, Prentice Hall.

SNAK (2007), *Naval Architecture and Ocean Engineering*, Dongmyungsa.

Samsung Construction Co. (2006), *Technology for Construction of Harbor*.

ANSYS (2005), *ANSYS 5.7, User's Guide*.

MIDAS (2006), *MIDAS/GTS, User's Manual*.
Park, S.K. (2001), *Coastal Structures Design*, Munwoondang.
Mansour, A.E. (2003), *Ship And Structures Congress, Proceedings of the 15th ISSC, Elsevier*.