EVALUATION OF EFFECTIVE WORKING DAYS CONSIDERING
MOORED SHIP MOTION IN POHANG NEW HARBOR

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This study proposes an estimation method for allowable wave heights for ship loading and unloading and evaluation of effective working days, considering moored ship motion that is affected by ship sizes, mooring conditions, and wave periods and directions. The method's validity was examined with wave field data at pier 8th in Pohang New Harbor. The wave field data, obtained when downtimes had occurred, indicated wave heights of 0.10–0.75 m and wave periods of 7–13 s for ship sizes ranging between 800–35,000 ton in weight. On the other hand, the estimated results for allowable wave heights for ship loading and unloading using this method yielded wave heights of 0.19–0.50 m and wave periods of 8–12 s for ship sizes of 5,000, 10,000 and 30,000 ton in weight. Thus, this method reproduced well the field data responses of ships of various sizes and at different wave periods. But the allowable wave heights proposed by Korea's technical standard are did not respond to various the ship sizes and wave periods. And the results of this method tended to decrease in 16–62 percent when have considered long wave, and it is decreased in 0–46 percent when did not consider long wave than Korea's technical standards in case of the ship sizes of 5,000–30,000 ton, wave period of 12 s and wave angle of 75 degree. The allowable wave heights for ship loading and unloading proposed by Korea's technical standards have indicated that overestimated for ships smaller than 10,000 ton in weight. On the other hand, the percentage rate of effective working days accounting for ship motion at pier 8th in Pohang New Harbor was 6.5 percent less compared to the corresponding results that did not consider ship motion.

Keywords: Allowable wave height for ship loading and unloading, Oscillation quantity of moored ship, Pohang New Harbor

INTRODUCTION

Korea's technical standards for ship loading and unloading regulate that the effective working day rate in a harbor is kept over 97.5 percent per year, and that the allowable wave height is under 0.3 m for small ships, 0.5 m for middle and large ships, and 0.7–1.5 m for mega ships. The allowable wave height refers to the wave height at the front of the berth; when exceeded, the loading and unloading of the ship becomes impossible. This wave height is used as a reference value for estimation of the ship's effective working days in a harbor, and it varies with ship types and sizes, and incident wave conditions. In particular, when a harbor resonance problem occurs by long waves exhibiting a natural frequency similar to that of the ship, the ship's loading and unloading downtime is increased. For accurate estimation of the allowable wave height, ship motion that is affected by ship size, mooring conditions, and short and long waves needs to be accounted for.

This study presents the estimation method of effective working days and allowable wave height for ship loading and unloading, considering ship motion. The allowable wave height was estimated in accordance to the ship sizes, wave periods, and incident directions. The validity of the estimated allowable wave height was examined through comparisons with actual field data, during loading and unloading downtimes. This estimation method was applied to Pier No. 8 at Pohang New Harbor, and was used to compare the effective working days against Korea's technical standards.

ESTIMATION METHOD OF ALLOWABLE WAVE HEIGHTS CONSIDERING SHIP MOTION

The estimation method of allowable wave height, considering ship motion, executes at first a procedure that simulates ship motion excited by short and long waves, followed by estimation of the wave height limit that allows loading and unloading, according to ship type and size, and wave directions and periods(Figure 1). The detailed procedure of this method is presented below. First, a simulation of ship motion at different wave and mooring conditions for different ship sizes is carried out. Then, a straight line regression equation is obtained for incident wave height and quantity of ship motion with wave period. The wave height that corresponds to the intersection point between the regression equation and the allowable quantity of ship motion for loading and unloading is then calculated. This procedure is repeated for each ship motion component. The allowable quantities for loading and unloading for the six types of ship motion components used by this method are shown on Table 1. And, the wave height that the maximum displacement of the fender not exceeds to acceptable

displacement is allowable wave height to the fender.

Finally, the allowable wave height become in the minimum value between wave height obtained from ship motion and acceptable displacement of the fender, according to the incident wave period. Meanwhile, if the minimum value exceeds the wave height value proposed by the technical standard of Korea, then the technical standard value choose the allowable wave height for loading and unloading.
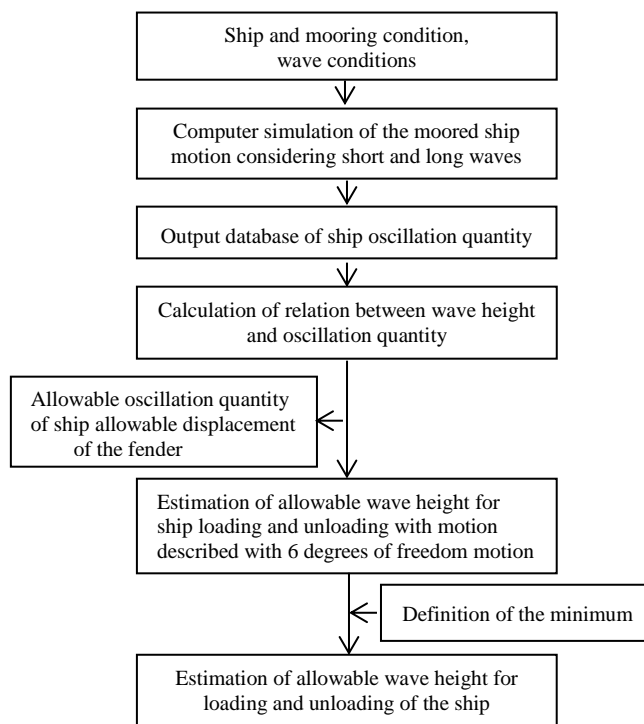
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Figure 1. Computation process on allowable wave height for ship loading and unloading, considering the ship's motion.

Table 1. Allowable oscillation quantity of ship motion for loading and unloading.

Type of ship	Surge (m)	Sway (m)	Heave (m)	Roll (°)	Pitch (°)	Yaw (°)
General cargo ship*	±1.0	+0.75	±0.5	±2.5	±1.0	±1.5
Grain carrier*	±1.0	+0.5	±0.5	±1.0	±1.0	±1.0
Ore carrier*	±1.0	+1.0	±0.5	±3.0	±1.0	±1.0
Oil tanker* (outer harbor)	±1.0	+0.75	±0.5	±4.0	±2.0	±2.0
Oil tanker* (inner harbor)	±1.5	+0.75	±0.5	±3.0	±1.5	±1.5
Container ship** (L0/L0)	±0.5	+0.3	±0.3	-	-	-
Container ship** (R0/R0-Side)	±0.3	+0.2	±0.1	-	-	-
Car carrier**	±0.3	+0.2	±0.1	-	-	-

*proposed by Ueda and Shiraishi (1988), **proposed by Bruun (1981)

SHIP MODEL FOR SIMULATING MOORED SHIP MOTION

Governing equations

The forces that affect a moored ship in fluid are fluid dynamic and static forces induced by ship motion, incident waves, and mooring equipment. Wave forces, which is one of the fluid dynamic forces, acts on a moored ship when the waves propagate around the ship. It is impossible to solve for these forces precisely. Therefore, instead of a physical model, we chose a numerical model with various assumptions. The numerical model used in this

study was developed by linearizing the fluid dynamic and wave forces, which are variables of ship motion. We assumed that moored ship motion was small, and introduced a potential velocity for the numerical model.

It is difficult to solve for moored ship motion directly due to the irregular wave field that occurs in a harbor. Therefore, we expressed the irregular wave field as a superposition of many regular waves. Furthermore, the numerical model was used to solve an irregular wave field by spectrum analysis, which was obtained from moored ship motion on a regular wave field. The Bretschneider spectrum, with parameters expressed in significant wave height and period, was used in this study.

Mooring equipment includes mooring lines and fenders that cause nonlinear moored ship motion. However, we assumed a mooring force of linear motion in order to analyze ship motion in the frequency domain. The linear momentum equation for ship motion on a regular wave field is shown below (Kwak et al., 2006; 2012).

$$[-\omega^2(M_{jk} + A_{jk}) + i\omega B_{jk} + R_{jk}]a_{jk} = F_j \tag{1}$$

Where,

M_{jk} = mass of the ship
A_{jk} = added mass of the ship
B_{jk} = damping coefficient
R_{jk} = restoring force
ω = wave angular frequency
i = $\sqrt{-1}$
a_{jk} = amplitude of the ship motion
F_j = Wave force

Simulation of the moored ship motion

• Simulation conditions for Pohang New Harbor

In this study, validation of this method with an actual field harbor was carried out at Pohang New Harbor. The validation of this method was done by numerical simulation of short waves only, and with short waves as well as harbor resonance. The berth used for validation was on pier 8, which is located near the east breakwater (Figure 2).
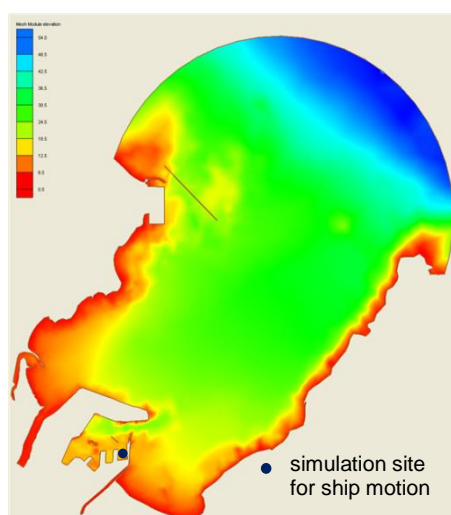

Figure 2. Bathymetry of Youngil-man area using wave field analysis and the location of simulation site for ship motion.

The ship type used for validation was a general cargo ship, and the ship sizes were 5,000 DWT, 10,000 DWT, and 30,000 DWT. The mooring conditions were similar to those shown in Figure 3, with 12 mooring lines and 8 fenders. The initial tension of the mooring lines was set to 7% of their breaking load. The water depth at the berth was 10 m. The ship and mooring conditions for the three ship sizes are listed in Table 2.
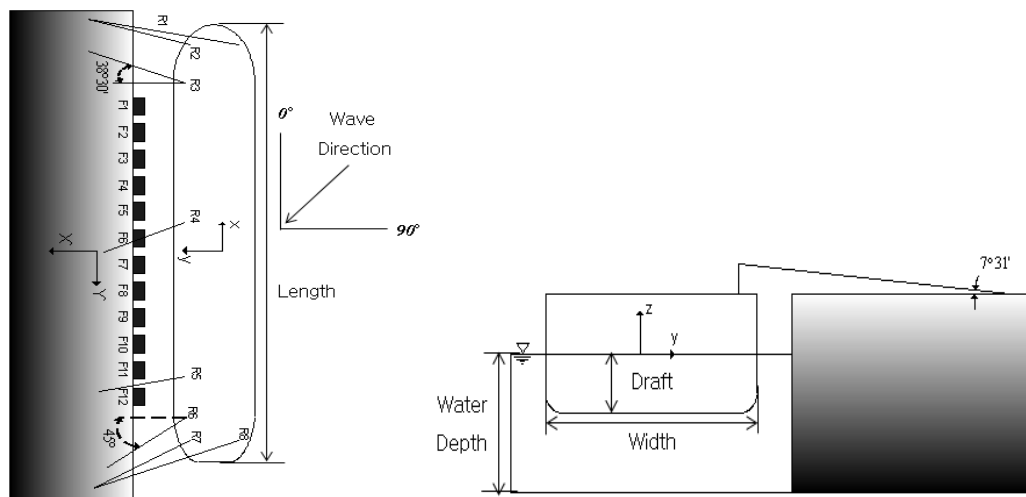
Figure 3. Definition sketches of the ship and mooring conditions.

Table 2. Ship and mooring conditions for simulation of ship motion.

Type of ship	General cargo ship		
Weight (ton)	5,000	10,000	30,000
Length (m)	98	120	171.6
Width (m)	14.0	17.42	26.0
Draft (m)	4.5	6.0	7.0
Wetted area (m^2)	2534.39	3876.04	4461.60
Mooring lines (ea)	8	8	8
Initial tension of the mooring rope (ton)	1.50	2.20	3.50
Modulus elasticity of the mooring rope (ton/m)	7.0	7.0	7.0
Fenders (ea)	12	12	12
Initial tension of the fenders (ton)	-1.05~-2.71	-1.05~-2.71	-1.05~-2.71
Modulus elasticity of the fender (ton/m)	130.0	130.0	130.0
Basin depth (m)	10.0	10.0	10.0

Table 3. Incident wave conditions for simulation of ship motion.

Short waves conditions	
H_s(m)	0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 1.0
T_s(s)	8, 9, 10, 11, 12
Wave direction (°)	15, 45, 75
Long wave condition	
H_s(m)	0.12
T_s(s)	60
Wave direction (°)	15

In addition, the incident wave conditions for simulation of ship motion are listed in Table 3. The short wave conditions consisted of wave heights ranging from 0.2–1.0 m, wave period ranging from 8–12 s, and three different wave directions. The wave conditions including harbor resonance added 0.12 m to the wave height, and a wave period of 60 s, which was obtained from field data. The wave direction to the moored ship was set at 15°, which was obtained from simulation results of the wave field (Kwak et al., 2012).

Simulation results of ship oscillation quantity

● **Simulation results for short waves only**
    An example of the simulation results from short waves, not including harbor resonance, is shown in Figure 4. This figure represents the ship motion from changing wave height and periods when the ship size is 10,000 DWT and the wave direction is 75°. In the figure, the horizontal axis is wave height and the vertical axis is the ship motion. With the same wave height, sway and roll motion tend to increase linearly as the wave period grows longer. Particularly, the roll motion increased significantly as wave period grew longer below wave periods of 8–10 s, but at wave periods 11–12 s roll motion changed only slightly as wave periods grew longer.

We can say that roll motion is more sensitive to short period waves than long period waves. With the same wave period, sway and roll motion tends to increase linearly as wave heights grow. However, there is very little change in surge, heave, and yaw motion as wave heights grow. In addition, sway and roll motion increase as wave direction moves closer to being perpendicular to the ship's side.

● **Simulation results for short waves and long wave together**

Simulation conditions when considering harbor resonance in addition to the short wave conditions included a wave at the resonant period. The ship and mooring conditions were similar to those under the short wave conditions alone. The simulation results while considering harbor resonance are shown in Figure 5. This figure represents the results for a ship size of 10,000 DWT and a wave direction of 75° to the ship.

The simulation results when considering harbor resonance in addition to short waves show an increase in ship motion of 10–30% over the results from short waves only.

In particular, surge motion is obviously different from when the simulation includes only short waves. The results show that surge motion when considering harbor resonance tends to remain constant as the short wave periods and heights grow larger. From this, we can see that harbor resonance has a dominant effect on surge motion.
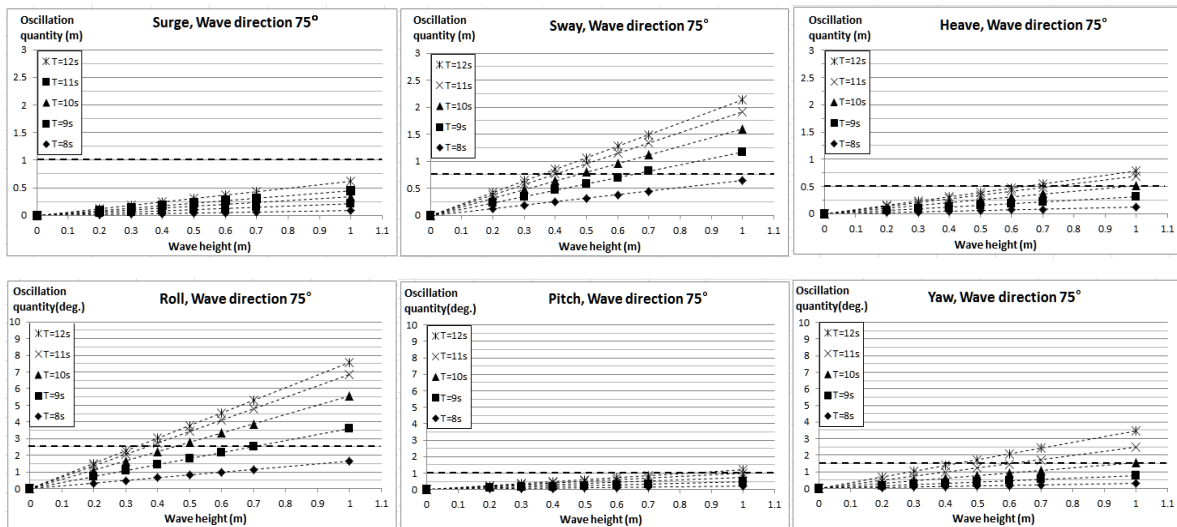

Figure 4. Computer simulation results for the ship oscillation quantity excited by short waves (10,000 tons, incident wave direction of 75˚).
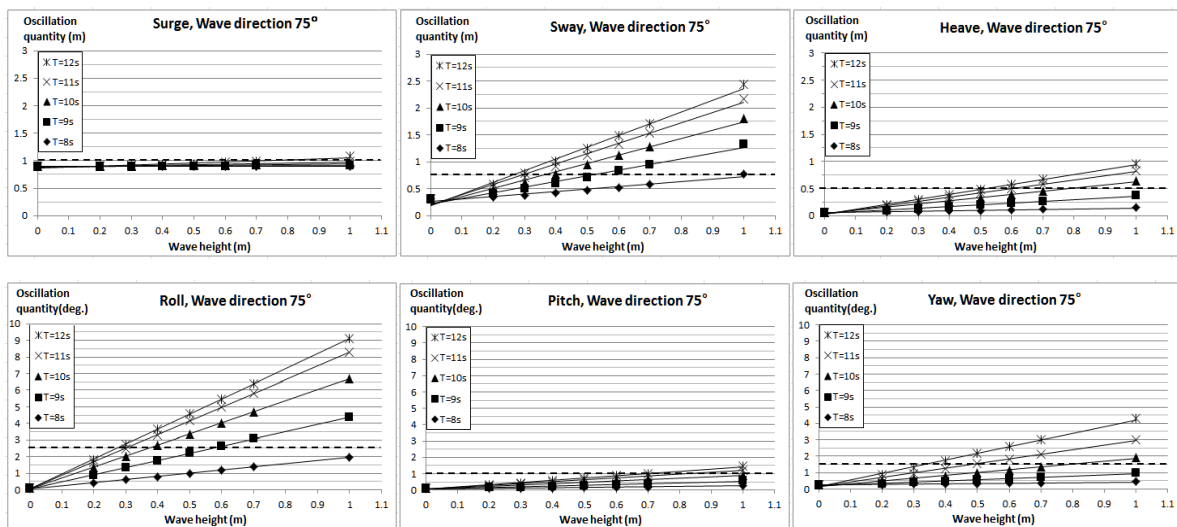

Figure 5. Computer simulation results for the ship oscillation quantity excited by short and long waves (10,000 tons, incident wave direction of 75˚).

ESTIMATION OF ALLOWABLE WAVE HEIGHT

Estimation method of allowable wave height considering long wave

The harbor resonance is induced when long waves occur. Additionally, if the resonance frequency corresponds to the natural frequency of a harbor, then the oscillation quantity of the ship highly increases. Thus, the allowable wave height decreases. Therefore, the allowable wave height for ship loading and unloading has to consider short and long wave effects. In this study, the allowable wave height, considering long wave effects, is estimated in accordance to the flow chart of Figure 6.

First, the specific resonance period and amplitude is estimated using computer simulation of the harbor resonance. This period and amplitude is then used as input data for the long wave condition in the ship model. Also computed are the hydrodynamic forces of short and long wave conditions, subject to various wave and mooring conditions, for each ship size studied. Such hydrodynamic forces are applied to the ship model as external forces. The ship's oscillation quantity is simulated by the ship model exhibiting in a graph a one to one correspondence with incident wave heights. Based on such work, the linear regression equation is obtained between wave height and oscillation quantity of ship at different wave periods. The next step progresses in a similar fashion to the procedure described above.
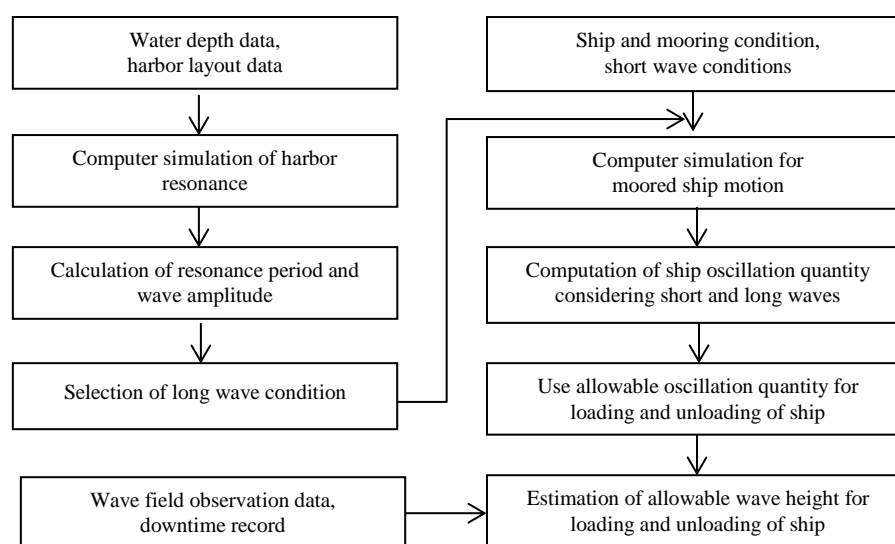

Figure 6. Flow-chart depicting the computation process on allowable wave heights for ship loading and unloading, considering ship motion excited by long waves.

Results for allowable wave height considering ship motion

In this study, allowable wave height was estimated in cases where long wave effects were considered (but without any consideration for the 5,000, 10,000 and 30,000 DWT) at pier no. 8 at Pohang New Harbor.

For example, Table 4 shows the results of allowable wave heights for a ship size of 10,000 ton and an incident wave direction of $75°$. Also shown in this table is the the ship condition, the allowable oscillation quantity of the ship, the allowable deformation range of fender, wave direction, the wave height for each ship motion with wave period, and the results of allowable wave height for loading and unloading with wave period.

The left side of Table 4 lists the results for short waves. The allowable wave height estimated to be 0.33–0.50 m with wave periods of 8–12 s. Correspondingly, the right side of Table 4 lists the results for short and long waves. In this case, the allowable wave height was estimated to range between 0.22–0.50 m.
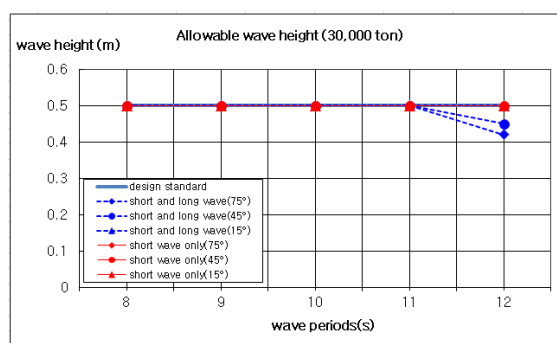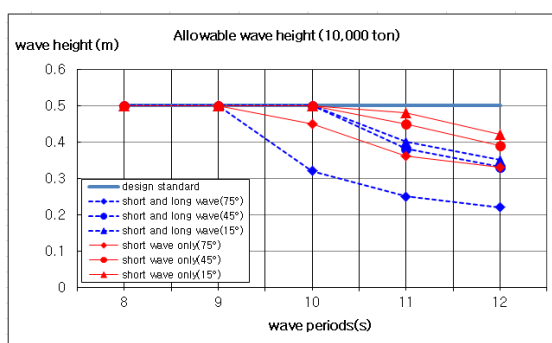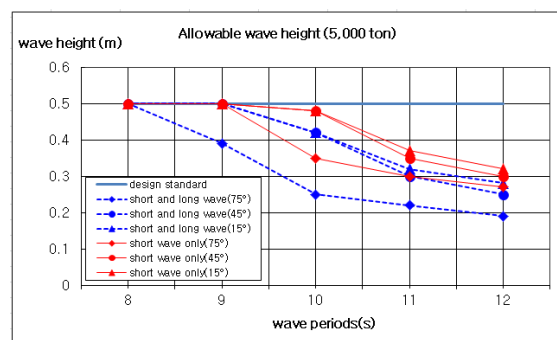
The comparison results for allowable wave height between this method and the Korea's rechnical standard are shown in Figures 7. In these figures, shown in a gray solid line is the allowable wave height proposed by the technical standard of Korea. The marked solid line is the result for short waves only, and the marked dotted line is the result for short and long waves. Figure 7 shows the allowable wave height for ships with 5,000, 10,000 and 30,000 ton in size. The result for short and long waves is shown to vary between 0.19–0.28 m at a wave period of 12 s, whereas the corresponding result for short waves only is shown to vary between 0.28–0.32 m at a wave period of 12 s for a ship size of 5,000 ton.

Table 4. Results of allowable wave height with wave period at pier 8 at Pohang New Harbor (10,000 ton, wave direction of 75°, short waves (left) and short and long waves (right))

Type of ship	General cargo	Allowable oscillation quantity	
Ship size	10,000 DWT	SURGE	1.0m
Wind dir	No wind	SWAY	0.75m
Wind speed	0m/s	HEAVE	0.5m
Wave dir.	75°	ROLL	2.5°
		PITCH	1.0°
		YAW	1.5°
		Fender	0.575m
Allowable wave height for loading and unloading (m)				

Wave period	8	9	10	11	12(s)
SURGE	12.2	4.84	2.97	2.23	1.64
SWAY	1.17	0.64	0.47	0.39	0.35
HEAVE	4.36	1.62	0.95	0.72	0.64
ROLL	1.53	0.69	0.45	0.36	0.33
PITCH	5.07	2.20	1.33	1.00	0.84
YAW	4.98	1.88	0.97	0.61	0.43
Results	0.50	0.50	0.45	0.36	0.33

Type of ship	General cargo	Allowable oscillation quantity	
Ship size	10,000 DWT	SURGE	1.0m
Wind dir	No wind	SWAY	0.75m
Wind speed	0m/s	HEAVE	0.5m
Wave dir.	75°	ROLL	2.5°
		PITCH	1.0°
		YAW	1.5°
		Fender	0.575m
Allowable wave height for loading and unloading (m)				

Wave period	8	9	10	11	12(s)
SURGE	30.59	5.06	2.03	1.21	0.70
SWAY	1.04	0.50	0.35	0.29	0.26
HEAVE	4.91	1.42	0.79	0.59	0.52
ROLL	1.27	0.52	0.32	0.25	0.22
PITCH	5.69	2.00	1.13	0.82	0.68
YAW	7.71	1.76	0.72	0.38	0.23
Results	0.50	0.50	0.32	0.25	0.22

In the case of a ship with size of 10,000 ton in weight, the allowable wave height for short and long waves varies between 0.22–0.35 m at a wave period 12 s, whereas the corresponding result when short waves only are considered, varies between 0.33–0.42 m at a wave period of 12 s. Similarly, for a ship that weighs 30,000 ton, the corresponding wave height accounting for short and long waves ranges between 0.42–0.50 m at a wave period of 12 s; but the result accounting for short waves only becomes greater than the technical standard for all wave periods studied.

Figure 7. Comparison results of allowable wave height between technical standards and computer simulations (for ships with 5,000, 10,000 and 30,000 ton in weight).

Comparison results between the allowable wave height and field data

The validation of the simulation results for allowable wave height was carried out by comparing them with field data at pier 8 at Pohang New Harbor (Pohang Regional Maritime Affairs and Port Office, 2010; Jeong et al., 2011). Table 5 shows the downtime duration, field ship size, field data, simulation results, simulated ship size, and the corresponding technical standard values. In this table, the simulation result refers to the allowable wave

height for an incident wave direction of $75°$, whereas the field data, collected at pier 8 from November 2008 to January 2009, represent the observed wave height during the loading and unloading downtime. The berthing ship sizes range from 800–3.5000 ton. The actual field data shows that the wave height ranges from 0.10–0.75 m and the wave periods from 8–16 s.

Simulation results, for ship sizes of 5000, 10,000 and 30,000 ton in weight, yield a wave height range between 0.27–0.50 m and a wave period range between 8–12 s in the case of only short wave excitation. The simulation results in the case of short and long wave excitation led to a wave height range of 0.19–0.50 m and a wave period range of 8–12 s. The simulation results considering long wave effects are in close agreement to the field data (which, however, did not account for long wave effects). Moreover, simulation results well represent the field data according to ship size and wave period.

On the other hand, the technical standard differs significantly from the field data because it does not account for changes in ship size and wave periods.

Table 5. Comparison results between field data and computer simulations

Downtime duration	Field ship sizes (ton)	Field data (H_s, T_p)	Simulation results		Simulated ship sizes(ton)	Technical standards
			Short waves (H_s, T_s)	Short and long waves (H_s, T_s)		
2008/11/09~11/11	3,500	0.35~0.45m, 8~16s	0.27~0.50m, 8~12s	0.19~0.50m, 8~12s	5,000	0.50m
2008/11/28~11/29	3,500~22,000	0.15~0.38m, 8~10s	0.27~0.50m, 8~12s	0.19~0.50m, 8~12s	5,000~30,000	0.50m
2008/12/14~12/15	3,700	0.10~0.38m, 7~10s	0.27~0.50m, 8~12s	0.19~0.50m, 8~12s	5,000	0.50m
2008/12/18~12/20	800~2,500	0.10~0.50m, 8~12s	0.27~0.50m, 8~12s	0.19~0.50m, 8~12s	5,000	0.50m
2008/12/21~12/23	4,500~17,000	0.15~0.65m, 8~11s	0.27~0.50m, 8~12s	0.19~0.50m, 8~12s	5,000~30,000	0.50m
2008/12/28~12/29	8,500	0.15~0.25m, 9~11s	0.33~0.50m, 8~12s	0.22~0.50m, 8~12s	10,000	0.50m
2008/12/31~2009/1/4	2,500~26,000	0.15~0.40m, 9~12s	0.27~0.50m, 8~12s	0.19~0.50m, 8~12s	5,000~30,000	0.50m
2009/01/09~01/15	1,500~35,000	0.10~0.50m, 9~13s	0.27~0.50m, 8~12s	0.19~0.50m, 8~12s	5,000~30,000	0.50m
2009/01/30~02/02	1,200~30,000	0.15~0.75m, 7~12s	0.27~0.50m, 8~12s	0.19~0.50m, 8~12s	5,000~30,000	0.50m

ESTIMATION OF EFFECTIVE WORKING DAYS FOR SHIP LOADING AND UNLOADING

The wave field data on outside harbor were based on measurement data collected from August 2008 to August 2009 at pier 8 (Pohang Regional Maritime Affairs and Port Office, 2010). Estimation results for the effective working days for ship sizes of 5,000, 10,000, 30,000 ton in weight, at incident wave directions of $15°$, $45°$, $75°$ are shown in Table 6. Table 6 also shows the rate of effective working days for an entire year at the same pier at Pohang New Harbor. The rate of effective working days, based on the technical standard in Korea, is shown to be 100 percent and does not reference at all the incident wave directions. However, the rate of effective working days when ship motion is considered is shown to vary from 93.5 percent to 100 percent. In particular, the rate of effective working days for ship size of 5,000 and 10,000 ton does not satisfy the 97.5 percent threshold limit proposed by the Korea's technicaln standard.

Table 6. Rate of effective working days at pier 8 at Pohang New Harbor

Ship size (DWT)	Design standard (%)	Considering ship motion		Wave direction (°)
		Short waves (%)	Including long waves (%)	
5,000	100	97.1	93.5	75
		98.0	96.7	45
		98.7	97.9	15
10,000	100	99.1	94.6	75
		99.4	98.8	45
		99.5	99.0	15
30,000	100	100.0	99.5	75
		100.0	99.7	45
		100.0	100.0	15

CONCLUSIONS

This study presented an estimation method on effective working days of ship loading and unloading, considering ship size, mooring and short and long wave conditions. This method was applied to pier 8 at Pohang New Harbor in Korea, and the results agree well with representative field data. The conclusions from this study are as follows:

*   The allowable wave heights considering ship motion represented well the field data that were observed at downtime.
*   The estimation method can account for ship size, mooring conditions, incident wave direction to the ship, and short and long wave conditions. The allowable wave height proposed by Korea's technical standards overestimates XX for ships with 5,000 and 10 000 ton in weight, primarily because such standards only consider wave height.
*   The rate of effective working days considering ship motion were shown to reduce from 1 to 6.5 percent compared to Korea's technical standards.
*   Future work will include evaluation of the number of effective working days, considering ship motion for a given harbor design.

ACKNOWLEDGEMENTS

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