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A Study on the Sensitivity Analysis of Ship Mooring Evaluation Factors According to Sea Level Rise in Mokpo Port

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목포항 해수면 상승에 따른 선박 계류평가요소의 민감도 분석 연구

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Abstract : *Sea level rise due to global warming is accelerating. According to the IPCC survey, the expected sea level rise in 2100 was analyzed to be 47cm in the low-carbon scenario (SSP 1-2.6) and 82cm in the high-carbon scenario (SSP 5-8.5). Sea level rise can cause serious damage to port infrastructure and reduce the safety of ships docked inside ports. In this study, Mokpo Port, which frequently suffers from flooding during high tide, was selected and the sensitivity of mooring evaluation factors was analyzed for actual berthing ships according to sea level rise scenarios. From the analysis, we found that the tension of mooring line, the load of bollard, vertical angle of mooring line, and ship's motion of 6-DOF, which are evaluation factors, generally increased when the sea level increased. The most sensitive evaluation factor was sway motion of 6-DOF. Also, we analyzed that the value of mooring evaluation factors decreased when the crown height was raised. This was beneficial in improving ship and pier safety. The results of this study can be used as basic data to secure measures to improve port and ship safety according to sea level rise in Mokpo Port.*

Key Words : *Sea level rise, Mokpo port, Crown height, Mooring safety evaluation, Mooring facilities*

요 약 : IPCC에서 발표한 제6차 기후변화 보고서에 따르면 지구온난화에 따른 해수면 상승이 가속화되고 있으며, 2100년 예상 해수면 상승은 저탄소 시나리오(SSP 1~2.6)에서는 47cm, 고탄소 시나리오(SSP 5~8.5)에서는 82cm로 분석되었다. 해수면 상승은 항만 인프라에 심각한 피해를 입히고, 항만 내에 정박 중인 선박의 계류안전성을 저하시킬 수 있다. 본 연구에서는 해수면 상승시 부두에 계류한 선박의 계류 안전성 향상 방안을 도출하기 위해 만조시 침수 피해가 잦은 목포항을 선정하여 해수면 상승 시나리오에 따른 실제 접안 선박에 대한 계류 평가 요소의 민감도를 분석하였다. 분석 결과, 해수면이 상승함에 따라 동일한 환경조건에서 계류라인 장력, 계선주 하중, 계류라인 수직각도, 선체 6자유도 운동값이 대체로 증가하는 것으로 분석되었다. 또한, 마루높이가 상향되면 모든 계류 평가 요소의 값이 대체로 감소하여 선박 및 부두의 안전성 향상에 유리한 것으로 분석되었다. 본 연구 결과는 목포항 해수면 상승에 따른 항만 및 선박의 안전성 향상 방안을 확보하기 위한 기초자료로 활용될 수 있을 것이다.

핵심용어 : 해수면 상승, 목포항, 마루높이, 계류 안전성 평가, 계류 시설

1. Introduction

The forecast for future sea level rise in the seas around Korea, announced by the Korea Hydrographic and Ocean Graphic Agency in March this year, is data applied with the Shared Socioeconomic Pathways (SSP) from the 6th report of the Intergovernmental Panel on Climate Change (IPCC).

In the high-carbon scenario (SSP 5-8.5), in which greenhouse gas emissions are unmitigated, sea level is projected to rise by 25 cm by 2050 and by 82 cm by 2100. On the other hand, in the low-carbon scenario (SSP 1-2.6) in which greenhouse gas reduction is well realized, the sea level is projected to rise by 20 cm by 2050 and by 47 cm by 2100 (IPCC, 2021).

In 2021, the rate of sea level rise around Korea analyzed by applying the IPCC's 5th climate change scenario was up to 73 cm by 2100 in the high-carbon scenario. However, as a result of applying the new SSP scenario at the 6th IPCC meeting, it was

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found that the sea level in the high-carbon scenario by 2100 increased by about 9 cm. This indicates that the rate of sea level rise due to climate change is accelerating further into the future.

According to Greenpeace's 'Global Temperature Rise Scenario' analysis, 5% of the Korean Peninsula will be submerged in water by 2030 due to sea level rise, and 3.32 million people are expected to suffer from this. If a typhoon overlaps here, it is predicted that the damage caused by sea level rise will be quite great (Greenpeace, 2020).

Sea level rise is indeed a real threat to the ports and increases flood risk, which undoubtedly could continue to threaten the part into the future (Wright, 2013; McLeod et al., 2018). Moreover, it can cause serious damage to port infrastructure and equipment (Zviely et al., 2015). In addition, sea level rise can reduce the safety of vessels in ports or interfere with loading and unloading operations, which can negatively affect port operations and port reputation (Wright, 2013; Hanson and Nicholls, 2020; Verschuur et al., 2020). In addition, sea level rise can increase the wind pressure area of a ship moored in a port, increase the 6-DOF movement according to the external force, and reduce the tension efficiency of the mooring line, which can be a hazard to mooring safety (Kim, 2018).

As a result of research related to the impact of sea level rise on ports, Jebbed et al. (2022) evaluated the future potential impact of Moroccan ports according to sea level rise scenarios. Joo (2015) analyzed the impact on the intertidal zone and design tide level by constructing two scenarios for sea level rise in the Mokpo sea area and predicted the degree of damage. Lee (2023) derived measures to minimize the impact on the ecological environment caused by sea level rise in Gyeonggi Bay. As such, studies on the prediction of sea level rise in domestic ports and sea areas have been conducted, but no study has been conducted on the safety effects of moored ships when sea level rises in specific ports.

As a result of research on the mooring safety of ships, Kwon et al. (2021) produced a measurement system to analyze the effect of moored ships by ship wave, measured the 6-DOF movement of the actual ship, and compared it with the simulation results. Kim et al. (2022) conducted a mooring safety evaluation on a car ferry moored in Jeju Port that exceeded its berthing capacity, analyzed the mooring safety of the ship according to the environmental conditions, and derived a plan to improve the mooring safety. Kim (2020) reviewed the safety and limitations of the mooring system through mooring analysis program when a training ship was moored at a pier that exceeded its berthing capacity. Kim and Lee (2018) proposed an appropriate crown height that reflected ship characteristics through modeling a virtual pier and evaluating the mooring safety of cruise ships and container ships. In this way, various studies are being conducted to improve the safety of ships moored at piers, but studies related to the sensitivity analysis of mooring evaluation factors of berthing ships when the sea level of a specific pier rises in stages are rarely conducted.

Therefore, in this study, in order to evaluate the safety of ships moored at the pier in case of sea level rise, Mokpo Port, where the sea level rise is evident, was selected and a mooring safety simulation evaluation was performed according to the IPCC's SSP scenario. At this time, a certified mooring safety evaluation program was used by modeling the actual target pier and selecting the largest ship among the ships berthing with the target pier. Based on the evaluation results, the sensitivity of the mooring factors of the berthing vessel according to the sea level rise in Mokpo Port was analyzed and an improvement plan to improve mooring safety was derived.

2. Selection of target port and pier

2.1 Analysis of sea level rise in Mokpo Port

For this study, Mokpo Port in Jeollanam-do, where the surrounding coastal lowlands are frequently damaged by seawater inundation due to rising tide levels, was selected. In Mokpo, flood damage occurred frequently after the successive construction of Yeongsan Estuary and Yeongam Embankment. Mokpo Port is located in a low-lying area lower than the high tide level, so at high tide in the summer, sea water flows back into the low-lying area around the Mokpo Inner Port, causing frequent damage to the residential area and the vicinity of the port (Joo, 2015).

In addition, according to the tide level information of the Korea Hydrographic and Oceangraphic Agency, the extreme highest tide level and mean sea level in Mokpo Port for the last 50 years (1972-2021) are shown in Fig. 1. It was analyzed that the extreme highest tide level in Mokpo Port rose by about 110 cm and the mean sea level by about 95 cm over the past 50 years.

According to the port design standards, the crown height in Mokpo Port is set by adding 0.5 to 1.5 m to the A.H.H.W. However, as the sea level rise accelerates, it can be seen that the sea level rises to about 10 cm below the crown height, becoming 5.5 m in the case of the extreme highest tide level in Fig.1.

In addition, since the expected degree of sea level rise by 2100 is 47 cm in the low-carbon scenario and 82 cm in the high-carbon scenario, it was analyzed that there is a possibility that the pier may be submerged in the sea level at the extreme highest tide level after the sea level rise has occurred.

Therefore, the target port for this study was selected as Mokpo Port, which suffers flood damage and has a clear rise in sea level.

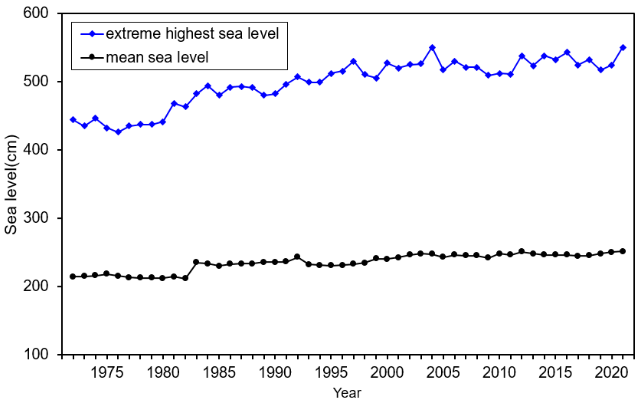

Fig. 1. Sea level rise in Mokpo Port for the last 50 years.
*Source: Korea Hydrographic and Oceangraphic Agency (2023)

2.2 Selection of Target Pier

For this study, the new port pier of Mokpo Port was selected. The new port pier is the pier facility located in the outermost sea among 11 piers in Mokpo Port. The effect of environmental external forces on moored ships is relatively greater than that of the inner port (Mokpo Regional Office of Oceans and Fisheries, 2023). Fig 2 is the location of the target pier selected for this study.

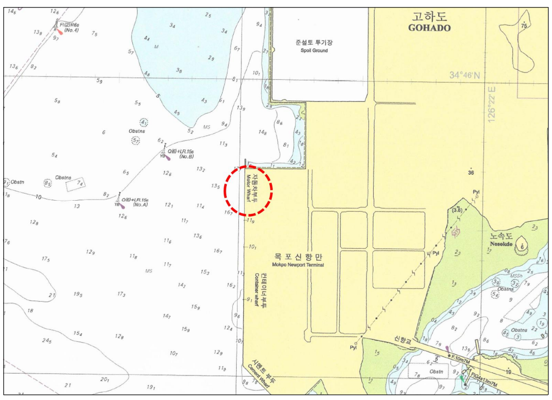

Fig. 2. Location of target pier.

The new port pier is composed of 7 berths, a pier for PCTC was selected to derive a plan to improve mooring safety according to sea level rise. The reason for the selection is that when the cargo handling performance of Mokpo Port in Fig. 3 was analyzed for the last 3 years, car cargo accounted for about 53~60% of the total cargo handling, which can be seen as the main cargo type of Mokpo Port (PORT-MIS, 2023). In addition, the PCTC corresponds to the largest ship among the ships docking at Mokpo Port. Due to the characteristics of a ship type with a large freeboard and wind pressure area, the sensitivity of mooring factors to external forces such as sea level rise is high, so it can be seen as a ship that needs to derive safety improvement measures based on mooring safety simulation evaluation.

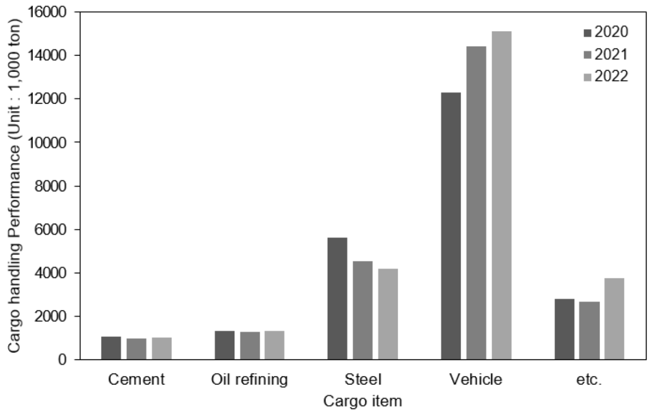

Fig. 3. Cargo handling performance at Mokpo Port.

Accordingly, a mooring safety simulation was performed when a DWT 30,000 ton PCTC was moored at a pier for PCTC in Mokpo Port in order to analyze the sensitivity of mooring evaluation factors of berthing vessels according to the sea level rise and to derive measures to improve mooring safety.

3. Mooring safety simulation evaluation

Mooring safety simulation was conducted to analyze the sensitivity of mooring factors according to the degree of sea level rise and to derive measures to improve mooring safety. This simulation was performed using TTI (Tension Technology International)'s OPTI-MOOR SW (Ver. 6.8.2). OPTI-MOOR is an analysis program that is representatively used for mooring safety evaluation simulation at home and abroad because it can apply accurate modeling through linear analysis and has high utilization (Kim et al., 2016).

3.1 Selection of target ship

For the selection of the target ship for the simulation, the largest ship, 8,000 units PCTC, was selected among the ships actually docking at the target pier, and the main specifications of the target ship are shown in Table 1. The main specifications of the target ship were set to those of ships with a history of actual port entry, and the mooring direction was set to starboard berthing. Since the wind pressure area is larger than that of the full load condition, the cargo loading condition was set to the light load condition, which is considered the worst condition for securing mooring safety.

Table 1. Specifications of target ship

Category		8,000 unit PCTC
LOA(m)		232.4
LBP(m)		227.0
Breadth(m)		32.3
Depth(m)		35.10
draft(m)	fore	7.5
	aft	7.5
Projected Windage Areas(m^2)	Transverse	914
	Lateral	7,130

3.2 Modeling of mooring conditions

Table 2 shows the detailed specifications of the pier length and crown height of the pier modeled for this numerical simulation evaluation of mooring safety, and the arrangement and specifications of mooring systems such as mooring lines, bollards, and fenders.

Table 2. Specifications of mooring condition

Category		Target pier
Length of pier(m)		302.9
Crown height(m)		5.6
Line	Type / Dia.(mm)	Nylon Rope / 68
	M.B.L(ton)	89
	S.W.L(ton)	44.5
Bollard	Interval(m)	22.2
	Max. Load(ton)	100
Fender	Type	Foam Filled $\phi 1,500 \times 4,300L$
	Interval(m)	18
	Max. Load(ton)	70

For the specifications of the mooring line of the target ship, a nylon rope with a diameter of 68 mm, which is actually used in the same ship, was selected. The M.B.L of the mooring line was 89 tons, and S.W.L was set at 44.5 tons, 50% of the breaking force (M.B.L), according to Table 3 (OCIMF, 2008).

Table 3. Safety working load of mooring rope

Material	S.W.L	SF(M.B.L/S.W.L)	× M.B.L
Wire	Highest load calculated for adopted standard environmental criteria	1.82	0.55
Polyamide		2.22	0.45
Other Synthetic		2.00	0.50

Fig. 4 shows the mooring line and mooring system modeling. A total of 12 mooring lines were set, with 6 bows and 6 sterns, in consideration of the mooring line arrangement of the actual target ship, and the detailed mooring arrangements are shown in Table 4.

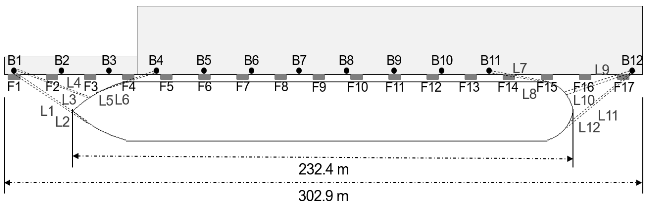

Fig. 4. Mooring arrangement of target ship.

Table 4. Mooring arrangement of target ship

Category			Arrangement
Line	Fore	Head	L1, L2, L3, L4
		Spring	L5, L6
	Aft	Spring	L7, L8
		Stern	L9, L10, L11, L12
Bollard	Fore	Head	B1
		Spring	B4
	Aft	Spring	B11
		Stern	B12
Fender	Fore		F1~F9
	Aft		F10~F17

3.3 Modeling of environmental external forces

The environmental external force for the simulation reflected the characteristics of the target pier. The current in Mokpo Port flows northward during flood tide and southward during ebb tide. The current near the target pier was northwest along to the topography, and the direction and speed of the current at the target pier were set at 160 degrees and 1.0 knots.

The wave height was set to 1.0 m, the 10-year frequency wave height, by reflecting the results of numerical model experiments among the 0.7 to 1.5 m limit wave heights for super-large ships in terms of port design standards. The wave direction was set at 315 degrees in the northwest direction, which is the main wave direction, reflecting the characteristics of the harbor. The wave period was set at 3.6 seconds measured as the main incident wave period of the target pier.

Fig. 5 is the wind direction condition of the simulation. Based on the centerline of the vessel, the direction was set at 90° from the inside of the pier to the sea (WD1), 45° from the bow to the inside of the pier (WD2), and 45° from the stern to the inside of the pier (WD3). The wind speed was evaluated by setting it to 20 knots, which is the mooring risk level at the actual target pier.

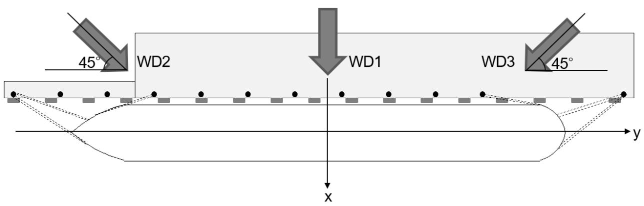

Fig. 5. Wind direction for simulation.

Table 5 shows four sea level scenarios for mooring safety evaluation. Based on H.W.O.M.T, it is the height of the rise by the 2100 SSP scenario, and the interval between the sea level scenarios is 0.5 m.

Table 5. Water level for simulation

Water Level(m)	Description
3.9	H.W.O.M.T in Mokpo Port
4.4	H.W.O.M.T + the height in SSP 1-2.6 by 2100
4.9	H.W.O.M.T + the height in SSP 5-8.5 by 2100
5.4	A.H.H.W + the height in SSP 1-2.6 by 2100

* Crown height of target pier : 5.6 m

3.4 Evaluation factors of simulation

Ship motion occurs when external forces such as wind, waves and currents act on the vibration system composed of the hull and mooring system. The evaluation factors of general mooring safety simulation are the tension acting on the mooring line, the load acting on the bollard, and the reaction force acting on the fender. And it is an unloading safety evaluation that evaluates whether the ship's normal unloading work is within the possible range when the hull is moving by an external force (Cho, 2017).

The evaluation factors of this simulation set the ship evaluation index for setting the crown height. This is the tension acting on the mooring line, the load acting on the bollard, the vertical angle of the mooring line, and the momentum due to the movement of the ship's 6-DOF (Kim, 2018).

4. Results of Evaluation

4.1 Tension of mooring lines

The maximum tension of the mooring line was analyzed according to the wind direction conditions during sea level rise. It was analyzed that it was within the S.W.L of mooring line in all scenario conditions. The sensitivity analysis results of mooring line tension according to sea level rise are as follows.

Fig. 6 is the maximum tension of mooring line according to sea level rise under WD1. When the sea level is 3.9 m, the tension of 13.8 tons is applied to the bow mooring line No. 2, and when the sea level is 4.9 m, the tension of 14.3 tons is applied. It was analyzed that the maximum tension of the mooring line increased by 3.6% when the sea level rose by 1.0 m. It was analyzed that the maximum increase in tension of the mooring line when the sea level rose by 1.0 m was a 4.4% increase in the head line No. 1.

Fig. 7 is the maximum tension of mooring lines according to sea level rise under WD2. When the sea level is 3.9 m, the tension of 15.9 tons is applied to the bow mooring line No. 2, and when the sea level is 4.9 m, the tension of 16.5 tons is applied. It was analyzed that the maximum tension of the mooring line increased by 3.8% when the sea level rose by 1.0 m. It was analyzed that the maximum increase in tension of the mooring line was a 3.9% increase in the head line No. 1.

Fig. 8 is the maximum tension of mooring line according to sea level rise under WD3. When the sea level is 3.9 m, the tension of 12.4 tons is applied at the stern mooring line No. 12, and when the sea level is 4.9 m, the tension of 12.8 tons is applied. Therefore, it was analyzed that the maximum tension of the mooring line increased by 3.2% when the sea level rose by 1.0 m. It was analyzed that the maximum increase in tension of the mooring line was a 4.8% increase in the stern line No. 11.

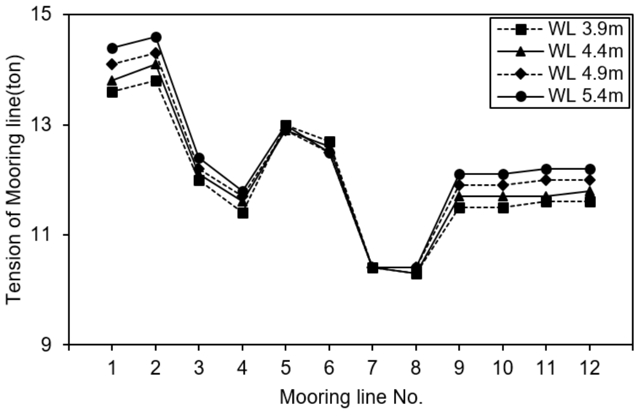

Fig. 6. Evaluation of mooring line tension by sea level rise (WD1).

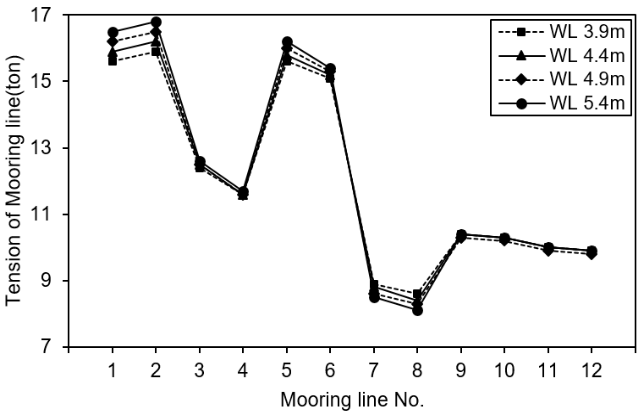

Fig. 7. Evaluation of mooring line tension by sea level rise (WD2).

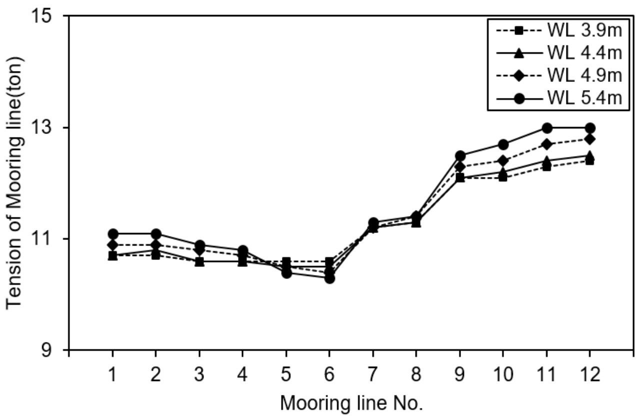

Fig. 8. Evaluation of mooring line tension by sea level rise (WD3).

4.2 Load of bollards

The maximum load of the bollard was analyzed according to the wind direction conditions during sea level rise. It was analyzed that it was within 100 tons, the permissible level of moorings, in all scenario conditions. The results of the sensitivity analysis of B1 and B12, which have the largest changes due to sea level rise, are as follows.

Fig 9 is an analysis of the sensitivity of the load according to the sea level rise of B1. In WD1, when the sea level is 3.9 m, 50.0 tons is applied, and when the sea level is 4.9 m, 51.5 tons is applied. It was analyzed that the load of the bollard increased by 3.0% when the sea level rose by 1.0 m. In WD2, the load of B1 according to the sea level was analyzed to be 54.8 tons when the sea level was 3.9 m and 56.0 tons when the sea level was 4.9 m.

Fig. 10 is an analysis of the sensitivity of the load according to the sea level rise of B12. In WD1, when the sea level is 4.4 m, 46.8 tons is applied, and when the sea level is 5.4 m, 48.5 tons is applied. It was analyzed that the load of the bollard increased by 3.6% when the sea level rose by 1.0 m. In WD3, the load of B12 to the sea level was analyzed to be 49.5 tons when the sea level was 4.4 m and 51.1 tons when the sea level was 5.4 m.

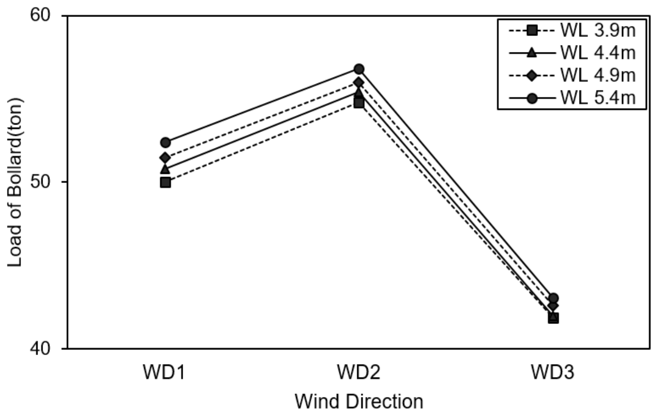

Fig. 9. Evaluation of bollard force by sea level rise (Bollard 1).

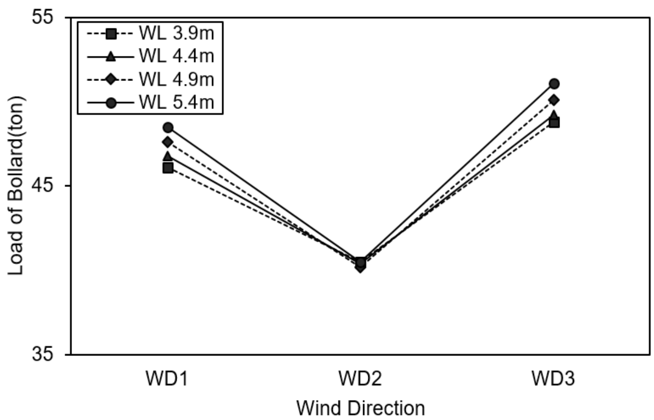

Fig. 10. Evaluation of bollard force by sea level rise (Bollard 12).

4.3 Vertical angle of mooring lines

The vertical angle of the mooring line was analyzed according to the wind direction conditions during sea level rise. When the sea level rises at a certain crown height, the vertical angle between the bollard and the berthing vessel also increases (Kim, 2018). As the vertical angle of the mooring line increases, the efficiency of horizontal tension of the mooring line decreases, so it is important to maintain an appropriate vertical angle. For example, when the vertical angle is 25°, the tension efficiency for wind-force is 91%, and when the vertical angle is 45°, the tension efficiency for wind-force is 71% (OCIMF, 2008). The Korea port design standards and OCIMF recommend a vertical angle of less than 30°.

Fig. 11 is an analysis of the vertical angle sensitivity according to the sea level rise of the mooring line. The largest vertical angle of the mooring line when the sea level rises is the stern spring line No. 7. At 3.9 m above sea level, the vertical angle is 31°, and at 4.9 m above sea level, the vertical angle is 33°. It was analyzed that the vertical angle increased by up to 6.5% when sea level rose by 1.0 m.

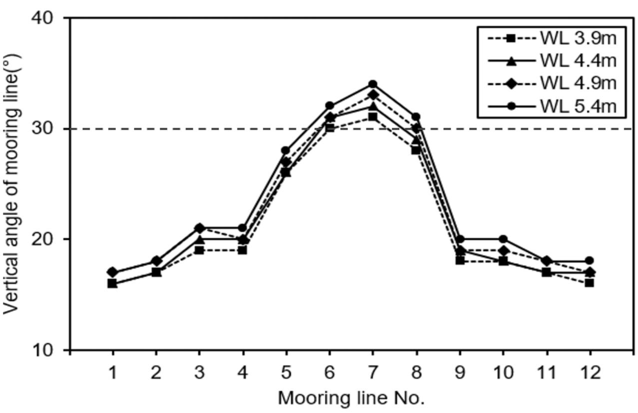

Fig. 11. Vertical angle of mooring line by sea level rise.

4.4 Ship motion in 6-DOF

As the sea level rises, the vertical angle of the mooring line increases and the tension efficiency decreases. And since the wind pressure area of the vessel increases according to the wind direction, the amount of ship's motion also increases (Kim, 2018).

Table 6 is the 6-DOF motion values of the ship according to the wind direction conditions during sea level rise. The motion with the greatest value of change according to sea level rise is Sway motion, and Fig 12 is the value of Sway motion according to sea level rise.

In WD1, when the sea level is 3.9 m, the value of sway was 0.73 m, and when the sea level is 4.9 m, the value of sway was 0.91 m. It was analyzed that the maximum value of sway increased by 24.7% when sea level rose by 1.0 m. In WD2, it was analyzed that the maximum value of sway increased by 15.1%, and in WD3, it was analyzed that the maximum value of sway increased by 46.2% when sea level rose by 1.0 m.

Table 6. Motion in 6-DOF by sea level rise

Wind direction	Water Level(m)	Surge (m)	Sway (m)	Heave (m)	Roll (°)	Pitch (°)	Yaw (°)
WD1	3.9	0.18	0.73	0.01	0.2	0.1	0
	4.4	0.17	0.82	0.01	0.2	0.1	0
	4.9	0.16	0.91	0.01	0.2	0.1	0
	5.4	0.16	1.01	0.01	0.2	0.1	0
WD2	3.9	0.4	0.81	0.01	0.5	0.1	0
	4.4	0.42	0.86	0.01	0.5	0.1	0
	4.9	0.44	0.91	0.01	0.6	0.1	0
	5.4	0.46	0.99	0.01	0.6	0.1	0
WD3	3.9	0.04	0.35	0.01	0.1	0	0
	4.4	0.03	0.39	0.01	0.1	0.1	0
	4.9	0.03	0.48	0.01	0.2	0.1	0
	5.4	0.04	0.57	0.01	0.2	0.1	0

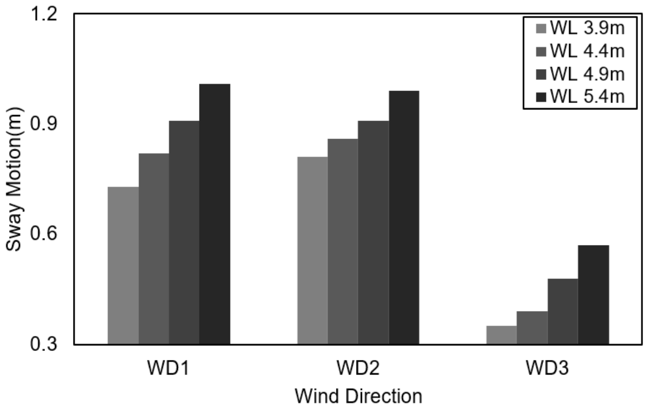

Fig. 12. Sway motion by sea level rise.

5. Results of raising the crown height

As a result of the mooring safety simulation analysis according to the sea level rise, it was analyzed that the value of each evaluation factor generally increased when the sea level rose, and there was a difference in sensitivity depending on the wind direction condition.

Therefore, it was analyzed that it was necessary to raise the crown height to improve the mooring safety of berthing ships in preparation for the forecast of sea level rise and to protect the cargo in the pier when the tide rises. When the sea level is 4.9 m, the mooring safety simulation was performed under the conditions of 6.6 m (CH 6.6 m) and 7.6 m (CH 7.6 m), where the crown height was raised by 1.0 m compared to the existing crown height of 5.6 m (CH 5.6 m) at the target pier, and the sensitivity of each evaluation factor was analyzed.

5.1 Tension of mooring lines

Fig. 13 is the maximum tension of mooring lines according to the crown height under WD1. When the crown height is 5.6 m, a tension of 14.3 tons is applied at the bow mooring line No. 2, and when the crown height is 6.6 m, a tension of 13.6 tons is applied. It was analyzed that the maximum tension of the mooring line decreased by 3.5% when the crown height was increased by 1.0 m. It was analyzed that the maximum decrease in tension of mooring line when the crown height was raised by 1.0 m was a 3.6% decrease in head line No. 1.

Fig. 14 is the maximum tension of mooring lines according to the crown height under WD2. When the crown height is 5.6 m, a tension of 16.5 tons is applied at the bow mooring line No. 2, and when the crown height is 6.6 m, a tension of 15.9 tons is applied. It was analyzed that the maximum tension of the mooring line decreased by 3.6% when the crown height was increased by 1.0 m. It was analyzed that the maximum decrease in tension of mooring line when the crown height was raised by 1.0 m was a 3.7% decrease in head line No. 1.

Fig. 15 is the maximum tension of mooring lines according to the crown height under WD3. It was analyzed that the maximum decrease in tension of mooring line when the crown height was raised by 1.0 m was a 3.2% decrease in stern line No. 11.

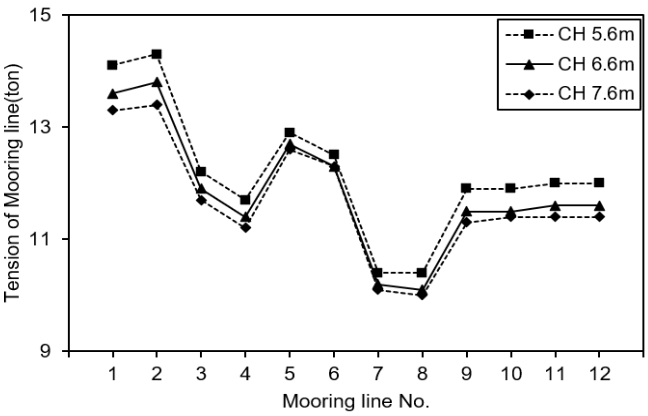

Fig. 13. Evaluation of mooring line tension by crown height (WD1).

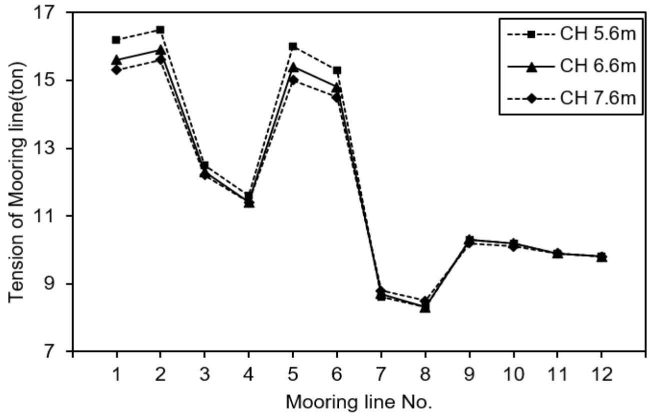

Fig. 14. Evaluation of mooring line tension by crown height (WD2).

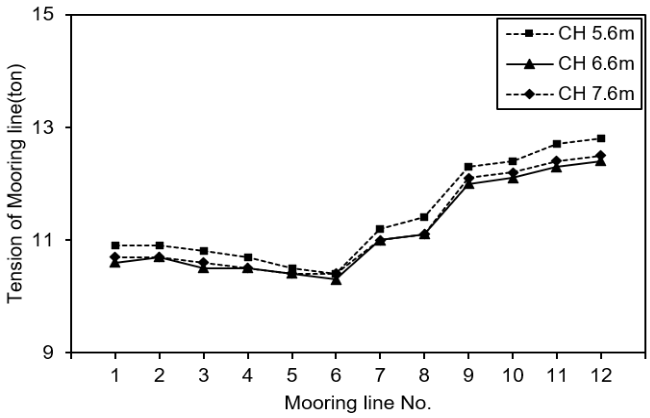

Fig. 15. Evaluation of mooring line tension by crown height (WD3).

5.2 Load of bollards

The maximum load of the bollard was analyzed according to the crown height. The results of the sensitivity analysis of B1 and B12, which have the largest changes due to crown height, are as follows.

Fig 16 is an analysis of the sensitivity of the load according to the crown height of B1. In WD1, when the crown height is 5.6 m, 51.5 tons is applied, and when the crown height is 6.6 m, 49.8 tons is applied. It was analyzed that the load of the B1 decreased by 3.3% when the crown height was increased by 1.0 m. In WD2, the maximum sensitivity of the bollard analyzed to be 2.7%, and in WD3, the maximum sensitivity of the bollard decreased to 2.4%.

Fig 17 is an analysis of the sensitivity of the load according to the crown height of B12. In WD1, when the crown height is 5.6 m, 47.6 tons is applied, and when the crown height is 6.6 m, 46.6 tons is applied. It was analyzed that the load of the B12 decreased by 3.4% when the crown height was increased by 1.0 m. In WD2, the maximum sensitivity of the bollard analyzed to be 0.3%, and in WD3, the maximum sensitivity of the bollard decreased to 2.8%.

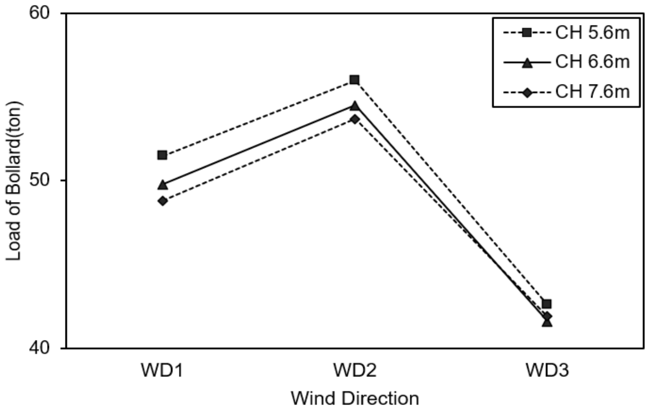

Fig. 16. Evaluation of bollard force by crown height (Bollard 1).

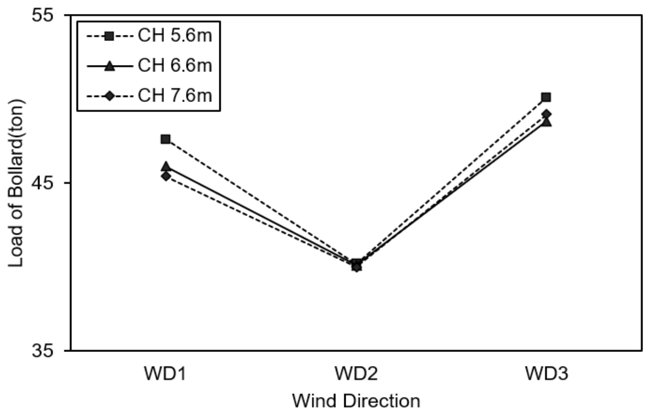

Fig. 17. Evaluation of bollard force by crown height (Bollard 12).

5.3 Ship motion in 6-DOF

Table 7 is the 6-DOF motion values of the ship according to the wind direction conditions when crown height is raised. The motion with the greatest value of change according to crown height is Sway motion, and Fig. 18 is the value of Sway motion according to crown height.

In WD1, when the crown height is 5.6 m, the value of sway is 0.94 m, and when the crown height is 6.6 m, the value of sway is 0.78 m. It was analyzed that the maximum value of sway decreased by 14.3% when the crown height was increased by 1.0 m. In WD2, it was analyzed that the maximum value of sway decreased by 7.7%, and in WD3, it was analyzed that the maximum value of sway decreased by 16.7% when the crown height was increased by 1.0 m.

Table 7. Motion for 6-DOF by crown height

Wind direction	Crown height(m)	Surge (m)	Sway (m)	Heave (m)	Roll (°)	Pitch (°)	Yaw (°)
WD1	5.6	0.16	0.91	0.01	0.2	0.1	0
	6.6	0.17	0.78	0.01	0.2	0.1	0
	7.6	0.18	0.71	0.01	0.2	0.1	0
WD2	5.6	0.44	0.91	0.01	0.6	0.1	0
	6.6	0.42	0.84	0.01	0.5	0.1	0
	7.6	0.39	0.79	0.01	0.5	0.1	0
WD3	5.6	0.03	0.48	0.01	0.2	0.1	0
	6.6	0.03	0.39	0.01	0.1	0.1	0
	7.6	0.03	0.37	0.01	0.1	0.1	0

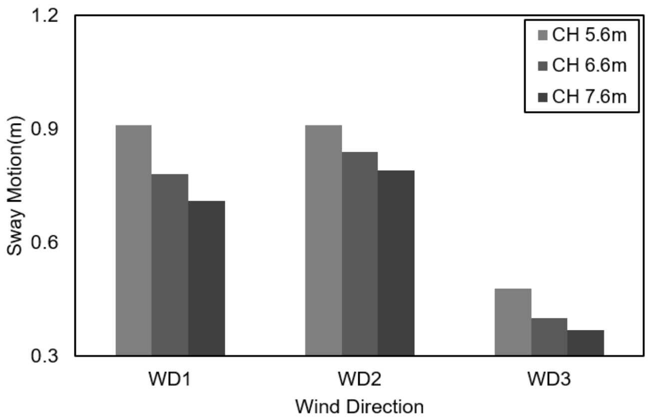

Fig. 18. Sway motion by crown height.

6. Conclusion

Sea level rise due to global warming is accelerating, and the expected sea level rise in 2100 was analyzed to be between 47 and 82 cm according to the carbon scenario by IPCC. Sea level rise can cause serious damage to port infrastructure and equipment and reduce the safety of ships docked inside ports.

Therefore, in this study, the sensitivity of mooring evaluation factors was analyzed for actual berthing ships according to sea level rise scenarios by selecting Mokpo Port, which has recently been marked by sea level rise and frequently suffers flood damage during high tide. Based on the analysis results, the following conclusions were drawn.

(1) In Mokpo Port, the extreme highest tide level has risen by 110 cm, and the mean sea level has risen by 95 cm over the past 50 years, accelerating sea level rise. In addition, the crown

height of Mokpo Port is 5.6 m, and the latest extreme highest tide level is 5.5 m, and it is analyzed that the sea level rises to 10 cm below the crown height. Accordingly, it was analyzed that there were risks such as deterioration in the safety of berthing ships and flooding of cargo.

(2) As a result of the mooring safety simulation according to the environmental external force scenario, it was analyzed that the mooring line tension increased by up to 4.8%, the load of the bollard increased by up to 3.9%, and the vertical angle of the mooring line increased by up to 6.5% when the sea level rose by 1.0 m. It was analyzed that the factor with high sensitivity according to sea level rise was the motion of 6-DOF motion, and the value of sway motion increased by up to 46.2% when the sea level rose by 1.0 m.

(3) In order to improve the safety of berthing ships and ports, as a result of mooring safety simulation according to the crown height, it was analyzed that the mooring line tension decreased by up to 3.7% and the load of the bollard decreased by up to 3.4% when the crown height increased by 1.0 m. It was analyzed that the factor with the high sensitivity according to the crown height was the motion of 6-DOF motion, and the value of sway motion decreased by up to 16.7% when the crown height was raised by 1.0 m.

(4) Therefore, it was evaluated that it is necessary to increase the crown height of Mokpo Port in the long term in order to improve the safety of mooring factors due to sea level rise and to prevent cargo damage due to dock flooding. When raising the crown height, it was necessary to set it in consideration of the expected sea level rise announced by IPCC, the wind pressure area of the vessel scheduled to berth, and the mooring evaluation factors.

The results of this study can be used as basic data to secure measures to improve the safety of port and ship in response to sea level rise in Mokpo Port. It is analyzed that if the crown height of the Mokpo Port is raised, the movement of the ship will be reduced, making safer loading and unloading work possible for both ship operators and stevedores. In future studies, we intend to analyze the sensitivity of mooring factors according to sea level rise for more diverse ports, wharfs and ship types, and propose the optimal crown height that reflects the environment and vessel characteristics.

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