International Journal on Advanced Science Engineering Information Technology

Vol.10 (2020) No. 4
ISSN: 2088-5334

Structural Performance Investigation of Ship Lift Hoist Pile Structure Exposed to Tropical Marine Environment

Wahyuniarsih Sutrisno[a], Harun Alrasyid[a,*]

[a] *Department of Civil Engineering, Institut Teknologi Sepuluh Nopember, Keputih, Surabaya, 60111, Indonesia*
*E-mail: niar1206@gmail.com; *harun@ce.its.ac.id (corresponding author)*

***Abstract*— This paper presents a field investigation and numerical analysis of a ship lift hoist pile structure exposed to the marine environment. This structure is located at Lamong Gulf in East Java Indonesia. This study focused on analyzing the structural performance of the steel pile of the ship lift hoist structure against gravity and seismic load. The field investigation was conducted using several methods such as visual observation, ultrasonic pulse velocity, half-cell potential and ultrasonic thickness to observe the current condition of the structure. Furthermore, a structural analysis was also performed to investigate the performance of the structure before and after the corrosion presented. Based on the field investigation result, it was found that the steel pile of the hoist structure suffers a loss of thickness due to corrosion. The thickness loss of each pile varies from 0 to 1.9 mm. The half-cell potential on the pile cap also shows that the corrosion potential in more than half the hoist pile cap is very high. Furthermore, the structural performance analysis shows that the hoist pile structure is within the safe limit against gravity load when receiving a maximum ship load of 1,650 tons. However, when the gravity load is combined with seismic load, the analysis result shows that the steel pile structure is overstressed and cannot withstands the applied load.**

***Keywords*— structural performance; ship lift hoist pile; marine environment; corrosion.**

I. INTRODUCTION

Corrosion is one of the durability problems which can cause damage and early failure for both steel and reinforced concrete structures [1]–[3]. A significant amount of maintenance cost should be spent on structures that suffered from corrosion. Structures located at the splash and tidal zone in the marine environment are more susceptible to corrosion compared with another area [4]–[6]. In the splash zone, structures are subjected to cyclic wetting and drying cycle which over time, will cause severe damage to the structure [7]–[9]. In reinforced concrete structure, cyclic wetting and drying cause continuous moisture and harmful materials movement through concrete pores. When concrete is exposed to sea water after fully or partially dry conditions, the salt solution will infiltrate into the concrete by the capillary suction mechanism. The concrete will continue to suck the salt solution until there is no more reservoir of salt solution. This condition makes the concentration of chloride will develop to some point in the inner part of the concrete. When the external environment becomes dry, the pure water will evaporate and chloride will precipitate at the concrete pores [10]. If this condition is repeated by the wetting and drying mechanism, more chloride solution will infiltrate into the concrete while re-dissolving existing chloride into the concrete. At some point, the chloride concentration will reach the threshold value and it can initiate or accelerate the corrosion process [9], [11], [12]. After corrosion starts, the volume of rust is increase and cause decrease on bond strength between concrete and steel reinforcement and eventually cause cracking and delamination of its cover [1], [13], [14]. The concrete can suffer from mild to severe cracking due to corrosion. This cracking will also accelerate the initial corrosion and as time passes, the structure will damage and lose its capacity [15]–[19].

The corrosion process for steel structure is less complex compared with a concrete structure, but the damage can be worse. The steel reinforcement in reinforced concrete structure has protection from the concrete cover. However, the steel structure mainly has direct contact with the environment. Even though several steel structures are coated before installation, in severe exposure conditions, it no longer effective. For the steel structure placed in the tidal zone, the corrosion can occur much faster compared to the immersion zone. In advanced condition, the corrosion in steel pile structure can occur along to pile length and cause localized perforation of the pile thickness and affect its overall structural capacity [20], [21].

The lack of understanding regarding the damage mechanism of structures results in insufficient planning and awareness for the environmental effects. There are many

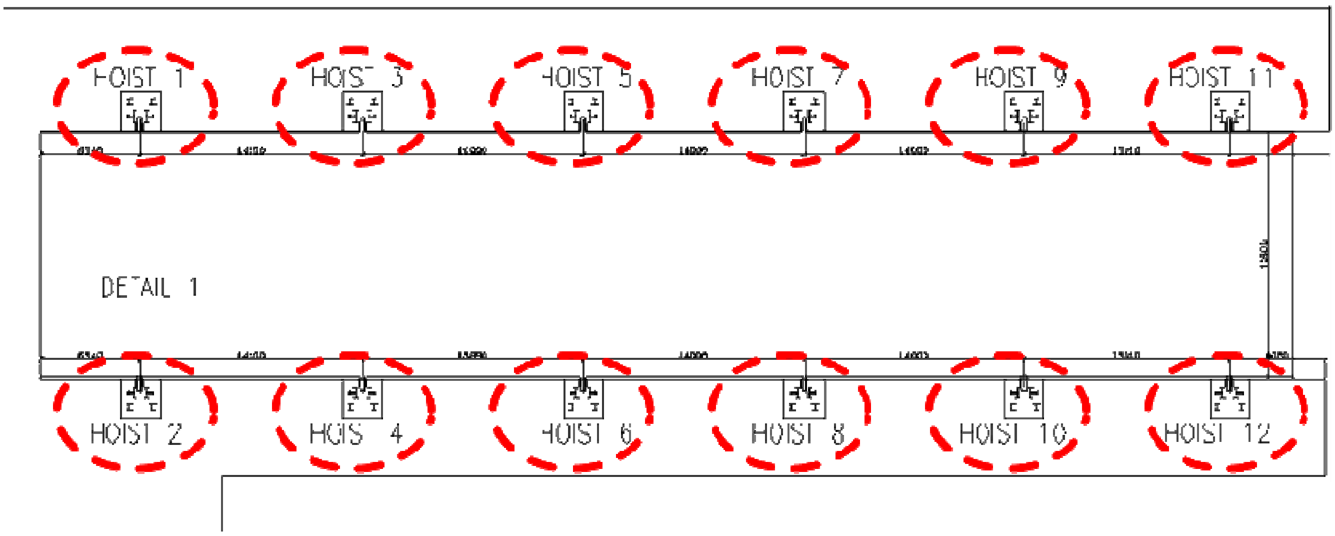

Fig. 1 The layout of ship left jetty structures

methods to prevent damage to the structure and used in the construction industry such as using mechanical barriers, cathodic protection, chemical protection using corrosion inhibitors, and improving the quality of materials. Corrosion induced by chloride ion is a major cause of damage to concrete structure located marine environments [18], [22], [23]. Corrosion can cause cracking and a reduction in the service life of structures, so a regular schedule for maintenance and repair protocol is essential to control the safety and efficient operation of a structure [24][21]. Furthermore, in a real concrete structure, the crack formation due to shrinkage and loading can accelerate the corrosion process [25].

The corrosion damage also could be happened not only in concrete structure, but also in steel structure, such as steel bridges, steel pile, etc. There are several parameters that can be used to assess the corrosion such as resistivity, half-cell potential, and corrosion rate [26]. The assessment of corrosion damage can lead to an effective repair technique selection. Consistent inspections after performing a repair at the structure are essential to ensure the overall performance of the repaired structure. In addition, regular investigations of repaired structures are necessary to develop guidelines for choosing the best repair systems, improved repair procedures, the extended durability of rehabilitated structures, and evaluation of discrepancies between laboratory results and field performance [27].

This paper presents a case study of a ship lift hoist structure exposed to the marine environment of the Lamong Gulf in East Java Indonesia. This study focused on analyzing the performance of a steel pile and pile cap of the ship lift hoist structure. The detailed field investigation of the structure was performed to assess the current condition of the structure. In the last section, the numerical modelling result is presented to analyse the performance of the steel pile. The performance of the steel pile is later presented in demand per capacity ratio of the hoist pile structure against gravity and seismic load.

II. Material and Method

The Ship Lift Hoist Structure, which investigated in this paper, is located on the east coast of Lamong Gulf East Java Indonesia. The function of this structure is to transfer the ship to its workshop for maintenance and repair purposes. The ship lift jetty structure is equipped with a 12-hoist structure used for lifting and lowering the steel platform. The hoist structure consists of two different materials which are a concrete structure at the top as a pile cap and WF steel structure at the bottom part of its foundation. The structural layout of the ship lift structure is shown in Fig. 1. The red mark indicates the twelve hoist structures that have been investigated and the result will be discussed in this paper.

The structure is exposed to a severe tropical marine environment with cyclic wetting and drying cycle. The average day temperature in this area is 26oC, and the highest temperature in summer can reach 37oC. This area also has high precipitation which can reach over 400 mm in rainfall season. The humidity also varies from 60% in October to 80 % in December.

The field investigation was conducted using several methods such as visual observation, ultrasonic pulse velocity, half-cell potential and ultrasonic thickness to observe the current condition of the structure. Furthermore, a structural analysis was also performed to investigate the performance of the structure before and after the corrosion presented. The visual observation was performed by inspecting and taking picture of each element of ship lift structure including pile cap and steel pile. Moreover, the ultrasonic pulse velocity was conducted to obtain data related to the quality of concrete. The quality of concrete was obtained by measuring the velocity of the ultrasonic pulse which passing through the concrete.

The numerical analysis was performed to evaluate the structural performance of the hoist structure to determine the current condition of the structure under gravity and seismic loading. The structural modelling was performed using the structural analysis program CSI SAP 2000.

Fig. 2 The layout of ship left jetty structures

III. Results and Discussion

The result of field investigation and numerical modelling is presented in this section. The field investigation included visual observation, thickness measurement of hoist pile and corrosion potential measurement of the hoist pile cap. Meanwhile, the structural modelling of pile cap and steel pile was performed by using CSI SAP 2000.

A. *Visual Observation*

The visual observation was performed for the hoist structure and mainly focused on the concrete pile cap and steel pile. The visual observation of the upper part of the pile cap structure showed that there was no visible cracking and damage to the structure. The boulder also has good condition. However, the investigation result at the bottom part of the pile cap structure indicated different results compared with the upper part. The bottom part of the pile cap structure showed that the concrete had deteriorated.

Detailed investigation of the pile cap structures showed that slab and beam part of the jetty indicated rust staining and cracking due to its contact with the marine environment. The different condition between the upper and lower part of the jetty structure happened because the bottom part has the closest distance with sea water and suffered from cyclic wetting and drying cycle. The cyclic wetting and drying causes constant movement of moisture and harmful materials through concrete pores. When concrete is exposed to sea water, the salt from the sea water, which contains harmful substances such as chloride and sulphate, will penetrate into the concrete by the capillary suction mechanism. The concrete will continue to absorb the salt

TABLE I
Thickness Measurement Result of Hoist Pile

WF 800x300	**Measured Thickness (mm)**					
	Hoist 10	**Hoist 8**	**Hoist 12**	**Hoist 7**	**Hoist 9**	**Hoist 11**
Flange	24.7	25.6	24.6	24.1	24.6	24.3
Web	13.5	13.6	14.0	14.0	13.5	13.8
WF 400x400	**Measured Thickness (mm)**					
	Hoist 10	**Hoist 8**	**Hoist 12**	**Hoist 7**	**Hoist 9**	**Hoist 11**
Flange	20.2	19.6	20.2	19.6	19.6	20.1
Web	13	12.4	12.6	12.4	12.4	12.5

solution until its pores are saturated. This condition means the concentration of chloride will increase to some point in the inner part of the concrete. When the external environment becomes fully or partially dry, the pure water will evaporate and chloride or sulphate will stay at the concrete pores. If the wetting and drying mechanism continues, more sea water will infiltrate into the concrete while re-dissolving the existing chloride to infiltrate deeper into the concrete and cause corrosion at the steel reinforcement. The exposure condition then causes the bottom part of concrete to be directly exposed to the marine environment and eventually causes corrosion on the steel reinforcement.

The infiltration of chloride and sulphate into the concrete also causes a decrease in concrete strength. This is because the concrete the chloride and sulphate form secondary ettrigites, such as chloroaluminates, which can expand in concrete pores and cause micro cracking in the concrete. As marine exposure continues, the permeability of concrete will increase as the micro cracking formed on the concrete.

For the hoist structure, the pile and pile cap have suffered from corrosion and damage, as shown in Fig. 4. The pile element of the hoist structure used structural steel WF 800 X 300 X 13 X 24. Based on field investigation, most of the hoist steel pile has been covered with shells and algae. The rust stain is very visible and covers almost all parts of the steel pile. For the pile cap, the cracking is already presented, which indicates that the steel reinforcement inside the structure has been corroded.

B. Thickness Measurement of The Hoist Pile

Ultrasonic thickness (UT) measurement is the most common method of measuring the thickness of the steel plate element of a structure. The technique measuring the thickness starts with placing the transducer on the surface of the measured material. The quality of the contact surface can be increased by the use of a couplant, usually in a gel form. The transducer emits ultrasonic waves that pass from a transmitter (T) through the material and reflect off the opposite wall and back to a receiver (R), providing there are no discontinuities or cracks that might first intercept the waves. The main advantage of this system (versus the use of calipers, for example) is that it needs access to only one side of the plate being measured. However, there is significant uncertainty about what is actually being measured when the probe is placed on a heavily pitted surface or if there is a corrosion layer between the probe and the steel. Therefore, the thickness measurement was performed after cleaning the surface of the steel. The test was performed using CMXDL Ultrasonic Thickness & Coating Gauge.

The ultrasonic thickness measurement is performed for a 6-hoist pile from a total of twelve piles. The hoist pile consists of two types of steel WF beams with an initial dimension 800x300x14x26 and 400x400x13x21. Table I shows the result of the hoist pile thickness measurement. The measurement result shows that the thickness of the flange and web of the hoist pile were decreased due to corrosion. The thickness loss of the steel piles varies from 0 to 1.9 mm. The minimum thickness of the WF 800x 300 web and flange is 13.5 and 24.1 mm, respectively, while for the WF 400 x 400, the minimum thickness of the web and flange is 12.4 and 19.6 mm, respectively.

C. Corrosion Potential Investigation of Hoist Pile Cap

The corrosion probability of the pile cap element of hoist structure was estimated using half–cell potential test in accordance with the ASTM C876 standard. The half-cell potential mapping is a common technique used in the laboratory and in-situ. The half-cell potential test is a qualitative and a non-destructive method for detecting corrosion state in the reinforcement bars of concrete elements. This test can identify the probability of reinforcement corrosion of concrete structure by measuring potential difference between the metal and reference electrode. The variation of the half-cell potential result is affect by quality of concrete, moisture content and surface condition [28]. The mechanism of potential difference measurement using a half-cell potential method is shown in Fig. 5.

For this investigation, the test was performed and analyzed using the PROCEQ CANIN+ corrosion analyzer, as shown in Fig. 6. This equipment used copper/copper sulphate (Cu-CuSO4) as the reference electrode. Potential measurements were performed with a single electrode. The condition of the concrete surface when performing the potential mapping is dry, which becomes electrically insulating. Therefore, to obtain a potential reading, it is necessary to pre-water the surface to allow ionic movement, prior to taking measurements. As stated at the beginning of this part, the probability of corrosion was evaluated based on the standard recommendations from ASTM C876-09. Table I below shows the dependence between potential and corrosion probability.

TABLE II
DEPENDENCE BETWEEN POTENTIAL AND CORROSION PROBABILITY BASED ON ASTM C878

Potential (E_{corr})	**Probability of Corrosion**
E_{corr} > - 200 mV	90% probability that no reinforcing steel corrosion is occurring in that area at the time of measurement (10% risk of corrosion)
– 350 mV ≤ E_{corr} ≤ - 200 mV	corrosion activity of the reinforcing steel in that area is uncertain
E_{corr} < -350 mV	greater than 90% probability that reinforcing steel corrosion is occurring in that area at the time of measurement

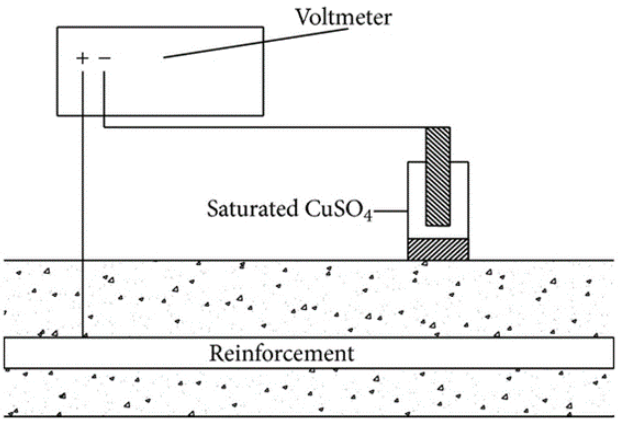

Fig. 3 The potential difference measurement method using a half-cell potential method

Twelve hoist structures were observed during field investigation. As shown in Fig. 8, the corrosion probability is different in each area of the hoist structure. On Hoist 2, 6, 7 and 11, the probability of corrosion is low or there is a probability that no reinforcing steel corrosion was occurring in that area at the time of measurement. This condition is indicated by the potential value which is still in the range of − 350 mV ⩽ Ecorr ⩽ - 1000 mV. Meanwhile, in other locations, the probability of corrosion was high. This condition is indicated by the potential values which are less than – 350 mV.

TABLE III
THE HALF CELL POTENTIAL RESULTS

Hoist Number	Minimum Measured Potential	Maximum Measured Potential
1	-1000	-275
2	-350	-200
3	-800	-180
4	-1000	-50
5	-975	-210
6	-200	-50
7	-275	-50
8	-1000	-150
9	-1000	-250
10	-1000	-250
11	-260	-50
12	-800	-250

D. Structural Performance Analysis of Hoist Pile Structure

This section presents the structural performance evaluation of the hoist structure to determine the current condition of the structure. The structural modelling was performed using the structural analysis program CSI SAP 2000. Dimensions and detailing of the pile and pile cap were obtained from the visual survey and measurement. The structure of the hoist consists of a pile cap and steel pile. The dimension and material properties of the structures are shown in Table IV.

TABLE IV
MATERIAL PROPERTIES AND DIMENSION OF HOIST STRUCTURE

Properties	Value
Concrete Compressive Strength, f'c	17 Mpa
WF pile yield strength, f_y	370 Mpa
Vertical pile profile	WF 800x300x13x24
Horizontal pile profile	WF400x400x12x19

The point of fixity was calculated using Equation (1) which depends on the stiffness of the soil. The stiffness value can be calculated using Equation (2). The factor for cohesionless soil (nh) can be obtained from Table III, as purposed by Terzaghi.

$$Z_f = 1.8T \quad (1)$$

Where:
T : stifness factor which can be calculated by

$$T=\sqrt{EI/n_h} \quad (2)$$

n_h : factor for cohesionless soil (Terzaghi), see Table III

TABLE V
COHESIONLESS FACTOR FOR CALCULATING SOIL STIFFNESS

Relative density	Loose	Medium dense	Dense
n_h for dry dan moist soil (MN/m^3)	2.5	7.5	20
n_h for submerged soil soil (MN/m^3)	1.4	5	12

Based on the calculation, the point of fixity for WF 800x300x12x24 and WF 400x400x12x21 are 6.01 m and 4.47 m from the ground surface, respectively. For the structural modelling of the hoist structure, the frame element was used for the steel pile and shell element for the pole cap. The model for the hoist structure can be seen in Fig. 4.

The load applied for the hoist structure includes the dead load, live load and earthquake load. The dead load consists of self-weight of the structure weight of the hoist machine and platform. Furthermore, the live load is taken from the weight of the ship, which varied, based on the type of the ship. The detailed values of the dead and live load are shown in Table VI.

TABLE VI
COHESIONLESS FACTOR FOR CALCULATING SOIL STIFFNESS

Load	Value
Dead load	
self-weight of concrete pile cap	2400 kg/m^3
self-weight of steel pile	7850 kg/m^3
weight of hoist machine	12 ton
weight of hoist platform	250 ton
Live load	
ship weight	500 ton – 2000 ton

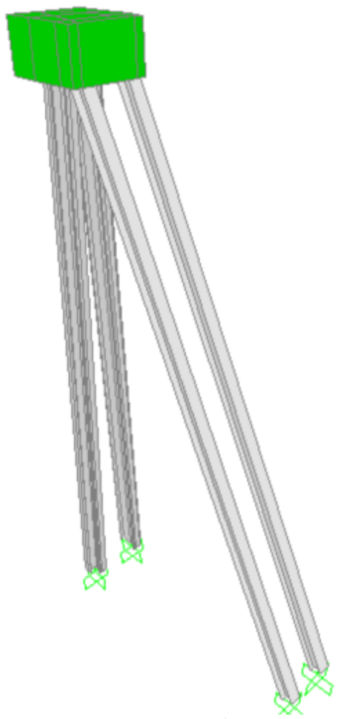

Fig. 4 The model of hoist structure

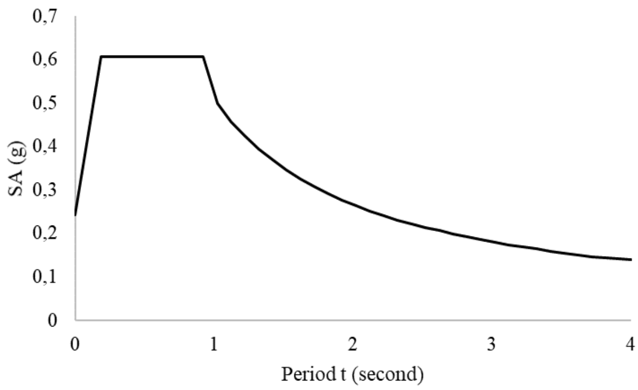

Fig. 5 The response spectrum graph for Surabaya area

The earthquake load for the structure was calculated using the earthquake specification code by the Indonesian Government, SNI 1726-2012.The structure was located in the Surabaya area of East Java. Based on the Indonesian earthquake hazard code, the site-specific response spectra acceleration for a short period is 0.69 g, and the one second period, S1, is 0.3 g. The response spectrum graph for the earthquake load is shown in Fig. 5.

The numerical analysis was performed using the SAP 2000. This analysis compared the demand and capacity of the structure against the gravity and seismic load. The hoist structure is concluded to be safe when the resistance ratio of the steel pile is below 1. The demand per capacity ratio more than 1 indicates that the hoist structure is overstressed and cannot withstand the ship load. The load is applied by increasing the ship's weight load gradually from 500 tons to 2000 tons. Fig. 6 shows the result of the numerical modeling of the hoist structure against the gravity load. From Fig. 6, it can be seen that the hoist structure is at a safe limit when receiving a maximum ship load of 1,650 tons. However, over the 1,650 ton of ship weight, the demand per capacity ratio of the WF 800 x 300 x 13 x 24 reaches over 1 and the section becomes overstressed.

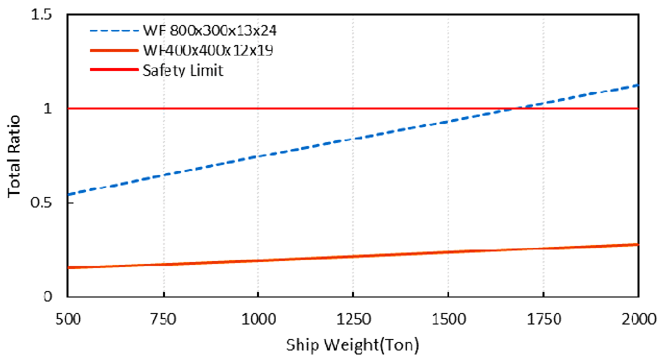

Fig. 6 The demans per capacity ratio of hoist structure against gravity load

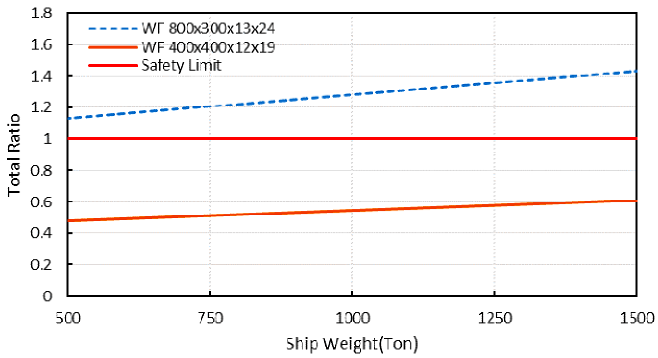

Fig. 7 The demand per capacity ratio of hoist structure against seismic load

In addition to the gravity load, the demand per capacity ratio of the hoist structure is also calculated against seismic load and the result is shown in Fig. 7. Different from Fig. 6, the analysis result shows that the performance of the hoist pile structure has exceeded the safety limit. Even though the WF 400 X 400 X 12 X 19 pile is still in the safe zone, another pile had clearly lost its capacity to withstand the applied load. This condition happened due to the corrosion of the hoist pile. The corrosion on the hoist pile causes the steel pile to loss its thickness of the web and flange which leads to the section being overstressed and decreases the overall performance level of the pile structure.

IV. CONCLUSIONS

A field investigation and structural performance analysis of a ship lift hoist pile structure exposed to the marine environment were performed in this study. This study focused on analyzing the structural performance of the steel pile of the ship lift hoist structure against gravity and seismic load. Based on the field investigation result, it was found that the steel pile of the hoist structure suffers from corrosion. The thickness of the pile structure also reduces due to corrosion. The thickness loss of each pile varied from 0 to 1.9 mm. The half-cell potential on the pile cap also showed that the corrosion potential in several hoist pile structure is very high. Besides performing field investigation, a structural performance analysis was also performed for the hoist structure using the measured thickness from the field investigation. The structural performance analysis shows that the hoist pile structure is at a safe limit against gravity load when receiving a maximum ship load of 1,650 tons. However, when the gravity load is combined with seismic load, the analysis result shows that the steel pile structure is overstressed and cannot withstand the applied load.

REFERENCES

[1] Y. Zhang, R. Kai, and L. Su, "Concrete cover delamination model for non-uniform corrosion of reinforcements," *Constr. Build. Mater.*, vol. 223, pp. 329–340, 2019.

[2] M. Otieno, J. Ikotun, and Y. Ballim, "Experimental investigations on the influence of cover depth and concrete quality on time to cover cracking due to carbonation-induced corrosion of steel in RC structures in an urban , inland environment," *Constr. Build. Mater.*, vol. 198, pp. 172–181, 2019.

[3] J. Hu, P. Deng, X. Li, J. Zhang, and G. Wang, "The vertical Non-uniform corrosion of Reinforced concrete exposed to the marine environments," *Constr. Build. Mater.*, vol. 183, pp. 180–188, 2018.

[4] C. Yang, L. Li, and J. Li, "Service life of reinforced concrete seawalls suffering from chloride attack: Theoretical modelling and analysis," *Constr. Build. Mater.*, vol. 263, p. 120172, 2020.

[5] S. Cheng, Z. Shui, X. Gao, J. Lu, T. Sun, and R. Yu, "Degradation progress of Portland cement mortar under the coupled effects of multiple corrosive ions and drying-wetting cycles," *Cem. Concr. Compos.*, vol. 111, no. April, p. 103629, 2020.

[6] M. Stefanoni, U. Angst, and B. Elsener, "The mechanism controlling corrosion of steel in carbonated cementitious materials in wetting and drying exposure," *Cem. Concr. Compos.*, vol. 113, no. July, p. 103717, 2020.

[7] M. H. F. Medeiros, A. Gobbi, G. C. Réus, and P. Helene, "Reinforced concrete in marine environment : Effect of wetting and drying cycles , height and positioning in relation to the sea shore," *Constr. Build. Mater.*, vol. 44, pp. 452–457, 2013.

[8] W. Sutrisno, P. Suprobo, E. Wahyuni, and D. Iranata, "Microstructural investigation of reinforced concrete exposed to cyclic wetting and drying," *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 8, no. 2, pp. 411–417, 2018.

[9] W. Sutrisno, P. Suprobo, and E. Wahyuni, "Experimental Test of Chloride Penetration in Reinforced Concrete Subjected to Wetting and Drying Cycle," *Appl. Mech. Mater.*, vol. 851, pp. 846–851, 2016.

[10] C. Tongning *et al.*, "Simulation of chloride ion transport in concrete under the coupled effects of a bending load and drying–wetting cycles," *Constr. Build. Mater.*, vol. 241, p. 118045, 2020.

[11] Y. Wang, H. Oleiwi, C. Y. Wang, N. Xiang, and J. Geng, "The characterization of chloride effect on concrete water sorption and its application in the modelling of concrete conditions in tidal zones," *Constr. Build. Mater.*, vol. 253, p. 119074, 2020.

[12] J. K. Das and B. Pradhan, "Long term effect of corrosion inhibitor and associated cation type of chloride ions on chloride profile of concrete exposed to composite chloride-sulfate environment," *Mater. Today Proc.*, 2020.

[13] C. Jiang, Y. Wu, and M. Dai, "Virtual Special Issue Durability of Innovative Construction Materials and Structures Degradation of steel-to-concrete bond due to corrosion," *Constr. Build. Mater.*, vol. 158, pp. 1073–1080, 2018.

[14] W. Zhu, J. Dai, and C. Poon, "Prediction of the bond strength between non-uniformly corroded steel reinforcement and deteriorated concrete," *Constr. Build. Mater.*, vol. 187, pp. 1267–1276, 2018.

[15] A. Ranjith, K. B. Rao, and K. Manjunath, "Evaluating the effect of corrosion on service life prediction of RC structures – A parametric study," *Int. J. Sustain. Built Environ.*, vol. 5, no. 2, pp. 587–603, 2016.

[16] Y. Zhao, B. Hu, J. Yu, and W. Jin, "Non-uniform distribution of rust layer around steel bar in concrete," *Corros. Sci.*, vol. 53, no. 12, pp. 4300–4308, Dec. 2011.

[17] Y. Zhao, A. R. Karimi, H. S. Wong, B. Hu, N. R. Buenfeld, and W. Jin, "Comparison of uniform and non-uniform corrosion induced damage in reinforced concrete based on a Gaussian description of the corrosion layer," *Corros. Sci.*, vol. 53, no. 9, pp. 2803–2814, 2011.

[18] M. Shekarchi, F. Moradi-Marani, and F. Pargar, "Corrosion damage of a reinforced concrete jetty structure in the Persian Gulf: A case study," *Struct. Infrastruct. Eng.*, vol. 7, no. 9, pp. 701–713, 2011.

[19] W. Sutrisno, I. Ketut Hartana, P. Suprobo, E. Wahyuni, and D. Iranata, "Analysis of corrosion induced crack in reinforced concrete with smeared crack approach," *Int. J. Appl. Eng. Res.*, vol. 11, no. 19, pp. 9970–9974, 2016.

[20] R. E. Melchers, R. J. Jeffrey, and K. M. Usher, "Localized corrosion of steel sheet piling," *Corros. Sci.*, vol. 79, pp. 139–147, 2014.

[21] H. Wall and L. Wadsö, "Corrosion rate measurements in steel sheet pile walls in a marine environment," *Mar. Struct.*, vol. 33, pp. 21–32, 2013.

[22] S. Tattoni and F. Stochino, "Collapse of prestressed reinforced concrete jetties: Durability and faults analysis," *Case Stud. Eng. Fail. Anal.*, vol. 1, no. 2, pp. 131–138, 2013.

[23] M. N. Haque, H. Al-Khaiat, and B. John, "Climatic zones-A prelude to designing durable concrete structures in the Arabian Gulf," *Build. Environ.*, vol. 42, no. 6, pp. 2410–2416, 2007.

[24] L. Jin, M. Liu, R. Zhang, and X. Du, "Cracking of cover concrete due to non-uniform corrosion of corner rebar: A 3D meso-scale study," *Constr. Build. Mater.*, vol. 245, p. 118449, 2020.

[25] I. Zafar and T. Sugiyama, "The influence of bending crack on rebar corrosion in fly ash concrete subjected to different exposure conditions under static loading," *Constr. Build. Mater.*, vol. 160, pp. 293–307, 2018.

[26] G. Samson, F. Deby, J. L. Garciaz, and M. Lassoued, "An alternative method to measure corrosion rate of reinforced concrete structures," *Cem. Concr. Compos.*, vol. 112, no. April, p. 103672, 2020.

[27] D. Cusson, S. Qian, and T. Hoogeveen, "Field performance of concrete repair systems on highway bridge," *ACI Mater. J.*, vol. 103, no. 5, pp. 366–373, 2006.

[28] W. Yodsudjai and T. Pattarakittam, "Factors influencing half-cell potential measurement and its relationship with corrosion level," *Meas. J. Int. Meas. Confed.*, vol. 104, pp. 159–168, 2017.