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INVESTIGATION ON MITIGATION OF MAINTENANCE BURDEN OF PILE-SUPPORTED PORT STRUCTURES BASED ON STRUCTURAL ANALYSIS

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ABSTRACT:

Pile-supported port structures are important infrastructures for physical distribution especially for island countries, for example, Japan. But the motivation for the maintenance of these structures is low and they are not maintained properly because of big burden of maintenance work and high cost. Therefore, the objective of this research is to mitigate maintenance burden of pile-supported port structures in order to increase the motivation for their maintenance and keep the seismic performance properly. Distinguishing between the parts that need to be maintained intensively and the parts where labor can be saved from maintenance to some extent can mitigate the maintenance burden reasonably. This research focuses on both of member scale (RC beam) and structure scale.

In case of member scale analysis, the influence of non-uniform corrosion of steel bars on the performance of RC beams was investigated by COM3 (Non-linear structural FE analysis of RC) because corrosion is non-uniform in real environment. By this investigation, it was found that when considering the seismic performance of RC beams of pile-supported port structure, the influence of non-uniformity of corrosion do not have to be considered. The influence of corrosion on the performance of the RC beam was governed by the distribution of the bending moment when the RC beam is loaded. Therefore the center and edge of the span of RC beams of pile-supported port structure should be maintained with high priority.

In case of structure scale analysis, the relationship between the position of the members (RC beams of superstructure) whose steel bars were corroded and the seismic performance of the pile-supported port structure was investigated by COM3 and T-DAP (Three dimensional dynamic analysis software). By this investigation, it was found that the corrosion of outside beams in the parallel direction to the shoreline and landside beams in the vertical direction to the shoreline gives more severe damage to pile-supported port structure than inside beams during earthquake. Therefore outside and landside beams need to be maintained intensively and the maintenance of inside beams can be simplified.

KEYWORDS: pile-supported port structure, maintenance, corrosion, seismic performance

1. Introduction

Pile-supported port structures are important infrastructure for physical distribution especially for island countries, for example, Japan. The deterioration is progressing because of aging under severe environment where salt damage occurs. But the motivation for the maintenance of these structures is low and they are not maintained properly. The main causes are the big burden of maintenance work and high cost. When a higher magnitude earthquake occurs, the pile-supported port structures that are not maintained properly may fail, resulting in delay of physical distribution. Such risk is high for Japan because Japan has higher magnitude earthquakes frequently.

Therefore, the motivation for the maintenance of these structures has to be increased to sustain the seismic performance properly. It can be considered that if the maintenance burden of pile-supported port structures is mitigated, this will be archived. The objective of this research is to mitigate the maintenance burden of pile-supported port structures. To distinguish between the parts that need to be maintained intensively and the parts when the labor can be saved from maintenance to some extent can lead to the mitigation of the maintenance burden reasonably.

2. Investigation focusing on RC beam

In real environment, corrosion is non-uniform. In this chapter, the influence of non-uniform corrosion of steel bars on the performance of RC beams is investigated by COM3 and the part that need to be maintained intensively or not is distinguished within a RC beam in order to mitigate maintenance burden.

COM3 is a non-linear structural FE analysis for RC. The structural behavior of concrete in consideration of cracks, generated stress and deformation can be evaluated by finite element analysis.

2.1 Outline of analysis

The property of analysis model and load position are shown in Figure 1 and Table 1. The loading cases are static and cyclic loading. In case of cyclic loading, the displacement at the load position is 0mm→+1mm→0mm→+2mm→0mm→+3mm→ 0mm→+4mm… (+: vertical downward direction).

The model cases are set considering non-uniform corrosion both in cross section and in axial direction (Figure 2). It can be considered that the yield strength of the beam is influenced by the corrosion at the area which receives the biggest bending moment. To compare the effect of non-uniform corrosion in axial direction, mass loss by corrosion at the most severe section is 30% and the corrosion position is placed in three patterns. In case of the analysis to compare the effect of non-uniform corrosion in cross section, average mass loss by corrosion in cross section is 30% for all cases.

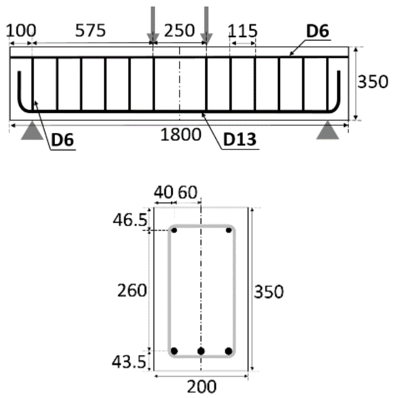
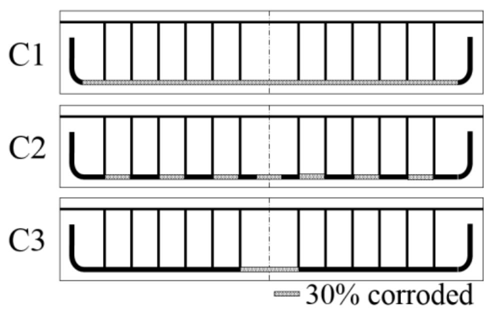


Figure 1 Analysis model and load position (unit: mm)

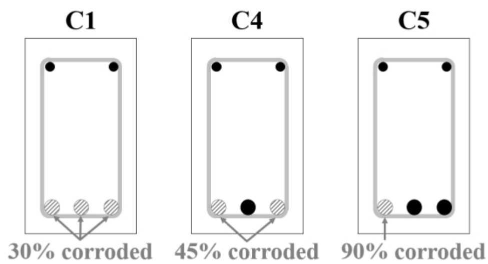
Table 1 Material property (upper: steel bars, lower: concrete)

	Main reinforcement	Stirrup
Initial stiffness (N/mm^2)	205939.7	205939.7
Yield strength (N/mm^2)	390.3	295.2
Poisson's ratio	0.2	0.2

Young's modulus (N/mm^2)	21574.6
Compressive strength (N/mm^2)	29.4
Tensile strength (N/mm^2)	2.2
Poisson's ratio	0.200



(a) Corrosion pattern in axial direction



(b) Corrosion pattern in cross section

Figure 2 Analysis case

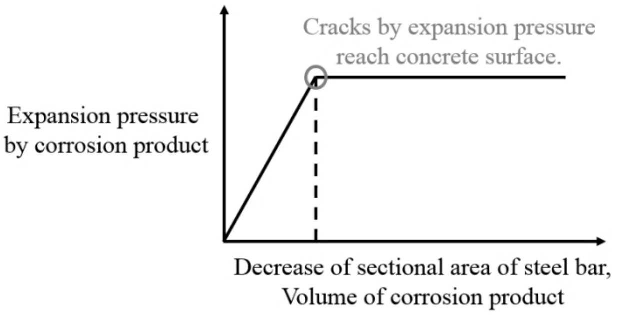


Figure 3 The relationship between expression pressure and decrease of sectional area of steel bar

In this research, the corrosion model that was shown in [1] is used. Decrease of sectional area of steel bar, expansion pressure by corrosion product and decrease of bond between steel bar and concrete are expressed as influence of corrosion in the model. Volume of corrosion product is set 3.7 times of decrease volume of steel bar and expansion pressure by corrosion product is set as shown in Figure 3. The decrease of sectional area of steel bar at the point when cracks by expansion pressure reach concrete surface is 10%. Decrease of bond between steel bar and concrete is expressed by increase of tension softening factor. Tension softening factor changes the relationship between tensile stress and strain. Decrease of crack dispersing effect by decrease of bond can be expressed by increase of tension softening factor.

2.2 Results and discussion

The load-displacement curves for different corrosion patterns in axial direction (Figure 4) and cross section (Figure 5) show the same tendency.

Regarding ductility, as localization of corrosion advances (C1<C2<C3, C1<C4<C5), ductility decreased in case of static loading. In this research, the definition of ductility is the displacement from the yield point to the point when the load starts to decrease significantly. This is because localization of damage advances, as localization of corrosion advances. Therefore, the critical crack occurs at early stage and the ductility decreases. On the other hand, there was no clear difference in ductility in case of cyclic loading and all cases had low ductility compared with static loading. It can be considered that this is because the critical crack occurs at small displacement by accumulation of damages regardless of corrosion pattern. By these results, it is understood that non-uniform corrosion of steel bars do not influence on structural performance of RC beam in case of cyclic loading.

The behavior of the beams in superstructure of pile-supported port structure subjected to seismic motion is imitated by cyclic loading on RC beams. So it can be said that when considering the seismic performance of RC beams of pile-supported port structure, the influence of non-uniformity of corrosion do not have to be considered. Then, the influence of corrosion on the seismic performance of the RC beam is governed by the distribution of the bending moment when the RC beam is loaded (Figure 6). The part that receives bigger bending moment need to be maintained intensively while the part that receives smaller bending moment can save maintenance burden to some extent.

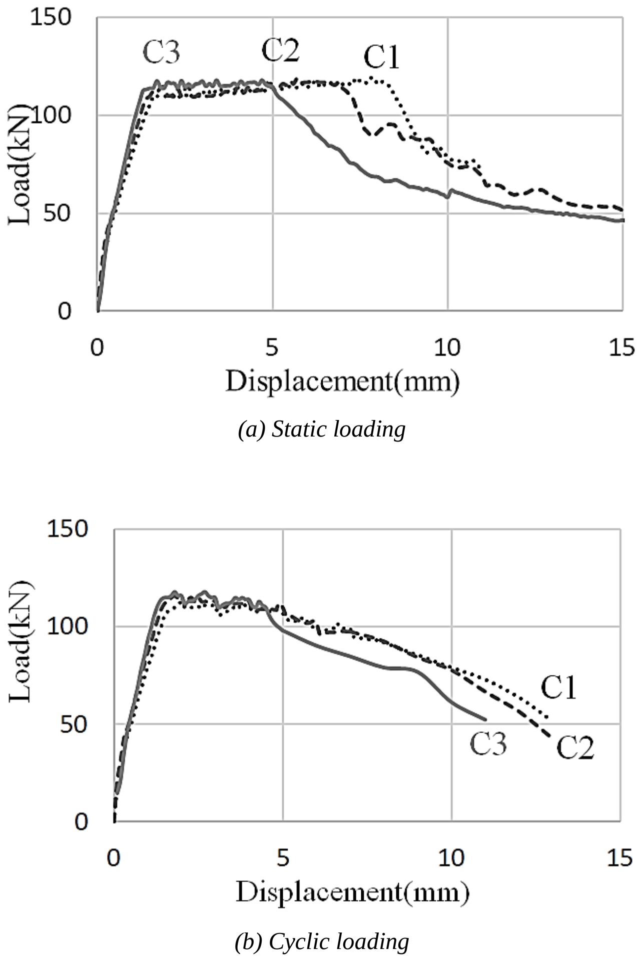
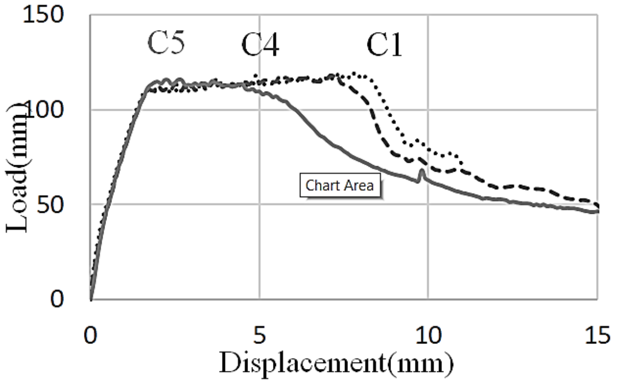
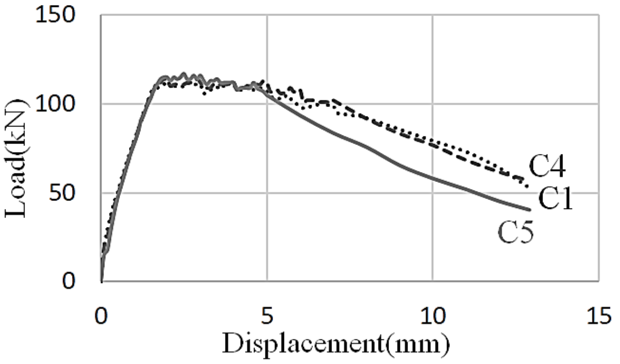


Figure 4 Load-displacement curve (corrosion pattern in axial direction)



(a) Static loading



(b) Cyclic loading

Figure 5 Load-displacement curve (corrosion pattern in cross section)

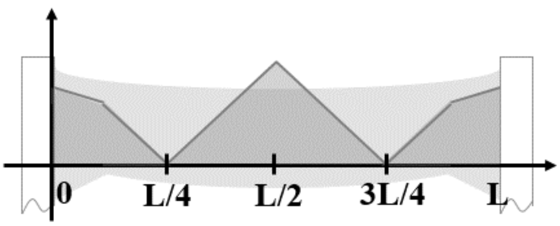


Figure 6 The degree of influence of corrosion

3. Investigation focusing on whole superstructure

The members of superstructure of pile-supported port structure are distinguished between that need to be maintained intensively and that maintenance can be simplified to some extent by investigating the relationship between the position of the member whose steel bars are corroded and the seismic performance of the pile-supported port structure. The target member of this research is RC beams of superstructure. Analysis models are based on the structure located at Maizuru West Port in Kyoto, Japan.

First, the constitutive laws when the sound or corroded RC beam receives the seismic motion are examined. Then, the total structural analysis is conducted by inputting the constitutive laws.

3.1 Constitutive laws of sound and corroded RC beams

The property of analysis model of the target RC beam of superstructure is shown in Figure 7 and Table 2. All steel bars in the RC beam are D22. To obtain the constitutive law when the beam receives the seismic motion, analysis was conducted by COM3. The loading method was cyclic loading, the load point was the center of the span and the beam was fixed at both ends. The displacement at the load position was 0mm→+1mm→-1mm→+2mm→-2mm→+3mm→-3mm→+4mm… (+: vertical downward direction). The corroded beam is defined as Figure 8. In this research, severe corrosion is assumed in order to clarify the relationship between the position of the member whose steel bars are corroded and the seismic performance of the pile-supported port structure and consider conservatively. The analysis results are shown in Figure 9.

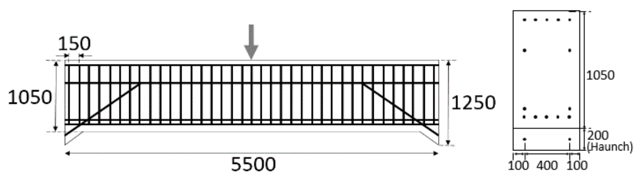


Figure 7 Analysis model and load position (unit: mm)

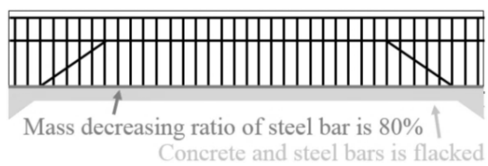


Figure 8 Corroded beam

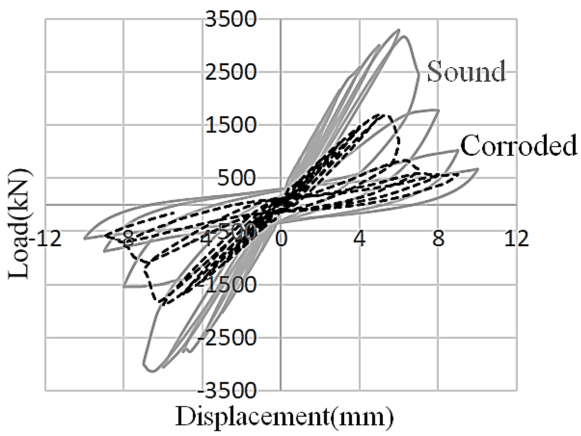


Figure 9 Analysis result by COM3

Table 2 Material property

	Steel bar
Initial stiffness (N/mm^2)	205800.0
Yield strength (N/mm^2)	345.0
Poisson's ratio	0.2
	Concrete
Young's modulus (N/mm^2)	21560.0
Compressive strength (N/mm^2)	35.0
Tensile strength (N/mm^2)	2.5
Poisson's ratio	0.2

To input the constitutive law into the model for total structural analysis conducted by T-DAP, the load-displacement curves were converted into a simple constitutive law, Degrading Tetra-linear Model (Figure 10). The bending stiffness and the curvature at each yield point of sound and corroded beam are shown in Table 3.

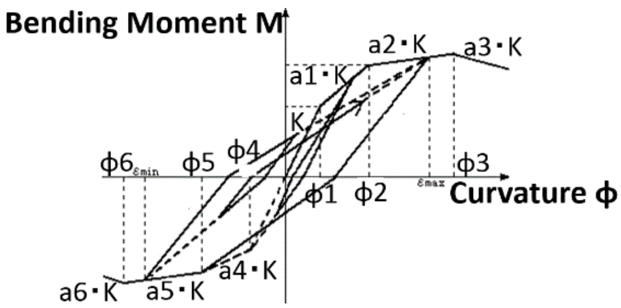


Figure 10 Degrading Tetra-linear model

Table 3 The bending stiffness and the curvature at each yield point (E:kN・m2 φ:1/m)

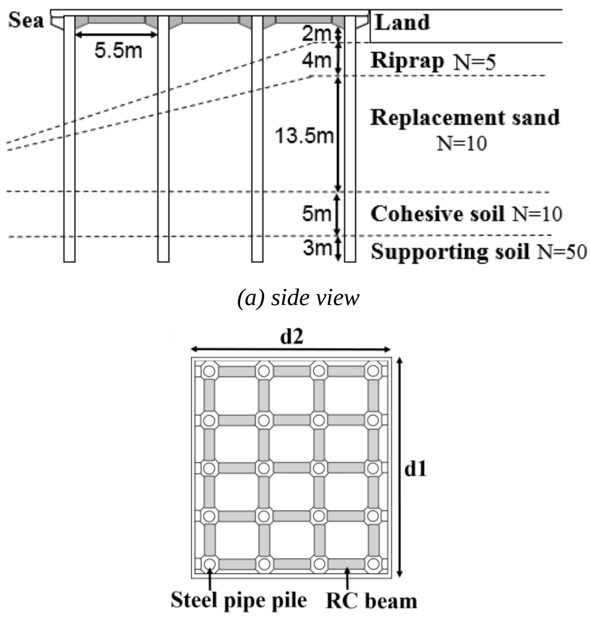
	sound	corroded		sound	corroded
E	111805963	71100744	a1	5.00×10^{-1}	3.95×10^{-1}
φ1	5.29×10^{-5}	5.29×10^{-5}	a2	2.83×10^{-1}	1.52×10^{-1}
φ2	4.50×10^{-4}	5.95×10^{-4}	a3	1.00×10^{-4}	1.00×10^{-4}
φ3	7.93×10^{-4}	7.01×10^{-4}	a4	4.35×10^{-1}	3.79×10^{-1}
φ4	-5.29×10^{-5}	-5.29×10^{-5}	a5	1.68×10^{-1}	2.42×10^{-1}
φ5	-5.95×10^{-4}	-6.61×10^{-4}	a6	1.00×10^{-4}	1.00×10^{-4}
φ6	-8.59×10^{-4}	-7.93×10^{-4}			

3.2 Total structural analysis

Three dimensional dynamic analysis by T-DAP was conducted on many different patterns of pile-supported port structures in order to get the general tendency of the relationship between the position of the member whose steel bars are corroded and the seismic performance of the pile-supported port structure.

3.2.1 Outline of analysis

The patterns of analysis model depended on size of superstructure, ground condition, length of steel pipe piles and type of seismic motion (Table 4). One of the target pile-supported structure is shown in Figure 11 and the simplified configuration of analysis model is shown in Figure 12. The ground is expressed by spring elements and the relationship of stress and strain of the spring elements is expressed by Nonlinear Elastic Model[1] (Figure 13). The spring constant and yield point are set by calculating soil pressure during earthquake for each spring element. The nonlinear model of steel pipe pile is Bilinear Model[1] (Figure 14, Table 5).



(a) side view

(b) superstructure

Figure 11 One of target structure

Table 4 Analysis parameter

Size of superstructure (d1×d2) (m^2)	25×16.5, 18.75×16.5, 31.25×16.5, 25×22.75, 25×29
Ground condition of replacement sand and cohesive soil	Soft(N=5), Soft(N=10), Hard(N=40)
Length of steel pipe piles	Short(28m), Long(33m)
Type of seismic motion	The Great Hanshin-Awaji Earthquake, The Tohoku-Pacific Ocean Earthquake

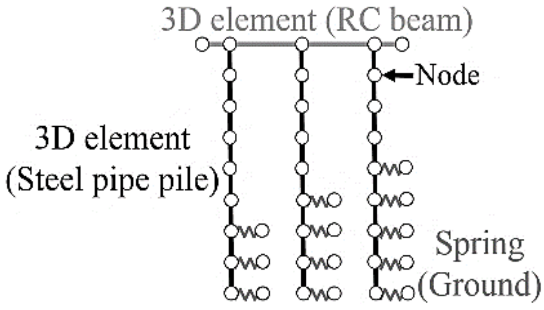


Figure 12 The simplified configuration

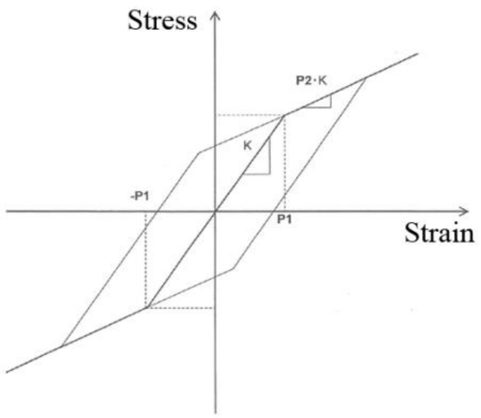


Figure 13 Bilinear Model (Ground)

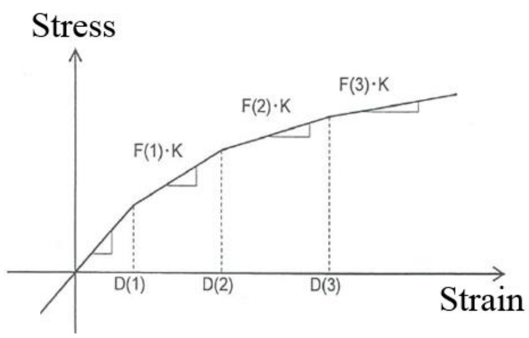


Figure 14 Nonlinear Elastic Model (Steel pipe pile)

Table 5 Parameter for Nonlinear Elastic Model (Steel pipe pile)

Strain at yield point (1/m)	4.247×10^{-2}
Rigidity reduction ratio	1.000×10^{-5}

3.2.2 Results and discussion

All patterns showed almost the same tendency. The tendency is explained by focusing on the result from one of them as an example (Figure 15).

The degree of damage is represented by rigidity reduction ratio. Rigidity reduction ratio is defined as the reduction ratio of the gradient of the hysteresis curve of curvature-bending moment from the first to final loading cycle. Beams in the parallel direction to the shoreline are named Beam1, and beams in the vertical direction to the shoreline are named Beam2.

In case of Case-a1, when all beams were sound (Figure 15 (a)), outside beams of Beam1 received bigger damage than inside beams of Beam1. This is because restriction of outside beams are less than inside beams. Regarding Beam2, landside beams received the biggest damage. This is because the length of landside piles is shorter than seaside piles and damage absorption of landside piles is little. In case of Case-a2, when all beams were corroded (Figure 15 (a)), the rigidity reduction ratio of almost all beams rose compared with Case-a1 and outside beams of Beam1 failed.

Regarding Beam1, when the outside beams were corroded (Figure 15 (b)), outside beams failed. When the inside beams are corroded (Figure 15 (c)), the increase in rigidity reduction ratio from Case-a1 of inside beams was small, and the rigidity reduction ratio of outside beams was reduced from Case-a1. From these results, the corrosion of the outside beams leads to the reduction in seismic safety of pile-supported structure and the corrosion of inside beams do not influence the seismic safety so much.

Regarding Beam2 (Figure 15 (d), (e) and (f)), when only one line of beams were corroded, the rigidity reduction ratio of corroded beams rose compared with Case-a1. It can be said that the corrosion of the landside beams that are originally easy to receive damage leads to reduction in seismic safety of pile-supported structure the most.

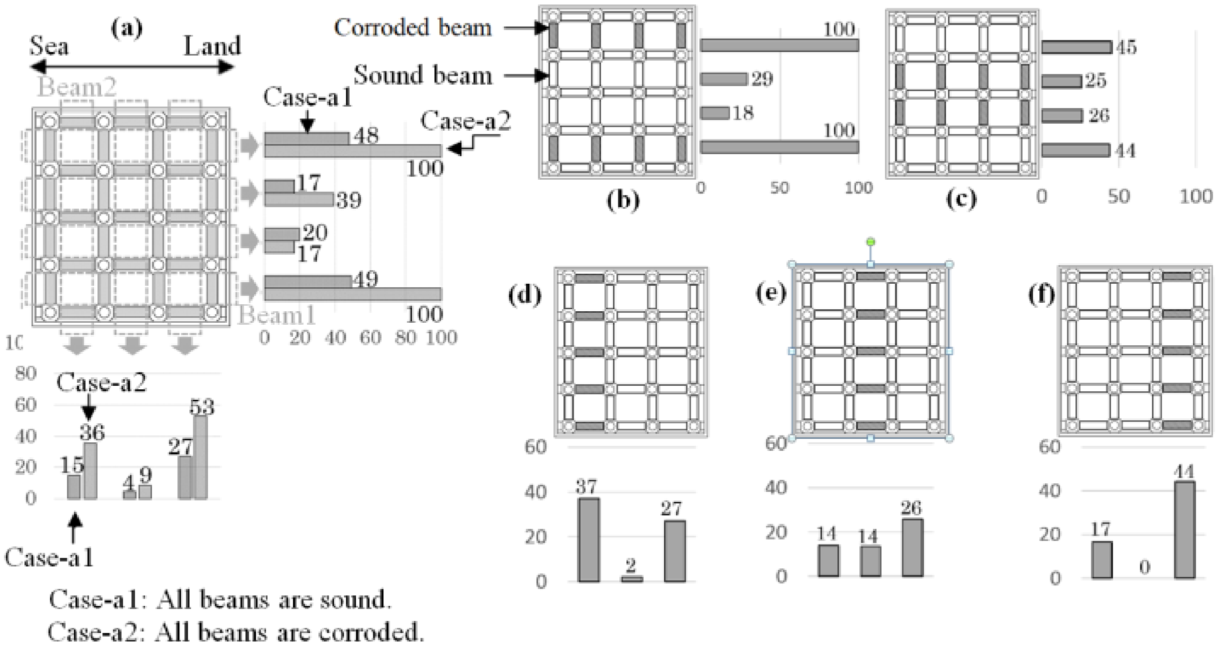


Figure 15 Rigidity reduction ratio of each beam

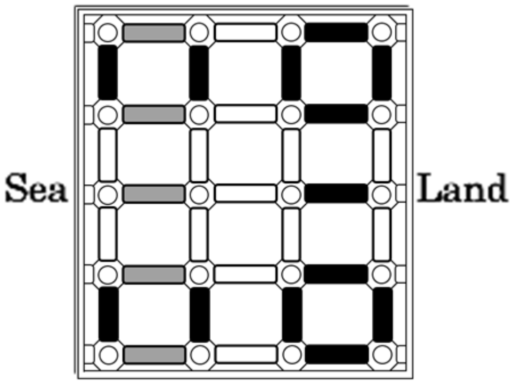


Figure 16 The beams need intensively maintenance (black) and allow simplified maintenance (white)

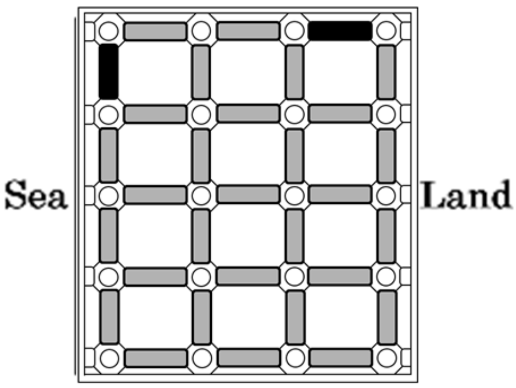


Figure 17 Appropriate position for corrosion monitoring sensor

3.3 Proposal for mitigation of maintenance burden

The corrosion of outside beams of Beam1 and landside beams of Beam2 gives more severe damage to seismic safety of pile-supported structure than the other beams. Therefore the black beams in Figure 16 need to be maintained intensively and the maintenance of the white beams in Figure 16 can be simplified.

For more labor saving, corrosion monitoring sensor is an effective method as mentioned earlier [2]. When considering application of corrosion monitoring sensor, selection of the position of the sensor is important for reasonable monitoring because the sensor system is expensive. It is considered that the black beams (Figure 17) are the appropriate positions for the sensor monitoring, because these beams need to be maintained intensively and face to the sea. The beams facing to the sea are relatively easier to be corroded as shown in [3].

4. Conclusions

In a RC beam, the center and edge of the span should be maintained with high priority.

When considering the whole superstructure, the outside beams of Beam1 and landside beams of Beam2 need to be maintained intensively and the maintenance of inside beams of Beam1 and Beam2 can be simplified.

The appropriate positions for corrosion monitoring sensor were proposed.

5. References

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