Evaluation of the Damage Level of Open-Type Wharf by Earthquake Focusing on the Natural Frequency

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Abstract: This paper discusses the method for the evaluation of the damage level of open-type wharf by earthquake. The proposed method uses the change in the natural frequency of the wharf before and after the earthquake.

1 Introduction

It is necessary to transport disaster recovery materials after the occurrence of a big earthquake disaster. Mooring facility at port plays an important role for transporting disaster recovery materials, however, as mooring facility is constructed on soft ground, there is a high possibility that mooring facility is also damaged by earthquake. Open-type wharf supports the superstructure by piles and major failure mechanism of the wharf is the occurrence of plastic hinges in the piles. Plastic hinges occurred at the pile head may be detected easily just after the earthquake but those occurred in the ground are very hard to be detected.

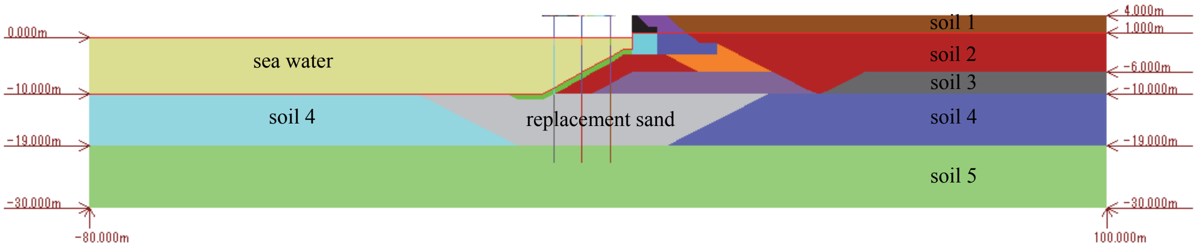
An open-type wharf in the port of Kobe was damaged by the 1995 Kobe earthquake because plastic hinges occurred in the ground but it was unable to detect the damage just after the earthquake [4]. The wharf had been used for passenger transport for few months after the earthquake and close investigation of the damage of the wharf by pulling piles out of the ground revealed the occurrence of plastic hinges in the piles. There was a possibility of the occurrence of the earthquake disaster if a large aftershock occurred.

Therefore, development of the evaluation method of damage level of open-type wharf by earthquake is very important. This study aims at proposing the method by focusing on the change in the natural frequency of the wharf before and after the earthquake. As the natural frequency of the open-type wharf can be estimated by microtremor observation [5], the proposed method is thought to be applicable in practice.

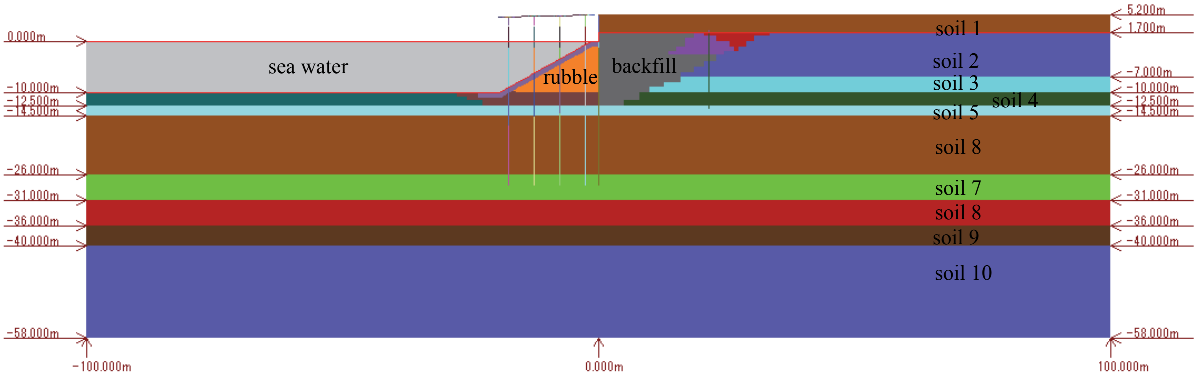
2 Method of Study

2.1 Study Target

Two-dimensional finite element earthquake response analysis was conducted for the evaluation of the damage level of open-type wharves. Based on open-type wharves constructed at K port and N port, models for earthquake response analysis were set as shown in Figure 1.



(i) K port



(ii) N port

Figure 1: Analysis model

*Table 1: Flexural rigidity of piles (unit: MN*m^2)*

(i) K port

	P1			P2			P3		
	pile 1	pile2	pile3	pile 1	pile 2	pile 3	pile 1	pile 2	pile 3
heavy duty coating portion	84.5	84.5	84.5	52.5	52.5	52.5	103.5	103.5	103.5
upper portion	71.1	71.1	71.1	52.5	52.5	52.5	103.5	103.5	103.5
lower portion	83.6	83.6	83.6	52.5	52.5	52.5	103.5	103.5	103.5

(ii) N port

	P1				P2			
	pile 1	pile 2	pile 3	pile 4	pile 1	pile 2	pile 3	pile 4
heavy duty coating portion	101.9	101.9	126.0	149.5	40.1	40.1	40.1	40.1
upper portion	88.7	88.7	112.7	136.3	40.1	40.1	40.1	40.1
lower portion	64.0	64.0	88.7	112.7	40.1	40.1	40.1	40.1

Conditions for pile rigidity are shown in Table 1. Cases P1 are of the original design results. Pile numbers are allocated from the sea side to landside as from pile 1 to pile 3 for K port and pile 4 for N port respectively.

As the damage level of open-type wharf is thought to be strongly influenced by the ground condition, we set three ground conditions for both wharves as shown in Table 2. Ground conditions called as G1 are in-situ conditions for each wharf. Ground conditions G2 are set to be of more soft ground conditions compared with G1 conditions. On the contrary, ground conditions G3 are set to be of more hard ground conditions compared with G1 conditions.

Table 2: Ground condition

(i) K port

			G1	G2	G3
	thickness (m)	density (t/m^3)	internal friction angle (degree)		
soil 1	3.0	1.9	30	30	39
soil 2	7.0	1.9	30	37	30
soil 3	4.0	1.9	30	30	38
soil 4	9.0	1.9	30	30	38
soil 5	11.0	1.9	44	385	39

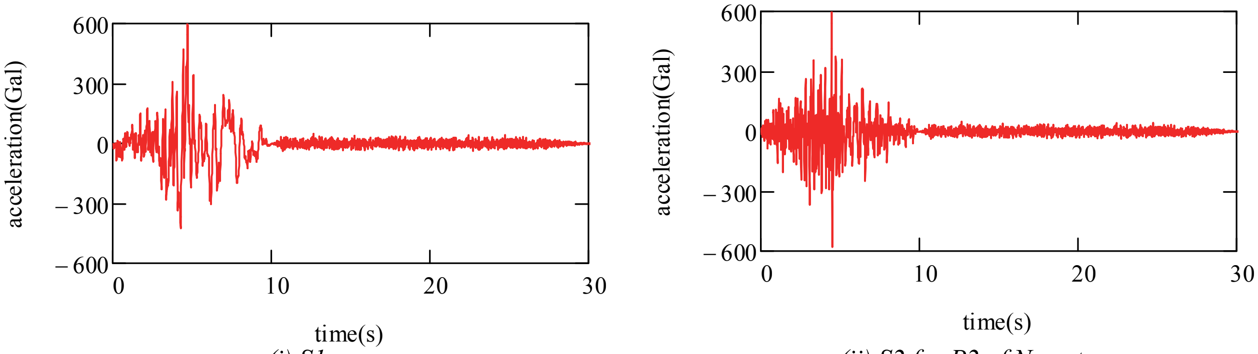
(ii) N port

			G1	G2	G3
	thickness (m)	density (t/m^3)	internal friction angle (degree)		
soil 1	3.0	1.7	38	38	38
soil 2	8.7	1.5	30	30	38
soil 3	3.0	1.7	38	36	39
soil 4	2.5	1.5	30	30	40
soil 5	2.0	1.7	38	38	40
soil 6	11.5	1.5	30	36	39
soil 7	5.0	1.8	40	38	39
soil 8	5.0	1.8	38	38	39
soil 9	4.0	1.7	40	38	39
soil 10	18.0	1.8	38	38	39

Earthquake response analysis code applied in this study is FLIP [2], which is frequently used for the evaluation of the seismic response of the ground [1, 6] and quay walls in Japan because it well reproduces the seismic response of quay walls damaged by earthquake such as those damaged by the 1995 Kobe earthquake. Parameters for analysis models are set according to the standard method established for the code [3]. Piles and superstructures are modeled as nonlinear beam elements.

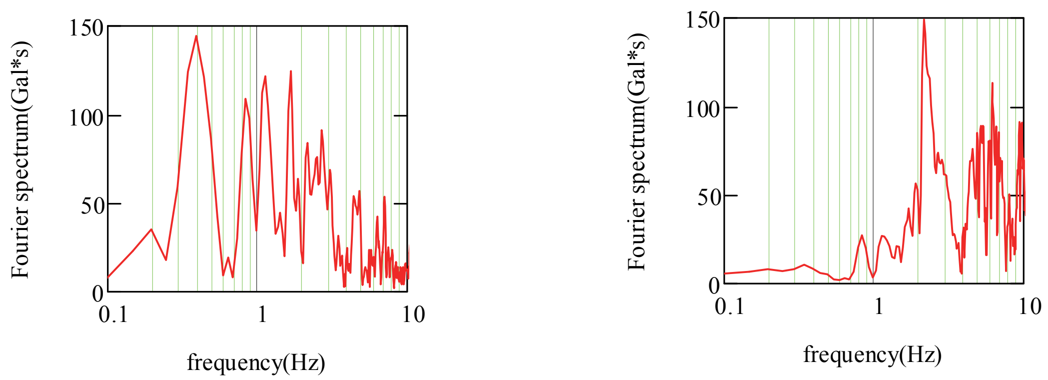
2.2 Input Seismic Motion

Input seismic motions are set based on the seismic motion observed at Hachinohe city during the 1968 Tokachi-oki earthquake. Original seismic motion is defined as seismic motion S1. Seismic motions S2 and S3 have the same predominant frequencies as wharves and revetments respectively. Those seismic waves are obtained by the parallel shift of the Fourier spectrum of S1 on the logarithmic axis. White noise having no predominant frequency is added to each seismic motion as coda wave. Figure 2 and Figure 3 show examples of time history and Fourier spectrum of input seismic motions respectively. Peak ground accelerations are set as 100 to 600 Gal (=m/s^2) with increment 100 Gal.



(i) S1 *(ii) S2 for P2 of N port*

Figure 2: Examples of input seismic motion



(i) S1 *(ii) S2 for P2 of N port*

Figure 3: Examples of Fourier spectrum of input seismic motion

3 Change of the Natural Periods of Wharves According to the Damage in Piles

3.1 Evaluation Method of the Natural Periods of Wharves

Natural period of open-type wharf is often evaluated by using the spring constant and the mass of the wharf. Spring constant is calculated either by the flexural rigidity of piles or load-displacement relationship obtained by the pushover analysis on the frame structure. As those methods cannot evaluate the natural period of the damaged wharf by the earthquake, this study evaluates the natural period of the wharf after the earthquake by using the results of two-dimensional earthquake response analyses. From the spectral ratio of earthquake response of superstructure to virtual fixed point of piles, natural periods of wharves are evaluated. Table 3 shows initial natural periods of the wharf and ground.

Table 3: *Initial natural period (unit : second)*

	wharf		ground	
K port	P1	0.90	G1	1.08
	P2	0.98	G2	1.37
	P3	0.79	G3	0.64
N port	P1	0.31	G1	1.14
	P2	0.44	G2	1.08
			G3	0.82

3.2 Change of the Natural Periods of Wharves

Change of the natural periods of wharves and the ground according to the increase of the peak ground acceleration is shown in Figure 4 for cases P3G1S1 of K port and P2G1S1 of N port as an example. Here, *Ts* is the natural period of the wharf and *Tg* is the natural period of the ground. PGA is the peak ground acceleration of input seismic motion. Natural period of the wharf increases according to the increase of peak ground acceleration due to the increase of section forces generated in piles. In addition, natural period of the ground increases according to the increase of peak ground acceleration due to the nonlinear characteristic of the soil layers.

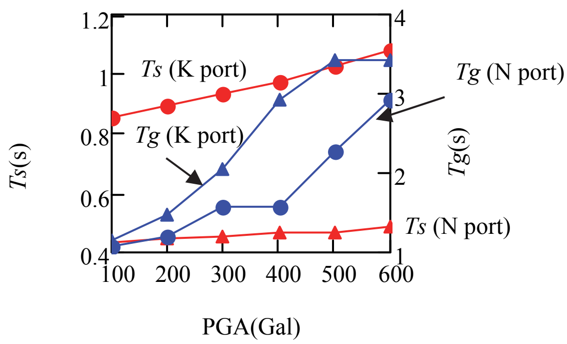
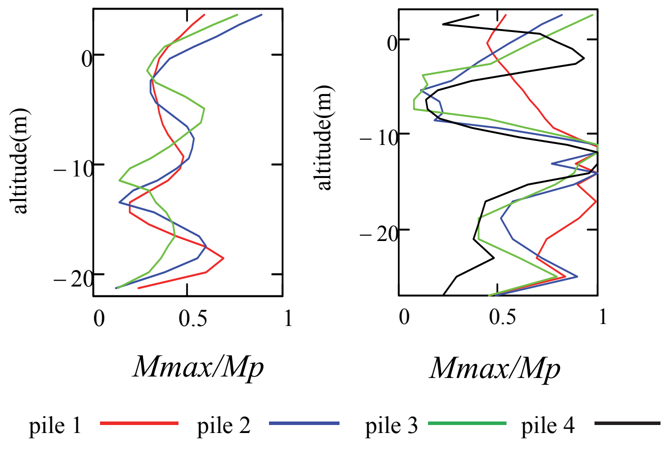


Figure 4: Examples of changes of natural period

Figure 5 shows examples of the distributions of the maximum bending moment ratio for cases P3G1S1 of K port and P2G1S1 of N port with peak ground acceleration 400 Gal. Here, the maximum bending moment ratio is defined as the ratio of the maximum bending moment (*Mmax*) to the plastic bending moment (*Mp*) of piles.

Bending moment becomes large not only at the pile head but also at the points in the ground. This is because the bending moment generated in the piles is strongly affected by the deformation of soil layers. As soil layers consist of many soil layers with different rigidities, deformations of soil layers by the earthquake are not uniform. The difference of the deformation of soil layers becomes large at the boundary of soil layers with strong contrast in rigidity. Therefore, large bending moment is generated in piles at the boundary of soil layers with strong contrast in rigidity.



(i) K port *(ii) N port*

Figure 5: Examples of distribution of maximum bending moment ratio

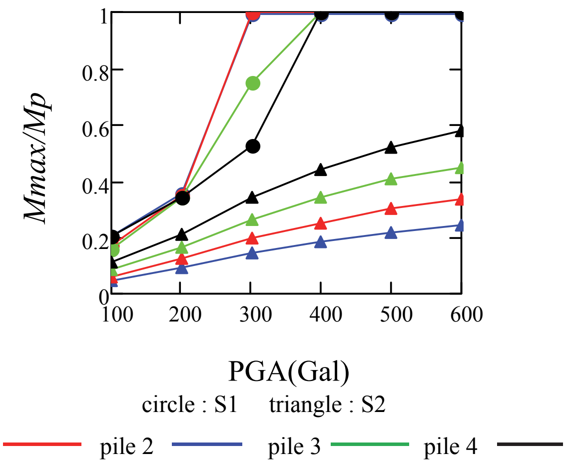
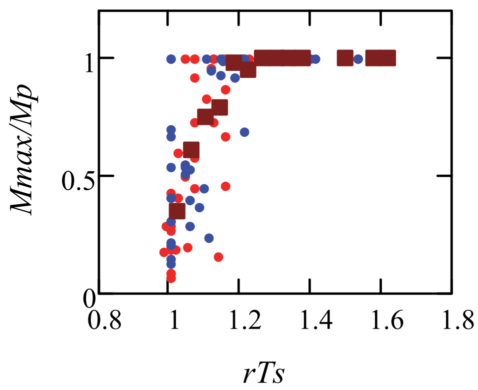


Figure 6: Examples of maximum bending moment ratio

Figure 6 shows examples of the change of the maximum bending moment ratio for cases P2G2S1 and P2G2S2 of N port. Seismic motion S1and S2 has predominant frequency 0.4 Hz and 2.3 Hz respectively as shown in Figure 3. Although seismic wave S2 has predominant frequency that corresponds to the natural frequency of the wharf, maximum bending moments of cases S2 are not so large compared with those of cases S1. Focusing on the residual displacements of the wharf and soil layers, those by S1 waves are larger than those by S2 waves because of the difference in the predominant frequency. Therefore, it is shown that the deformation of soil layers has more influence on the bending moment in piles than the resonance of the wharf. In addition, it is suggested that single degree of freedom system analysis of the rigid frame cannot necessarily evaluate the maximum bending moment generated in piles.

Figure 7 shows the relationship between the natural period ratio and the maximum bending moment ratio. Here, natural period ratio (*rTs*) is defined as the ratio of the natural period of the wharf after the earthquake to that before the earthquake. Natural period of the wharf becomes longer in accordance with the increase in bending moment. It can be pointed out that the natural period of the wharf becomes approximately 1.2 times longer when plastic hinge occurs in the pile.



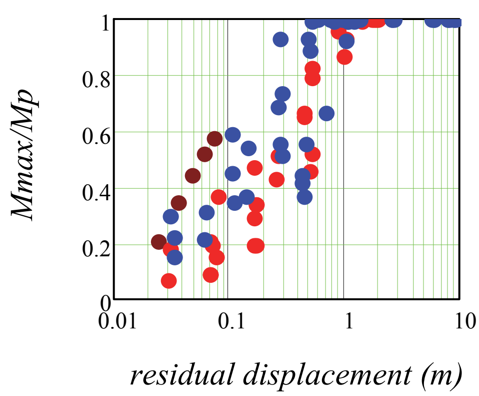
blue : K port   red : N port   brown : mean value

Figure 7: Relationship between natural period ratio and maximum bending moment ratio

4 Relationship between Residual Displacement and Bending Moment Ratio

When a big earthquake occurs, the residual displacement of the wharf is supposed to be investigated by the port management body in order to judge the serviceability of the wharf. Discussion thus far indicates that deformation of soil layers by the earthquake is one of the main cause of the generation of the maximum bending moment in piles. Consequently, it is advantageous if the damage level of the wharf can be estimated by the residual displacement of the wharf with enough accuracy.

Figure 8 shows the relationship between the residual displacement of the wharf and the maximum bending moment ratio. Maximum bending moment ratio increases in accordance with the increase in the residual displacement. The damage level of the wharf may be assumed by using the residual displacement of the wharf for a rough estimate. However, it should be noted that there are some cases that resonance effect has great influence on the generation of the bending moment. The results of the cases P2G2S2 for N port are shown with the brown circles in the figure and the maximum bending moments are larger than other cases with same level of residual displacement. Attention should be paid that estimation of maximum bending moment by using the residual displacement may lead to the judgement on the dangerous side.



blue : K port   red : N port   brown : P2G2S2 for N port

Figure 8: Relationship between residual displacement and maximum bending moment ratio

5 Conclusion

In this paper, estimation method of open-type wharf was studied using finite element earthquake response analysis. Bending moments generated in piles of the wharf is strongly influence by the deformation of soil layers. As the results, it was made clear that the natural period of the wharf becomes approximately 1.2 times longer when plastic hinge occurs in the pile. As the natural frequency of the wharf can be evaluated in field by microtremor measurement, the proposed is thought to be highly applicable in practice.

References

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