A SIMULATION MODEL FOR MAINTENANCE/REHABILITATION OF SHEET-PILE STRUCTURES IN A PORT FACILITY WITH REFERENCE TO SEISMIC RISK

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***ABSTRACT*:** This study presents a methodology for determining the stability of sheet-pile structures in the construction of sea-port system, and thus proposes a priority plan for maintenance and rehabilitation (M&R) of sheet-pile structures. In details, we formulate a mechanical model to evaluate the stability of sheet-pile structures, which are measured by means of ground stability or shrinkage in account of risks associated with seismic forces. Based on the formulation of mechanical model, we develop a hybrid simulation model for determining a set of priority rule in M&R activities. This hybrid model enables managers of sea-port system to minimize the M&R expenditure in their expected management term. The usefulness and practicability of our model are proved through the implementation of an empirical study using monitoring data on sea-port structures in Osaka city.

KEYWORDS: asset management, seismic risk, simulation model.

1. INTRODUCTION

The construction of sea-port facilities in Japan is in a vast numbers as the country is totally surrounded by the sea. In the construction of sea-port facilities, sheet-pile structures are used as one of the most prominent supporting system. If this supporting system in some extends is instable or collapse due to various types of disasters, the negative impact on society could become enormous. In general, the stability of sheet-pile structures is weakened due to the corrosion process. Numerous accident cases have been observed over the past decades in Japan. In a worst scenario of earthquake occurrence, like the devastated earthquake in Kobe in 1996, sheet-pile structures are exposed with high possibility of collapse, resulting in not only destruction of infrastructure facilities but also thousand lost of life. It is therefore important for us to manage the sea-port system in general and sheet-pile structures in particular so as it can assure the stability of sea-port system and safety for the society.

However, management of sea-port facilities faces various types of difficulties. In which, lack of budget is among the most prominent. In view of management, it is desirable to propose a plan of action that takes into consideration of social and

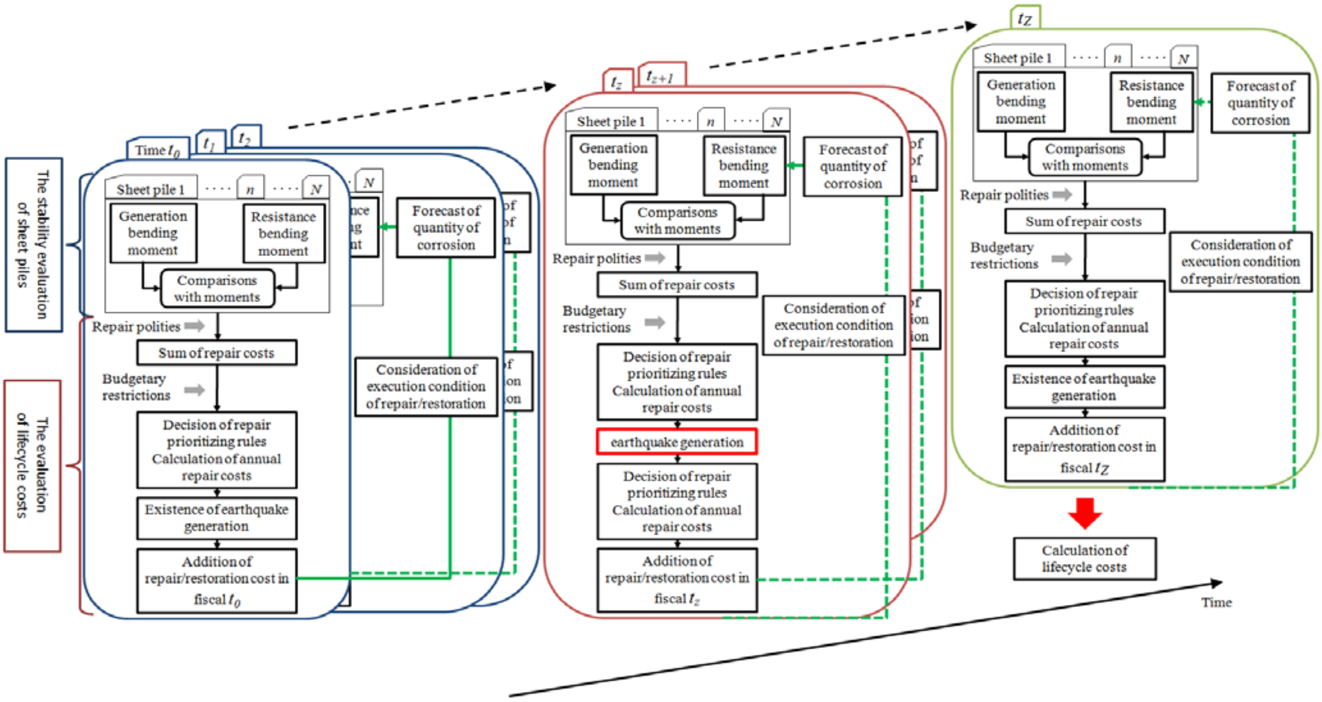

Figure 1 the hybrid model's basic composition

economic risk in case of accident of sheet-pile structures, the maintenance and rehabilitation (M&R) for sheet-pile structures under risky situation and budget limitation. In order to propose this plan, in the first place, it is mandatory to understand the dynamic stability of sheet-pile structures through engineering point of view, and secondly to understand the technique of economic evaluation for engineering structure, with respect to the life cycle of that structure.

In view of the above-mentioned problems, in this study, we develop a mechanical model to evaluate the stability of sheet-pile structures based on measurement of ground stability. The seismic force resulting from earthquakes is also considered in our model as an important risk factor. The hybrid model is discussed in section 3 of this paper, in which, we present in details of mathematical formulation. The methodology for prioritization of M&R activities based on life cycle cost evaluation is also discussed in this section. Empirical study section details the simulation of model on a set of monitoring data provided by Osaka port management bureau. Finally, we conclude some important findings and recommendation for further research investigation in the last section.

2. BACKGROUND

2.1 Characteristics of sheet-pile structures.

With regard to life cycle cost evaluation of sheet-pile structure, it is suffice to say that, in the event of disaster like hurricanes, storms, earthquakes, tsunamis, etc, the cost to heal and recover primarily damages (immediate impacts on human and social-economic activities) and secondary damages (aftermath impacts on socio-economic activities) are in a large scale, with no significant comparison to the direct cost for M&R, or renewal the wounded sheet-piles.

The management of sheet-pile structures need not only care for overall performance of entire sheet-pile structures but also need to specifically care for the performance of individual sheet-pile, or at least a group of sheet-piles. This is because the risk of destruction due to seismic forces and the risk in

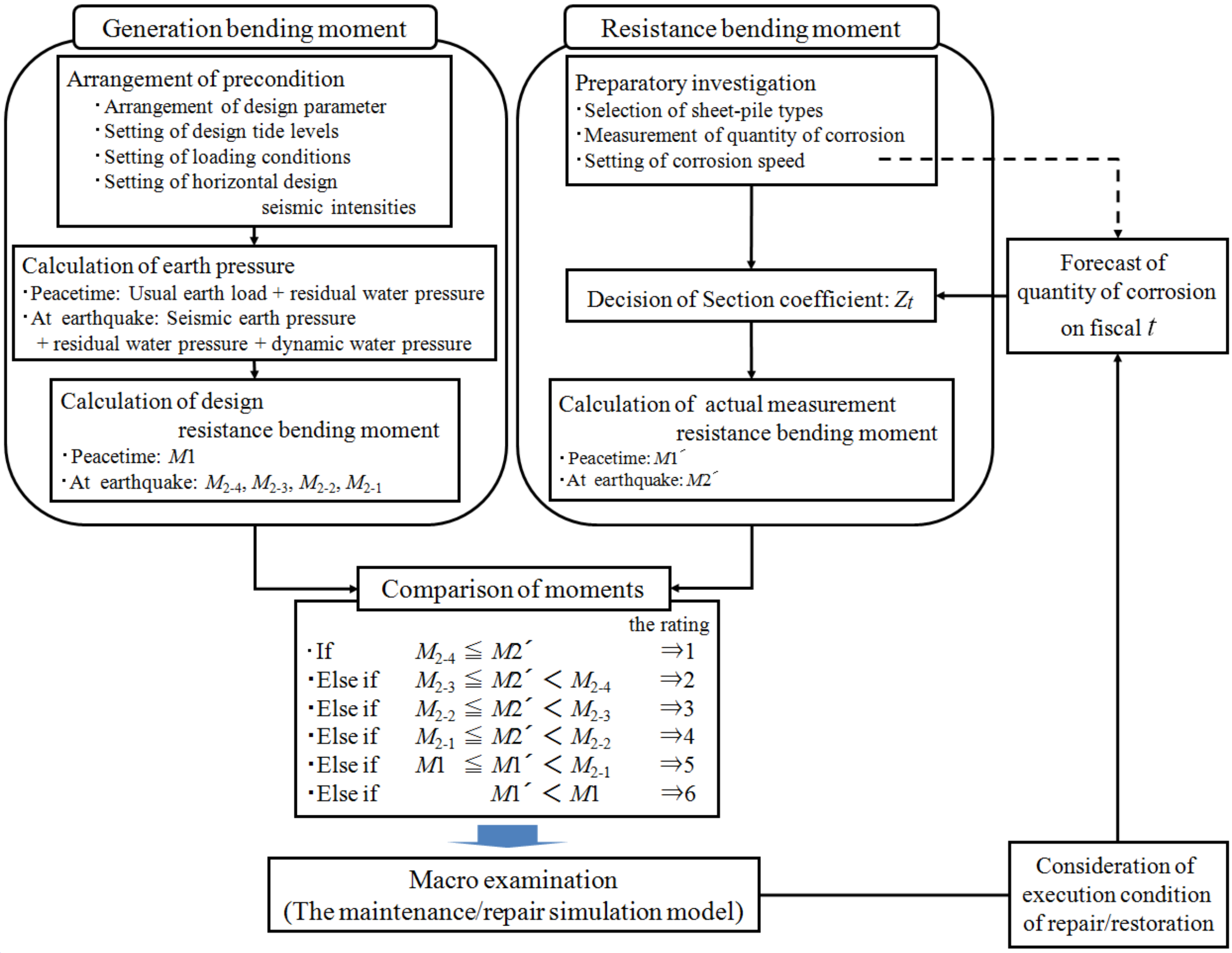

Figure 2 the ground stability evaluation process of sheet piles

socio-economic loss vary differently location by location. This dynamic process has not been successfully discussed in the past studies with use of statistical modeling approach. Thus, in this study, we propose a new approach, in which, we consider the importance of both microscopic and macroscopic evaluations of risk. Microscopic evaluation focuses on potential and economic lost due to the risk of damage of individual sheet-pile. For this purpose, we apply the mechanical model to evaluate the ground stability. Macroscopic evaluation focuses on a group of sheet-piles and determines the life cycle cost under budget constraints for prioritizing the M&R activities.

2.2 Seismic risk.

Poisson arrival model of the seismic ground motion expresses "occurrence risk of the earthquake that when happening is not understood". Poisson arrival model targets phenomena without a past memory, and the arrival rate of the earthquake is fixed through time. According to Poisson arrival process, in case of seismic risk, there is no difference in the decision of the repair timing of sheet piles~~,~~ and the calculation of expected life cycle costs. However, in case where seismic risk and the dynamic performance are considered, specifying the optimal M&R timing and evaluating its life cycle cost have not been specifically discussed in the past research. Thus, this study is partially developed with respect to overcome this remaining limitation.

2.3 Components of the hybrid model.

The model proposed in this study is the hybrid model, in which, the mechanical evaluation of the ground stability and individual sheet piles (the

Table 1 the definition of generation bending moment

The generation bending moment	The design horizontal seismic intensity	The amusing earthquake
M_{2-4}	$k_h=0.25$	Epicentral earthquake level
M_{2-3}	$k_h=0.2$	Tonankai and Nankai earthquake level
M_{2-2}	$k_h=0.15$	—
M_{2-1}	$k_h=0.1$	—
$M1$	$k_h=0.0$	In peacetime

stability evaluation model of sheet piles)— are integrated with the M&R simulation model. In M&R simulation model, we consider seismic risk and budgetary restrictions for all sheet-pile groups (the M&R simulation model). The hybrid model's basic composition is shown in figure 1.The purpose of the stability evaluation model of sheet piles is to examine micro repair strategy for individual sheet piles, and the purpose of the M&R simulation model is to examine macro repair strategy that examines repair strategy for all sheet-pile groups and budgetary restrictions. The purpose of the hybrid model is to evaluate the dynamic stability of sheet piles while considering seismic risk of each annual from the present time. In addition, it aims to analyze the M&R strategy of sheet-pile groups that minimizes expected life cycle costs through the entire management term.

3. THE STABILITY EVALUATION MODEL OF SHEET-PILE STRUCTURES.

3.1 The stability evaluation of sheet piles

The ground stability evaluation process of sheet- pile structures is shown in Figure 2. As shown in this figure, the ground stability of sheet-piles is evaluated by comparing the generation bending moment at the earthquake (expected value in design) and with the resistance bending moment estimated from the measured quantity of corrosion (the actual measurement value). Among these, the generation bending moment is calculated based on the active earth pressure, the residual water pressure, and the dynamic water pressure calculated from the pre-conditions. On the other hand, the resistance bending moment is calculated based on the actual measurement value of the quantity of corrosion. Liquefaction risk of ground at the earthquake is not considerable large in the study region. Therefore, in this study, we narrow the focus to corrosion management problems of the sheet-pile groups. In addition, the ground liquefaction accompanying with and earthquake is not considered.

3.2 The rating evaluation and the repair method selection.

The rating of sheet-pile structures is evaluated based on the M&R manual of port facilities. There is a problem that the number of check parts becomes huge though it is also possible to evaluate the rating of each individual sheet piles. Therefore, it is realistic to make plural sheet-pile groups while considering structural forms and deterioration situations, etc. based on the check investigation data in the past, and to recognize each group as the rating evaluation basis unit. In the rating evaluation, the number of the evaluation ranks and the standard of each rank are established based on the relation of the seismic intensity and the resistance bending moment generated in sheet piles.

The rating is divided into six ranks. About the setting of the rating, the rating 1 is the highest health, and has the strength that can endure the seismic intensity assumed the epicenter earthquake level ($0.25<k_h$). After this, the strength of the rating 2 can endure the seismic intensity assumed Tonankai and Nankai earthquake level ($0.2<k_h\leq 0.25$), the strength of the

rating 3 can endure the seismic intensity of $0.15 < k_h \leq 0.2$, the strength of the rating 4 can endure the seismic intensity of $0.1 < k_h \leq 0.15$, the strength of the rating 5 can endure the seismic intensity of $0.0 < k_h \leq 0.1$, and the strength of the rating 6 is insufficient at peacetime. The rating is evaluated based on the resistance bending moment. First of all, the generation bending moment at $k_h = 0.25$ is calculated, and the value is defined as M_{2-4}. In addition, M_{2-4} is compared with the actual measurement resistance bending moment $M2'$ at the earthquake, and if it is $M_{2-4} \leq M2'$, the rating of this sheet pile is set as 1. On the other hand, if $M_{2-3} \leq M2'$ is formed against the generation bending moment M_{2-3} calculated by using $k_h = 0.2$, the rating becomes 2. In the same way, if $M_{2-2} \leq M2'$ and $M_{2-1} \leq M2'$ are formed against the generation bending moment M_{2-2} and M_{2-1} at $k_h = 0.15$ and $k_h = 0.1$, the ratings are set as 3 and 4 respectively. In addition, the generation bending moment $M1$ at $k_h = 0.0$ is assumed when the seismic force doesn't act is compared with the actual measurement resistance bending moment $M1'$ in peacetime, and if $M1' < M1 \leq M_{2-1}$ and $M1 \leq M1'$ are formed, the ratings become 5 and 6 respectively. As mentioned above set, the relation between the generation bending moment and the design horizontal seismic intensity is arranged in Table 1.

4. THE HYBRID MODEL'S FORMULATION

4.1 The precondition of modeling.

In the case managers of sea-port facilities expect to care for a group of sheet-piles. The entire sheet-pile groups are composed of N pieces (the elementary unit). M&R works that execute the repair of sheet piles according to the budgetary restriction and prioritizing rules that are at the discrete time provided on the axis of the calendar time at equal intervals, are assumed. Hereafter, the calendar time is called "Time". In addition, the axis of the discrete time to make the initial time t_0 a starting point is introduced.

$$t_z = t_0 + zu \,(z = 0,1,\cdots) \tag{1}$$

It is assumed that sheet piles where states are worse than the rating $\bar{k}$ set beforehand break when the earthquake of the given scale occurs. The rating of sheet pile n at time t_z is expressed by using the state variable to show the discrete rating of K piece as

$$\zeta_n(t_z) = k \quad (k = 1,\cdots,K) \tag{2}$$

Repair method to recover the rating of sheet piles where deteriorations progress is selected. The rule that decides the repair industrial method according to the rating is called "the repair action". The repair action vector $\boldsymbol{\eta}^d$ of sheet pile n is shown as

$$\boldsymbol{\eta}^d = (\eta^d(1),\cdots,\eta^d(K)) \tag{3}$$

The repair policy $d \in D$ shows a series of rule that specifies the repair action executed at the time for each rating. Moreover, D shows sets of repair policies that can be applied. The repair action $\eta^d(k) \in \{1,\cdots,k\}$ that composes the repair policy d means the repair is executed to the rating k, and the rating changes to $\eta^d(k)$. If the cost to recover the rating of sheet pile n from k to j $(1 \leq j \leq k)$ is c_n^{kj}, then $c_n^d(k) = c_n^{kj}$ is approved at $\eta^d(k) = j$. At this time, the content of the repair policy $d \in D$ of sheet pile n is described by pairs $(\eta^d(k), c_n^d(k))$ $(k = 1,\cdots,K)$ of the repair action $\eta^d(k)$ and repair cost $c_n^d(k)$ that are selected to each rating k.

4.2 Decision of repair prioritizing.

The rating of sheet pile $n(n = 1,\cdots,N)$ at time t_z is defined as $\zeta_n(t_z) = k$. The change in the rating of sheet pile n can be described as follows by the application of repair actions that compose the repair policy $d \in D$.

$$q_{n,kj}^d(t_z) = \begin{cases} 1 & when\ \eta^d(k) = j, k \neq j \\ 0 & otherwise \end{cases} \tag{4}$$

$(j,k = 1,\cdots K)$

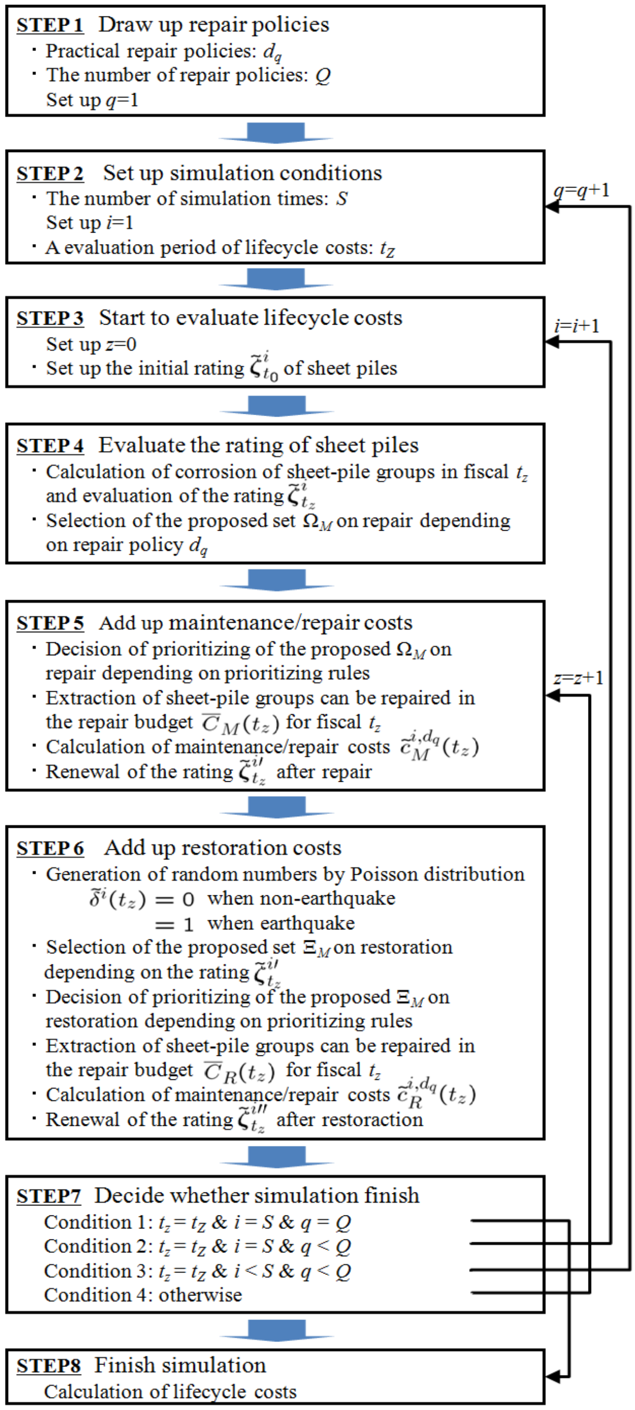

Figure 3 the process of calculation

In addition, sheet-pile set Ω_M (it is called the proposed set on repair) for repairing is defined as

$$\Omega_M = \{n \mid \eta^d(\varsigma_n(t_z)) \neq \varsigma_n(t_z); n = 1, \cdots, N\} \quad (5)$$

At this time, the number of sheet piles where the repair is needed is as follows among sheet-pile groups of total N.

$$Q(t_z) = \sum_{n=1}^{N} \sum_{j=1}^{K-1} q^d_{n,\varsigma_n(t_z)j}(t_z) \quad (6)$$

The number is set based on the prioritizing rules set beforehand against these proposed set Ω_M on repair. In addition, the budgetary restriction at time t_z is assumed $\overline{C}_M(t_z)$, repair costs are piled up from sheet piles where the prioritizing is high and the proposed set Ω_M on repair to the range where the budgetary restriction is not exceeded is actually repaired. The above is M&R works to sheet-pile groups in peacetime, and the prioritizing is similarly decided since the next fiscal year as long as the seismic ground motion is not generated, and the M&R works will be executed.

In the next step, attention is on restoration works after the earthquake occurs. It is understood that the earthquake occurs after completing the frequent M&R work in a fiscal year. In this simulation, it is assumed that the earthquake occurs according to a certain probability. When the earthquake occurs, sheet piles with states worse than the rating $\bar{k}$ are destroyed. At this time, the total of destroyed sheet piles can be defined as

$$R(t_z) = \sum_{n=1}^{N} I_{\zeta_n(t_z) \geq \bar{k}} \quad (7)$$

However, $I_{\zeta_n(t_z) \geq \bar{k}}$ means the following.

$$I_{\zeta_n(t_z) \geq \bar{k}} = \begin{cases} 1 & \text{when } \zeta_n(t_z) \geq \bar{k} \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

Moreover, the proposed set Ξ_M on restoration is defined as

$$\Xi_M = \{n \mid I_{\zeta_n(t_z) \geq \bar{k}} = 1; n = 1, \cdots, N\} \quad (9)$$

In addition, the number is set based on the prioritizing rules set beforehand against these proposed set Ξ_M on restoration. The budgetary restriction of restoration at time t_z is assumed $\overline{C}_R(t_z)$, restoration costs are piled up from sheet piles where the prioritizing is high and the proposed set Ξ_M on restoration to the range where the budgetary restriction is not exceeded is actually restored. In this study, it is thought that restoration costs of sheet piles destroyed due to the earthquake are not the range of the usual M&R budget, and are separately procured as the restoration budget.

4.3 Repair simulation that considers seismic risk

In this study, the arrival rate of the earthquake is calculated from the record of past earthquake occurrences. The earthquake occurrence sample passes in the future are expressed by random number generations from Poisson distribution based on the arrival rate. It is assumed that the present ratings of sheet-pile groups are calculated now. The M&R simulation of sheet-pile groups that considers seismic risk is assumed. If the repair policy is assumed to be given, the repair costs and restoration costs along the time axis against one earthquake occurrence sample pass that generated by Monte Carlo simulation is obtained. Such costs are regarded as the pass life cycle cost pass. The M&R process in the future is a set of innumerable pass life cycle cost, and the repair policy for minimizing expected life cycle costs when seismic risk is considered by calculating sets of passes is decided. The calculation process is arranged to Figure 3 in the form of the flow chart.

The life cycle cost passes of total S piece concerning M&R process of making at the time of now at the time of initial can be acquired to each the repair policy d_q $(q=1,\cdots,Q)$ by the M&R simulation. The content of the life cycle cost passes can be represented by the next expression.

$$\tilde{\xi}^{i,d_q} = (\tilde{\xi}^{i,d_q}_{t_0},\cdots,\tilde{\xi}^{i,d_q}_{t_Z}) \tag{10a}$$

$$\tilde{\xi}^{i,d_q}_{t_z} = (\tilde{\delta}^{i}(t_z),\tilde{c}^{i,d_q}_{M}(t_z),\tilde{c}^{i,d_q}_{R}(t_z)) \tag{10b}$$

In addition, the life cycle cost pass $\tilde{C}^{i,d_q}$ and expected life cycle cost LCC^{d_q} to the sheet-pile repair policy d_q on the sample pass i are calculated based on this information.

$$\tilde{C}^{i,d_q} = \sum_{z=0}^{Z}\frac{\tilde{c}^{i,d_q}_{M}(t_z)+\tilde{\delta}^{i}(t_z)\tilde{c}^{i,d_q}_{R}(t_z)}{(1+\rho)^{t_z}} \tag{11a}$$

$$LCC^{d_q} = \frac{1}{S}\sum_{i=1}^{S}\tilde{C}^{i,d_q} \tag{11b}$$

The life cycle cost minimization model to minimize expected life cycle costs of sheet-pile groups finally can be formulated, and the best repair policy d^* of considering seismic risk of sheet-pile groups is obtained.

$$LCC^{d^*} = \min_{d_q\in D}\left\{\sum_{i=1}^{S}\sum_{z=0}^{Z}\frac{\tilde{c}^{i,d_q}_{M}(t_z)+\tilde{\delta}^{i}(t_z)\tilde{c}^{i,d_q}_{R}(t_z)}{(1+\rho)^{t_z}}\right\} \tag{12}$$

In addition, when seismic risk does not exist, the life cycle cost minimization model can be formulated as follows:

$$\overline{LCC}^{d^\circ} = \min_{d_q\in D}\left\{\sum_{i=1}^{S}\sum_{z=0}^{Z}\frac{\tilde{c}^{i,d_q}_{M}(t_z)}{(1+\rho)^{t_z}}\right\} \tag{13}$$

Where the symbol "$\overline{\quad}$" is used for noting that it is the expected life cycle cost when seismic risk is not considered, and the best repair policy when seismic risk does not exist is shown d°.

5. EMPIRICAL STUDY

5.1 Outline of application experience

The model proposed in this study is empirically tested using monitoring data of sheet-pile structures collected by Osaka City Ports and Harbors Bureau. The extension of this structure is approximately 26.6 km. The structures constructed in around 1970 are not considered in our study. We assume a scenario of large-scale earthquake occurrence. Thus, we come up with a list of primary and secondary damages due

Table 2 date and interval of Nankai earthquake generation

Date	Interval
29/11/684	—
26/8/887	202.7
22/2/1099	211.5
3/8/1361	262.4
9/7/1498	136.9
3/2/1605	106.6
28/10/1707	102.7
24/12/1854	147.2
21/12/1946	92.0
Average interval	157.8

to this event. In addition, decisions concerning both short-term and long-term management plan are also considered.

The numbers of sheet piles are categorized into 116 groups, with their specification on corrosion rating, ground condition behind the sheet piles, land use condition, and the important rank of individual sheet pile. There is a fact that monitoring data of deterioration process on sheet piles are in few numbers.. In many cases, only the data concerning the thickness of sheet piles at first and at the time of the check can be used, and the corrosion rating of sheet piles can do nothing but be calculated by a linear interpolation for at the time of two based on these data. In this study, it is assumed the corrosion speed v_n(mm/year) of sheet piles is constant (the determinate value) from the above-mentioned situation through time though it is different in each sheet pile. Moreover, the generation history of the large-scale earthquakes in the object region is shown in table 2. The occurrence of the earthquake and the tsunami forecast that it is a high incidence is feared. In the same place region, the occurrence of plate type earthquake of Nankai Trough earthquake (Nankai earthquake) and the ~~epicentral~~epicenter earthquake caused by Uemachi fault etc. forecast that the incidence will be high in the near future is feared. In this research case, it is thought that the occurrence of the large-scale earthquake obeys Poisson process where the one occurs at rate once 157.8 year in the consideration of the earthquake occurrence year and the generation interval. In addition, it is thought that the examination period is set to 100 years, sheet piles of the rating 3 or more is assumed to be destroyed by the earthquake generation, and all destroyed sheet piles are restored in fiscal year at the time of which it was struck.

5.2 The hybrid model.

The electric anti-corrosion method, the RC coating method, and the sheet-pile exchanging method are adopted as repair measures methods of sheet piles. The effect, the application rating, and the repair unit price of each method are described in Table 3. The electric anti-corrosion method is a preventive repair method among these, and only sheet piles of the rating 1 or 2 become objects. About the electric anti-corrosion method, the service life of the effect of the electrolytic protection is set to 20 years and it is assumed that the corrosion rating is made a delay for the period.

On the other hand, both the RC coating method and sheet-pile exchanging method are the repair methods. They are adopted when the rating becomes 3 or more. About the RC coating method, the service life of RC is set to 50 years, it is assumed that the corrosion does not progress for a while in the period. In brief, by executing this method, the rating is maintained during the period of the RC coating service life. However, when the rating is maintained is time when the earthquake does not occur, and it is assumed that all sheet-pile structures of the rating 3 or more collapse by the occurrence of

Table 3 the relation of the rating and the repair/restoration methods

Measures methods	Methods	Effect	Applied rating	Repair unit price
Electric anti-corrosion method	1	Making of corrosion speed delay	1,2	36.5505
RC coating method	2	Making of corrosion speed control	3,4,5,6	61.5720
Sheet-pile exchanging method	3	Improvement of quantity of corrosion Making of corrosion speed control	3,4,5,6	300.0000
Restoration method	4	Improvement of quantity of corrosion Making of corrosion speed control	6 (3~6)*	3000.0000

*: When the earthquake, the restoration exchanging method is applied to rating 3 or more.

Table 4 the repair policies

Policy's number	Rating 1	Rating 2	Rating 3	Rating 4	Rating 5	Rating 6
1	1	1	3	3	3	4
2	—	1	3	3	3	4
3	—	—	3	3	3	4
4	—	—	—	3	3	4
5	—	—	—	—	3	4
6	1	1	2	2	2	4
7	—	1	2	2	2	4
8	—	—	2	2	2	4
9	—	—	—	2	2	4
10	—	—	—	—	2	4
11	—	—	—	—	—	4

the earthquake.

The service life of new sheet pile is set to 50 years about sheet-pile exchanging method. The anti-corrosion method is given to new sheet pile, and it is thought that corrosion doesn't progress for the period of the service life. It is thought that the rating recovers to 1, and the rating 1 is maintained for the period of the service life by executing this method. However when the deterioration of sheet piles reaches the rating 6, the sheet-pile exchanging construction work is executed at once regardless of the budgetary restriction. It is thought that sheet-pile structures of the rating 3 or more collapse if the large-scale earthquake occurs. In this case, it is necessary to consider not only the restoration cost of sheet-pile structures but also the restoration cost of facilities located in the hinterland in restoration costs. However, the restoration cost when sheet piles collapse is uniformly set to 30 million yen per sheet-pile 1m in this study because there is a restriction in the data use.

It is possible to think about repair policies shown in table 4 by combining these sheet-pile repair methods. However, the number in the table is method's number shown in Table 3. Under budgetary restrictions, sheet-pile repair spots of every year are

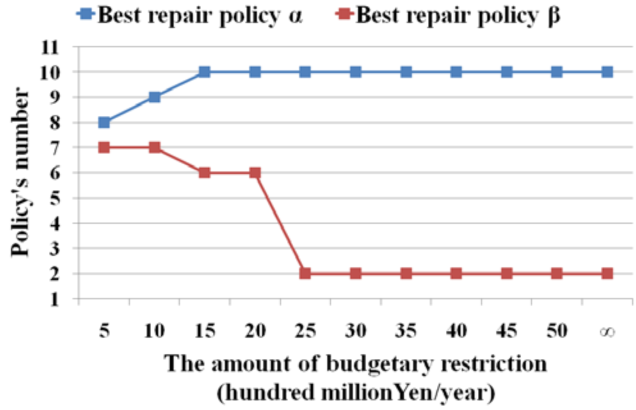

Figure 4: best repair policy α, β

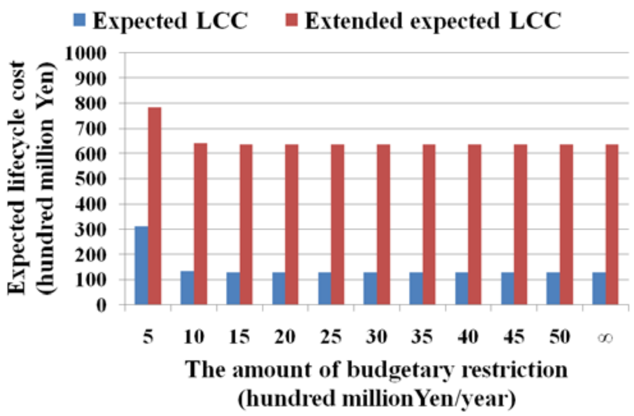

Figure 5: expected LCC on best repair policy α

selected in order of 1) facilities where importance rank is high and 2) facilities where safety rate (resistance bending moment/generation bending moment in object fiscal year) at the earthquake is low against facilities of the same importance, from among sheet-pile set extracted as repair targets. Moreover, because sheet piles that collapse in the struck fiscal year are assumed that everything is restored, the restoration prioritizing is not installed.

~~5.2~~5.3 Consideration of analysis result

On evaluating expected life cycle costs, two kinds of the best repair policies such as 1) the best repair policy α when seismic risk is not considered and 2) the best repair policy β when seismic risk is considered are defined to analyze the meaning of the consideration of seismic risk. In addition, two kinds of evaluation indexes such as 1) the discounted present value of expected life cycle costs when only M&R costs are summed up (expected LCC) and 2)

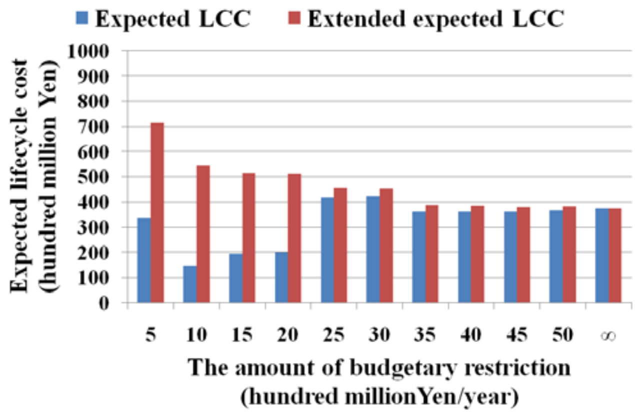

Figure 6: expected LCC on best repair policy β

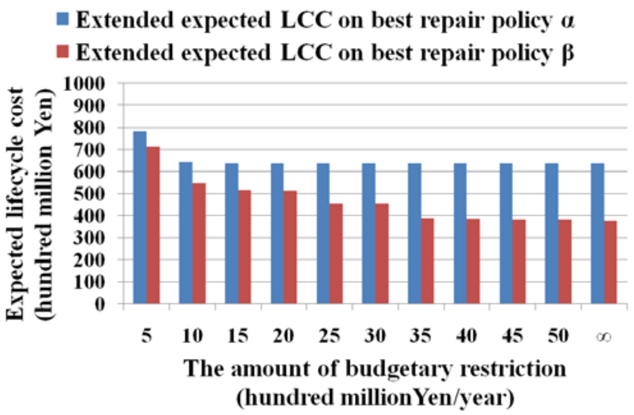

Figure 7: extended expected LCC

the discounted present value of expected life cycle costs when both of M&R costs and restoration costs by seismic hazard are considered (extended expected LCC) are defined. In any case, 4% adopted by the cost effectiveness analysis on public works as a discount rate is used. Figure 4 shows the best repair policy α and β under restrictions concerning the amount of the budget upper bound (between 500 million yen/year and 5 billion yen/year). When there is enough amount of the budget upper bound, the repair policy 10 is selected as the best repair policy α and the repair policy 2 is selected as β. That is, the repair policy after the fact (the repair policy 10) of exchanging sheet piles where the deterioration progresses, is selected under the principle of expected LCC minimization. It can be understood that the preventive repair policy (the repair policy 2) of using the electric anti-corrosion method and the sheet-pile exchanging method is preferable to achieve extended expected LCC minimization that

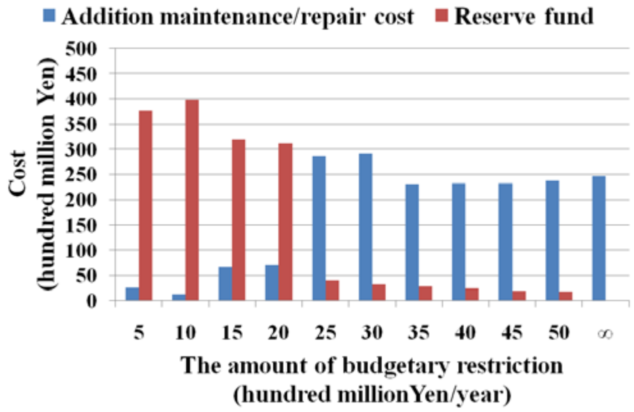

Figure 8: additional M&R cost and reserve fund

considers disaster risk. However, when the amount of the budget upper bound is small, the repair policy 6 or 7 of using the RC coating method rather than the sheet-pile exchanging method, is selected.

Figure 5 shows results of calculating expected LCC and extended expected LCC under budgetary restrictions on the best repair policy α. Extended expected LCC including restoration costs indicates a large value though expected LCC that doesn't consider restoration costs is restrained to low and the difference between expected LCC and extended expected LCC is large results. From this, when expected LCC is evaluated without considering disaster risk, it can be understood that damage costs due to the disaster is beyond restraint enough. Next, Figure 6 shows results of calculating expected LCC and extended expected LCC under budgetary restrictions on the best repair policy β. Expected LCC doesn't monotonously change into the change in budgetary amount for this case. Extended expected LCC minimization doesn't necessarily bring expected LCC minimization. Moreover, the difference between expected LCC and extended expected LCC is small when budgetary amount is large. Specially, when budgetary restriction doesn't exist, expected LCC and extended expected LCC are corresponding. It becomes possible to control struck risk due to the large-scale earthquake because the repair policy β is selected as a preventive repair policy that minimizes extended expected LCC when budgetary amount is large as shown in Figure 4.

Figure 7 shows results of calculating extended expected LCC under budgetary restrictions on the best repair policy α and β. Naturally, it is always results in which extended expected LCC is small to adopt the best repair policy β. The difference of extended expected LCC when the best repair policy α and β are adopted is growing by increase of budgetary amount.

~~5.3~~5.4 Suggestion in practical use

In this study, the life cycle cost evaluation of the asset management measures for port facilities was done based on expected life cycle costs when seismic risk was considered. To date, M&R policies to deterioration risk of structures and investments for quake-resistance in seismic risk have been independently examined in the asset management in a lot of civil engineering facilities. The case where the asset management policy to these risks is examined in the overall analytical framework of evaluation of extended expected life cycle costs.

In this study, though the application is limited civil engineering facilities of sheet-pile structures, being not able to reduce struck risk by the occurrence of the large-scale earthquake when the life cycle cost evaluation was done without considering seismic risk became clear. Specially, extended expected life cycle costs including restoration costs reach about five times expected life cycle costs when only M&R costs was considered, when the best repair policy α that does not consider seismic risk was adopted as shown in Figure 5. The importance of evaluation of expected life cycle costs when seismic risk is considered can be understood.

The disaster recovery reserve fund system is available at present in the management bureau. The analysis result of Figure 5 suggests that reserving the difference between extended expected life cycle costs and expected life cycle costs as the reserve fund (it makes to the discounted present value and evaluate it) be necessary when the policy after the fact(the best repair policy α) is adopted as a M&R policy . However, there is little separation of extended expected life cycle costs and expected life cycle costs to the annual budget enough when the best repair policy β that minimizes extended expected life cycle costs is applied as showing in Figure 6. In other words, when the preventive repair policy is applied systematically, the disaster recovery reserve fund need not be drawn. For example, when there is no budgetary restriction, it is necessary to reserve the reserve fund of about 50 billion yen as the discounted present value when the best repair policy α is adopted as shown in Figure 5.

It is clear in Figure 5 and Figure 6 that the result of expected LCC increasing more than the case to adopt the best repair policy α by adopting the best repair policy β. Figure 8 shows the result of comparing needed the reserve fund by using the best repair policy α and increasing expected LCC (M&R costs) by using the best repair policy β. As shown in this figure, if the amount of the budget upper bound is secured enough, the amount of the saved reserve fund by adopting the best repair policy β is larger than that of increasing M&R costs by executing the preventive repair. It can be understood that it is effective to evaluate extended expected life cycle costs with considering seismic risk, and to execute the preventive repair of sheet-pile groups.

6. CONCLUSION

This paper has presented a new methodology, with proposing a hybrid model to determine the priority plan for M&R activities under the limitation of budget. In the model, we apply Poisson process for generating random seismic risk events. Based on this method, we integrate the results into hybrid model to estimate the outcome. Empirical study was carried out on monitoring data of sheet pile structures in Osaka city. Outcome of empirical study is highlighted in section 5.4. However, the study need to further consider following recommendations for future extension.

Firstly, epicenter seismic risk according to Poisson arrival is targeted in this model. However, the plate type earthquake to which the generation is feared in recent years is known according to the arrival process of non-Poisson type into which the probability of occurrence changes with the time passage. It is necessary to consider a hybrid model which can analyze the repair strategy that considers such non-Poisson type seismic risk.

Secondly, the deterioration process of sheet-pile structures was formulated by using the determinate deterioration forecasting model. Estimating a statistical deterioration forecasting model concerning the deterioration process of sheet-pile structures if data concerning the state of deterioration of them is accumulated becomes possible. It is necessary to develop a hybrid model which uses such a statistical deterioration forecasting model.

Thirdly, the generation of the fluidizing phenomenon at the earthquake is not considered in this study. It is not possible to deal with the fluidizing phenomenon by only the M&R policy of sheet-pile structures. The fluidizing phenomenon exceeds the region in this study, and future investigation of this matter should be addressed.

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