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Study on Seismic Retrofit Planning Method for Sewage Treatment Plants on the Basis of Seismic Risk Management

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STUDY ON SEISMIC RETROFIT PLANNING METHOD FOR SEWAGE TREATMENT PLANTS ON THE BASIS OF SEISMIC RISK MANAGEMENT

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ABSTRACT

Japanese sewerage has more than 100 years of history, and many facilities have passed their durable years. For the sake of economy, life lengthening of the equipment and facilities is required. Rational life extension of the equipment and facilities calls for aseismic reinforcement of structures with damage risks considered. Based on this, the author *et al.* suggested a method that will help planning rational aseismic reinforcement for sewage treatment plants. This method quantitatively evaluates the relationship between the earthquake risk and aseismic reinforcement cost by introducing the concept of risk management. In this study, availability of this method also has been verified with exemplification.

INTRODUCTION

In Japan, sewerage facilities were heavily damaged by the Hyogoken-Nanbu Earthquake, which hit in 1995. Severe damage to facilities in Kobe City, where the sewerage diffusion rate was more than 90%, made us realize the importance of sewerage as one of the infrastructures and consider its influence on the environment.

The Japan Society of Civil Engineers presented two proposals on the ideal earthquake-resistant design for infrastructures. According to the second proposal (The Japan Society of Civil Engineers, 1996), input earthquake motion (Level II earthquake motion) is determined based on identification of active faults that threaten an area and assumptions of source mechanism. However, it also states that considerable effort must be put into establishing engineering methods. Introducing the earthquake risk management concept, not being overconfident in earthquake-resistant design, taking into account that, no matter how good the earthquake-resistant design, we must recognize the fact that we will never be able to make absolutely safe structures as prerequisites, it states that the important thing for planning effective measures and enhancing the necessity of the project from the viewpoint of risk management is to have organizations and governments who continuously consider disaster alleviation measures based on the function analysis of a stricken infrastructure system. Risk evaluation takes the damage risk made by an earthquake as a prerequisite thereby defining the impossibility of constructing absolutely safe structures. This has been the reason that it was not obviously evaluated in actual practices, such as designing, planning, construction, and maintenance of infrastructure facilities. For establishment of the risk evaluation of sewerage facilities, they need to be evaluated

with: ① detailed risk evaluation of sewerage facilities hit by an earthquake based on the analysis of bed and texture as well as earthquake incidence rate; ② suggestion of its remedy; ③ calculation of the estimated maximum damage for each seismic intensity; and ④ effective distribution of thereclamation and insurance expenses.

The damage risk by an earthquake having been considered as a prerequisite, this evaluation was not broadly evaluated in actual practices, such as planning, designing, construction, and maintenance. Since this clarifies that no absolutely safe structure can be made, the importance lies in calculating the extent of required additional budget for lessening the damage probability of structures and defining the relationship between the degree of damage and preventive measures when actual damage is done.

Considering these, the author *et al.* examined disaster alleviation measures based on the function analysis of a stricken sewerage. Specifically, we performed quantitative evaluation of the effect of aseismic reinforcement acquired with risk analysis after calculating the present state of an exemplification structure and degree of damage after calculation of aseismic reinforcement, as well as costs for reinforcement and repair.

EARTHQUAKE RISK EVALUATION METHOD

This method explains earthquake risk in order of calculation of annual risk, damage calculation method, selection of the most suitable reinforcement method. Aseismic reinforcement selection method and exemplification as following.

Aseismic reinforcement selection method

The flow of selection for aseismic reinforcement is shown in Fig. 1 (Mizutani, 1995). First, we calculated the intensities of earthquake motion on the basis of occurrence probability with the earthquake motion prediction program. Also, the relationship between the intensity of earthquake motion and the amount of damage is estimated with a method the author *et al.* invented, the non-linear seismic coefficient method, which considers the non-linear characteristics of ground and structures.

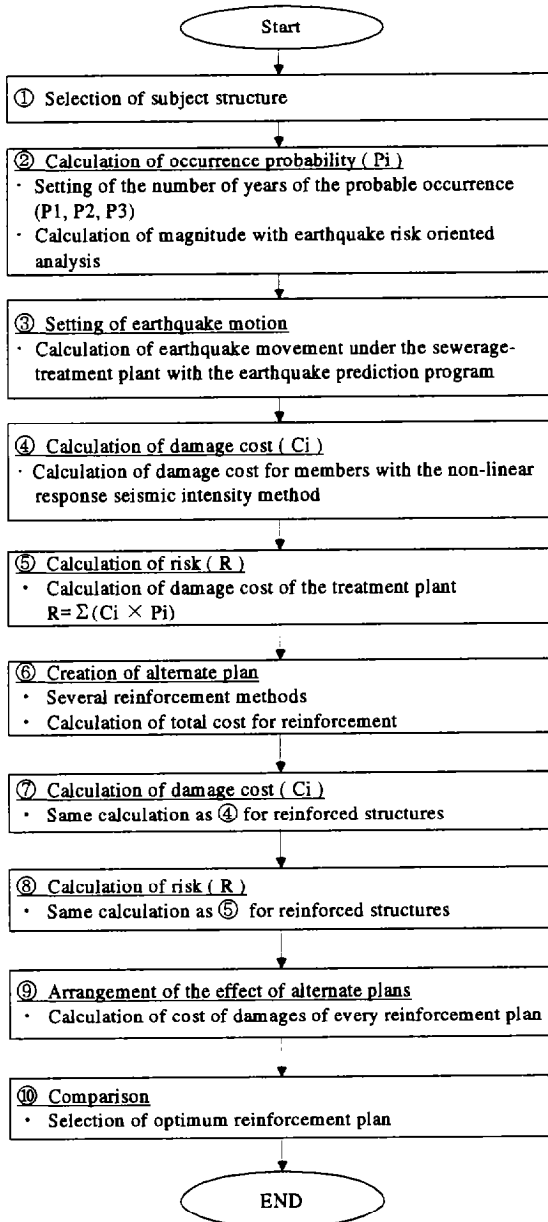


Fig. 1. Flow of selection for aseismic reinforcement method.

Calculation of annual risk. The calculation process of the annual risk is shown in Fig. 2-4. The annual risk is calculated by acquiring the amount of damage on the size of several earthquake motions set for each occurrence probability. We set 3 intensities of earthquake motion (L_1 , L_2 , and L_3) for each occurrence probability (Fig. 2). Then, we calculated the damage of both the present state (with no reinforcement) and the state after reinforcement for each earthquake motion (Fig. 3). Further calculation methods for more concrete damage will be described in "How to calculate damage." From the above, the annual risk is calculated as the sum of each risk (Fig. 4), and the effect of a year is the difference in the annual risks between the risk with no reinforcement and the risk after reinforcement.

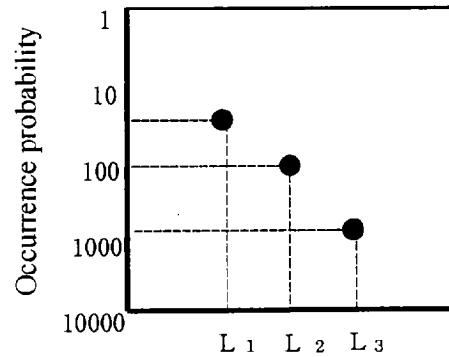


Fig. 2 Occurrence probability.

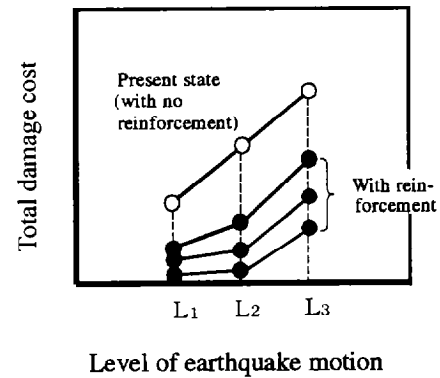


Fig. 3 Earthquake motion and total damage cost.

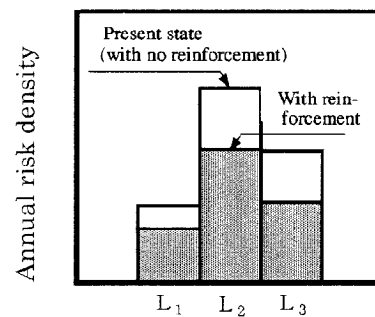


Fig. 4 Annual earthquake risk density.

Damage calculation method. The damage calculation method in the annual risk calculation is conducted in the following order:

- ① Calculation of ductility factor (Φ_{max}/Φ_y) from the analysis result using the response seismic intensity method
- ② Setting the damage level for each member of framework using the ductility factor using Fig. 5.

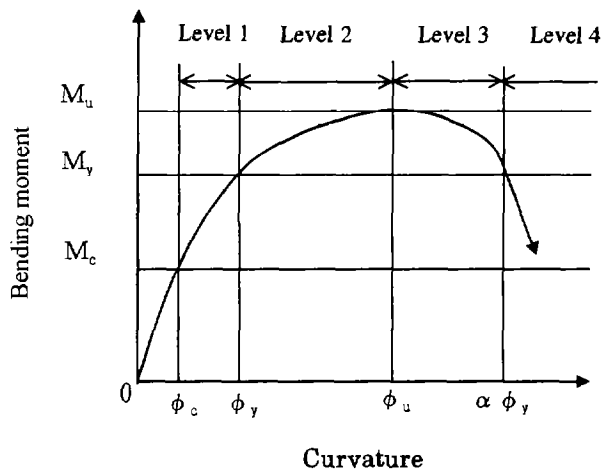


Fig. 5 Damage level concept.

- ③ Calculation of the damage amount by setting the repair costs separately for each aseismic capacity shown in Table 1. The damage level represents the load condition of Table 2.

Selection of the most suitable reinforcement method. Here we compare several possible aseismic reinforcement plans. The effect of the aseismic reinforcement per year is acquired using the following formulas: Effect of aseismic reinforcement = Annual

risk with no reinforcement – Annual risk after reinforcement. Then, considering reinforcement costs (N: number of in-service years), Effect of aseismic reinforcement – Costs of aseismic reinforcement/N. The aseismic reinforcement plan that makes the above value the greatest should be selected.

Exemplification

Conditions for exemplification. The subject structure is a water treatment plant that has a double structure where the sedimentation pond is incorporated into buildings. Waveforms of earthquake motion L_1 , L_2 , and L_3 are decided as follows for the prediction of earthquake motion. We performed earthquake risk oriented analysis and set the frequency of the target earthquake (occurrence probability: P) and the earthquake scale which possibly hit the area concerned (magnitude: M) as $P=30, 300, 1000$, and $M=7.0, 7.9, 8.3$, respectively. We used data of the Minami-Kanto earthquake for earthquake motion waveforms and created an artificial waveform for each earthquake motion using the Harada/Ohsumi method (Ohsumi *et al*, 1997). The maximum acceleration in earthquake-resistant basements is 99 gal, 680 gal, and 800 gal for each. In regard to the damage, we performed non-linear seismic coefficient method analysis (Yuasa *et al*, 2000) to judge the fracture mode for each member of framework and then acquired the ductility factor.

The procedure to follow to perform cost calculations and suggestions for aseismic reinforcement is shown in Fig. 6.

- ① Using seismic response analysis, calculation of repair costs for no reinforcement and selection of members that need to be reinforced.
- ② Consideration of damage to the members and the analysis distribution, followed by selection of countermeasure construction.

Table 1 Relationship between earthquake-resistant performance and damage level of each member of framework.

Aseismic capacity	Damage level in the flexure fracture mode		Damage level in the shear fracture mode
	Member for which repair/reinforcement is easy (slab, beam).	Member for which repair/reinforcement is difficult (wall, column).	
Aseismic capacity 1	Member damage level 1	Member damage level 1	No damage
Aseismic capacity 2	Member damage level 2 or 3	Member damage level 2	No damage
Aseismic capacity 3	Member damage level 3 (member damage level 4 for some members)	Member damage level 3 (member damage level 4 for some members)	No damage

Table 2 Standard for damage level of a member.

Fracture mode	Level	Description	Remarks
Flexure fracture	Damage level 1	Reinforcing bars in axial direction do not reach tensile yield (before flexural yield).	Range from crack to yield.
Flexure fracture	Damage level 2	Cover concrete does not reach compression fracture (generated loads do not reach the maximum proof stress).	Range from yield to maximum proof stress. In this proposal, ductility factor is less than 3.
Flexure fracture	Damage level 3	Member has a proof stress that can endure loads which are larger than that of flexural yield.	Range from maximum proof stress to ductility factor 10 ($\alpha=10$)
Flexure fracture	Damage level 4	Proof stress of member is less than the loads of flexural Yield.	Range that ductility factor is more than 10.
Shear failure	_____	Shearing force exceeds shear capacity.	_____

③ Confirmation of damage and calculation of repair costs when reinforcement based on the seismic response analysis is conducted (after aseismic reinforcement).

Regarding repair costs, the repair cost to be used per member should be previously decided separately for each damage level (defined by a member's bending rate), and each member's repair cost appropriate to the damage level should be acquired using the ductility factor. The total sum of these costs is the total of the repair costs.

Next, is the degree of damage to the members. The number of members whose present ductility factor is more than 1 by the seismic response analysis, and the repair costs are shown in Table 3. It is clear that the present state will damage more members and cost more. For the aseismic reinforcement plan, two construction methods are selected, which can satisfy the aseismic capacity aiming to improve the proof stress of the whole structure (Fig. 7). Construction method ① is one that places more concrete on columns and beams, and construction method ② is one that uses side walls and buttresses. The aseismic reinforcement costs are shown in Table 3. Also shown in Table 3 are the number of the members whose ductility factor is more than 1 and the repair cost amount acquired by performing seismic response analysis on both sections of construction methods ① and ②. The repair costs of earthquake motion L_1 is the value of less than the ductility factor 1 (crack). As it is obviously shown, construction method ① costs more for reinforcement and the damage by an earthquake is less.

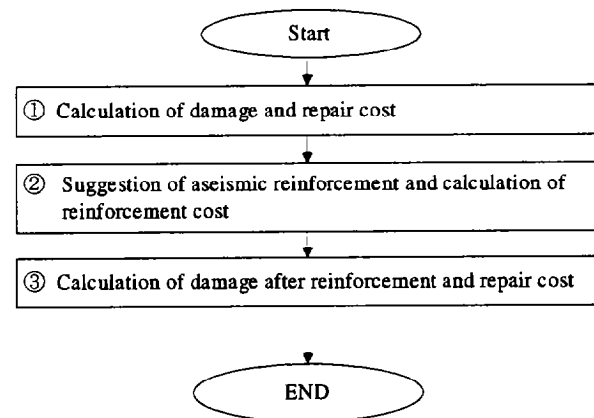


Fig. 6 Flow to acquire damage and cost.

Risk evaluation. The risk R of the present state (with no reinforcement) and of reinforced structure are acquired by the following formula:

$$R = \sum_{i=1}^3 (P_i \times C_i) \times A_i + p \times E \quad (1)$$

Here, P_i is the occurrence probability of the earthquake motion L_i ($i=1, 2, 3$), C_i is the total cost for earthquake motion L_i with/without reinforcement ($i=1, 2, 3$), and A_i is the area proportion, p is the probability of the aseismic reinforcement

Table 3 List of damage and cost.

	Level of earthquake motion	Number of members that have more than ductility factor 1	Total repair cost (yen)	Reinforcement cost (yen)
Present state	Earthquake motion L ₁	0	65,950,000	
Present state	Earthquake motion L ₂	30	3,844,800,000	
Present state	Earthquake motion L ₃	43	6,675,000,000	
Construction ① method	Earthquake motion L ₁	0	11,480,000	
Construction ① method	Earthquake motion L ₂	4	189,300,000	242,699,000
Construction ① method	Earthquake motion L ₃	6	208,260,000	
Construction ② method	Earthquake motion L ₁	0	2,418,000	
Construction ② method	Earthquake motion L ₂	12	304,244,000	193,296,000
Construction ② method	Earthquake motion L ₃	13	575,357,000	

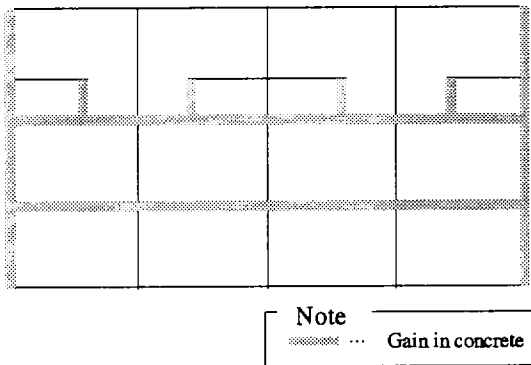


Fig.7 Construction ① method.

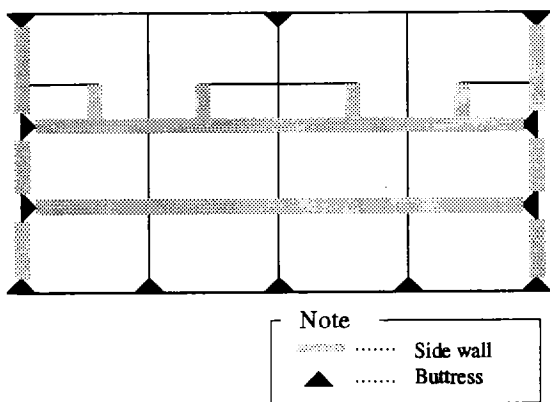


Fig.7 Construction ② method.

Table 4 Annual risk and the effect of aseismic reinforcement (unit: million yen/year).

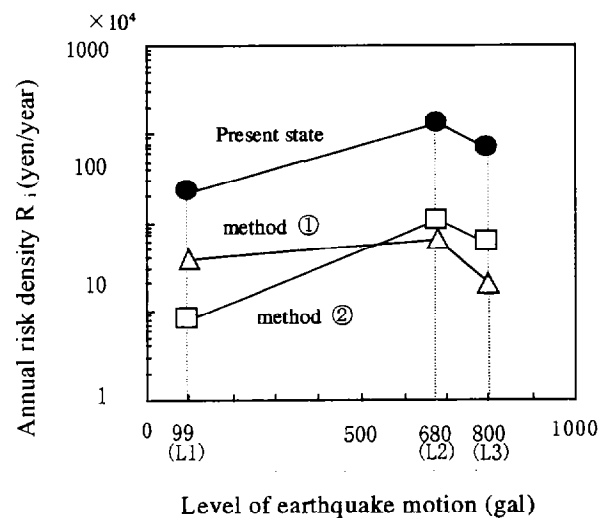


Fig.8 Annual risk density

(present: $p=0$, after reinforcement $p=1$), and E is the cost for aseismic reinforcement. $P_i \times C_i$ is termed the annual risk density, which shows the risk of each scale of earthquake motion. In Fig. 8, the relationship between the annual risk density and the scale of earthquake motion is shown. In the case of earthquake motion L₁, construction method ① is more effective in aseismic reinforcement than method ②, however, when the earthquake motion is more than L₂, the effect reverses; this leads to the

	① Annual risk without reinforcement	② Annual risk after reinforcement	③ Effect of earthquake reinforcement per year (①-②)	④ Costs of aseismic reinforcement (unit: million yen)	Effect ③-④/N
Construction method ①	2169	606	1563	242.7	956
Construction method ②	2169	483	1686	193.3	1202

conclusion that construction method ① is more brittle to the scale of earthquake motion. Table 4 shows the annual risk and the effect of aseismic reinforcement. Assuming 10 years passed from the time of construction, we set the in-service years $N=40$. This shows that the cheaper construction method ② is more effective than method ①.

The sewerage of five cities and four river-basin sewerage were damaged in Hyogoken-Nanbu earthquake. The average amount of damage was 3.83 billion yen (Editorial Committee for the Report on the Hanshin-Awaji Earthquake Disaster, 1997), which almost equaled 3.84 billion yen, which is the damage at earthquake motion L_2 , calculated with this method. From this, it is safe to say that the validity of this method is verified.

CONCLUSION

By applying earthquake risk management, we outlined the methodology to select the optimum aseismic reinforcement method for the existing structures. The conventional evaluation of earthquake-resistant structures has been conducted with an exemplification structure, only considering a specific earthquake motion. In the meantime, the earthquake risk management method enables the calculation of annual risks that are acquired by adding up the risks separated for each earthquake scale and the occurrence probability of an earthquake. This gives us the ability to monistically compare the reinforcement plan, which contributes the quantitative evaluation of the effect for aseismic reinforcement of existing structures.

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