STUDY ON SEISMIC RETROFIT PLANNING METHOD FOR SEWERAGE FACILITIES ON THE BASIS OF SEISMIC RISK MANAGEMENT

下水道処理場の地震に対するリスク評価に関する検討

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1995年兵庫県南部地震において，下水道施設も，甚大な被害を被った．特に下水道普及率が 9 割を越える神戸市を襲った施設の被害は，社会基盤としての重要性および環境への影響においても重要な課題となることを認識させた．現在，下水道施設を含む土木構造物の設計は，損傷を許容する変形性能照査型に移行されている．構造物の損傷が許容されるということは，その定量的評価が必要となる．下水道施設構造物の耐震診断及び補強方法の選定について地震リスクマネージメントの概念を導入し，「耐震設計基準をいかに強化してもその効果には限界がある」ということを前提に，地震時の機能分析に基づいた効果的な対策を検討する手法を提案するものである．

Key Words *: sewage treatment plant, earthquake risk, aseismic reinforcement design, level 2 earthquake, non-linear analysis*

1．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.

Recntly, the concept of risk analysis would be applied to the design of general infra strucure. One of trial methodology to be used id based on cost - benefit - analysis, decision - making process of the Reinforcement of Slopes base.

However, it also states that considerable effort must be put into establishing engineering methods. Introducing the concept of earthquake risk management put another way means, not being overconfident in earthquake-resistant design. Taking into account that, no matter how good the earthquake-resistant design, the fact must be recognized that we will never be able to make absolutely safe structures. It states that the most important thing is the planning of effective measures and enhancing the necessity of the project from the viewpoint of risk management. Disaster alleviation measures should be continuously considered on the basis of the functional 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, those 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

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maximum damage for each seismic intensity; and ④ effective distribution of the reclamation and insurance expenses.

For 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.

2. 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 follow:

(1) 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.

(2) Calculation of annual risk

The calculation process of the annual risk is shown in **Fig. 2 to 4**. The annual risk is calculated by acquiring the amount of damage on the size of several earthquake motions set for each occurrence probability. Three intensities of earthquake motion (L1, L2 and L3) for each occurrence probability was set. Then, the damage of both the present state (with no reinforcement) and the state after reinforcement for each earthquake motion (**Fig. 2**) was calculated. 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. 3**), and the effect of a year is the difference in the annual risks between the risk with no reinforcement and the risk

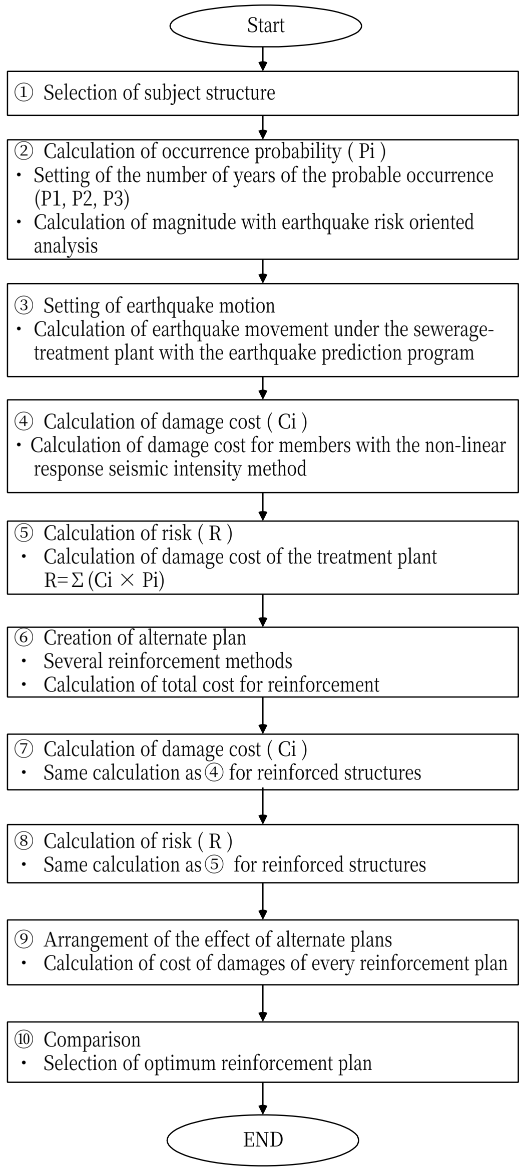

Fig. 1. Flow of selection for aseismic reinforcement method.

after reinforcement.

(3) Damage calculation method.

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

①Calculation of ductility factor ($\Phi max/\Phi y$) from the analysis result using the response seismic intensity method.

②Setting the damage level for each member of framework using the ductility factor using **Fig. 4**.

③Calculation 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**.

(4) Selection of the most suitable reinforcement method.

Here, are comparisons of several possible aseismic reinforcement plans. The effect of the aseismic reinforcement

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 (α=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.	―――

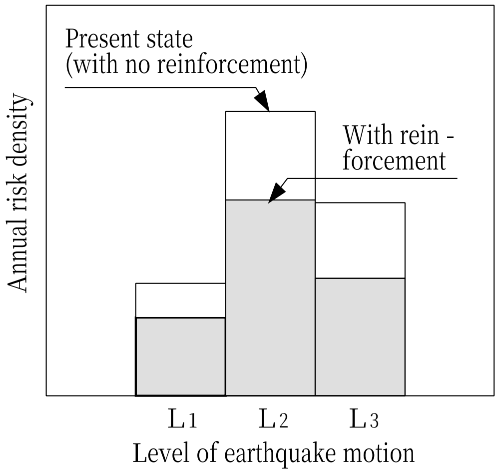

Fig. 2 Earthquake motion and total damage cost.

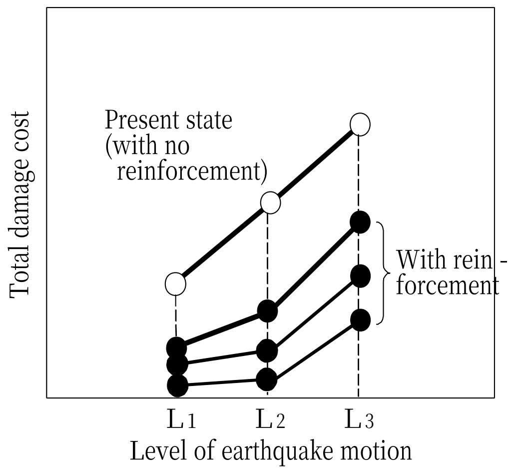

Fig. 3 Annual earthquake risk density.

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.

(5) Exemplification

For an 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 L1, L2, and L3 are decided as follows for the prediction of earthquake motion. Earthquake risk oriented analysis is performed and the frequency of the target earthquake

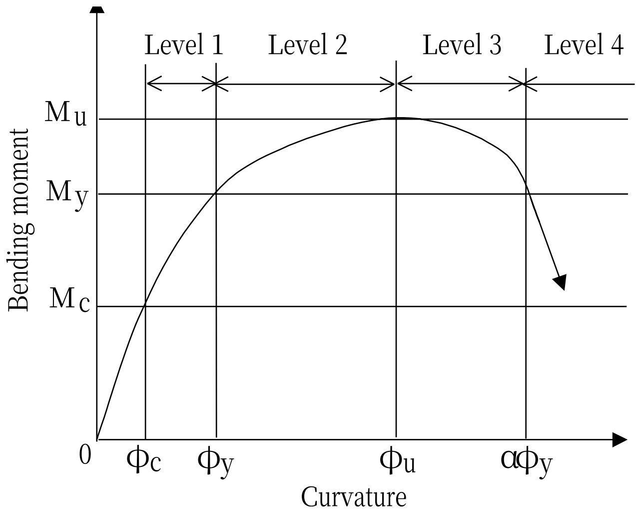

Fig. 4 Damage level concept.

is set (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, by using the seismic hazard analysis system (ERISA, shown in **Fig. 5 to 6**).

It uses 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 (**Fig. 7**). 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. 8**.

①Using seismic response analysis, calculation of repair costs for no reinforcement and selection of members that need to be reinforced.

②Consideration of damage to the members and the analysis distribution, followed by selection of countermeasure construction.

③Confirmation 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) separately, and each member ' s repair cost appropriate to the damage level should be acquired using the ductility factor. The sum of these costs is the total of the repair costs.

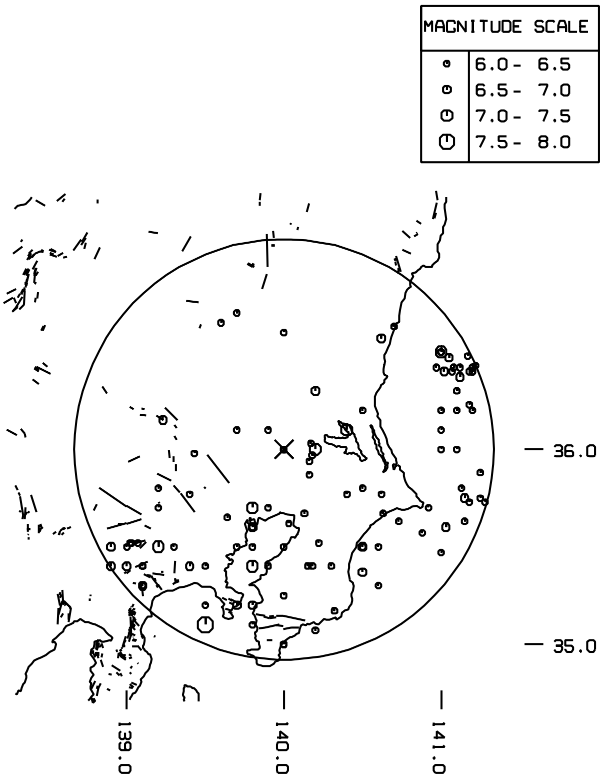

Fig. 5 Epicenter Distributions (ERISA)

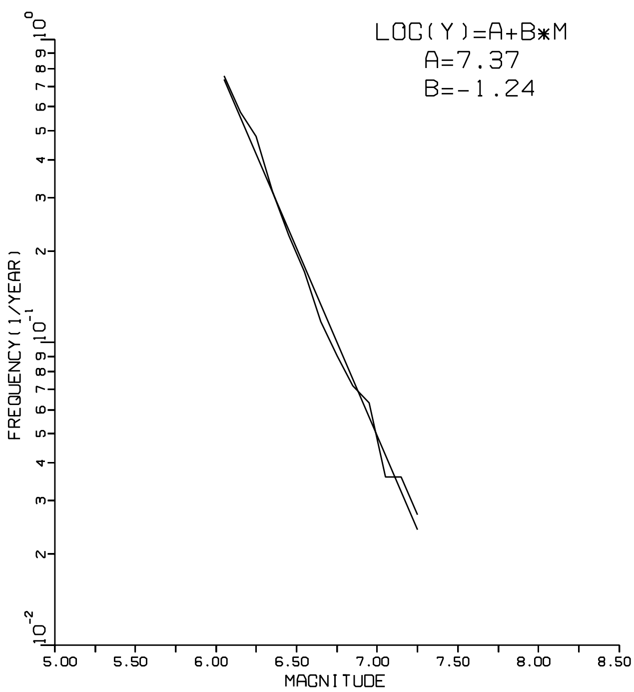

Fig. 6 Log Frequency of Magnitude (ERISA)

Next, factor is the degree of damage to the members. The number of members whose present ductility factor is more than 1 by the aseismic response analysis, and the repair costs are shown in **Table 3**. It is clear that the present state will damage

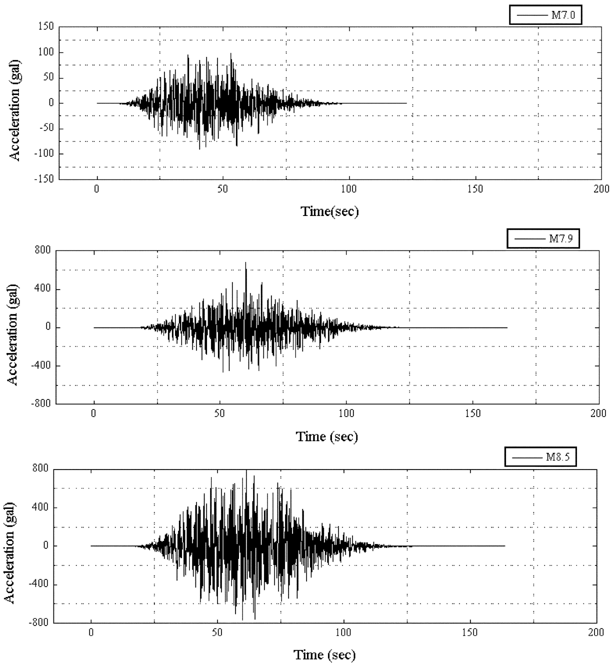

Fig.7 Waveforms of earthquake motion L1, L2, and L3

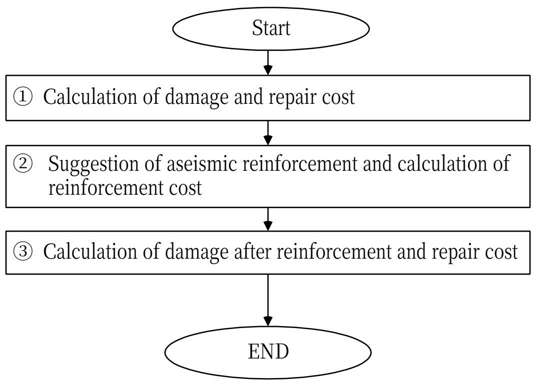

Fig. 8 Flow to acquire damage and cost.

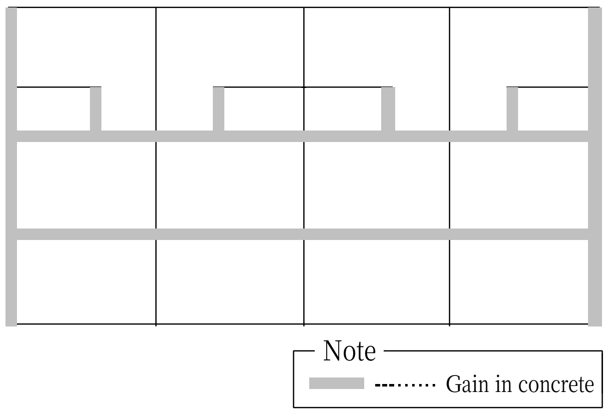

Fig.9a Construction ① method.

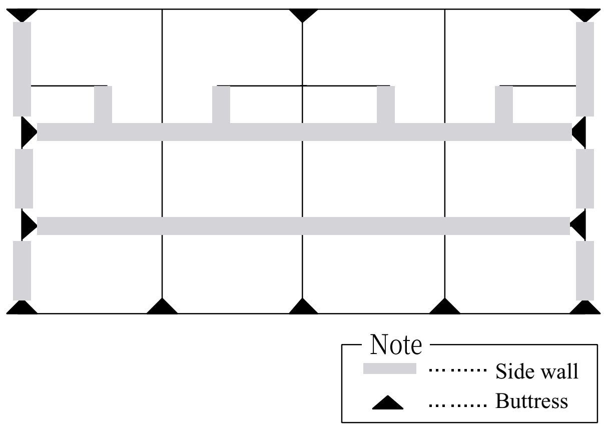

Fig.9b Construction ② method.

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. 9**). 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 L1 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 would be less.

(6) Risk evaluation.

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

$$R=\sum_{i=1\sim 3}(\mathrm{Pi}\times\mathrm{Ci})\times \mathrm{A_i}+p\times E \qquad (1)$$

Here, Pi is the occurrence probability of the earthquake motion Li (i=1, 2, 3).

Ci is the total cost for earthquake motion Li with or without reinforcement (i=1, 2, 3).

Ai is the area proportion, p is the probability of the aseismic reinforcement (present: p=0, after reinforcement p=1).

E is the cost for aseismic reinforcement. Pi x Ci is termed the annual risk density, which shows the risk at each scale of earthquake motion. In **Fig.10**, 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

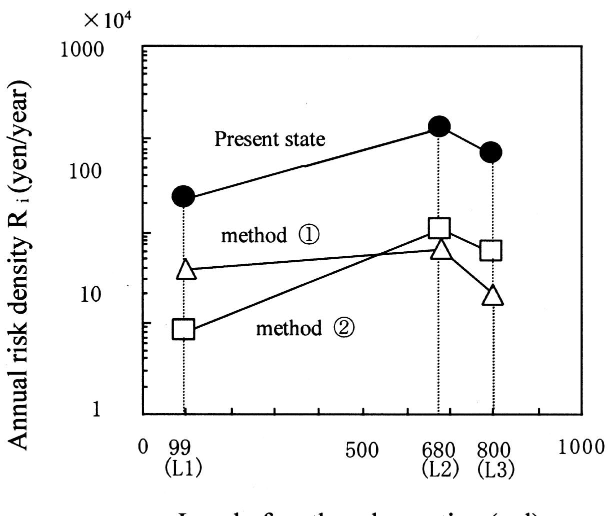

Fig.10 Annual risk density.

more effective in aseismic reinforcement than method ②. However, when the earthquake motion is more than L2, the effect reverses; that is, this leads to the conclusion that construction method ①is 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 to 3.84 billion yen, which is the damage at earthquake motion L2, calculated with this method. From this, it is safe to say that the validity of this method is verified.

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) cost (yen)	Reinforcement
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	method①	Earthquake motion L_1	0	11,480,000	
Construction	method①	Earthquake motion L_2	4	189,300,000	242,699,000
Construction	method①	Earthquake motion L_3	6	208,260,000	
Construction	method②	Earthquake motion L_1	0	2,418,000	
Construction	method②	Earthquake motion L_2	12	304,244,000	193,296,000
Construction	method②	Earthquake motion L_3	13	575,357,000	

Table 4 Annual risk and the effect of a seismic reinforcement

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

3. 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 monastically compare the reinforcement plan, which contributes the quantitative evaluation of the effect for aseismic reinforcement of existing structures.

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