Earthquake proofing of water treatment plants through seismic system risk analysis

Kenta Hayashi, Kimiyasu Ohtake, Keisuke Baba, Takaki Suto and Hiromichi Yoshikawa

ABSTRACT

In Japan, earthquake resistance improvement (earthquake proofing) of drinking water infrastructure is not as developed as for other types of infrastructure such as gas and electricity. To facilitate earthquake proofing, it is important for water utilities to encourage customers to better understand its importance and effectiveness. So that water consumers could instinctively understand the effectiveness of earthquake proofing, we applied the concept of 'recovery time expectancy' as an indicator of earthquake resistance of water treatment plants. In this study, we performed a recovery simulation of a medium-scale water treatment plant based on the system reliability theory, and then evaluated the effectiveness of earthquake proofing using recovery time expectancy as an indicator. The simulation was performed with five cases: the present condition of the facility and four hypothetical cases with different levels of earthquake proofing. As a result, the effectiveness of earthquake proofing was able to be expressed by a recovery curve showing the reduction of recovery time expectancy, and the priority became clear for seismically proofing each component of the plant according to the earthquake scale. Finally, the optimum capital investment was determined by comparing total costs (damage cost plus investment cost) of the five cases, which were computed according to recovery time expectancy after earthquake proofing.

Key words | cost-benefit analysis (CBA), recovery curve, recovery simulation, recovery time expectancy, seismic system risk analysis

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INTRODUCTION

In Japan, earthquake resistance improvement (earthquake proofing) measures for drinking water infrastructure have not been implemented as thoroughly as other types of infrastructure, such as gas and electricity. This is partly because water customers do not have intimate knowledge about the current levels, necessity, and particularly effectiveness of earthquake proofing. As a result, utilities have not been able to obtain agreement from customers to make enough investment in earthquake proofing.

The earthquake resistance level of drinking water infrastructure is usually represented by the ratio of earthquake-resistant facilities (earthquake-resistant ratio). For pipes, this is represented by the length ratio of earthquake-resistant pipes to the whole pipes. The earthquake-resistant ratio is a convenient indicator, helping water utilities to understand the achievement of earthquake proofing comprehensively. From the general public's viewpoint, however, this ratio alone is insufficient if they want to know the effectiveness of earthquake proofing or to assess whether related capital investments made by the water utility are appropriate. Therefore, we applied the concept of 'recovery time expectancy' as an indicator of earthquake resistance of water treatment plants so that water consumers could instinctively understand the effectiveness of earthquake proofing.

In this study, we performed a recovery simulation of a medium-scale water treatment plant based on the system

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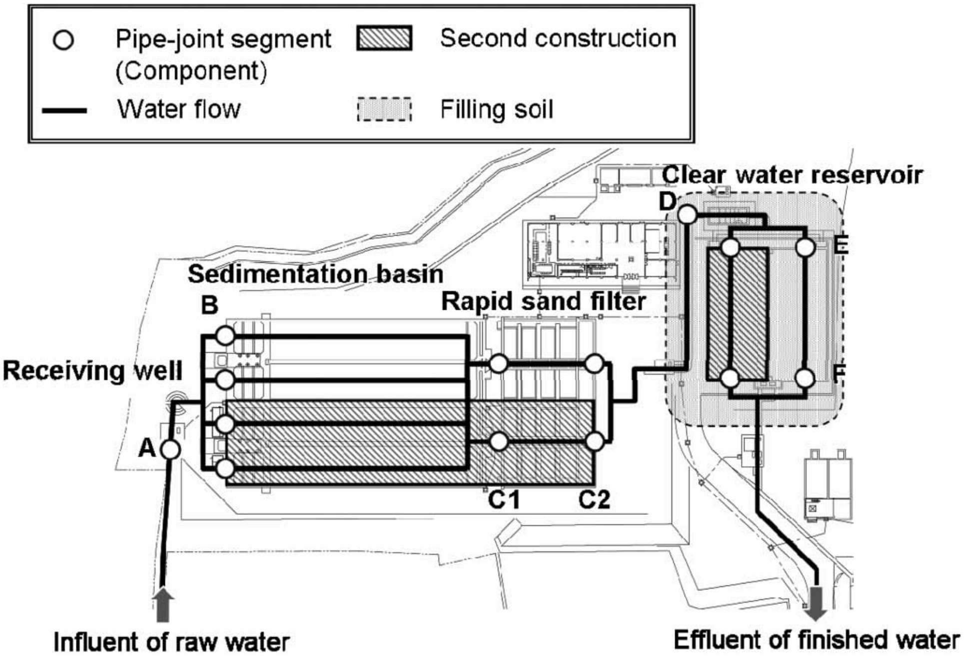

Figure 1 | Two-dimensional layout of the water treatment plant.

reliability theory, and then evaluated the effectiveness of earthquake proofing using recovery time expectancy as an indicator. The result demonstrates that the effectiveness of earthquake proofing can be transformed into a monetary value, which corresponds to reduction in recovery time. This method can be used for water utilities in determining the optimum capital investment in earthquake proofing.

ANALYSIS MODEL AND METHODS

Analysis model

As the analysis model for performance recovery simulation, we assumed a model water treatment plant located in Kanagawa Prefecture with the following specifications:

- Purification system: Rapid sand filtration
- Diameter of pipes: 600–1,000 mm
- Purification capacity: 100,000 m^3/day
- Population served: 200,000 people
- Maximum daily water supply: 100,000 m^3/day (including 20,000 m^3/day for industrial use).

A two-dimensional layout of the plant is shown in Figure 1. The model plant was assumed to be constructed in two stages. The pipes installed in the first construction stage have lower earthquake resistance because of older joint type than those installed in the second construction stage. The clear water reservoir is on soft, filling soil. In past earthquakes, damage to the water treatment plant occurred primarily at joints of pipes connected to structures. Therefore, our analysis model was constructed using pipe-joint segments as components of the plant (Figure 2). Block A1–F2 in Figure 2 shows the configuration of the system, comprising 14 pipe joints. The description under

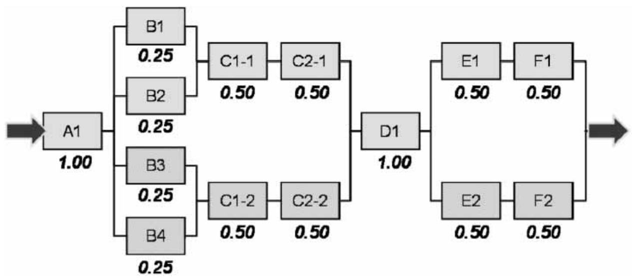

Figure 2 | Analysis model for recovery simulation.

each block shows the water flow capacity (referred to as 'performance' in the following section) of each component when the performance of the whole system is 1.00.

Seismic system risk analysis

In this study, we conducted a seismic system risk analysis based on the method of Nakamura *et al.* (2010). The outline is provided below.

System performance assessment considering model components

R_{sys}, which is the performance of the mixed serial-parallel system in Figure 2, is expressed in the following equation:

$$R_{sys} = \min(R_{A1},\ \min(R_{B1} + R_{B2},\ R_{C1-1},\ R_{C2-1}) + \min(R_{B3} + R_{B4},\ R_{C1-2},\ R_{C2-2}),\ R_{D1},\ \min(R_{E1},\ R_{F1}) + \min(R_{E2},\ R_{F2})) \quad (1)$$

R_i is a randomly determined variable of the component i's performance ($i = A1, A2, \ldots, F2$), which is based on the probability that the component i will suffer damage in an earthquake.

According to the equation above, the performance of the serial portion of the system is calculated as the components' minimum values, whereas the performance of the parallel portion of the system is calculated as the sum of the components' values. Also, the probability function of each component's performance is obtained from the fragility curve, which represents the probability of damage.

Vulnerability assessment of system components

The *Earthquake resistant design code for drinking water facilities* (Japan Water Works Association 2009) states that for the purposes of simple calculations, the degree of the pipe-joint expansion may be calculated from the sum of the ground displacement and the structural displacement at the connection of the structure and the pipeline.

The various types of purification structures in this study, such as chemical sedimentation basin, rapid sand filter, clear water reservoir, have high aspect ratios and high stiffness. In structural analysis, their structural displacement is calculated to be less than one-tenth of the ground displacement. Therefore, in this study, we consider only ground displacement in the assessment of pipe-joint expansion.

Table 1 shows the peak base-rock velocity (PBV) and the recovery time expectancy when the components suffer damage in an earthquake. The PBV was assumed to be the value when the damage probability of the components is 50%, obtained by converting the maximum displacement of the pipe-joints based on the relation between the maximum displacement and the amplification factor of ground (Ohtake *et al.* 2010). In this calculation, the maximum displacement was assumed to be 20 mm in the first construction stage while it was 100 mm in the second construction stage because of the installation of the expansion joint.

Recovery process and bottleneck of the system performance

In order to represent the recovery process of the system performance, a recovery curve was used. As shown in Figure 3,

Table 1 | PBV and recovery time expectancy for model components

Component			1st construction stage		2nd construction stage	
Symbol	Number	Performance	PBV (cm/s)	Recovery (days)	PBV (cm/s)	Recovery (days)
A	1	1.00	65	5	–	–
B	4	0.50	65	2	325	2
C	2	0.25	65	3	325	3
D	1	1.00	20	5	–	–
E	2	0.50	20	3	98	3
F	2	0.50	20	3	98	3

Note: The PBV was assumed to be the value when the damage probability of the components is 50%.

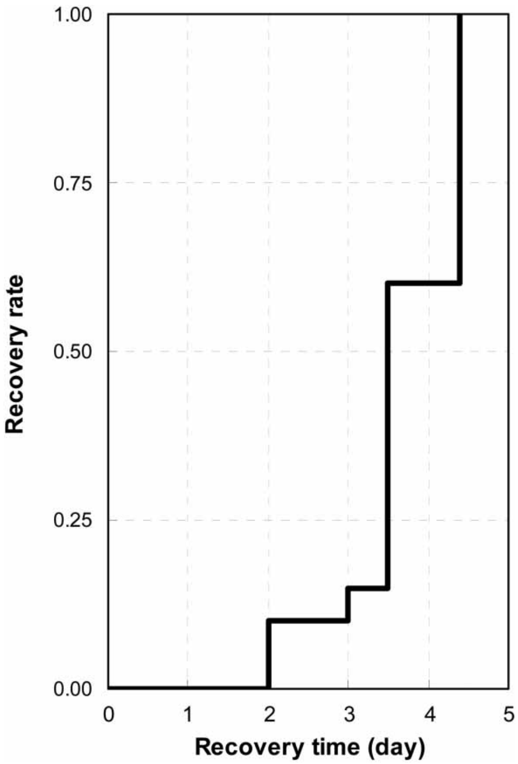

Figure 3 | Conceptual diagram of recovery curve.

the abscissa of the figure represents the recovery time expectancy, and the ordinate represents the recovery rate of the performance with the primary value 1.00.

The bottleneck index (B.I.) was applied to effectively extract the bottleneck component (Nakamura & Endo 2009). B.I. is defined by the following equation:

$$\text{B.I.} = \textit{significance of each component} \times \textit{vulnerability} \times \textit{difficulty of recovery} \quad (2)$$

where *significance of each component*: performance of each component shown in Figure 2; *vulnerability*: the probability of damage occurring to each component calculated by the fragility curve shown in Figure 4; and *difficulty of recovery*: recovery time expectancy of each component.

Calculation of the optimum capital investment

The optimum capital investment for earthquake proofing was determined by computing the total costs (damage cost plus investment cost) using the economic verification method

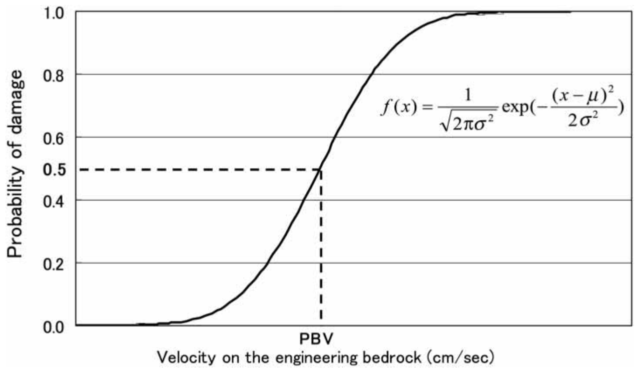

Figure 4 | Conceptual diagram of fragility curve. *Note:* fragility curve is a cumulative distribution function of log-normal; the deviation is set to 0.5, which is the sum of uncertainty (standard deviation) of strength of pipe joint and ground motions.

described in the *Earthquake resistant design code for drinking water facilities*. The calculation period was set at 50 years. The recovery time expectancy, obtained from seismic system risk analysis, was applied to calculate the damage cost.

Calculation of the damage cost

The damage cost due to the water suspension was calculated based on The Manual of Cost-benefit Analysis for Waterworks (Ministry of Health, Labour and Welfare 2011). The indirect damage costs to domestic, commercial, and industrial customers were calculated according to the recovery time expectancy and the performance recovery process. The indirect damage cost is expressed in Equation (3):

$$C_d = \sum_{i=0}^{1.00} \left\{ \left(C_{l(i)} + C_{b(i)} + C_{i(i)} \right) \times T_{(i)} \times R_{sys(i)} \right\} \quad (3)$$

where C_d: indirect damage cost (million Japanese yen (yen)); C_l: damage cost to domestic customers (million yen/day) = damage cost to domestic use (thousand yen/person/day) × population served (person); C_b: damage cost to commercial customers (million yen/day) = damage cost in commerce (thousand yen/day) × influence (%); C_i: damage cost to industrial customers (million yen/day) = damage cost per industrial water unit (thousand yen/m^3) × industrial water demand (m^3/day); T_i : recovery time expectancy (day); i: performance of the water treatment plant (0.00–1.00), e.g., $T_{(0.50)}$

indicates the number of days necessary for the plant to recover to the performance level of 0.50.

The average damage cost for a single year was obtained by multiplying the indirect damage cost by the probability of an earthquake occurrence for the year. The total damage cost for 50 years was calculated with conversion factor 21.48 derived from The Manual of Cost-benefit Analysis for Waterworks.

$$C_{td} = \frac{C_d \times P_{e(50)}}{50} \times 21.48 \qquad (4)$$

where C_{td}: total damage cost (million yen/50 years); $P_{e(50)}$: 50 year probability of an earthquake occurrence.

Calculation of the investment cost

The total investment cost was computed by multiplying the improvement cost for earthquake proofing of each component A1–F2 by a conversion factor corresponding to the service life of the facility. For earthquake proofing of components, the maximum displacement of pipe joints was assumed to be upgraded to 200 mm (PBV, 195 cm/s), and pipes linked to the components were replaced with ductile iron pipes with earthquake-resistant joints. Five cases, including the present condition (no improvement), were set up based on the B.I.

Calculation of total cost

Economic verification is an optimization technique to decide the earthquake proofing level at which the total cost becomes minimum value. In this technique, the total costs are expressed as the sum of the total damage cost and the total investment cost.

The conceptual diagram of economic verification is shown in Figure 5. In this scheme, the total cost is minimized at the point of intersection of the plots. This value represents the optimum investment cost for the earthquake proofing. In this study, the optimum investment cost is determined by calculating the damage cost and the total cost for the five examination cases. In the trial calculation, the earthquake proofing level was expressed using the recovery time expectancy.

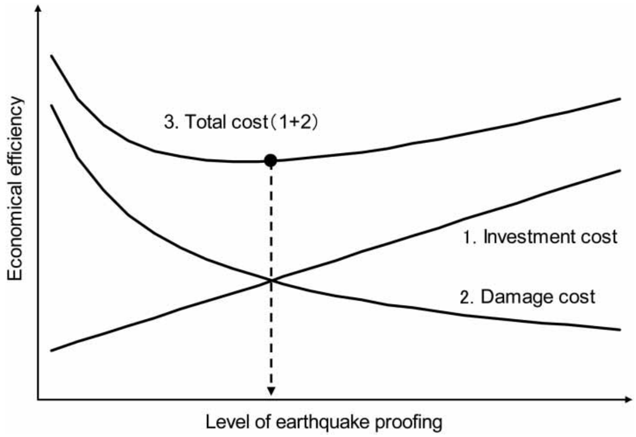

Figure 5 | Conceptual diagram of economic verification (cited from the *Earthquake resistant design code for drinking water facilities* (Japan Water Works Association 2009)).

RESULTS

Recovery time expectancy

For the recovery simulation, we selected two earthquake scenarios of magnitude (M) 7.0 and 8.0 in the Kanto region (Ugata 2001). The PBV values at the location around the model plant were calculated, using the equation for distance decay by Annaka *et al.* (1997). As a result, PBV values were calculated to 91 cm/sec in the case of M 8.0 earthquake and 28 cm/sec in the case of M7.0 earthquake. The possibility of an earthquake occurrence during the simulation period was calculated using

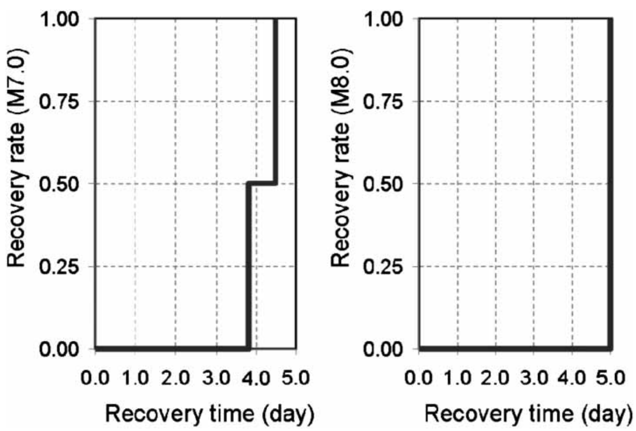

Figure 6 | Recovery curve under the present condition (left: M7.0, right: M8.0).

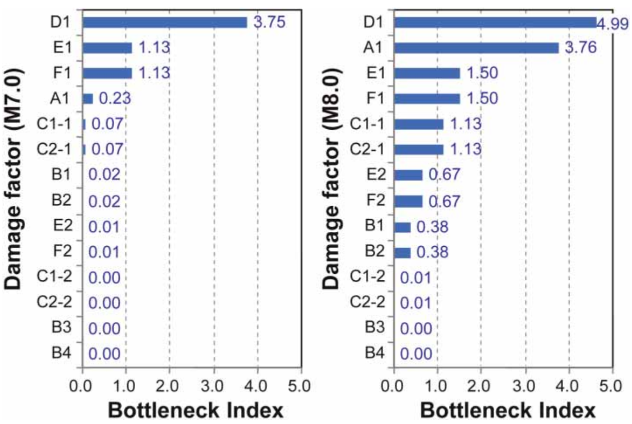

Figure 7 | B.I. of the present condition (left: M7.0, right: M8.0).

Table 2 | Four cases of earthquake proofing

Case	Parts improved
Present	No improvement
Case-1	D1
Case-2	D1, E1, F1
Case-3	A1, D1, E1, F1
Case-4	All components

the Poisson process. The following description is based on the assumptions that each component is damaged independently and that damaged structures are restored at the same time.

Recovery simulation under the present condition (no improvement)

Figure 6 shows the recovery curve in the case of the present condition. In the case of M7.0 earthquake, 50% of the system performance is recovered within 4 days. In the case of M8.0 earthquake, the system performance is not recovered until the end of the 5th day. However, in both cases, the system performance recovers significantly after a certain period of time. System component D1 represents the single route to the clear water reservoir (Figure 2); when D1 is seriously damaged, the route remains blocked even after the other components recovered.

Figure 7 shows the B.I. of the two cases (M7.0 and M8.0 earthquakes). The B.I. indicates the influence of each component for the recovery of the whole system. In this figure, the B.I. values of components A1 and D1 are especially large in the case of the M8.0 earthquake. In the case of M7.0, B.I. values are relatively large for components D1, E1, and F1, which have weak earthquake resistance.

Recovery simulation of the cases after earthquake proofing

The four cases of earthquake proofing shown in Table 2 were set where components of higher B.I. values would be reinforced with higher priority.

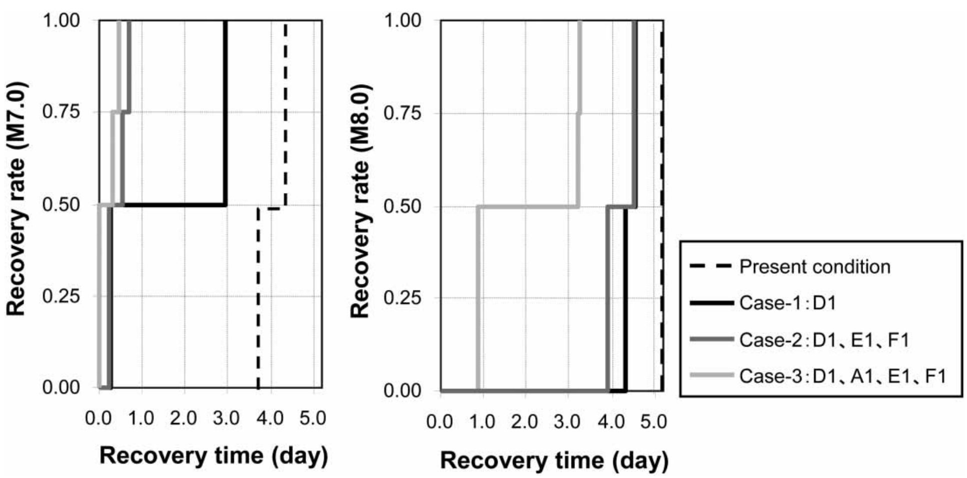

Figure 8 | Recovery curve after earthquake proofing (left: M7.0, right: M8.0). *Note:* Case-4 is not included in this figure because all the components are seismically upgraded in Case-4 and the plant suffers no damage.

Table 3 | Difference in recovery time expectancy

Earthquake	Recovery time (day) Present	Case-2	Case 3
M7.0	4.5	0.7	0.5
M8.0	< 5.0	4.5	3.2

Figure 8 shows the recovery curve for the cases described above, after earthquake proofing. In the M7.0 earthquake scenario, recovery time expectancy in Case-2 and Case-3 do not differ significantly as shown in Figure 8 and Table 3. The difference between Case-2 and Case-3 is a reinforcement of A1, which shows a small B.I. value in the M7.0 earthquake scenario. On the other hand, in the M8.0 earthquake, the recovery time expectancy in Case-2 and Case-3 shows a large difference. Improvements of the high-B.I. components are most likely to substantially reduce the recovery time expectancy.

As discussed above, the recovery curve can express the effectiveness of earthquake proofing in terms of the reduction of the recovery time expectancy. In addition, this approach identifies the components that should be prioritized for improvement in each earthquake scenario.

Optimum investment

The optimum investment can be determined by comparing the total costs (damage cost plus investment cost) of each case.

Table 4 | Calculations of the damage cost

Kanto earthquake	Damage cost (million yen)	50-years probability (%)	Average cost of single-year (million yen)	Conversion factor (–)	Total damage cost (million yen)
M7.0					
Present	9,965	53.4%	106	21.48	2,277
Case-1	3,082		33		709
Case-2	882		9		193
Case-3	327		3		64
Case-4	0		0		0
M8.0					
Present	12,246	6.2%	15	21.48	322
Case-1	10,782		13		279
Case-2	10,139		13		279
Case-3	4,309		5		107
Case-4	0		0		0

Table 5 | Calculations of the investment cost

Case	Parts improved	Pipeline length (m)	Expansion joint (location)	Improvement cost for construction (million yen)	Conversion factor	Total investment cost (million yen)
Present	No improvement	0	0	0	1.13	0
Case-1	D1	50	1	55		62
Case-2	D1, E1, F1	90	3	117		132
Case-3	A1, D1, E1, F1	120	4	156		176
Case-4	All components	200	14	324		366

Note: if the service life of the pipeline was 38 years, the conversion factor should be 1.13 (The Manual of Cost-benefit Analysis for Waterworks (Ministry of Health, Labour and Welfare 2011)).

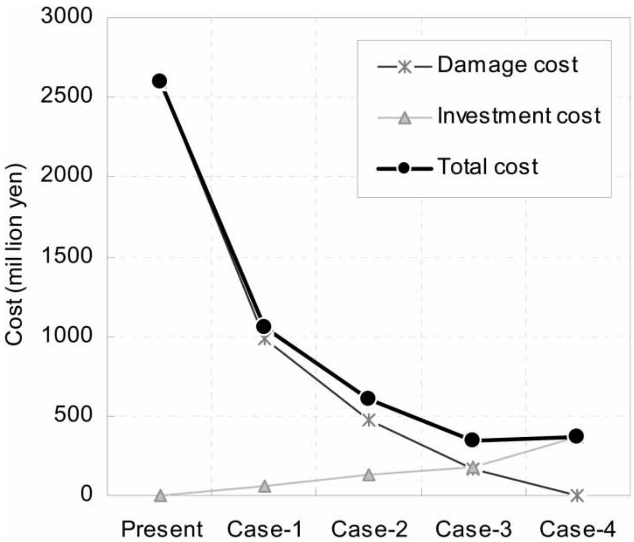

Figure 9 | Calculations of the total cost.

The results of the trial calculations of damage cost for the M7.0 earthquake and the M8.0 earthquake scenarios in the Kanto region are shown in Table 4. Assuming each earthquake scenario occurred independently, the total damage cost of the model plant can be expressed as the sum of the damage cost from the two earthquakes scenarios. The investment cost for each experimental case is shown in Table 5.

The result of a trial calculation of the total cost is shown in Figure 9. This result suggests that 2,600 million Japanese yen (yen), the total cost under the present condition, could be significantly decreased by earthquake proofing (Case-1 to Case-4). Additionally, the total cost of Case-3 is lower than that of Case-4, indicating that Case-3 is the most advantageous case. The reason for that is because as the B.I. of the target component for the earthquake proofing becomes larger, the damage cost becomes smaller. In the trial calculation, the investment cost for construction was calculated as 156 million yen.

CONCLUSIONS

In this study, we performed a recovery simulation of water purification capacity after an earthquake. As a result, the effectiveness of earthquake proofing of water treatment plants was able to be expressed as a reduction in the recovery time expectancy. Furthermore, the optimum capital investment was able to be determined by transforming the effectiveness of earthquake proofing into a monetary value as a decrease of the indirect damage cost.

There still remains a need for improvement of the accuracy of the study results for practical use. Additionally, we plan to apply the method described here to evaluate the whole water supply system, including the water distribution network from the water treatment plant.

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