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Practical Paper

Development of comprehensive evaluation procedure for anti-seismic strategies: evaluating Kobe City's earthquake resistance improvement plan from the customer's viewpoint

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ABSTRACT

In Japan, the 'earthquake-resistant pipe ratio' and the 'amount of stored water for emergency' have been used to evaluate the anti-earthquake performance of water supply facilities. In the past, however, those evaluations were made mainly from the viewpoint of the supplier, and evaluations from the customer's (citizen's) viewpoint have been insufficient. For simpler explanations to customers, the evaluation model based on 'living conditions,' related to emergency water use in the restoration period, has been established and a verification study has been conducted using an analysis model for evaluating the effect of various seismic upgrade measures adopted in Kobe City. Verification results show that the seismic improvement measures would produce a shorter restoration period compared with the time for the 1995 Great Hanshin–Awaji earthquake and that a greater amount of water would be available in the restoration period, leading to wider and more frequent use of water by citizens.

Key words | customer's viewpoint, estimation model, living conditions, seismic upgrade

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INTRODUCTION

In July 1995, Kobe City Waterworks Bureau drew up the 'Kobe City Basic Plan for Earthquake-resistant Water Supply Facilities' (hereinafter the 'Earthquake-resistant Basic Plan') based on a review of, and lessons learned from the Great Hanshin–Awaji earthquake of January 1995. Since fiscal 1996, the Bureau has been undertaking various seismic upgrade measures according to the Earthquake-resistant Basic Plan to make its supply system more resistant to disasters and capable of quick recovery (Table 1).

The progress in each seismic upgrade measure has been evaluated with indicators such as the 'earthquake-resistant pipe ratio' and the 'amount of stored water for emergency.' However, because such evaluations have been made mainly from the viewpoint of the supplier, evaluations from the customer's (citizen's) viewpoint are considered to be insufficient. Hence, Kobe City is required to find indicators easier for customers to understand.

The present paper evaluates the effect of the city's seismic upgrade measures comprehensively and quantitatively in terms of both hardware and software. Made through a mathematical model, this evaluation is based on citizens' 'living conditions' related to emergency water use in the event of a hazardous earthquake.

Kobe City basic plan for earthquake-resistant water supply system

In the Earthquake-resistant Basic Plan, the Kobe City Waterworks Bureau aims to complete the emergency recovery operation within 4 weeks. To achieve this target, the Bureau has been mainly undertaking three seismic upgrade measures: 'seismic upgrade of distribution pipes' for damage mitigation and quick recovery, 'emergency storage system development' for storing water for emergency supply, and

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Table 1 | Progress of Kobe City seismic upgrade measures

Measures	Plan	1995	2011
Earthquake-resistant pipes	Replace higher priority pipelines with seismic-resistant pipes	9.0%	33.2%
Water storage facility	47 tanks	21 tanks	44 tanks
Large-capacity transmission mains	12.8 km	–	3.8 km

'large-capacity transmission mains development' for emergency water supply and backups in urban areas.

MATERIALS AND METHODS

As part of evaluating the seismic upgrade measures from the citizen's viewpoint, we investigated citizens' living conditions in an emergency from the perspective of water use for drinking, toilet, face washing, bath, laundry, and cooking. Using the earthquake-resistant ratio of distribution pipes and others as evaluation factors, this evaluation was made through the numerical analysis model of emergency water supply (Hirayama *et al.* 2011; Sakaki *et al.* 2012).

Recovery operation model

Summary

In the recovery operation model, Kobe City was represented by a 500 m grid cell. Each cell was assigned data including the population, earthquake motion, and total length of distribution pipes by pipe type and diameter to calculate the number of damaged locations, water availability ratio, number of people with water suspension, etc. per day and per cell. The number of damaged locations per cell was calculated through the Monte Carlo technique (N = 100). Considering the actual restoration process, it was assumed that the recovery operation could start only after flow test was ready to be conducted in the relevant cell. It was also assumed that the recovery operation would first be conducted in the cells containing key facilities such as distribution reservoirs located right below the water source and/or major connecting tanks, and then would make its way outward in a radial pattern. In this evaluation, emergency water supply means tanker truck delivery from supply bases (e.g., treatment plants and reservoirs), direct access to supply bases by citizens, and temporary water taps connected to distribution pipes.

Calculation conditions

The calculating conditions were determined as shown in Table 2 by referring to the Report of the Kansai Water Project Workshop (1996). Under these conditions, the actual values from the Great Hanshin–Awaji earthquake and the reproduced calculation results were compared. The results showed that the R^2 value was high, or 0.934, meaning that the tendency was roughly reproduced.

Living condition estimation model

Objective

The purpose of making evaluations based on living conditions is to estimate, through psychological analysis, how water is used by citizens in an emergency and from this estimation identify viable usage of emergency water, clarifying what kinds of water use would be feasible how long after a disaster occurs and how often a week. Making these results known to citizens is considered to enable them to better prepare themselves for emergency situations and work towards reducing disaster risks, including initial responses in a disaster and preparedness in normal times.

Calculation method

In the evaluation based on living conditions, water obtained in an emergency was assumed to be used for six purposes, namely, drinking, toilet, face washing, bath, laundry, and cooking. The calculation process is as follows: (i) determine the daily amount of emergency water supplied according to the recovery prediction model results; (ii) for each purpose of use, obtain the number of days citizens have not used water from the last day of use; (iii) calculate the satisfaction level by purpose of use based on the number of days

Table 2 | Calculating conditions of recovery operation

Item	Unit	Input value – 2011 (1995)	Remarks
Area evaluated	–	Kobe City	500 m cell
Earthquake scale	–	Great Hanshin–Awaji earthquake	
Ratio of damage to distribution pipe	Location/km	0.28 (0.43)	2011: P-DES value, 1995: Actual value
Date to start recovery operation	–	From the fourth day	Only emergency water supply from the 1st to 3rd days
No. of locations to start recovery operation	Location	31 (25)	Distribution reservoirs located right below the water source, major connecting tanks
No. of people involved in recovery operation	Person	No. of people mobilized from other cities for assistance	Actual values in 1995 (daily variables)
No. of people per recovery operation squad	Person	24	According to observations in 1995
Recovery rate per recovery operation squad	Day/location	Small (– φ250): 0.5; Large (φ300 –): 1.6	According to observations in 1995
No. of emergency water supply bases	Location	71 (18)	Actual values both in 2011 and 1995
No. of tanker trucks	Vehicle	Max. 350	Actual value at 1995
Amount of stored water for emergency	ℓ/person/day	Water supply by tanker trucks: 3	Planned value in the Earthquake-resistant Basic Plan
		Recovery of 500 m water distribution networks: 20	
		Recovery of 200 m water distribution networks: 100	

obtained in (ii) and the number of days citizens could go without water; and (iv) determine the purpose of water usage using the algorithm that makes assessments based on the amount of stored emergency water, the amount of water required, and the satisfaction level by purpose of use.

The satisfaction level, which decides the priority of water usage, was determined as the time interval between the number of days citizens could go without water (Table 3) as indicated in the questionnaire results by Hirayama (2005), and the time when citizens actually use water for each purpose. More specifically, the satisfaction level was quantified using the linear equation as shown in Figure 1 by referring to the concept of the value function in the prospect theory in the field of psychology (Hashimoto 2012).

For each purpose of use, two types of water requirement were considered: the minimum amount of water required in emergencies and the amount of water consumed in normal times. In the present calculation, the minimum amount of water required in emergencies was applied until the fourth week, which is the target recovery period of the Earthquake-resistant Basic Plan, and the amount of water required in normal times was applied from the fifth week since the state of emergency is assumed to be raised by then.

Table 3 | Conditions for calculations condition

Purpose	Number of days citizens could go without water (day)	Amount of water required in emergencies (ℓ/person/day)	Amount of water required in normal times (ℓ/person/day)
Drinking	2.0	1.0	3.0
Toilet	1.7	8.0	19.0
Face washing	6.5	4.0	16.0
Bath	7.2	80.0	84.0
Laundry	7.8	40.0	47.0
Cooking	4.4	2.0	59.0

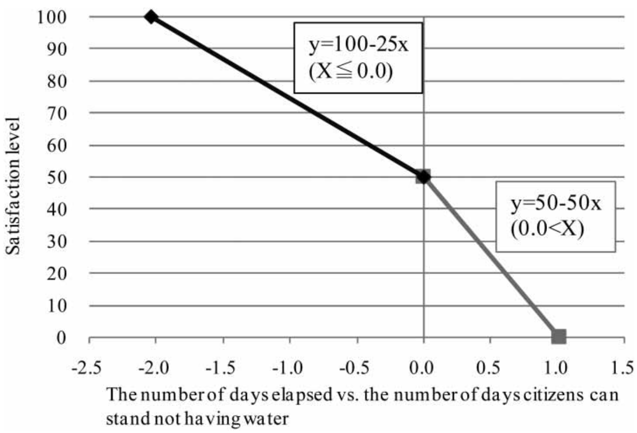


Figure 1 | Satisfaction level function (e.g. drinking).

RESULTS AND DISCUSSION

Result of recovery operation

Figure 2 compares the water availability ratio and the number of damage locations between the reproduced result of the Great Hanshin–Awaji earthquake (hereinafter '1995') and the result where an earthquake of the same scale is assumed to hit the city's current water supply facilities (hereinafter '2011').

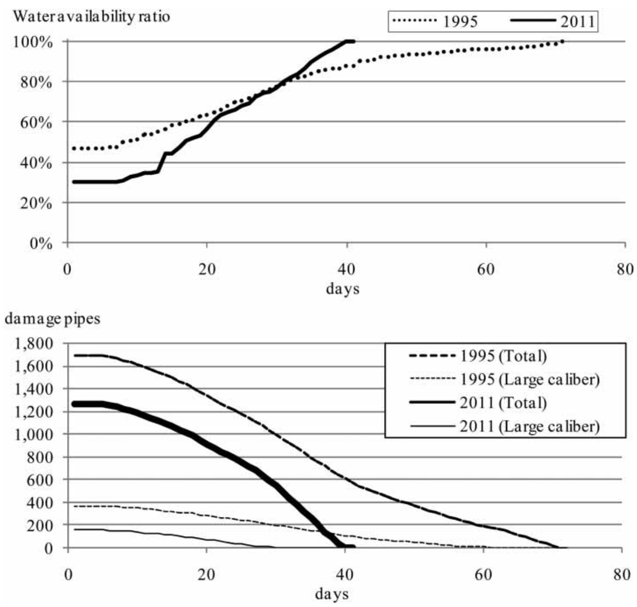


Figure 2 | Comparison of results in the water availability ratio and damage incidence.

In terms of recovery speed, to recover from the disaster requires about 6 weeks at present, which is 4 weeks less than in 1995. The water availability ratio has also improved. These are considered attributable to a reduction in the total number of damage locations due to the seismic upgrade of distribution pipes, particularly the result of seismically upgrading large diameter mains, which require a long recovery time, in a well-planned manner.

Opportunity loss

In the context of this paper, opportunity loss of water is defined as the difference between the amount of water available in emergency and normal times, water which would be available if the disaster does not occur. Figure 3 compares the amount of water associated with opportunity loss in 1995 and 2011 for those with water supply suspended. In the case of 2011, the target is achieved immediately after the disaster; however, the difference from the target increases on the tenth and subsequent days. This is considered attributable to the time required to restore the distribution mains, on which fire hydrants are installed.

This result suggests that even though the effect of seismic upgrade measures can be observed, it will be necessary to continue to promote seismic upgrades in the future because some targets are not achieved.

Result of living conditions

Figure 4 shows the result of evaluating living conditions in 1995 and 2011 for those with water supply suspended. As for water for drinking purpose, it was available at a secure

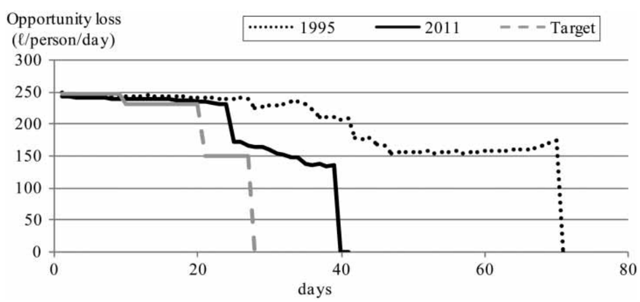
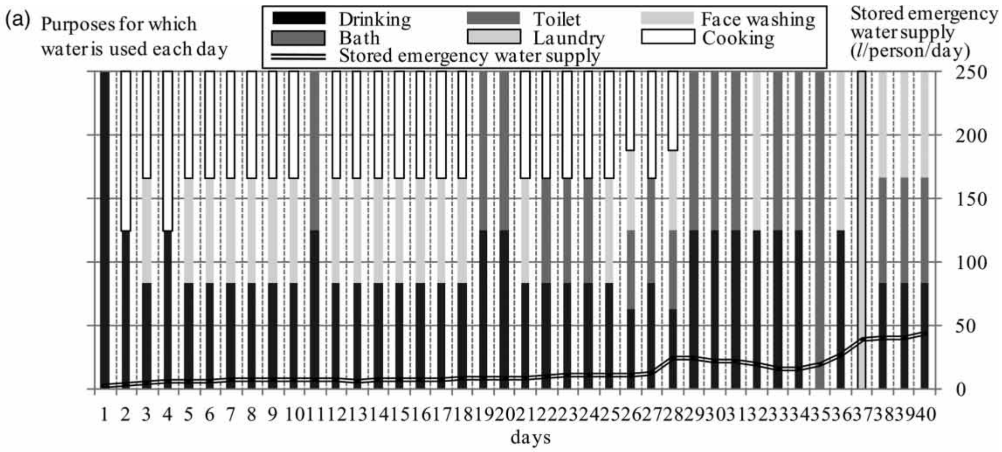


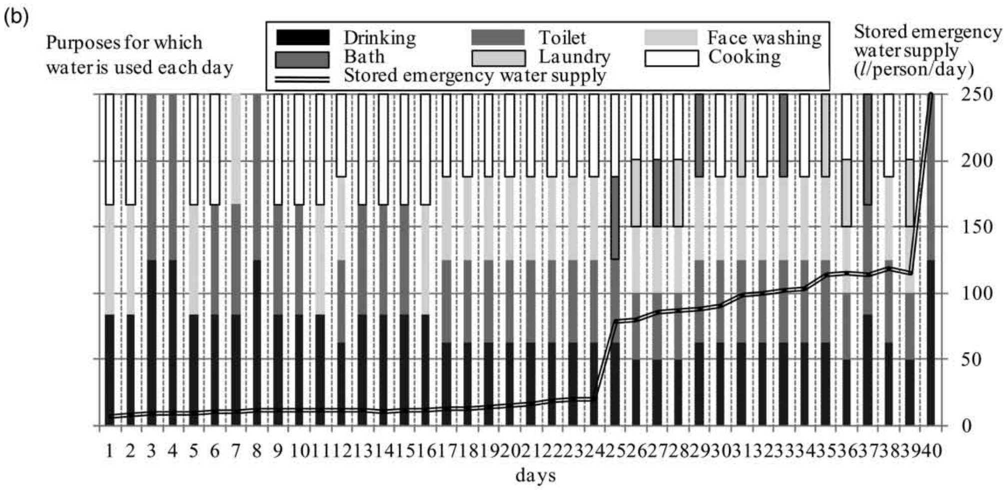
Figure 3 | Comparison of opportunity loss results for those with water supply suspended.

(a)



	First week	Second week	Third week	Fourth week	Fifth week
Drinking	7/7	7/7	7/7	7/7	6/7
Toilet	0/7	1/7	2/7	6/7	6/7
Face washing	4/7	6/7	5/7	3/7	1/7
Bath	0/7	0/7	0/7	0/7	0/7
Laundry	0/7	0/7	0/7	0/7	0/7
Cooking	6/7	6/7	5/7	7/7	0/7
Amount of water required	Emergencies	Emergencies	Emergencies	Emergencies	Normal times

(b)



	First week	Second week	Third week	Fourth week	Fifth week
Drinking	7/7	7/7	7/7	7/7	7/7
Toilet	4/7	6/7	6/7	7/7	7/7
Face washing	4/7	2/7	6/7	6/7	7/7
Bath	0/7	0/7	0/7	2/7	2/7
Laundry	0/7	0/7	0/7	2/7	2/7
Cooking	4/7	6/7	7/7	7/7	3/7
Amount of water required	Emergencies	Emergencies	Emergencies	Emergencies	Normal times

Figure 4 | (a) Evaluation results of living conditions in 1995. (b) Evaluation results of living conditions in 2011.

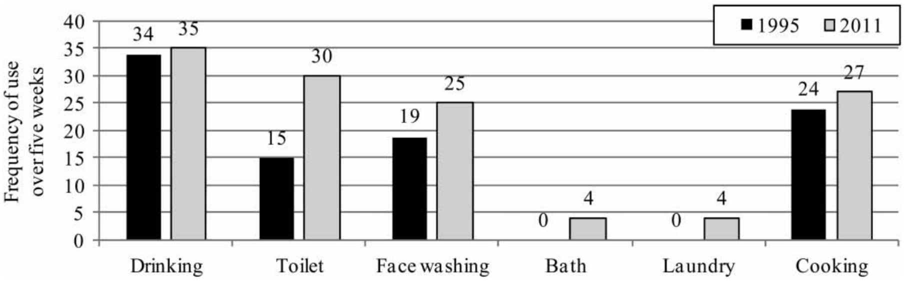


Figure 5 | Frequency of use over 5 weeks for each purpose.

amount almost every day in both 1995 and 2011. In terms of water for toilet, it was hardly available until the fourth week in 1995 while in 2011 it was available once in 2 days throughout the post-earthquake weeks. For bath and laundry, which requires a large water consumption per use, water was not available even in the fifth week in 1995, whereas in 2011 it was available twice a week from the fourth week. Furthermore, Figure 5 shows that the frequency of water use over the first 5 weeks is greater for all six purposes in 2011 than in 1995. These results indicate that earthquake-resistant upgrades of water supply facilities would increase the amount of water available as well as the frequency of its use for all six purposes.

Next, the living conditions in the fourth week and the fifth week – a transition period from an emergency to non-emergency – was compared. In 1995, no water was available for either bath or laundry, and the frequency of use for drinking, toilet, face washing, and cooking decreased in the fifth week, particularly for cooking. This is considered attributable to the difference in the demand for cooking water with 60 liters in normal times and 3 liters in emergencies. In 2011, on the other hand, the frequency of use for cooking reduced by half in the fifth week, but water for drinking, toilet, and face washing was available every day, even to the standards of the amount of water required in normal times. Also, in 2011, the frequency of use for bath and laundry did not change between the fourth and fifth weeks, available on a twice-a-week basis. Accordingly, the difference between the amount of water required in emergencies and normal times was less at present than that at the time of the Great Hanshin–Awaji earthquake. Hence, it is estimated that the stress caused to citizens brought about by the transition from an emergency to non-emergency state would be reduced.

CONCLUSION

In this paper, the effect of various seismic upgrade measures taken by Kobe City Waterworks Bureau was quantitatively evaluated based on living conditions, assuming a major earthquake hit the city's present water system. As a result, it was indicated that these seismic improvement measures would make the restoration period shorter than the time of the 1995 Great Hanshin–Awaji earthquake, allowing for wider and more frequent use of water by citizens. However, the amount of water was still limited for some purposes because of incompletion of the emergency recovery operation within 4 weeks, which is the target restoration period. Therefore, it is desirable to further promote seismic upgrade measures and reinforce strategies for recovery operation and emergency water supply. To verify this effect, it is necessary to work for higher accuracy of the evaluation model and encourage more research on methods to ensure efficient and quick recovery.

The evaluation procedures based on living conditions would require improvement to various aspects, including the methods to select the purpose of water usage and define water demand in the restoration period as well as the concept of satisfaction level. It is essential to conduct further studies in order to develop this evaluation method into a tool useful for informing the public in the event of a disaster.

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