Probabilistic Estimation of Time Required for Disaster Waste Disposal Generated by both Ground Motion and Tsunami due to the Anticipated Nankai Trough Earthquake

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ABSTRACT: Risk-based disaster waste management must be established in Japan to enhance the resilience of a coastal community subjected to the anticipated Nankai Trough earthquake. This study presents a novel framework for the resilience assessment of disaster waste disposal systems with incineration facilities and bridge networks under both seismic and tsunami hazards. The resilience of disaster waste disposal systems is quantified by the risk associated with a residual amount of disaster waste conditioned upon the elapsed time from the earthquake occurrence. As an illustrative example, the proposed methodology is applied to a hypothetical disaster waste disposal system in Mie Prefecture, Japan, which would be subjected to both ground motion and tsunami caused by the anticipated Nankai Trough earthquake.

1. INTRODUCTION

A catastrophic earthquake occurrence over Nankai Trough is predicted in the Pacific coastal region of Japan. The ground motion and subsequent tsunami caused by the anticipated Nankai Trough earthquake could damage many individual structures, resulting in serious functionality deterioration of civil engineering systems in a community. As observed in past natural disasters, this earthquake would cause a huge amount of disaster waste, which could hinder the post-disaster recovery processes in the affected areas. Therefore, an effective disaster waste management must be established in Japan to enhance community resilience before the occurrence of the anticipated Nankai Trough earthquake.

Disaster waste management strategies to dispose of disaster waste within a specific time have been proposed (Asai et al. 2021; Brown et al. 2011; Cheng et al. 2018; Kim et al. 2018). However, the time required to dispose of disaster waste could be underestimated since the correlation between the amount of disaster waste and the functionality deterioration of road networks, where the disaster waste is transported, was not considered. In addition, the effects of uncertainties associated with activities related to disaster waste disposal have not been investigated. Moreover, these previous studies were only limited to a single hazard. Therefore, resilience assessment of disaster waste disposal systems in coastal regions subjected to ground motions and tsunamis should be developed to establish more

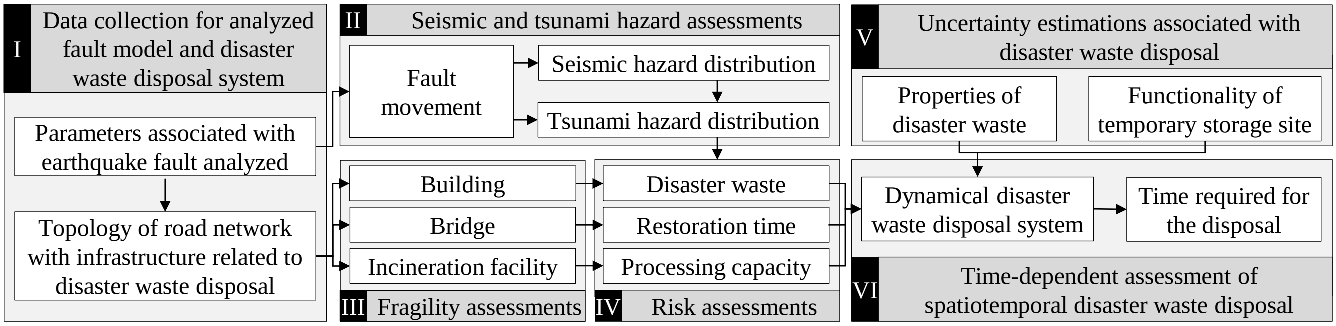


Figure 1: Resilience assessment of disaster waste disposal system under seismic and tsunamis considering both uncertainties associated with risks estimations and activities related to the disposal.

effective disaster waste management (Ishibashi et al. 2021b).

This paper presents a novel framework for the resilience assessment of disaster waste disposal systems with incineration facilities and bridge networks under both seismic and tsunami hazards. The resilience of disaster waste disposal systems is quantified by the risk associated with a residual amount of disaster waste conditioned upon the elapsed time from the earthquake occurrence. Uncertainties associated with the estimation of fault movement, structural vulnerability, recovery process of the disposal system (e.g., capacities of incineration facilities given a time after the event), and activities related to the disaster waste disposal are considered when estimating the resilience using Monte Carlo simulation (MCS). As an illustrative example, the proposed methodology is applied to a hypothetical disaster waste disposal system in Mie Prefecture, Japan, given the occurrence of the Nankai Trough earthquake.

2. RESILIENCE ASSESSMENT OF DISASTER WASTE DISPOSAL SYSTEM

Figure 1 presents the proposed framework for resilience assessment of disaster waste disposal system under seismic and tsunami hazards. The proposed procedure consists of six steps: (I) data collection for earthquake model and analyzed disaster waste disposal system, (II) seismic and tsunami hazard assessments, (III) fragility assessments for buildings, bridges, and incineration facilities, (IV) risk assessments for the individual structures, (V) uncertainty estimations of disaster waste disposal based on the past disaster data, and (VI) time-dependent assessment of spatiotemporal disaster waste disposal based on MCS considering uncertainties associated with the risk estimations and activities related to disaster waste disposal. The details of each step are described in the following subsections.

2.1. Data collection for analyzed disaster waste disposal system

The data associated with earthquake models, buildings, bridges, incineration facilities, and road networks are collected and defined as key components of the analyzed disaster waste system. The disaster waste generated from damaged buildings is transported over the road network and sequentially processed through the following facilities: primary temporary storage site, secondary temporary storage site, and incineration facilities. Therefore, the analyzed disaster waste disposal system can be represented by an undirected graph (Bondy and Murty 1976) as follows:

$$G = \left(G_{fr}, G_{st}\right) \quad (1)$$

$$G_{fr} \supseteq \left(V_{bu}, V_{br}, V_{if}\right), G_{st} \supseteq \left(V_{1s}, V_{2s}, V_{ju}, E\right) \quad (2)$$

where G is the disaster disposal system consisting of fragile structures G_{fr} and sturdy components G_{st}. The fragile structures G_{fr} consist of buildings V_{bu}, bridges V_{br}, and incineration facilities V_{if}. The study components G_{st} consisting of primary temporary storage sites V_{1s}, secondary temporary

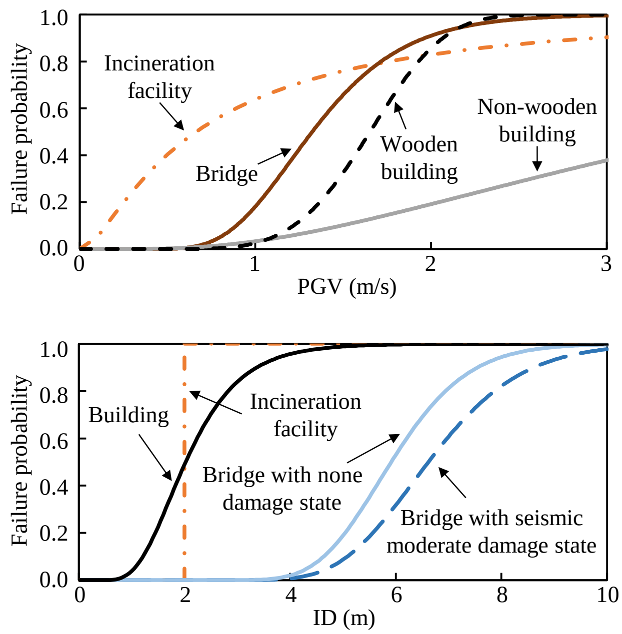


Figure 2: Seismic and tsunami fragility curves associated with complete damage state for building (Ishibashi et al. 2021b), bridge (Ishibashi et al. 2021a), and incineration facility.

storage sites V_{2s}, road intersections V_{ju} and road segments E are assumed to remain in sound condition during the disaster.

2.2. Seismic and tsunami hazard assessments

Seismic and tsunami hazard curves are evaluated at all the fragile structures' locations. The peak ground velocity (PGV) and inundation depth (ID) are used as seismic and tsunami intensity measures, respectively. The PGV is estimated according to the attenuation relationship considering the associated model uncertainties (Fujimoto and Midorikawa 2006; Si and Midorikawa 1999). ID is evaluated based on tsunami propagation analysis (Goto and Ogawa 1997; Okada 1992) considering various tsunami fault movements. The detailed procedure of seismic and tsunami hazard assessments can be found in Ishibashi et al. (2021b).

2.3. Seismic and tsunami fragility assessments

Seismic and tsunami fragility assessments are conducted for fragile structures (i.e., buildings, bridges, and incineration facilities) based on

Table 1: Random variables associated with disaster waste disposal

Object	Variable	Unit
Disaster waste storage	Denstiy	ton/m^3
	Combustible rate	-
Secondary temporary storage site	Prepartion preiod	day
	Commencing time for incinertion	day
	Sepration capacity	ton/day
	Incineration capacity	ton/day

analytical and empirical approaches. Although the fragility curves depend on not only structural types but also structural dimensions and details, a single fragility curve is adopted for each type of structure due to the high computational cost and limitation of the past disaster data.

Figure 2 shows the seismic and tsunami fragility curves associated with complete damage state for building (Ishibashi et al. 2021b), bridge (Ishibashi et al. 2021a), and incineration facility. The tsunami fragility curve for bridge is estimated considering damage due to ground motion. It should be noted that the fragility curves of the incineration facility are developed based on the data obtained during the 2011 Great East Japan earthquake (Japan Waste Management Association 2011).

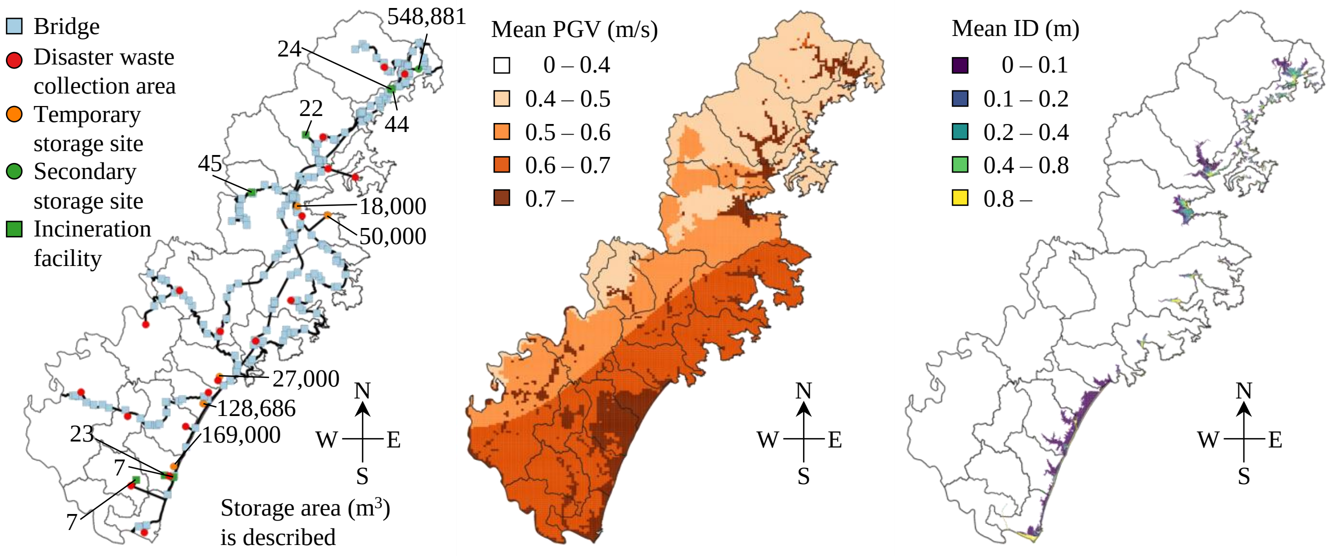
2.4. Risk assessments for individual structures

2.4.1. Reliability assessments

The reliability assessments for buildings, bridges, and incineration facilities over road network are carried out by convolving the seismic and tsunami hazards in each structure's location with the corresponding fragility curves. The probabilities associated with damage state $f(ds_i)$, where ds_0, ds_1 and ds_2 represent none, moderate, and complete damage states, respectively, are estimated for each structure by considering the corresponding seismic and tsunami hazards.

2.4.2. Disaster waste generated from damaged buildings

Disaster waste generated from damaged buildings can be expressed as follows (Ishibashi et al. 2021):



(a) (b) (c)

Figure 3: (a) Analyzed hypothetical disposal system and contours associated with the mean (b) PGV and (c) ID.

$$f\left(q_{dw}\right)=\sum_{i=1}^{2} f\left(q_{dw}\left|c_s, c_t, ds_{i,bu}\right.\right) f\left(ds_{i,bu}\right) \quad (3)$$

where $f(\cdot)$ is the probability density function, q_{dw} is the amount of disaster waste, c_s and c_t are the generation units for disaster wastes generated by ground motion and tsunami, respectively, and $ds_{i,bu}$ is the damage state i of building.

The amount of disaster waste is associated with the dominant hazard estimated at the building's location. Disaster waste is transported to the incineration facility through road networks, whereas the performance of the road network depends on the damage state of individual bridges.

2.4.3. *Disruption and restoration of road network based on bridge damages*

Time-dependent disruption of road network $G_d(t)$ due to bridge damage after an earthquake is evaluated considering the restoration of bridges as follows:

$$f\left\{G_d\left(t\right)\right\}= \int_{t_{br}} \sum_{i=1}^{2} f\left\{G_d\left(t\right)\left|t_{br}\right.\right\} f\left\{t_{br}\left|ds_{i,br}\right.\right\} f\left(ds_{i,br}\right) dt_{br} \quad (4)$$

where t_{br} is the time required for the restoration of bridge with damage state $ds_{i,br}$.

The time-dependent transportation of the disaster waste disposal system, including the incineration facilities and temporary storage site, can be simulated considering the restoration of bridge network connectivity according to Eq. (4) based on the MCS.

2.4.4. *Processing capacity of affected incineration facilities*

Time-dependent processing capacity of the affected incineration facility $c_{if}(t)$ is estimated considering the damage state $ds_{i,if}$ as follows:

$$f\left\{c_{if}\left(t\right)\right\}=\sum_{i=1}^{2} f\left\{c_{if}\left(t\right)\left|ds_{i,if}\right.\right\} f\left(ds_{i,if}\right) \quad (5)$$

2.5. *Probabilistic assessment of spatiotemporal disaster waste disposal*

The necessary time to dispose of the disaster waste depends on the properties of disaster waste and temporary storage sites. First, the disaster waste transported from damaged building's location is stored at primary temporary storage site, where its capacity depends on density and combustible rate of disaster waste. The secondary temporary storage site is installed in a certain preparation period after an earthquake occurrence and used as the separator and incinerator of disaster waste.

In order to simulate the probabilistic activities related to the disaster waste disposal, the random variables listed in Table 1 are considered using the detailed data on disaster waste disposal obtained during the 2011 Great East Japan earthquake (Ministry of the Environment 2014, 2017).

Probabilistic assessment of the disposal time is carried out based on spatiotemporal disaster waste disposal simulation considering uncertainties associated with activities for the disposal by employing MCS. The time-dependent disaster waste transportation over the disrupted road network can be evaluated with the minimum-cost flow assumption and the principle of mass conservation. The residual amount of disaster waste conditioned upon the elapsed time from the earthquake occurrence is estimated for the analyzed affected area.

3. ILLUSTRATIVE EXAMPLE

3.1. Analyzed area

Figure 3(a) shows the schematic layout of a hypothetical disaster waste disposal system in Mie Prefecture subjected to ground motion and tsunami caused by the anticipated Nankai Trough earthquake. To simplify the disaster waste transportation model, the disaster waste generated in each affected region is assumed to be located at the corresponding disaster waste collection area.

3.2. Spatial distribution of seismic and tsunami hazard intensities

Spatially varying seismic and tsunami hazard intensities are calculated according to Ishibashi et al. (2021b) and Alhamid et al. (2022). The mean PGV and ID are shown in Figures 3 (b) and (c), respectively. As shown in Figure 3, the seismic and tsunami hazards estimated in the region near the coastline are higher than those in other regions.

3.3. Probabilistic assessment of time required for disaster waste disposal

Figure 4 shows the probabilistic assessment of disaster waste conditioned upon the elapsed time after the occurrence of the anticipated Nankai

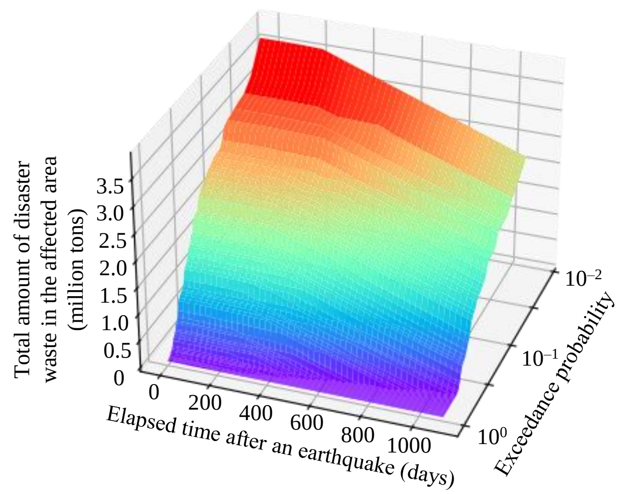


Figure 4: Time-dependent amount of disaster waste considering uncertainties associated with restoration estimation for structures and disposal activities.

Trough earthquake. The result shows that the disaster waste could not be disposed of within three years with a high probability since the processing capacity of incineration facilities are much smaller than the estimated amount of disaster waste.

4. CONCLUSIONS

The procedure for probabilistic assessment of the time required for disaster waste disposal generated by ground motion and tsunami is presented. As an illustrative example, the proposed methodology was applied to a hypothetical disaster waste disposal system given the occurrence of the anticipated Nankai Trough earthquake. The following conclusions are drawn:

1. The resilience assessment of disaster waste disposal systems under seismic and tsunami hazards is established. The resilience of disaster waste disposal systems is quantified by the risk associated with a residual amount of disaster waste conditioned upon the elapsed time from the earthquake occurrence.
2. The MCS-based spatiotemporal disaster waste disposal simulation is proposed considering uncertainties associated with estimations for disaster waste disposal system restoration and activities related to disaster waste disposal. The random variable associated with disaster

waste disposal is quantified based on the records of the disposal during the 2011 Great East Japan earthquake.

3. As an illustrative example, the resilience of a hypothetical disaster waste disposal system in Mie Prefecture, Japan, is evaluated given the occurrence of the anticipated Nankai Trough earthquake. The probabilistic time necessary to dispose of disaster waste is estimated based on the topology of bridge networks, the spatial distribution of seismic and tsunami intensities, fragilities of structures, and processing capacity for disaster waste in the analyzed disaster waste disposal system.

REFERENCES

Alhamid, A. K., M. Akiyama, H. Ishibashi, K. Aoki, S. Koshimura, and D. M. Frangopol. 2022. “Framework for probabilistic tsunami hazard assessment considering the effects of sea-level rise due to climate change.” *Struct. Saf.*, 94. https://doi.org/10.1016/j.strusafe.2021.102152.

Asai, S., T. Akiyama, H. Tanouchi, and N. Egusa. 2021. “A numerical simulation of disaster waste disposal in wakayama city by using dht model.” *Int. J. GEOMATE*, 20 (80): 23–28. https://doi.org/10.21660/2021.80.6155.

Bondy, J. A., and U. S. R. Murty. 1976. *Graph Theory with Applications*. *Graph Theory with Appl.*

Brown, C., M. Milke, and E. Seville. 2011. “Disaster waste management: A review article.” *Waste Manag.*

Cheng, C., L. Zhang, and R. G. Thompson. 2018. “Reliability analysis for disaster waste management systems.” *Waste Manag.*, 78: 31–42. https://doi.org/10.1016/j.wasman.2018.05.011.

Fujimoto, K., and S. Midorikawa. 2006. “Relationship between average shear-wave velocity and site amplification inferred from strong motion records at nearby station pairs.” *J. Japan Assoc. Earthq. Eng.*, 6 (1): 11–22. https://doi.org/10.5610/jaee.6.11 (in Japanese).

Goto, C., and Y. Ogawa. 1997. “Numerical Method of Tsunami Simulation with the Leap-Frog Scheme.” *IOC Manuals Guid. No. 35*.

Ishibashi, H., M. Akiyama, D. M. Frangopol, S. Koshimura, T. Kojima, and K. Nanami. 2021a. “Framework for estimating the risk and resilience of road networks with bridges and embankments under both seismic and tsunami hazards.” *Struct. Infrastruct. Eng.*, 17 (4): 494–514. https://doi.org/10.1080/15732479.2020.1843503.

Ishibashi, H., M. Akiyama, T. Kojima, K. Aoki, S. Koshimura, and D. M. Frangopol. 2021b. “Risk estimation of the disaster waste generated by both ground motion and tsunami due to the anticipated Nankai Trough earthquake.” *Earthq. Eng. Struct. Dyn.*, 50 (8): 2134–2155. https://doi.org/10.1002/eqe.3440.

Japan Waste Management Association. 2011. “Survey of facility damage caused by the Great East Japan Earthquake.” http://www.jwma-tokyo.or.jp/asp/saigai/20110420sisetuhigai_syukei.pdf.

Kim, J., A. Deshmukh, and M. Hastak. 2018. “A framework for assessing the resilience of a disaster debris management system.” *Int. J. Disaster Risk Reduct.*, 28: 674–687. https://doi.org/10.1016/j.ijdrr.2018.01.028.

Ministry of the Environment. 2014. “Record of the disaster waste disposal in the three prefectures affected by the Great East Japan Earthquake (Iwate, Miyagi, and Fukushima prefectures).”

Ministry of the Environment. 2017. “Report on technical matters for disaster waste disposal based on the experience of the Great East Japan Earthquake.” http://kouikishori.env.go.jp/document_video/pdf/wg_report_02.pdf.

Okada, Y. 1992. *Surface deformation to shear and tensile faults in a halfspace*. *Bull. Seismol. Soc. Am.*

Si, M., and S. Midorikawa. 1999. “New attenuation relationships for peak ground acceleration and velocity considering effects of fault type and site condition.” *J. Struct. Constr. Eng.*, 64 (523): 63–70. https://doi.org/10.3130/aijs.64.63_2 (in Japansese).