DAMAGE PROPAGATION CAUSED BY INTERDEPENDENCY AMONG CRITICAL INFRASTRUCTURES

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ABSTRACT :

When critical infrastructures are damaged by the large-scale disaster such as a powerful earthquake, the damage interacts among infrastructures and increases especially in urban areas. The damage spreads society and economic function, possibly lead to enormous social loss. For mitigating such damage, it is necessary to understand the structure of interdependency, then planning suitable damage propagation prevention and restoration strategies. However, there has been insufficient research for interdependency among today's urban infrastructures.

In this study, the effect of interdependency among critical infrastructures during earthquake disaster is analyzed qualitatively and quantitatively. First, interdependency among critical infrastructures such as electric power, waterworks, gas, transportation, telecommunication, finance, medical services, administrative services, etc. is investigated from past disasters, sorted out as matrices and analyzed by influence diagrams. Next, a propagation model is developed using interdependency structure matrices. Then, the influence of the interdependency is surveyed quantitatively through a case study of an anticipated earthquake disaster in the Tokyo metropolitan area. The results show that almost all the infrastructures are interdependent, and electric power, telecommunications, and highway systems have a greater influence on other infrastructures.

KEYWORDS: interdependency, infrastructure, damage propagation, mitigation, earthquake, influence diagram

1. INTRODUCTION

Our everyday lives and industrial activity are supported by various infrastructures such as roads, railroads, electric power, gas, waterworks, sewerage, and telecommunications. These various infrastructures, especially in urban areas, are highly complex. If a large-scale disaster such as an earthquake occurs in such areas, each infrastructure is damaged not only by the disaster itself, but also by damage to interdependent infrastructures. These kinds of damage propagate to one another and affect society and economic activities that support urban functions, possibly leading to enormous social loss.

For example, in the Kobe Earthquake (the South Hyogo Prefecture Earthquake in 1995), traffic congestion caused by paralysis of highways, etc. and breakage of lifelines caused by bridge collapses seriously hampered the emergency functions of hospitals, administrative services, etc. This showed the need for a well prepared recovery strategy that takes into account the damage propagation among interdependent infrastructures in a massive urban disaster.

Existing researches on the damage propagation and its effects in Japan include fundamental research by Nojima (1988), et al. and Kameda (1992), et al.; research on the propagation structure by Katayama (1989), Sato, et al.;

research on the earthquake disaster propagation structure in urban areas by Kawashima (1993), et al. and Otsuka (1996), et al.; and investigation reports on the interaction among cases of lifeline damage during the Kobe Earthquake by Nojima (1996), et al. and Kameda (1997), et al. However, there has been insufficient research on practical countermeasures to damage propagation resulting from the deepening interdependency among today's urban infrastructures, and on the effect of the rapid development of telecommunications.

Goto (2007), et al. of the Kawasaki Laboratory of the National Research Institute for Earth Science and Disaster Prevention (this laboratory was closed in March 31, 2007) and the Earthquake Disaster Prevention Division of the National Institute for Land and Infrastructure Management cooperated in investigating the details of damage propagation among infrastructures during recent disasters. They analyzed the damage propagation of today' urban infrastructures, estimated the effect of the interdependency quantitatively through a case study, and investigated mitigation measures. This paper reports the part of these results.

Here, the authors would like to express their appreciation for the advice of the Investigative Commission, which consisted of Professor Fumio Yamazaki of Chiba University, Professor Tadanobu Sato of Kobe Gakuin University, Professor Nobuoto Nojima of Gifu University, professionals of lifeline companies, etc.

2. SURVEY OF DAMAGE PROPAGATION DURING RECENT DISASTERS

Actual cases of damage propagation among critical infrastructures during recent earthquake were investigated. Here, the critical infrastructures comprise "electric power", "gas", "waterworks", "sewerage", " telecommunications", "road", "railroad", "port", "airport" and social functions such as "transportation (including physical distribution and passenger services)", "finance", "medical treatment", and "administration (including police and fire-fighting)."

2.1. Damage Propagation Cases in Earthquake Disaster

Cases of damage propagation during the Kobe Earthquake and the Mid Niigata Prefecture Earthquake (October 2004) were investigated. Information was obtained from literature on both earthquakes and from hearing investigations on the Mid Niigata Prefecture Earthquake. 10 business units of critical infrastructures in Niigata prefecture were visited in the end of November 2006.

The results of the investigation are outlined as follows:

The effects of damage propagation were identified, although emergency response and restoration activities by each infrastructure organization generally functioned. For example, although almost all business places were equipped with a backup power supply, there were problems with transportation for refueling operations. Moreover, cooperation among infrastructure organizations through regional liaison council did not function effectively during the restoration activities.

There were 127 actual cases of damage propagation extracted from the literature on the Kobe Earthquake. There were 89 such cases for the Mid Niigata Prefecture Earthquake, including hearing investigation results. The collected cases were classified into damage propagation from other infrastructures (terminal) and damage propagation to other infrastructures (origin), as shown in Table 1.

In the Kobe Earthquake, there were many cases of propagation from electric power, road, and railroad to other infrastructures. Conversely, there were many of propagation to gas and sewerage from other infrastructures.

In the Mid Niigata Prefecture Earthquake, there were many cases of propagation from electric power and road to other infrastructures, and many cases of propagation to gas and sewerage from other infrastructures, as in the case of the Kobe Earthquake. However, there were very few cases of damage propagation from railroad to other infrastructures. This clearly showed the dependence on road traffic in the mountainous area of Mid Niigata Prefecture.

Table 1 Number of Actual Cases of Disaster Propagation

	The Kobe Earthquake		The Mid Niigata Prefecture Earthquake	
	From others (Terminal)	To others (Origin)	From others (Terminal)	To others (Origin)
Electric power	6	21	8	29
Gas	13	2	6	1
Waterworks	8	16	6	7
Sewerage	16	1	12	4
Telecommunications	15	18	12	16
Road	7	38	14	24
Railroad	8	22	9	6
Port	4	4	0	0
Airport	0	0	0	0
Transportation	13	1	9	0
Finance	11	0	0	0
Medical treatment	15	0	8	0
Administration	11	4	5	2

In both earthquakes, there were many cases of the influence of telecommunications on other infrastructures. However, in the Mid Niigata Prefecture Earthquake, there were many cases involving cellular phones, thus reflecting the rapid change in the telecommunications environment since the Kobe Earthquake.

3. ANALYSIS OF DAMAGE PROPAGATION STRUCTURE

3.1 Arrangement of Damage Interdependency Matrix

The collected damage propagation cases were arranged in matrix form. The infrastructure that causes damage to others (origin), and the infrastructure that suffers damage from others (terminal) were allotted to a sequence and, respectively. This matrix is called “damage interdependency matrix”. It was divided into three phases: "damage propagation immediately after disaster", "damage propagation in emergency response activity", and "damage interdependency influence in restoration work".

Addition to and reexamination of the initial damage interdependency matrix were performed through brainstorming by the Investigative Commission (noted in **1.**) imagining a disaster caused by a Tokyo metropolitan near-field earthquake. Furthermore, experts of the relevant infrastructure organizations checked and added items through weighting evaluation work (discussed in ***4.1***). Thus, the final damage interdependency matrix was created, as shown in Table 2 - 4. These tables omit description of each element due to space limitation, and existence of interdependence is shown by hatching.

The "damage propagation immediately after disaster" matrix shows that the origin infrastructures in the order of electric power, road, telecommunications and gas influence many other infrastructures. The "damage propagation in emergency response activity" matrix shows that roads and railroads have the greatest influence on other infrastructures, and that telecommunications have the second-greatest influence. The "damage interdependency influence in restoration work" matrix also shows that roads and telecommunications influence other infrastructures in many ways.

Among the collected cases arranged into these matrices, "road block by collapse of buildings", "shortage of space for restoration work base because of school grounds being occupied by temporary houses", etc. are noted as examples in which confined space affects restoration works. The scarcity of open spaces in the mega cities in Japan is a problem.

Table 2 Damage Propagation Immediately after Disaster

Origin Terminal	Electric power	Gas	Water-works	Sewerage	Telecom	Road	Railroad	Port	Airport	Trans-porta-tion	Finance	Medical treat-Ment	Admin-istra-tion
Electric power	▨	▨	▨			▨							
Gas	▨	▨	▨	▨	▨	▨	▨	▨					
Waterworks	▨	▨	▨	▨	▨	▨	▨						
Sewerage	▨	▨	▨		▨	▨	▨						
Telecommunication	▨	▨			▨	▨	▨						
Road	▨	▨	▨	▨	▨	▨	▨						
Railroad	▨	▨	▨	▨	▨	▨	▨						
Port	▨	▨	▨		▨	▨	▨						
Airport	▨	▨	▨	▨	▨	▨	▨						
Transportation	▨	▨	▨	▨	▨	▨	▨						▨
Finance	▨	▨			▨	▨	▨						▨
Medical treatment	▨	▨	▨	▨	▨	▨							
Administration	▨	▨	▨	▨	▨	▨	▨	▨				▨	

Table 3 Damage Propagation in Emergency Response Activity

Origin Terminal	Electric power	Gas	Water-works	Sewerage	Telecom	Road	Railroad	Port	Airport	Trans-porta-tion	Finance	Medical treat-Ment	Admin-istra-tion
Electric power		▨		▨	▨	▨	▨						
Gas	▨		▨		▨	▨	▨						
Waterworks	▨				▨	▨	▨	▨					
Sewerage	▨		▨		▨	▨	▨	▨					
Telecommunication	▨		▨		▨	▨	▨						
Road	▨			▨	▨	▨	▨						▨
Railroad	▨				▨	▨	▨						
Port	▨				▨	▨	▨	▨					
Airport					▨	▨	▨						
Transportation	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨			
Finance	▨	▨		▨	▨	▨	▨						
Medical treatment	▨	▨	▨	▨	▨	▨	▨						▨
Administration	▨		▨	▨	▨	▨	▨					▨	

Table 4 Damage Interdependency Influence in Restoration Work

Origin Terminal	Electric power	Gas	Water-works	Sewerage	Telecom	Road	Railroad	Port	Airport	Trans-porta-tion	Finance	Medical treat-ment	Admin-istra-tion
Electric power			▨	▨	▨	▨	▨	▨					▨
Gas	▨		▨	▨	▨	▨	▨	▨					
Waterworks	▨		▨	▨	▨	▨	▨	▨					
Sewerage	▨		▨		▨	▨	▨	▨	▨				
Telecommunication	▨				▨	▨	▨	▨		▨			
Road	▨	▨	▨	▨	▨	▨	▨	▨					
Railroad	▨	▨	▨	▨	▨	▨	▨	▨					▨
Port	▨				▨	▨		▨	▨				
Airport					▨	▨		▨					
Transportation	▨	▨	▨	▨	▨								
Finance		▨			▨	▨	▨						
Medical treatment	▨				▨								
Administration	▨	▨	▨		▨								

3.2 Analysis by Influence Diagram

The mechanism of damage propagation, written in the damage interdependency matrix above, can be typified as physical damage propagation, functional damage propagation and restoration trouble. Functional damage propagation has the feature of having time and spatial spread of influence and physical damage propagation generates physical functional damage immediately after a disaster. Restoration trouble affects the time during which restoration takes. However, these three damage connection relations were analyzed by influence diagrams (influence charts), which show the many infrastructures as origin points or terminal points of influence.

In the influence diagram, the influence relations between infrastructures are connected by arrows. An infrastructure is expressed as a node, and influence relations are expressed as effective arcs. The result of the analysis on the Kobe Earthquake is shown with nine infrastructures other than social functions in Figure 1.

In physical damage propagation, road and railroad act as an origin point and affect other infrastructures. Meanwhile, electric power is an origin point of many arcs in functional damage propagation. And, for restoration trouble, road and telecommunications are the origins of many arcs.

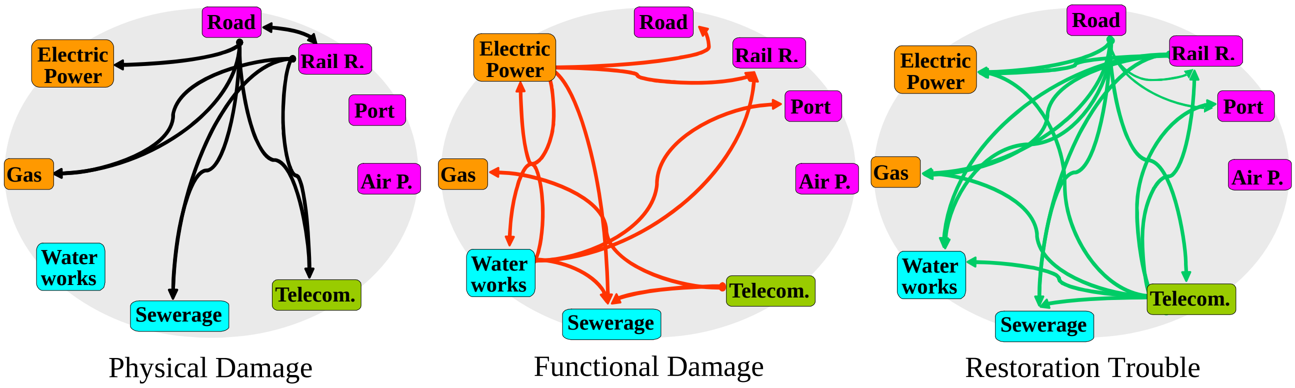

Figure 1 Influence diagrams

It is characteristic that roads are not origin points in functional damage propagation. However, for physical damage propagation and restoration trouble, roads are origins of influence to many infrastructures. They are connected with almost all infrastructures, especially for restoration trouble. Thus, it is suggested that the functional recovery of roads will greatly affect the progress of restoration of other infrastructures. In contrast, there is little that makes roads terminal points, i.e., roads rarely receive damage propagation from other infrastructures.

Then, as roads are the major contributor to physical damage propagation and restoration problems, a prior measure that minimizes physical damage propagation and enables prompt recovery of its own function after damage would greatly assist in early restoration of other infrastructures.

4. QUANTITATIVE EVALUATION OF DAMAGE PROPAGATION

Based on the analysis of the damage propagation noted above, a quantitative method for evaluating damage propagation between infrastructures was developed. A case study assuming a disaster caused by a Tokyo metropolitan near-field earthquake was then performed, and the influence of infrastructure interdependency was discussed basing on this evaluation.

4.1 Fundamental Consideration

Damage expansion due to damage propagation between infrastructures starts from the moment of a disaster occurrence and continues for several days to several weeks. Moreover, restoration problems resulting from damage of other infrastructures may occur during restoration work. Damage expansion and restoration problems accumulate with time. Then, a model containing a time concept, like a system dynamics model, is needed to estimate this cumulative increase. In this study, however, the total damage caused by the interdependency was estimated simply, in snapshot form one day, one week and one month after a disaster occurrence.

The socio-economical damage increased by damage propagation between infrastructures can be expressed conceptually by the following formula.

TSI: Socio-economical damage due to damage propagation among infrastructures = **SI**: Socio-economical damage factor

X **FD**: Functional deficiency degree when damage occurs to infrastructure X **RD**: Rate of damage occurrence when damage to other infrastructures influences the infrastructure concerned X ***X***: Initial damage of each infrastructure

As the damage interdependency matrix mentioned in ***3.1*** only denotes "on or off" of the interdependency, we divided the matrix into the FD and the RD to include weighting evaluation of quantitative influence. Then, this study evaluated the functional damage to each infrastructure by multiplication; FD x RD x ***X***, when the each infrastructure suffered an initial physical damage due to the earthquake. However, the SI were not investigated in this study. So, the TSI evaluation is reserved as a future research tasks.

In the case study, the damage propagation modeling (the formula (1)) expressed in matrix form was used. Here, the input vector ***X*** is the initial damage to each infrastructure, and the interdependency structure matrix ***C*** (FD_{ij} x RD_{ij}) denotes the greatness of the influence of damage propagation among infrastructures.

Output (damage due to first cycle damage propagation) ***Y***

Interdependency structure matrix ***C***

Input (initial damage) ***X***

$$\begin{pmatrix} \sum_{j}^{?} x_j c_{j1} \\ \sum_{j}^{?} x_j c_{j2} \\ . \\ . \\ \sum_{j}^{?} x_j c_{jm} \end{pmatrix} = \begin{pmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ . & \cdots & \cdots & \cdots \\ . & \cdots & \cdots & \cdots \\ c_{m1} & c_{m2} & \cdots & c_{mn} \end{pmatrix} \cdot \begin{pmatrix} x_1 \\ x_2 \\ . \\ . \\ x_n \end{pmatrix} \qquad \text{--- (1)}$$

In addition, if there is no change in interdependency structure, the damage due to multi-cycle damage propagation can be obtained from formula (2).

$\boldsymbol{Y}_k$: Damage due to k-th cycle damage propagation

$$\boldsymbol{y}_k = \sum_{?}^{?} \boldsymbol{C}^k \boldsymbol{X} \qquad \text{--- (2)}$$

Evaluation of Input Vector ***X*** and Interdependence Structure Matrix ***C*** will be shown in presentation.

4.2 Calculation Result of Case Study

Damage expansions for each infrastructure under the interdependency influence at timings of one day, one week and one month after disaster occurrence were calculated up to the 3rd propagation cycle. The result one day after disaster occurrence is shown in Figure 2. Functional damage beyond the initial damage appeared in all the infrastructures under the propagation influence among infrastructures. Functional damage of "Airport" was influenced by damage to other infrastructures, although no initial damage to itself was assumed.

Figure 3 shows the terminal infrastructures according to each origin infrastructure. The influence of "electric power", whose weight of functional damage propagation was evaluated to be great, turned out to be small in comparison with "road", "telecommunications" and "railroad". This is considered to result from the rather small setup of “electric power” damage rate in comparison with "road", "railroad", etc. in the initial damage set of a Tokyo metropolitan near-field earthquake.

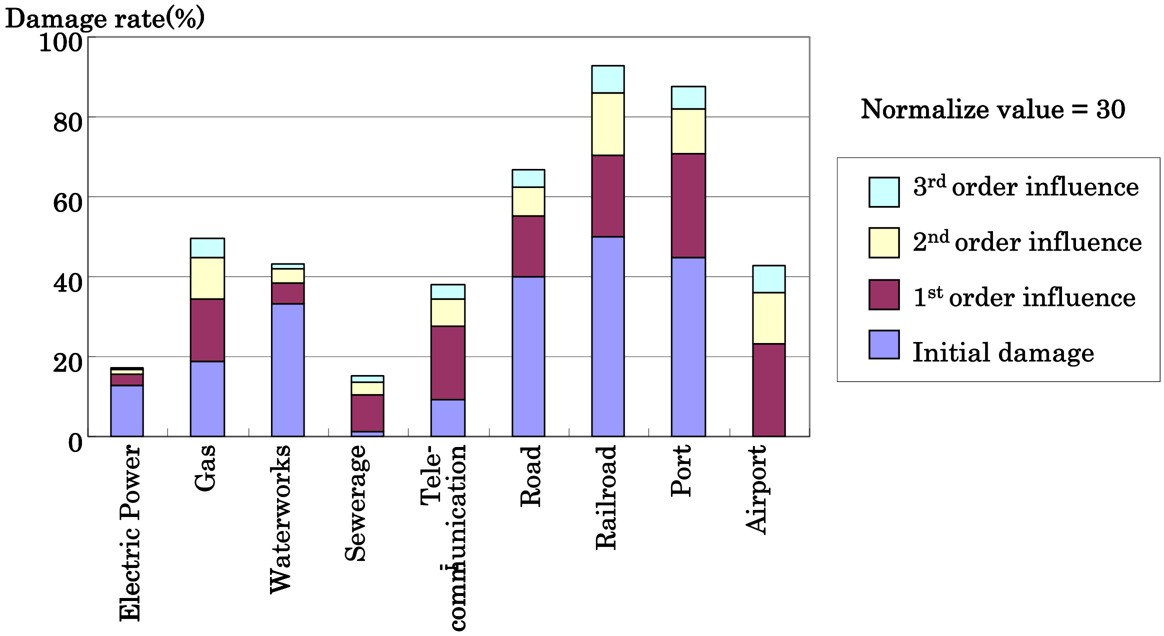

Figure 2 One day after disaster outbreak

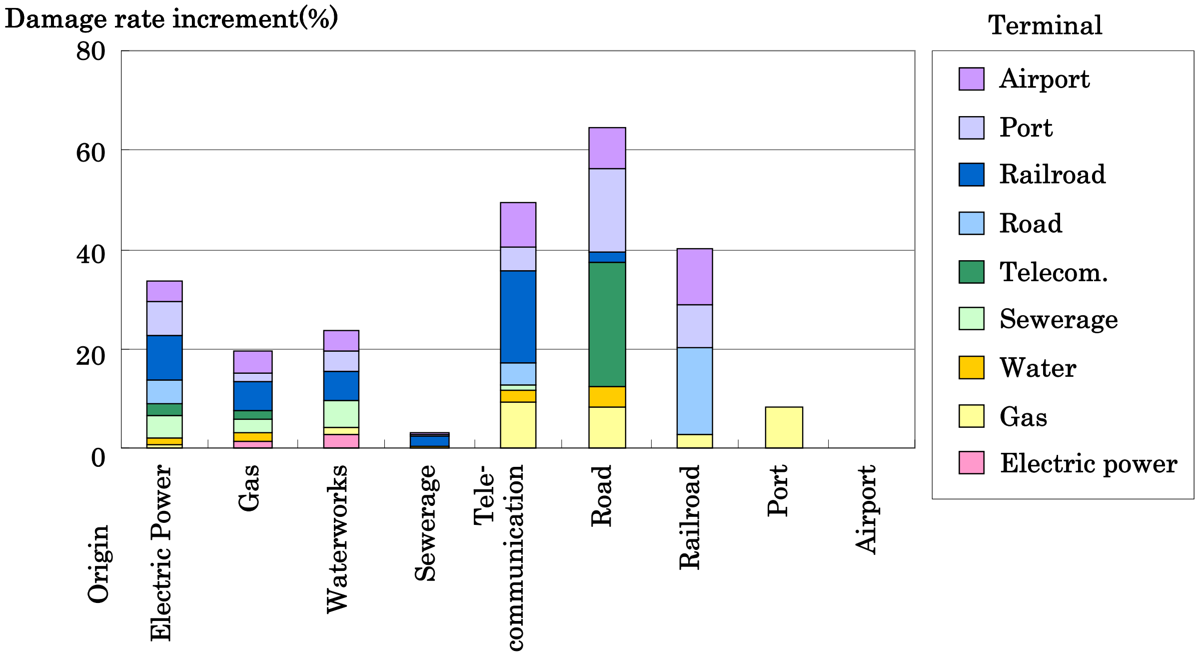

Figure 3 Terminal infrastructure according to origin infrastructure

The weighting value might vary with different conditions assumed by different evaluators. It is therefore necessary to achieve homogeneity of weighting evaluation by clarifying the standard and by including two or more evaluators from different positions etc.

5. CONCLUSION AND FUTURE SUBJECT

5.1 Results of This Research

(1) Damage propagation among infrastructures occurred in almost all infrastructures immediately after a disaster. “electric power”, “gas”, “telecommunications” and “road” had high probabilities of affecting other

infrastructures.

(2) In the case study assuming a Tokyo metropolitan near-field earthquake, functional problems beyond initial physical damage appeared in all infrastructures due to damage propagation among infrastructures. In particular, large effects of damage propagation originated from "road", "telecommunications" and "railroad".

(3) In addition, a setup of initial damage had a big influence on the result.

5.2 Future Extensions and Subjects.

(1) The damage interdependency matrix created by this research is also utilizable for prediction of damage propagation phenomena in each infrastructure at the time of the disaster mitigation response.

(2) It is also applicable to carrying out emergency drills for a scenario assuming damage propagation among infrastructures. It is expected that new subjects and new measures corresponding to a disaster will be identified by implementation of such training.

(3) Further investigations of phenomena not generated in previous disasters are required, especially considering the maintenance situation of today's infrastructure.

(4) For more reliable quantitative evaluation of damage propagation, further development is required of calculation techniques, etc. In particular, since many infrastructures have network structures, evaluation considering damage spreading through a network is needed.

(5) Construction of a simulation model that can quantitatively evaluate socioeconomic propagation influence is needed for evaluation of the overall damage effect on our lives and economic activities, and for developing mitigation measures.

As for the item (4), the authors have been developing a new simulation model based on system dynamics for evaluation of functional damage propagation. The system dynamics model makes it feasible to evaluate time-history of the damage propagation quantitatively. A case study using the new model shows that restoration of the infrastructures is delayed by the functional damage propagation. Further, as for the item (5), preliminary study on the damage propagation influence on industrial production has also been conducted; details of these results are forthcoming.

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