DAMAGE PROPAGATION CAUSED BY INTERDEPENDENCY AMONG CRITICAL INFRASTRUCTURES

Yozo GOTO[1], Takeyasu SUZUKI[2], Iwao SUETOMI[3], Yasuhiro SHOJI[4], Mai TSURUTA[4], Shojiro KATAOKA[4] and Hikari SUZUKI[5]

[1] Environment and Disaster Research Institute, Fuji Tokoha University a.p. National Research Institute for Earth Science and Disaster Prevention
[2] Graduate Schools of Medicine and Engineering, Yamanashi University
[3] Department of Research Engineering, Japan Engineering Consultants Co., Ltd
[4] Earthquake Disaster Prevention Division, National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure and Transport
[5] Environment and Disaster Division, Tokyo Office, Mikuniya Corporation

ABSTRACT

Interdependency among critical infrastructures such as electric power, water, gas, transportation, telecommunication, finance, medical services, administrative services, etc. is investigated from past disasters, sorted out as matrices and analyzed by FTAs and 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. Furthermore, active utilization of cellular-phone mail, car-navigation systems, marine transportation, air transportation and pre-agreement with related organizations are found to be effective for quick restoration.

KEYWORDS

interdependency, infrastructure, disaster, mitigation, earthquake, flood, FTA, influence diagram

INTRODUCTION

Our everyday lives and industrial activity are supported by various infrastructures such as roads, railroads, electric power, gas, water, sewerage, and telecommunications. 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 in 1995, traffic congestion caused by paralysis of signals, 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 structure among interdependent infrastructures in a massive urban disaster.

Existing researches on the damage propagation structure 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 influence of a massive blackout accompanying a typhoon by Katayama (1992), Yamasaki, et al; research on the earthquake disaster propagation structure in urban areas by Kawashima (1993), et al.; Otsuka (1996), et al.; and investigation reports on the interaction among cases of lifeline damage during the Great Hanshin 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 information-and-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 structure of today’ urban infrastructures, estimated the effect of the interdependency quantitatively through a case study, and investigated mitigation measures. This paper reports 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.

SURVEY OF DAMAGE PROPAGATION DURING RECENT DISASTERS

Actual examples of damage propagation among critical infrastructures during recent earthquake and heavy rain disasters were investigated. Overseas examples of disasters that may happen in Japan were also checked. Here, the critical infrastructures comprise "electric power", "gas", "waterworks", "sewer", "information-and-telecommunications", "road", "railroad", "port", "airport" and "social functions" such as "transportation and physical distribution", "passenger services", "finance", "medical treatment", and "administration (including police and fire-fighting)."

Damage Propagation Examples in Earthquake Disaster

Examples of damage propagation during the Kobe Earthquake (January, 1995) and the Niigata Chuetsu Earthquake (October, 2004) were investigated. Information was obtained from literature on both earthquakes and from hearing investigations on the Niigata Chuetsu Earthquake. 10 business units of critical infrastructures in Niigata prefecture were visited in the end of November, 2006.
The investigation items were as shown below.

(1) Influence from other infrastructures that suffered a great deal of damage
(2) Action taken to prevent damage propagation to other infrastructures
(3) Prior measures whose effectiveness was verified
(4) Measures that other infrastructures need to take
(5) Foreseeable damage propagation in mega cities

The results of the investigation are outlined as follows.
The effects of damage propagation were identified. However, emergency response and restoration activities by each infrastructure organization generally functioned effectively. 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 examples of damage propagation extracted from the literature on the Kobe Earthquake. There were 89 such examples for the Niigata Chuetsu Earthquake, including hearing investigation results. The collected examples were classified into damage propagation from other infrastructures (terminal) and damage propagation to other infrastructures (origin), as shown in Table 1.

TABLE 1
Number of Actual Examples of Disaster Propagation

	Great Kobe Earthquake		Niigata Chuetsu Earthquake		Heavy Rain & Snowfall	
	From others (Terminal)	To others (Origin)	From others (Terminal)	To others (Origin)	From others (Terminal)	To others (Origin)
Electric power	6	21	8	29	1	14
Gas	13	2	6	1	1	0
Waterworks	8	16	6	7	4	0
Sewer	16	1	12	4	2	2
Information-and-telecommunications	15	18	12	16	5	7
Road	7	38	14	24	2	13
Railroad	8	22	9	6	2	0
Port	4	4	0	0	0	0
Airport	0	0	0	0	0	0
Transportation and Physical distribution, Passenger service	13	1	9	0	7	0
Finance	11	0	0	0	1	0
Medical treatment	15	0	8	0	3	0
Administration including Police and Fire-fighting	11	4	5	2	9	1

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

In the Niigata Chuetsu Earthquake, there were many examples of propagation from electric power and road to other infrastructures, and many examples of propagation to gas and sewer from other infrastructures, as in the case of the Kobe Earthquake. However, there were very few examples of damage propagation from railroad to other infrastructures. This clearly showed the dependence on road traffic in the mountainous area of Niigata Chuetsu.
In both earthquakes, there were many examples of the influence of information-and-telecommunications on other infrastructures. However, in the Niigata Chuetsu

Earthquake, there were many examples involving cellular phones, thus reflecting the rapid change in the information-and-telecommunications environment since the Kobe Earthquake.

Damage Propagation Examples in Heavy Rain and Heavy Snowfall Disaster

Damage propagation was also investigated in the disasters of the Fukuoka flood (June, 1999), Tokai heavy rain (September, 2000), Fukushima and Niigata heavy rain (July, 2004), typhoon No.16 (August, 2004), typhoon No.23 (October 2004), and the 2004 heavy snowfall. The information was obtained from the literature. As the result, 37 examples of damage propagation were acquired. These examples are also shown in Table 1.

As for the earthquakes, there were many cases of propagation of electric power and road to other infrastructures. However, there were many stoppages of electric equipment and apparatuses due to submersion in water, which does not generally occur in seismic hazards.

Overseas Damage Propagation Example

A massive power blackout occurred in northeastern North America, including parts of the United States and Canada, in August, 2003, and Hurricane Katrina struck the southern United States in August, 2005. These events were investigated to study actual examples of damage propagation among critical infrastructures and to examine the possibility of similar events occurring in Japan.

The investigation comprised a study of the literature, and news stories were also investigated from websites as a supplement. 21 examples were acquired from the northeastern North America power failure, and 12 were acquired from Hurricane Katrina. The "origin infrastructure" and the "terminal infrastructure" were obtained for each example. They were then classified according to their occurrence probability in Japan under three categories: "unlikely to occur in Japan", "similar examples occurred in Japan" and "could occur in Japan, but no examples seen up to now".

The following six examples fell into the "could occur in Japan" class.
[Electric power to Road] Street tunnel closed due to stop of ventilator caused by power failure
[Electric power to Aviation] Airport closed due to power failure
[Electric power to Administration] Impossible to use cameras and various electronic bulletin boards, thus hampering information gathering and dissemination.
[Waterworks to Medical treatment] Dialysis treatment difficult due to low water pressure.
[Waterworks to Administration] Fire-fighting hampered by low water pressure.
[Information-and-telecommunications to Administration] Trouble extends to communication with outside.

ANALYSIS OF DAMAGE PROPAGATION STRUCTURE

Arrangement of Damage Interdependency Matrix

The collected damage propagation examples 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 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 below. Thus, the final damage interdependency matrix was created, as shown in Table 2 – Table 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, information-and-telecommunications and gas influence many other infrastructures. Some actual examples of damage propagation in a mega-city are "damage to telegraph poles and electric wires due to building-collapse", "communication obstacle by two or more place cutting of a multiplex circuit", "stop of stock market due to damage to network infrastructure", etc.

The "damage propagation in emergency response activity" matrix shows that roads have the greatest influence on other infrastructures, and that information-and-telecommunications has the second-greatest influence The "damage interdependency influence in restoration work" matrix also shows that roads and information-and-telecommunications influence other infrastructures in many ways.

Among the collected examples 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, and the scarcity of unused lands in the mega cities in Japan is a problem.

Table 2
Damage Propagation Immediately after Disaster

Terminal \ Origin	Electric power	Gas	Water	Sewer	I.& T.	Road	Railroad	Port	Airport	Trans-porta-tion	Finance	Medical treat-Ment	Admin-istra-tion
Electric power	▨	▨	▨			▨							
Gas	▨	▨	▨	▨	▨	▨	▨	▨					
Waterworks	▨	▨	▨	▨	▨	▨	▨						
Sewer	▨	▨	▨		▨	▨	▨						
Information & Telecom.	▨	▨			▨	▨	▨						
Road	▨	▨	▨	▨	▨	▨	▨						
Railroad	▨	▨	▨	▨	▨	▨	▨						
Port	▨	▨	▨		▨	▨	▨						
Airport	▨	▨	▨	▨	▨	▨	▨						
Transportation	▨	▨	▨	▨	▨	▨	▨						▨
Finance	▨	▨			▨	▨	▨						▨
Medical treatment	▨	▨	▨	▨	▨	▨							
Administration	▨	▨	▨	▨	▨	▨	▨	▨				▨	

Table 3
Damage Propagation in Emergency Response Activity

Origin / Terminal	Electric power	Gas	Water	Sewer	I.& T.	Road	Railroad	Port	Airport	Trans-porta-tion	Finance	Medical treat-Ment	Admin-istra-tion
Electric power		■		■	■	■	■						
Gas	■		■		■	■	■						
Waterworks	■				■	■	■	■					
Sewer	■		■		■	■	■	■					
Information & Telecom.	■		■		■	■	■						
Road	■			■	■	■	■						■
Railroad	■				■	■	■						
Port	■				■	■	■	■					
Airport					■	■	■						
Transportation	■	■	■	■	■	■	■	■	■	■			
Finance	■	■		■	■	■	■						
Medical treatment	■	■	■	■	■	■	■						■
Administration	■		■	■	■	■	■					■	

Table 4
Damage Interdependency Influence in Restoration Work

Origin / Terminal	Electric power	Gas	Water	Sewer	I.& T.	Road	Railroad	Port	Airport	Trans-porta-tion	Finance	Medical treat-ment	Admin-istra-tion
Electric power			■	■	■	■	■	■					■
Gas	■		■	■	■	■	■	■					
Waterworks	■		■	■	■	■	■	■					
Sewer	■		■		■	■	■	■	■				
Information & Telecom.	■				■	■	■	■		■			
Road	■	■	■	■	■	■	■	■					
Railroad	■	■	■	■	■	■	■	■					■
Port	■				■	■		■	■				
Airport					■	■		■					
Transportation	■	■	■	■	■								
Finance		■			■	■	■						
Medical treatment	■				■								
Administration	■	■	■		■								

Analysis by FTAs

The micro propagation structure was analyzed by using FTAs (Fault Tree Analysis). Typical FTAs are shown in Figure 1 and Figure 2. It is shown out that gas influences the water examination and information-and-telecommunications influences system control of the sewer function. It is also shown that waterworks influences many hospital functions. If the patient-conveyance function is included, road and telecommunication also influence hospital functions.

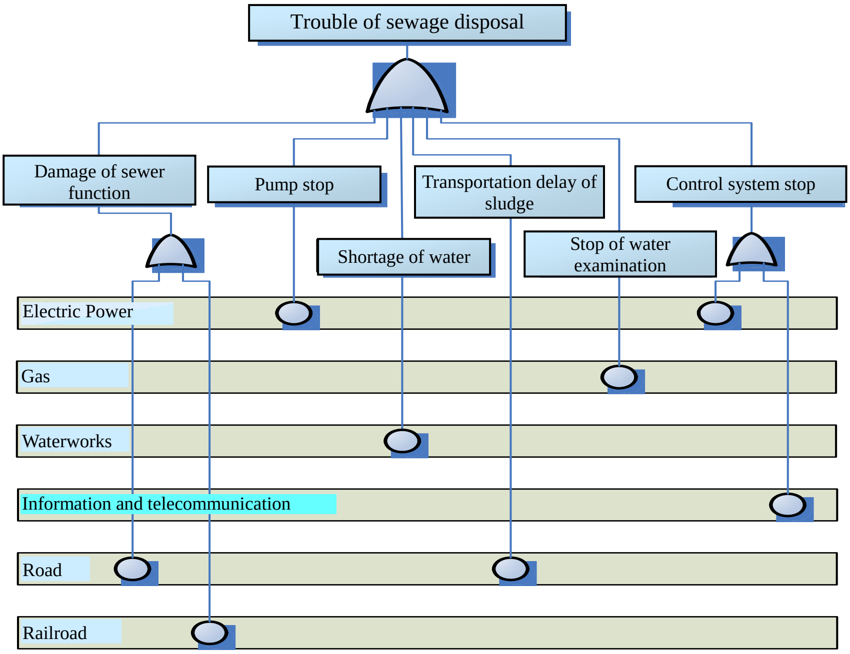

Figure 1: FTA for sewage disposal

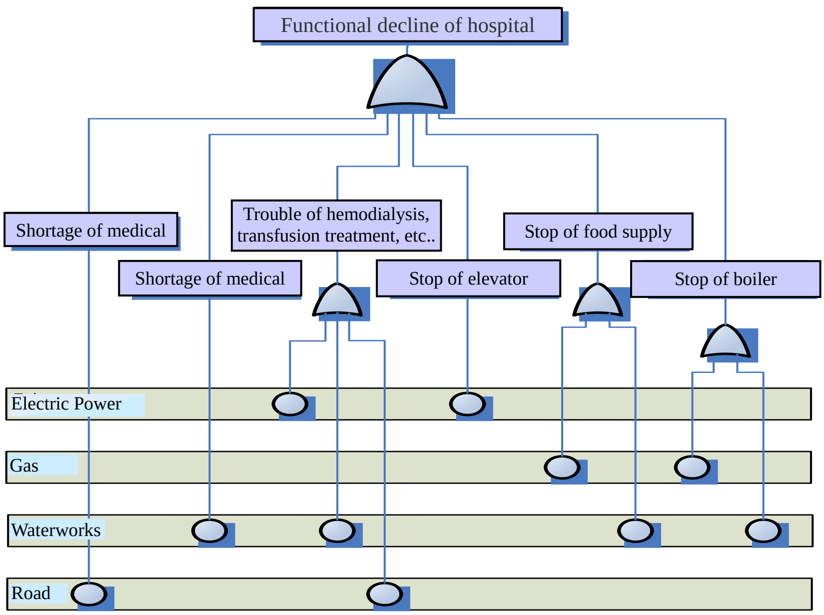

Figure 2: FTA for hospital function

Analysis by Influence Diagram

The mechanism of damage propagation currently written in the damage interdependency matrix 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. 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 3 to Figure 5.

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

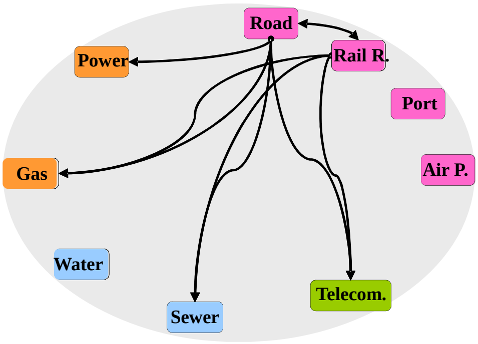

Figure 3: Influence diagram of Physical Damage Propagation

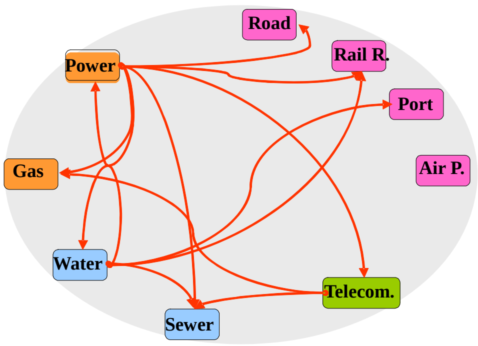

Figure 4: Influence diagram of Functional Damage Propagation

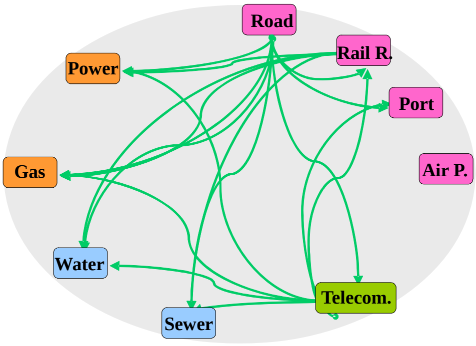

Figure 5: Influence diagram of Restoration Trouble

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 interdependence of many infrastructures. They are connected with almost all infrastructures, especially for restoration trouble. So,it is suggested that the functional recovery of roads will greatly affect the progress of restoration of other infrastructures. Meanwhile, there is little that makes roads terminal points, i.e., roads rarely receive damage propagation from other infrastructures.

Speaking about road more, as it is mainly the origins in the physical damage propagation and the restoration trouble, a prior measure not generating physical damage propagation and recovering its own function promptly after damage would lead to early restoration of other infrastructures in considerable extents.

QUANTITATIVE EVALUATION OF DAMAGE PROPAGATION

Based on the damage propagation structure analyzed 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.

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, depending on the size of the disaster. Moreover, restoration problems resulting from damage to other infrastructures may occur during restoration work. Damage expansion and restoration problems also result from infrastructure interdependency, and accumulate with time. 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	

This study, taking into account the interdependency influence, we evaluated the functional damage to each infrastructure, namely, FD x RD x ***X***, when the origin infrastructure suffered a great deal of physical damage due to the earthquake. However, the TSI and the SI were not investigated. They are 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***

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

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

Y_k: Damage due to k-th cycle damage propagation

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

Evaluation of Input Vector X

The input vector ***X*** was evaluated assuming a Tokyo metropolitan near-field earthquake. Each element of the input vector was set into "outage rate" (1- "supply rate") of the main function of each infrastructure. The outage rate within the Tokyo metropolitan area was considered and was evaluated using the damage assessment result of the Central Disaster Prevention Council of the Japanese Government. The set result of the outage rate is shown in Table 5

Table 5
Assumed Outage Rate of Infrastructure Function due to Tokyo Metropolitan Near-field Earthquake

	1 day	1 week	1 month
Electric power	0.129	0.000	0.000
Gas	0.190	0.175	0.104
Waterworks	0.333	0.064	0.012
Sewer	0.011	0.006	0.001
Information & Telecom.	0.093	0.052	0.000
Road	0.400	0.250	0.100
Railroad	0.500	0.300	0.100
Port	0.448	0.445	0.411
Airport	0.000	0.000	0.000

Evaluation of Interdependence Structure Matrix C

In quantifying interdependence structure matrix ***C***, which describes the damage propagation influence among each infrastructure, weighting for functional damage propagation was evaluated through questionnaire surveys of specialists contributing to the Investigative Commission and of experts in each infrastructure organization. The respondents evaluated FD and RD from the standpoint of the influenced infrastructure (terminal) in the Tokyo metropolitan area.

The functional deficiency degree FD was evaluated in five steps of 4-0 (4: fatal influence - 0: with no influence) considering the functional damage propagation phenomena indicated in Table 3. The rate of damage occurrence RD was evaluated in five steps of 5-1 (5: serious influence spreads to the whole - 1: hardly influences the whole system) considering the vulnerability of the infrastructure system in the Tokyo metropolitan area and the system forms (facility density, multiplicity, redundancy, etc.) that become effective in the mitigating the damage propagation influence. The elements of interdependency structure matrix ***C*** were evaluated in twenty-one steps according to FD_{ij} x RD_{ij}.

In addition, weightings concerning physical damage propagation and restoration problems (considering Table 2 and Table 4) were also evaluated in a similar way, but they are not shown in this paper because of space limitation.

The evaluated elements of the interdependency structure matrix are shown in Table 6. The influences from origins such as "electric power", "information-and-telecommunications", and "road" are great. However, for convergence of the high cycle propagation calculation, it is necessary to normalize the value of each coefficient of an interdependency structure matrix. By trying some normalizing numbers, 1.5 times (=30) the maximum of the weighting values was found to be optimal.

Table 6
Interdependence Structure Matrix ***C***

Terminal \ Origin		**Origin (Infrastructure)**								
		Power	Gas	Water	Sewer	Telecom.	Road	Railroad	Port	Airport
Terminal (Infrastructure)	Electric power	**---**	**1**	**2**	**0**	**0**	**0**	**0**	**0**	**0**
	Gas	**1**	**----**	**1**	**0**	**8**	**4**	**1**	**3**	**0**
	Water	**3**	**1**	**----**	**1**	**2**	**2**	**0**	**0**	**0**
	Sewer	**8**	**2**	**4**	**----**	**1**	**0**	**0**	**0**	**0**
	Telecom.	**4**	**1**	**0**	**0**	**----**	**12**	**0**	**0**	**0**
	Road	**9**	**0**	**0**	**0**	**4**	**----**	**6**	**0**	**0**
	Railroad	**16**	**4**	**4**	**4**	**16**	**1**	**----**	**0**	**0**
	Port	**12**	**1**	**3**	**1**	**4**	**8**	**3**	**----**	**0**
	Airport	**8**	**3**	**3**	**3**	**8**	**4**	**4**	**0**	**----**
Terminal (Social function)	Transportation	**12**	**1**	**4**	**1**	**12**	**16**	**4**	**1**	**1**
	Finance	**8**	**1**	**1**	**1**	**20**	**6**	**2**	**0**	**0**
	Medical treatment	**12**	**6**	**16**	**4**	**6**	**12**	**0**	**0**	**0**
	Administration	**16**	**2**	**8**	**1**	**20**	**2**	**2**	**12**	**0**

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 6. Functional damage beyond the initial damage appeared in all the infrastructures under the propagation influence among infrastructures. Functional damage of "aviation" was influenced by damage to other infrastructures, although no initial damage to itself was assumed.

Figure 7 shows the terminal infrastructures according to each origin infrastructure. The influence of "electric power", whose weight of functional damage propagation was great, turned out to be small in comparison with "road", "information-and-telecommunications" and "railroad". This is considered to result from the rather small setup of damage rate in comparison with "road", "railroad", etc. in the initial damage set of a Tokyo metropolitan near-field earthquake.

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

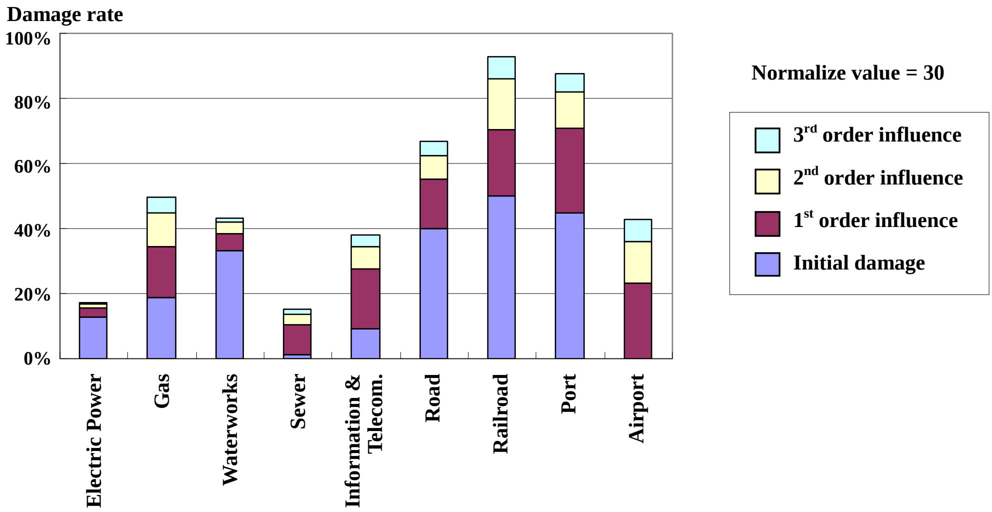

Figure 6: One day after disaster outbreak

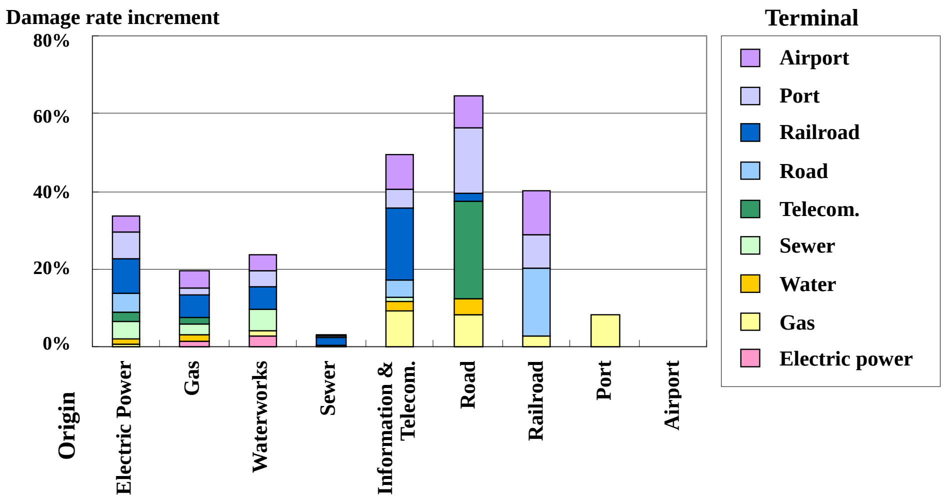

Figure 7: Terminal infrastructure according to origin infrastructure

INVESTIGATION OF DAMAGE MITIGATION MEASURES

Measures for mitigating damage propagation implemented by each infrastructure organization were investigated from the literature and hearing examination. Results were divided into commonly used measures and measures peculiar to particular infrastructures.

Typical common measures were "formation of many routes and networks of supply route", "placing backup functions in a distant area", "disposition of satellite cellular phones", "equipping business-use vehicles with car-navigation systems", "practical use of cellular phone e-mail ", "practical use of marine transportation and air transportation", "temporary restoration by temporary piping", "pre-agreement with related organizations", etc.

Typical peculiar measures were "disposition of dynamo car (electric power)", "blocking of pipe and aqueduct (gas and waterworks)", "practical use of a restoration support system (gas)", "water supply to tall building by pressuring-type pump car (waterworks)", "power backup to relay stations by portable dynamo (information-and-telecommunications)", "relief of congestion by message service at disaster (information-and-telecommunications)", "practical use of well water, adjustment reservoir and desalination plant of sea water (medical treatment)", "conveyance of medical supply by motorcycle delivery service (medical treatment)", "change to distributed type network from put-together type network (finance)" and "allocating habitation of emergency response personnel to neighborhood to business place (finance)".

CONCLUSION AND FUTURE SUBJECT

The results of this research are as follows:

(1) Damage propagation among infrastructures occurred in almost all infrastructures immediately after a disaster. Electric power, gas, information-and-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", "information-and-telecommunications" and "railroad".
(3) In addition, a setup of initial damage (rate of problems) had a big influence on the result.
(4) "Installation of back up generator against power failure", "formation of many routes and networks against stoppage of lifeline", "habitation of initial response staff to neighborhood of business place" etc. have been commonly implemented in infrastructure organizations. These measures are thought to be effective for disaster mitigation in a mega-city. "Deliberations and adjustments over road burial at time of restoration", "advance base for restoration team" etc, are the measures that can be implemented commonly in the future.

The following are future extensions and subjects.

(1) The damage interdependency matrix created by this research is 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) Damage propagation influence in case of a Tokyo metropolitan near-field earthquake was evaluated

by weighting the damage propagation based on the damage interdependency matrix. For more reliable quantitative evaluation, 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,.

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