System Dynamics Modeling and Simulation of Disaster Recovery Process of Interdependent Infrastructure Systems

by

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ABSTRACT

A simulation model is developed for disaster recovery process of infrastructure systems. The model is based on the system dynamics and the interdependency among infrastructures is taken into account. Disaster recovery process of the infrastructure system in the Tokyo metropolitan area, where the infrastructures are highly interdependent, is simulated using the model and the effects of the interdependency are investigated.

KEYWORDS: Infrastructure System, Influence Diagram, System Dynamics, Interdependency

1. INTRODUCTION

Infrastructures such as roads, railroads, electric power, gas, and water supplies, sewerage, and telecommunications are vital for our daily lives and industrial activities. Natural and human disasters, however, have damaged the infrastructures and the damage has caused social and economic losses from time to time. The longer the disaster recovery takes, the larger the losses become; thus, prompt recovery is important to mitigate the losses.

Since the infrastructures are interdependent and compose a highly complex system, especially in urban areas, damage to one of the infrastructures may affect the others (damage spreading). For example, if the electric power supply is damaged, the road traffic capability is deteriorated until the electric power recovers traffic lights. If the gas supply and the road network are damaged, the recovery of the gas supply is delayed because road traffic is necessary for the recovery works.

Tsuruta *et al.* (2008) surveyed interdependency of the infrastructure system during past disasters and developed a damage propagation model based on matrix equation [1]. Though the case study simulation using the model successfully demonstrated the earthquake damage spreading among infrastructures, dynamic behavior such as recovery process of the infrastructure system was not investigated.

In this study, the disaster recovery process of the infrastructure systems is modeled based on the system dynamics and the time history of the recovery process from a hypothetical earthquake (M7.3) in the Tokyo metropolitan area is simulated taking account of the interdependency.

2. SYSTEM DYNAMICS MODELING

First, the functions and components of infrastructures and their relationships are organized as influence diagrams. A base model that shows relationships among facilities, resources, and infrastructures necessary for disaster recovery is developed for each of infrastructures. Then the base models are assembled into a system dynamics model of disaster recovery process of the infrastructure system. The details of the modeling are described in Kataoka *et al.* (2009).

The influence diagrams illustrate the functions and components of infrastructures and their relationships; the diagram of the gas supply system is shown in Fig. 1 as an example. The gas supply system consists of many facilities but only the low pressure pipes are assumed to be damaged during earthquakes. Not only the facilities managed by gas suppliers but also the electric power are necessary to maintain the gas supply function.

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Then, based on the influence diagrams, the base models are developed taking account of facilities, resources, and infrastructures that are necessary for disaster recovery. For example, the base model of the gas supply system is developed as shown in Fig. 2. The road traffic and telecommunication functions are considered necessary for the disaster recovery of the gas supply function. Since the electric power is required to maintain the gas supply function, either backup electric power or physical recovery of substations is necessary for the recovery of the system.

The system dynamics model is constructed by assembling the base models of all infrastructures. Given the initial damage to the infrastructures, the disaster recovery process of the whole infrastructure system can be simulated using the model.

3. SIMULATION CASE STUDY

Disaster recovery process of the infrastructure system in the Tokyo metropolitan area, where the infrastructures are highly interdependent, is simulated using the system dynamics model.

3.1 Initial Damage and Interruption

Central Disaster Management Council (CDMC) announced the estimated damage due to Tokyo metropolitan earthquakes in 2005 [3]. The most disastrous one is the hypothetical northern Tokyo Bay earthquake (M7.3), which causes strong ground motion with JMA seismic intensity of 6 upper in the eastern half area of the 23 special wards of Tokyo as shown in Fig. 3. Following CDMC, Tokyo Metropolitan Government (TMG) also conducted estimation of damage caused by the earthquake [4]. In this study, the damage to the infrastructures estimated by TMG is used as the initial damage in the simulation. Table 1 shows the damage in Chiyoda and Sumida wards and the 23 wards in total.

Railroads are ordered a halt for inspection just after earthquakes even though no damage is reported. Road traffic is also controlled and only emergency vehicles can be admitted to path through disaster areas. Thus, the initial interrupted ratios are assumed as follows:

- 100% for the railroad network (all lines are once halted for inspection of the damage),
- 0% everywhere for emergency vehicles,
- 100% in “the road traffic prohibited area” and 50 % in the other area with seismic intensity of 6 upper for non-emergency vehicles.

Once a Tokyo metropolitan earthquake occurs, Metropolitan Police Department regulates the traffic so that non-emergency vehicles are prohibited to pass through “the road traffic prohibited area”, which covers 75% of the area of the 23 special wards. In this study, the traffic regulation is assumed to last for 10 days.

3.2 Recovery Rate without Interdependency

CDMC surveyed the recovery rates of the infrastructures based on interviews and obtained the following results [3]:

- 95% of electric power recovers in 6 days,
- 95% of telecommunications recovers in 14 days,
- 80% of gas supply recovers in 55 days,
- 95% of water supply recovers in 30 days,
- 95% of sewerage pipes recover in 30 days.

The recovery rates for railroads and roads are assumed as follows:

- 100% of railroads are available in 1 day in the area with seismic intensity of 5 upper (no damage and only inspection),
- 90% of railroads are available in 1 day, then 95% recover in 5 days in the area with seismic intensity of 6 lower,
- 80% of railroads are available in 1 day, then 95 % recover in 15 days in the area with seismic intensity of 6 upper,
- 95% of roads recover in 18 days in the area with seismic intensity of 6 upper.

These rates are assumed to be those when the recovery process is not influenced by the interdependency among infrastructures and used as initial recovery rates. For example, the “recovery rate of low pressure pipe” in Fig. 2 is set to be the recovery rate of the gas supply mentioned above.

3.3 Simulation Results

Fig. 4 shows the time histories of recovered ratios of the infrastructures in Chiyoda and Sumida wards. In this simulation, 10% of the vehicles used for the disaster recovery work are assumed to be the emergency vehicles. Thus, 90% of them are affected by the traffic regulation or interruption. The recovery of the infrastructures is delayed significantly compared with the recovery rates mentioned in 3.2. The delays are longer in Sumida wards because it suffers greater damage than Chiyoda wards (Table 1).

Fig. 5 is the same as Fig. 4 but 90 % of the vehicles used for the disaster recovery work are assumed to be the emergency vehicles. In Fig. 5, the delays still exist but much shorter than those in Fig. 4. To achieve this improvement, road facilities must not collapse during earthquakes so that the road networks maintain the traffic at least for emergency vehicles.

4. CONCLUSIONS

A simulation model is developed to investigate the effects of the interdependency among infrastructures on the recovery process of the infrastructure system. The simulation case study shows the importance of smooth traffic of emergency vehicles for prompt disaster recovery of the highly interdependent infrastructure systems.

Further research and investigation are needed to improve accuracy and actuality of the simulation model and data in order to discuss the simulation results quantitatively.

5. REFERENCES

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2. Kataoka, S., Tsuruta, M. and Shoji, Y.: Model development of interdependency among critical infrastructures and simulation of earthquake damage spreading, *Technical Note of National Institute for Land and Infrastructure Management*, No. 510, 2009.
3. Central Disaster Management Council: Documents of the 15th Tokyo metropolitan earthquake disaster management council, 2005.
4. Tokyo Metropolitan Government: Estimated damage in Tokyo due to the Tokyo metropolitan earthquakes, 2006.

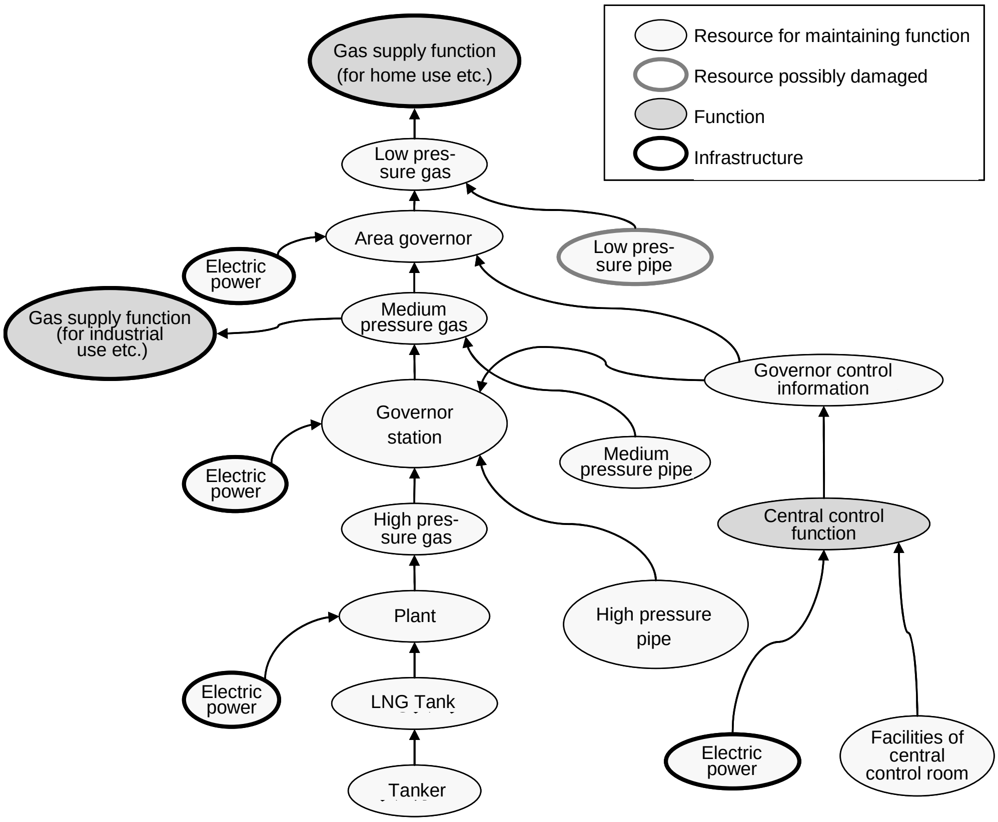


Fig. 1 Influence diagram of the gas supply system.

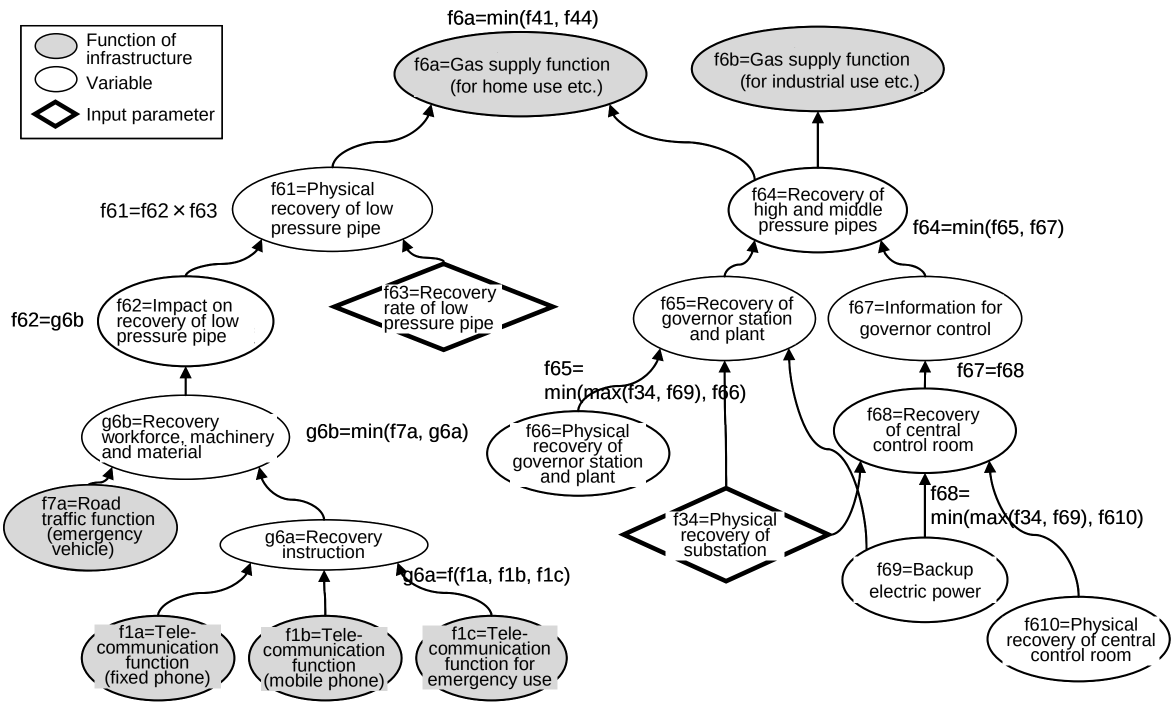


Fig. 2 Base model showing relationships among facilities, resources, and infrastructures necessary for disaster recovery of the gas supply system.

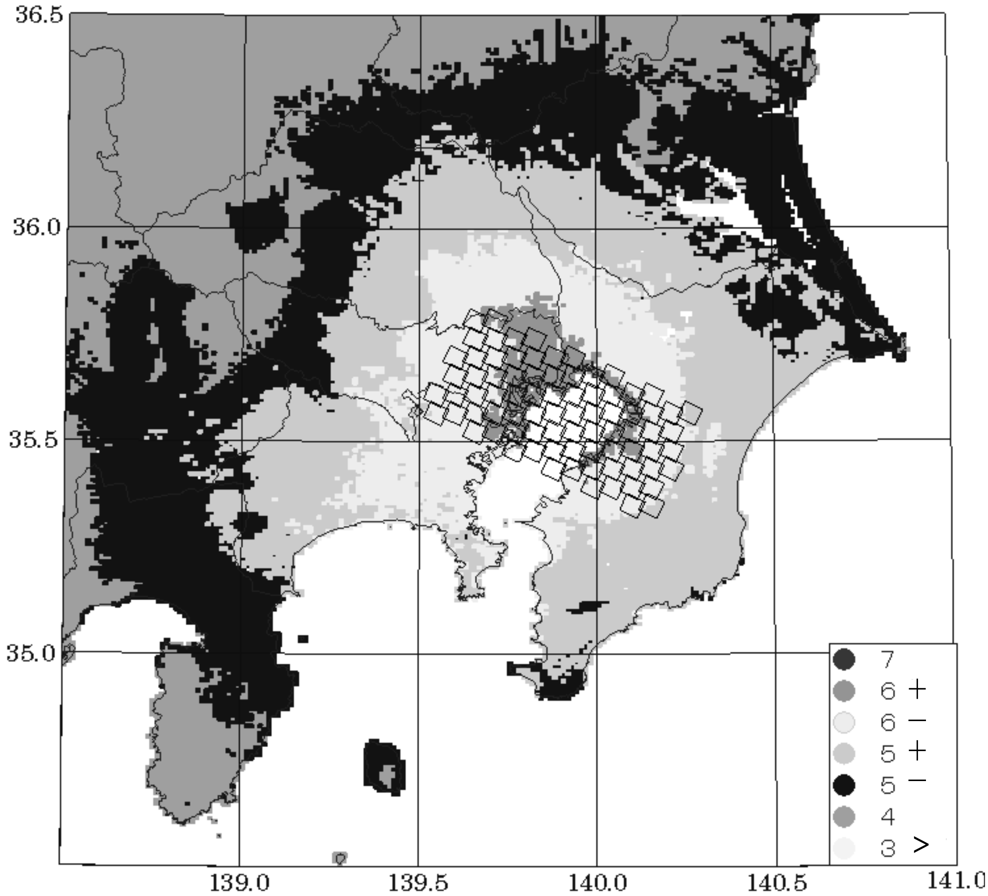
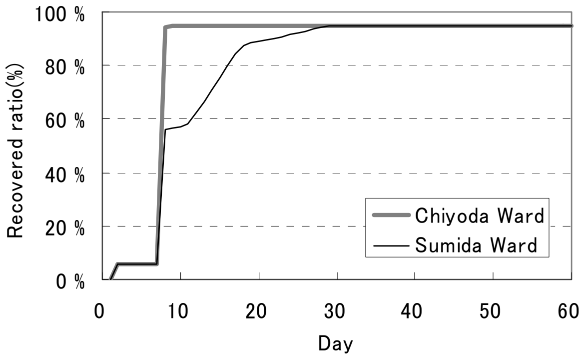


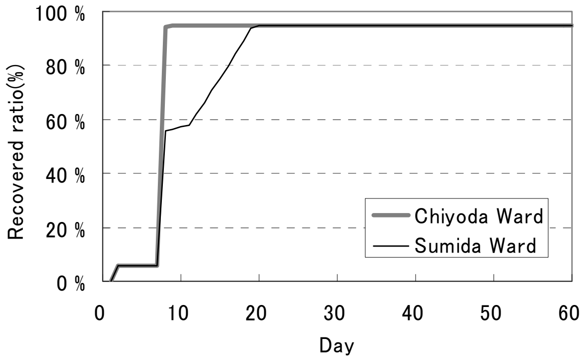
Fig. 3 Map of Kanto region showing JMA seismic intensity due to the northern Tokyo Bay earthquake (M7.3) and its source fault (Central Disaster Management Council, 2005)[3].

Table 1 Estimated damage to infrastructures caused by the northern Tokyo Bay earthquake (M7.3) in Chiyoda and Sumida wards and the 23 wards in total (Tokyo Metropolitan Government, 2006)[4].

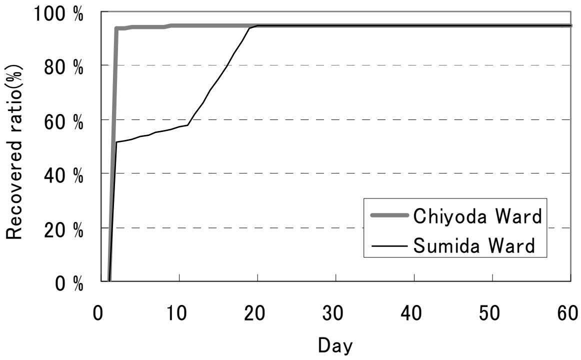
Wards	Electric power supply (power failure ratio)	Telecommunications (interrupted ratio)	Gas supply (cut off ratio)	Water supply (cut off ratio)	Sewerage (ratio of damaged pipe)
Chiyoda	6.1%	0.9%	59.4%	37.4%	23.3%
Sumida	48.6%	17.6%	100.0%	79.5%	31.8%
23 wards total	22.9%	13.2%	22.9%	46.3%	25.4%



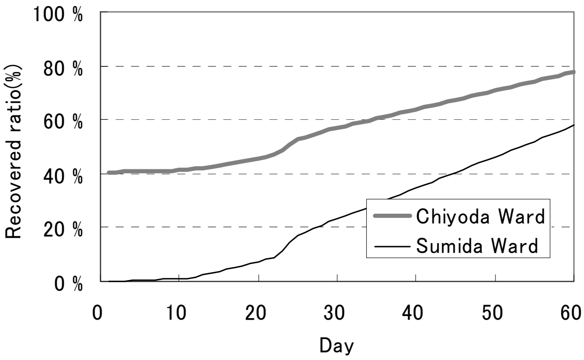
(a) Telecommunication (fixed phone)



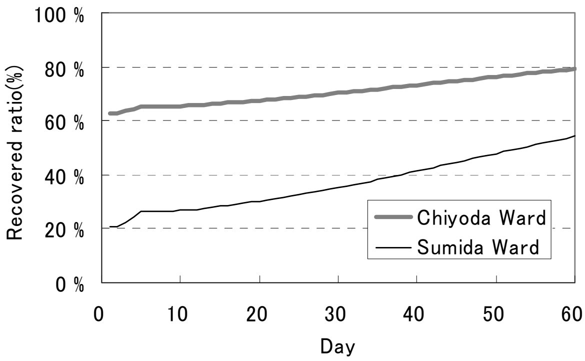
(b) Telecommunication (mobile phone)



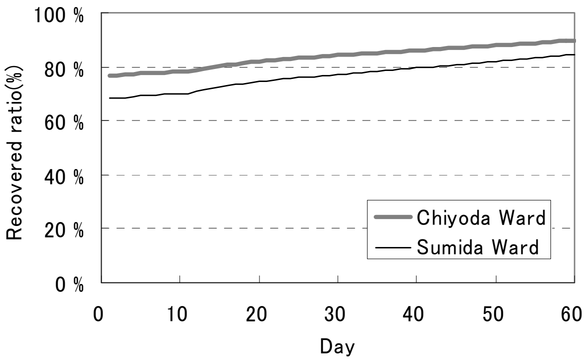
(c) Electric power supply



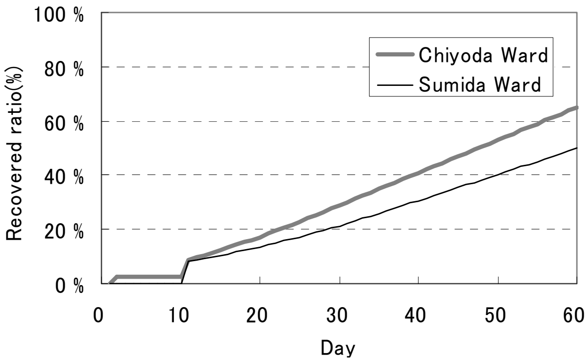
(d) Gas supply



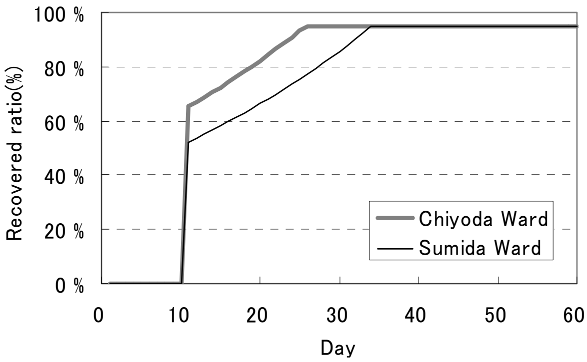
e) Water supply



(f) Sewerage

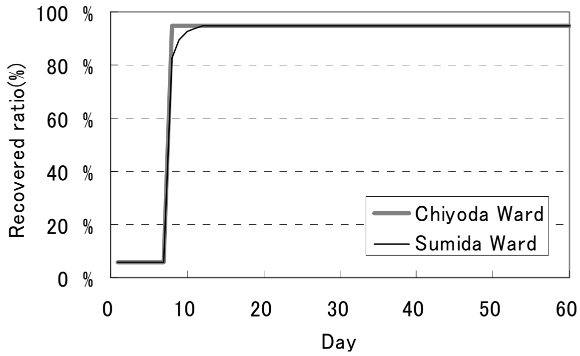


(g) Railroad

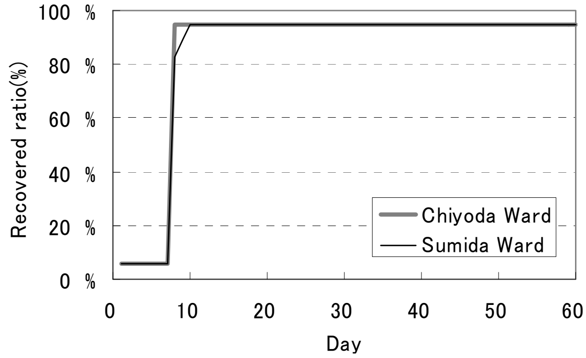


(h) Road

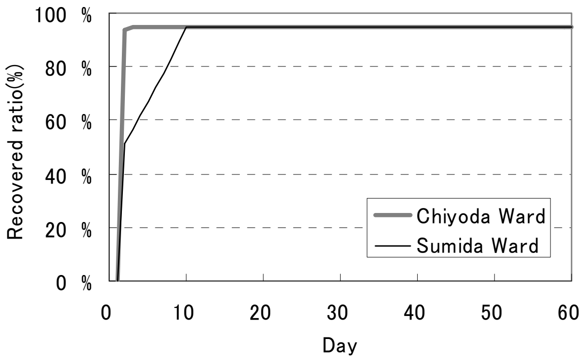
Fig. 4 Time histories of recovered ratios of the infrastructures in Chiyoda and Sumida Wards. 10% of the vehicles used for disaster recovery work are assumed to be the emergency vehicles.



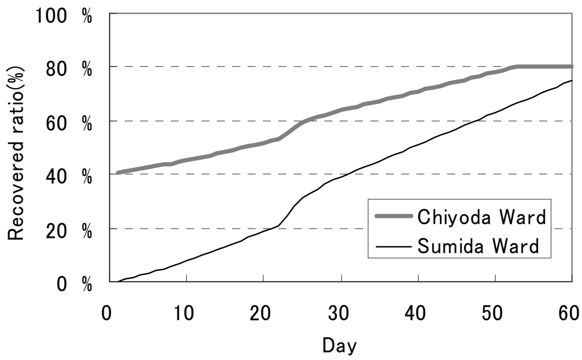
(a) Telecommunication (fixed phone)



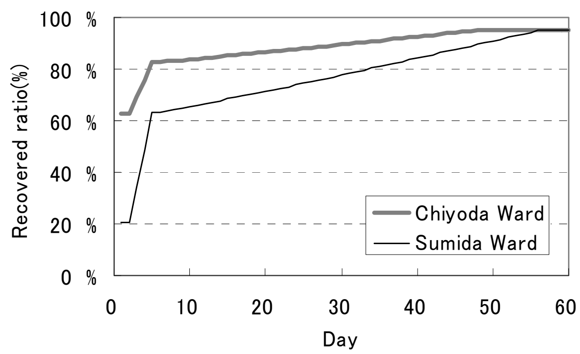
(b) Telecommunication (mobile phone)



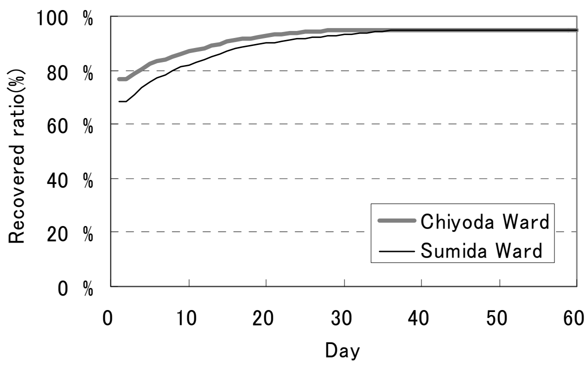
(c) Electric power supply



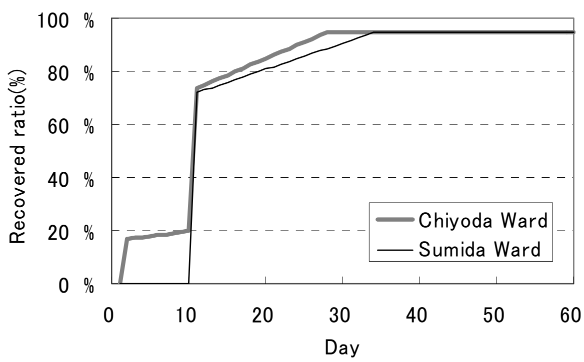
(d) Gas supply



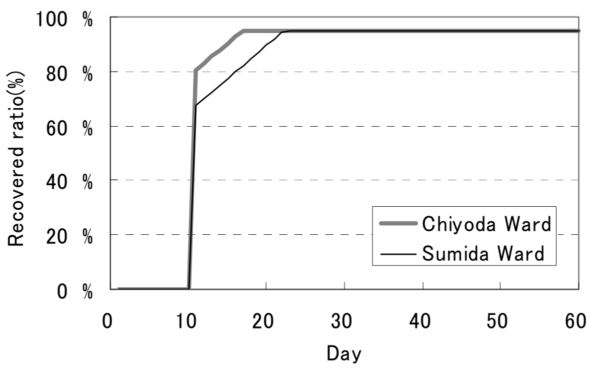
(e) Water supply



(f) Sewerage



(g) Railroad



(h) Road

Fig. 5 Time histories of the recovered ratios of the infrastructures in Chiyoda and Sumida Wards. 90% of the vehicles used for disaster recovery work are assumed to be the emergency vehicles.