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Damage Estimation Improvement of Electric Power Distribution Equipment Using Multiple Disaster Information

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Additional information is available at the end of the chapter

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1. Introduction

Electric power distribution equipment has a high damage potential due to disasters and requires a long time for restoration. This is because a huge number of electric power distribution equipment is installed under various ground and regional conditions and is located near vulnerable trees and old residential buildings. Thus, during the restoration work after a large scale earthquake, it takes a long time to collect reliable disaster information. It is also even difficult to accurately estimate the damage degree of electric power distribution equipment. Therefore, in Japan, electric power companies pay particular attention to technologies associated with a quickly understanding and estimating the damage degree of the entire electric power distribution system during the emergency restorations.

On the other hand, with the progress in information technologies, practical disaster information services are increasing in Japan. For example, the Japan Metrological Agency has started a general delivery service of real-time earthquake information since October, 2007[1]. Moreover, in recent years, remote sensing images, such as satellite, aero and synthetic aperture radar (SAR) images, are now available and open to the public after a large scale disaster [2]. On the basis of such information technologies, more reasonable ways to support the restoration work for utility lifelines can be developed.

Based on this background, our research team has developed an sequentially updated damage estimation system called RAMPER, which stands for “*Risk Assessment and Management System for Power lifeline Earthquake real time*” [3][4]. RAMPER enables us to provide the damage estimation results of electric power distribution equipment during the emergency restoration process against an earthquake.

Reference [3] proposed a damage estimation function installed in RAMPEr which used the earthquake ground motion intensity as an input parameter, and applied the proposed function to actual electric power distribution equipment damaged by the 2007 Niigata-ken Chuetsu Oki earthquake to clarify the estimation accuracy of the proposed function.

This paper focuses on the updated damage estimation process of RAMPEr. RAMPEr enables us to improve the damage estimation accuracy using sequentially updated disaster information which a power company can collect during the emergency restoration period against a large-scale earthquake. Chapter 2 introduces the necessary disaster information for three emergency restoration stages and emphasizes the significance of RAMPEr. Chapter 3 describes the formulation of the proposed model. Chapter 4 discusses the advantage and limitation of the proposed model using the actual damage records due to the 2007 Niigata-Ken Chuetsu-Oki earthquake.

2. Information required for the emergency restoration work

Fig.1 shows the differences in the information required for the efficient restoration of a seismic damaged electric power distribution system. The restoration process is generally divided into the initial, emergency, and permanent restoration periods. During the initial restoration period, the information associated with the damage degree of the entire electric power system is needed to judge how many staff members should be dispatched for the restoration. During the emergency restoration period, the information associated with the damage point and mode to judge whether restoration staff members can immediately restore the power is needed. During the permanent restoration process, the information associated with all damaged equipment to be physically repaired is needed.

In order to collect this information, the power company dispatches inspection teams. In addition, some power companies have tried to apply remote sensing technologies, including helicopters and satellites, to quickly collect damage information. However, at the current time, the inspection teams and remote sensing technologies are not very effective to quickly collect seismic damage information especially for the restoration resource allocation during the initial restoration period.

Fig.2 shows the restoration process of an electric power distribution system located in the Tohoku region just after the 2011 earthquake off the Pacific coast of the Tohoku (the 311 earthquake) occurrence. The horizontal axis and the vertical axis show the elapsed time (days) and the number of inspected damaged equipment (%), respectively. Fig.2 indicates that the damage information had not been effectively collected, especially during the initial restoration period. This is because the Tohoku area had frequent aftershocks, much debris, and some coastal regions which were not able to be entered for the restoration analysis. This result illustrates that when a large-scale earthquake occurs, there is the possibility that the restoration work, including damage information collection, is highly limited by the damage related to residential buildings and other infrastructures.

During the limited damage information condition, RAMPEr becomes an effective tool to support some decision makings. RAMPEr is a seismic damage estimation system whose basic concept is a sequential updated damage estimation based on real-time hazard and damage information. RAMPEr was used by Tohoku Electric Power Co., Inc., to support its actual initial restoration work due to the 311 earthquake [10].

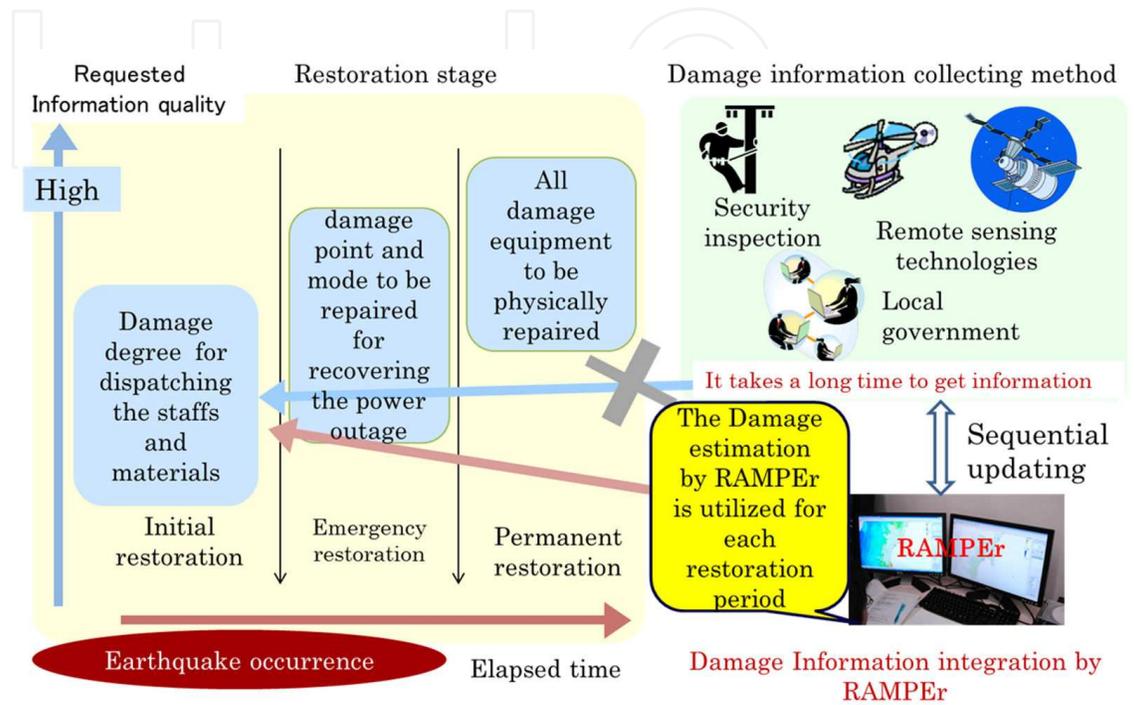


Figure 1. Differences in required information according to restoration stages

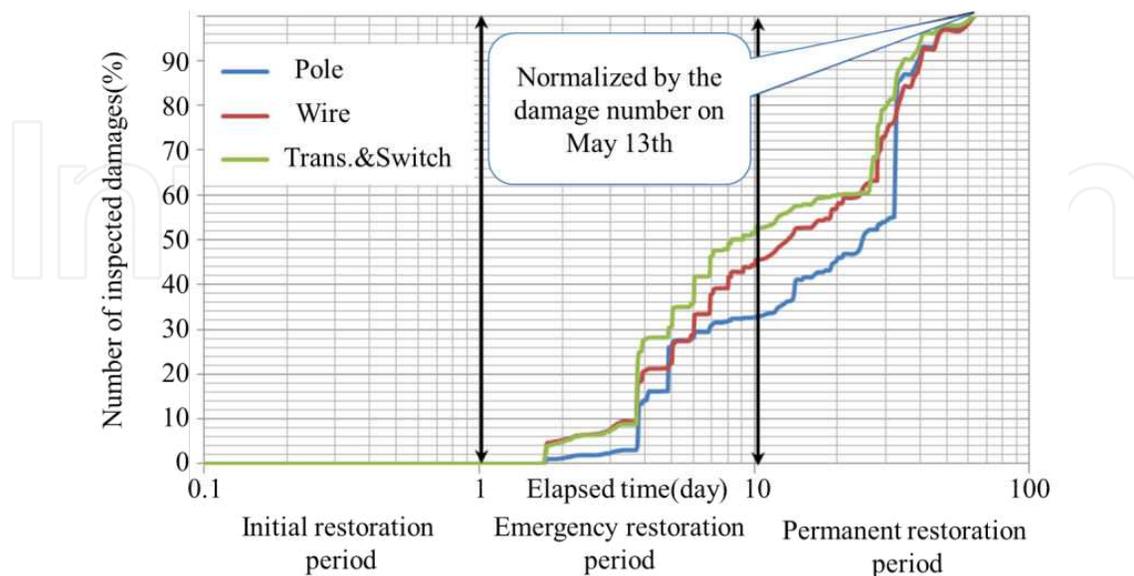


Figure 2. Time required for the damage detection of electric power distribution equipment [9]

3. Consecutive integrated process of multiple disaster information

3.1. Multiple disaster information used by RAMPER

Disaster information needed by an electric power company can be usually collected after an earthquake occurrence includes four categories; (1) Earthquake, (2) Power outage, (3) Damage inspection, and (4) Damaged area image by remote sensing.

As for the earthquake information, RAMPER, which has been already installed in some electric power companies, is supposed to automatically receive the earthquake information through the Internet including the epicenter, magnitude, and seismic ground motion intensities recorded on seismographs from the Japan Meteorological Agency within several minutes just after the earthquake occurrence. Based on the received earthquake information, RAMPER evaluates the seismic ground motion intensity distribution. As other sources, the National Research Institute for Earth Science and Disaster Prevention (NIED) opens seismic ground motion records including K-NET and KiK-net[5]. RAMPER collects Instrumental Seismic Intensity (ISI), Peak Ground Velocity (PGV), and Peak Ground Acceleration (PGA) recorded from K-NET and KiK-net to improve the evaluation accuracy of the seismic ground motion distribution.

Power outages and damage inspection information are usually confidential information that the power company collects. The power outage information is usually collected for every high voltage distribution line (feeder) with power outages obtained from an online business support system maintained by the electric power company. The inspection information includes damaged equipment information including distribution poles, distribution lines, transformers, and switches. The inspection information is collected by portable transceivers, mobile phones and Personal Digital Assistances (PDA) as offline information. RAMPER uses this confidential information to improve the damage estimation accuracy [4].

On the other hand, a seismic damage area image provided by remote sensing devices, such as satellites, is also one of the effective resources to understand the damage degree of the earthquake stricken area. However, as mentioned in Chapter 2, at the current technology stage, because it usually takes a long time to take and provide the images, it is difficult for RAMPER to get the satellite image during an emergency restoration period. Thus, this paper focuses on (1) Earthquake information, (2) Power outage information, and (3) Damage inspection information to formulate the damage information integration as follows.

3.2. Basic idea of damage information integration

This paper focuses on a Bayesian network as a basic model to integrate the multiple disaster information. Details of the Bayesian network can be found in reference [6]. This chapter only introduces the basic concept of the Bayesian network for a better understanding of the following chapters.

Fig.3 shows a simple Bayesian network. It describes the relationships between variables X_1 and X_2 . The X_1 and X_2 variables are binary (taking a value of either 0: false or 1: true). The

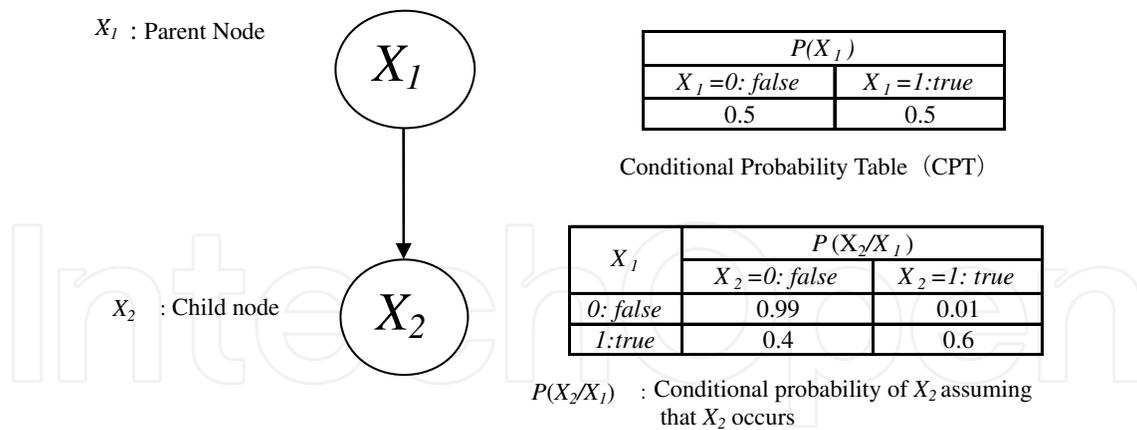


Figure 3. A basic element of a Bayesian network

causality of both nodes is defined as a Conditional Probability Table (CPT). The CPT defines the causal relationship between X_1 as a parent node and X_2 as a child node in the Bayesian network. The arrow between the nodes defines the causal relationship between the parent node and child node. The conditional damage probability of the child node $P(X_2/X_1)$ can be determined by the CPT in Fig.3.

For example, according to the marginalization [6], the probability $P(X_2=1)$ can be estimated as

$$P(X_2 = 1) = \frac{\sum_{X_1=0}^1 P(X_2 = 1 / X_1) \cdot P(X_1)}{\sum_{X_1=0}^1 \sum_{X_2=0}^1 P(X_2 / X_1) \cdot P(X_1)} = 0.305 \quad (1)$$

When variable $X_1=1$ on the parent node is given, the probability $P(X_2=1/X_1=1)$ can be estimated as

$$P(X_2 = 1 / X_1 = 1) = \frac{P(X_2 = 1 / X_1 = 1) \cdot P(X_1 = 1)}{\sum_{X_2=0}^1 P(X_2 / X_1 = 1) \cdot P(X_1 = 1)} = 0.6 \quad (2)$$

On the contrary, when variable $X_2=1$ on the child node is given, the probability $P(X_1=1/X_2=1)$ can be estimated as

$$P(X_1 = 1 / X_2 = 1) = \frac{P(X_2 = 1 / X_1 = 1) \cdot P(X_1 = 1)}{\sum_{X_1=0}^1 P(X_2 = 1 / X_1) \cdot P(X_1)} = 0.984 \quad (3)$$

If the causal relationships among disaster events can be defined by a Bayesian network with two or more nodes, which includes the 2 nodes of Fig.3 as a minimum unit, the conditional probability of a target node can be improved with an increase in the observed information of the parent or child nodes.

3.3. Improvement of damage probability using Bayesian network

Fig.4 shows a proposed Bayesian network. The proposed Bayesian network consists of 4 nodes; (1) Earthquake Ground Motion ($EGM(a)$), (2) Electric Power Distribution Equipment damage ($EPDE$), (3) Damage Inspection (DI), and (4) Power Outage (PO). The CPT of the proposed Bayesian network is defined as follows.

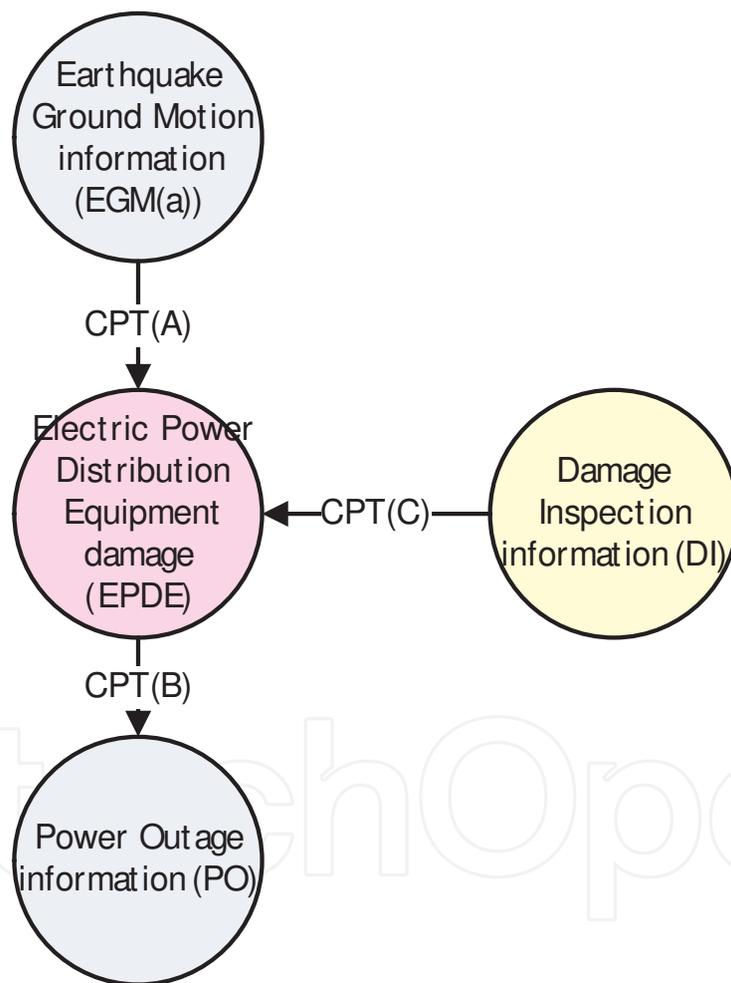


Figure 4. The proposed Bayesian network model

- a. Causal relationship between earthquake ground motion and electric power distribution damage (CPT(A))

Table 1 shows the CPT which defines the casual relationship between earthquake ground motion and electric power distribution equipment damage shown as CPT(A) in Fig.4.

$EGM(a)=1$ indicates that the information of the maximum seismic ground motion intensity a for every target equipment is given. $EGM(a) = 0$ indicates that no earthquake ground motion information is given. $EPDE=1$ and $EPDE=0$ indicate the damage and no damage that occurs to equipment, respectively. $P_i(a)$ indicates the estimated damage rate of equipment i with the maximum seismic ground motion a . $P_i(a)$ is estimated by appendix[A]. This paper assumes that when an earthquake occurs, the maximum ground motion a is always given for every target equipment within several minutes. Thus, in Table 1, P_i ($EPDE=1/EGM(a)=1$) and P_i ($EPDE=0/EGM(a)=1$) are equivalent to $P_i(a)$ and $1-P_i(a)$, respectively, and $P_i(EPDE/EGM(a)=0)$ is neglected in Table 1.

CPT(A)	$P_i(EPDE/EGM(a))$	
$EGM(a)$	No Damage $EPDE=0$	Damage $EPDE=1$
1: maximum seismic ground motion a occurs	$1-P_i(a)$	$P_i(a)$

Table 1. Conditional probability table between the earthquake intensity and the damage of electric power distribution equipment (CPT(A))

b. Causal relationship between the electric power distribution damage and the power outage (CPT(B))

Table 2 shows the CPT which defines the causal relationship between the electric power distribution damage and the power outage shown as CPT(B) in Fig.4. According to CPT(B), when $EPDE = 1$ is given, which indicates that equipment i is damaged, the conditional no power outage probability of equipment i , $P_i(PO=0/EPDE=1)$, and the conditional power outage probability of equipment i , $P_i(PO=1/EPDE=1)$, are assumed to be 0 and 1, respectively.

On the other hand, when $EPDE=0$ is given, which indicates that equipment i is not damaged, the conditional power outage probability of equipment i , $P_i(PO=0/EPDE=0)$, and no power outage probability of equipment i , $P_i(PO=1/EPDE=0)$, are, respectively, estimated as

$$P_i(PO = 0 / EPDE = 0) = \prod_{i=1}^{Ne-1} (1 - P_i(a)) \tag{4}$$

$$P_i(PO = 1 / EPDE = 0) = 1 - \prod_{i=1}^{Ne-1} (1 - P_i(a)) \tag{5}$$

where Ne indicates the total number of equipment connected to the same distribution line (the same feeder). Equation (4) and Equation (5) assumes that when equipment is damaged, a power outage occurs to all equipment connected to the distribution line of the damaged equipment.

CPT(B)		$P_i(PO/EPDE)$	
EPDE		No Power Outage $PO=0$	Power Outage $PO=1$
0: No damage		Equation (4)	Equation (5)
1: Damage		0	1

Table 2. Conditional probability table between the damage to electric power distribution equipment and the power outage (CPT(B))

c. Causal relationship between damage inspection and electric power distribution equipment damage (CPT(C))

Table 3 shows the CPT which defines the causal relationship between the damage inspection and the electric power distribution equipment damage shown as CPT(C) in Fig.4. The damage inspection information indicates the inspection result of equipment with the same attribute as the target equipment i , which includes the number of damaged and non-damaged equipment on the condition that the target equipment i has no inspection. According to CPT(C), when $DI=0$ is given, which indicates that equipment i has no inspection information, the conditional damage probability of equipment i , $P_i(EPDE=1/DI=0)$, and the conditional no damage probability of equipment i , $P_i(EPDE=0/DI=0)$, are equivalent to $P_i(a)$ and $1 - P_i(a)$, respectively.

On the other hand, when $DI=1$ is given, which indicates that equipment i has inspection information, the conditional damage probability of equipment i , $P_i(EPDE=1/DI=1)$, and the conditional no damage probability of equipment i , $P_i(EPDE=0/DI=1)$, are evaluated as

$$P_i(EPDE = 1 / DI = 1) = \frac{n_i^0 + n_i^1 + 1}{M_i^0 + M_i^1 + 2} \tag{6}$$

$$P_i(EPDE = 0 / DI = 1) = 1 - \frac{n_i^0 + n_i^1 + 1}{M_i^0 + M_i^1 + 2} \tag{7}$$

where M_i^0 is the total number of inspected equipment with the same attribute as equipment i . n_i^0 is the total number of damaged equipment with the same attribute as equipment i . On the other hand, M_i^1 and n_i^1 are, respectively, evaluated as

$$M_i^1 = \frac{\mu_{p_i(a)}(1 - \mu_{p_i(a)})}{\sigma_{p_i(a)}^2} - 3 \tag{8}$$

$$n_i^1 = \mu_{p_i(a)} \left\{ \frac{\mu_{p_i(a)}(1 - \mu_{p_i(a)})}{\sigma_{p_i(a)}^2} - 1 \right\} - 1 \tag{9}$$

where, $\mu_{p_i(a)}$ and $\sigma_{p_i(a)}$ are the average and standard deviation of the estimated damage probability of equipment with the same attribute as equipment I , $p_i(a)$, on the condition that the maximum ground motion intensity a is given, respectively. For this formulation, it is assumed that the estimated damage probabilities of equipment with the same attribute i follow the beta distribution based on the theory of Bayesian statistics [7].

Note that when the damage inspection information of equipment i is given, the conditional damage probability of equipment i , $P_i(EPDE/DI=1)$, becomes 1 (damage) or 0 (no damage) as the definitive value instead of that by Table 3.

CPT(C)	$P_i(EPDE/DI)$	
DI	No Damage EPDE=0	Damage EPDE=1
0: No inspection	$1 - P_i(a)$	$P_i(a)$
1: Inspection	Equation (7)	Equation (6)

Table 3. Conditional probability table between the inspection information and the damage of electric power distribution equipment

d. Combination of the joint occurrence probability

Based on Table1, Table2, and Table 3, Table 4 shows the combination of all the joint occurrence probabilities in Fig.4. Based on Table 4, all the conditional damage probabilities of the equipment can be evaluated. For example, when the earthquake ground motion information, $EGM(a)=1$ and power outage information, $PO=1$, are given, the conditional damage probability of equipment i , $P_i(EPDE=1/EGM(a)=1,PO=1)$, is evaluated as

$$P_i(EPDE = 1 / EGM(a) = 1, PO = 1) = \frac{[1] + [5]}{[1] + [3] + [5] + [7]} \tag{10}$$

On the other hand, when the earthquake ground motion information, $EGM(a)=1$ and the damage inspection information, $DI=1$, are given, the conditional damage probability of equipment i , $P_i(EPDE=1/EGM(a)=1,DI=1)$, is evaluated as

$$P_i(EPDE = 1 / EGM(a) = 1, DI = 1) = \frac{[1] + [2]}{[1] + [2] + [3] + [4]} \tag{11}$$

Combination No	EGM(a)	DI	EPDE	PO	Joint occurrence probability
[1]	1	1	1	1	Equation(6)
[2]	1	1	1	0	0
[3]	1	1	0	1	(1-Equation(6)) (1- Π (1-Equation(6)))
[4]	1	1	0	0	(1-Equation(7)) Π (1-Equation(7))
[5]	1	0	1	1	$P_i(a)$
[6]	1	0	1	0	0
[7]	1	0	0	1	(1- $P_i(a)$) (1- Π (1- $P_i(a)$))
[8]	1	0	0	0	(1- $P_i(a)$) Π (1- $P_i(a)$)

Table 4. Combination of the joint probability (CPT(A)+CPT(B)+CPT(C))

The following positive analyses discuss the estimation accuracy for the situations of Equation (10) and Equation (11).

4. Positive analyses based on the 2007 Niigata-Ken Chuetsu Oki earthquake

4.1. Precondition of positive analyses

This chapter discusses the effectiveness of the proposed model based on an actual power outage and damage records of an electric power distribution system struck by the 2007 Niigataken-Chuetsu-Oki earthquake (hereafter, called the Chuetsu-Oki earthquake). The target electric power distribution system consists of 32,295 poles including 18,474 high voltage electric power distribution poles and 63 feeders, which indicates a high voltage distribution line.

Fig.5 shows the distribution of the seismic intensity scale of the Japan Meteorological Agency (JMA) due to the Chuetsu-Oki earthquake. The Chuetsu-Oki earthquake caused the 6 upper on the seismic intensity scale of the Japan Meteorological Agency (JMA 6+) as the maximum ground motion intensity to the struck area. In the analysis, it is assumed that the earthquake ground motion information related to Fig.5 has already been given as EGM(a) in Fig.4.

Fig.6 shows the power outage area caused by the Chuetsu-Oki earthquake. Power outages also occurred to 15,074 high voltage poles, which is about 80 % of the total number of high voltage poles in the target system. The power outage information is given as the power outage information (PO) in Fig.4.

Fig.7 shows the observed points of the damaged poles due to the Chuetsu-Oki earthquake. The pole damages mainly consisted of two damage modes; i.e., breakage and inclination [8]. The damaged pole information is given as the damage inspection information (DI) in Fig.4.

In order to discuss the effectiveness of the proposed model, two situations are assumed in the following positive analysis;

1. The earthquake ground motion and power outage information are given (discussed in 4.2).

2. The earthquake ground motion and the damage inspection information are partially given (discussed in 4.3).

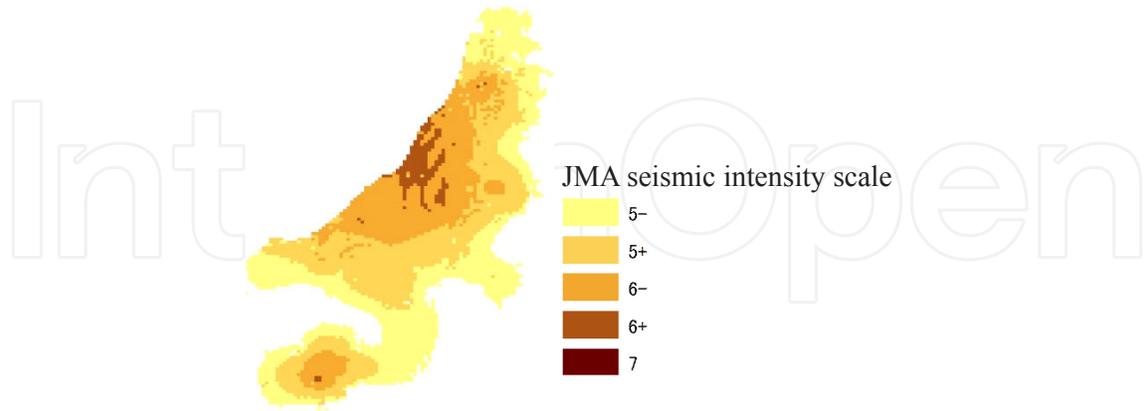


Figure 5. The distribution of the seismic intensity scale of the Japan Meteorological Agency (JMA) due to the Chuetsu-Oki earthquake (treated as EGM(a) in Fig.4)

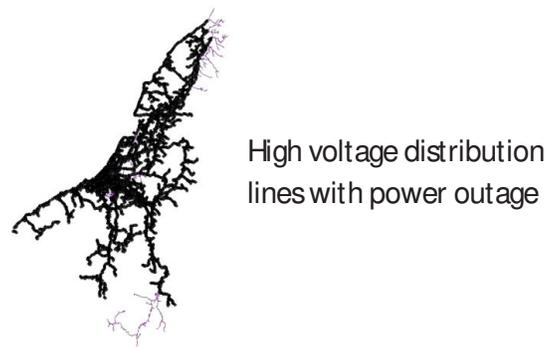


Figure 6. The observed power outage of high voltage distribution lines due to the Chuetsu-Oki earthquake (treated as PO in Fig.4)

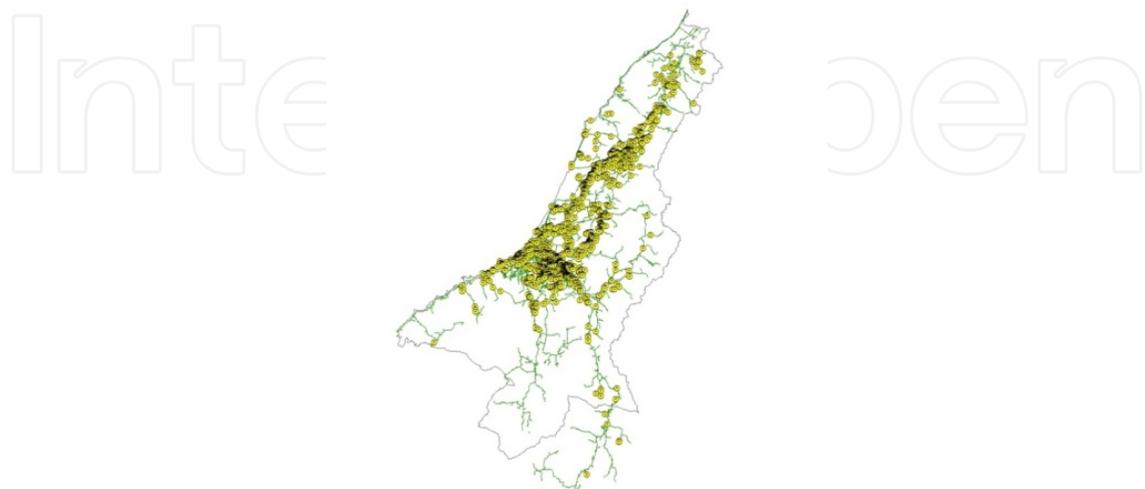


Figure 7. The observed points of the damaged poles due to the Chuetsu-Oki earthquake (treated as DI in Fig.4)

4.2. The effect on accuracy improvement of power outage information

Fig.8 shows a comparison between the observed and estimated number of damaged high voltage poles, which are normalized by the total number of observed damage poles. The caption [Observed] indicates the total number of observed poles damaged by the Chuetsu-Oki earthquake. The caption [without POI] indicates the total number of estimated damaged poles based on the causal relationship defined by Table 1, which is CPT (A) in Fig.4. The damage probability for pole i , which indicates the estimated damage number of pole i , is estimated as P_i ($EPDE=1/EGM(a)=1$). On the other hand, the caption [with POI] indicates the total number of estimated damage poles based on the two causal relationships including CPT(A) and CPT(B) in Fig.4 evaluated by Equation (10).

Fig.8 indicates that the normalized damaged number of [with POI], 1.06, is closer to that of the [Observed], 1.00, than that of [without POI], 1.25. This result suggests that the proposed model using the power outage information can effectively improve the damage estimation accuracy of the electric power distribution poles.

Fig.9, on the other hand, shows a comparison of the number of damaged poles for every third mesh (1km×1km) among [Observed], [with POI], and [without POI]. R indicates the correlation coefficients between [Observed] and [with POI], and between [Observed] and [without POI]. Fig.9 indicates that the correlation coefficient R between [Observed] and [with POI] is slightly higher than that between [Observed] and [without POI].

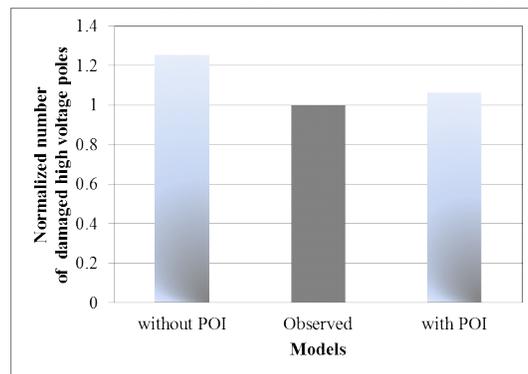
In order to discuss the improved effect of the power outage information on the damage estimation accuracy, Fig.10 shows the relationship among the damage probability of a pole without power outage information, the damage probability of a pole with power outage information, and the total number of poles connected to the same feeder. The horizontal axis indicates the damage probability of a pole without power outage information (PO), which is estimated as P_i ($EPDE=1/EGM(a)=1$) based on Table 1. The vertical axis indicates that with POI, which is estimated as P_i ($EPDE=1/POI=1$) based on Equation (10). N_e , the total number of poles on the same feeder, imitates the actually installed feeder conditions of the target electric power distribution system.

Fig.10 illustrates that when the damage probability of a pole without POI is 0.001, POI improves the damage probability to 0.5, 0.1, 0.02 and 0.0015 on the condition that $N_e=2$, $N_e=10$, $N_e=50$, $N_e=100$, and $N_e=1000$, respectively. This result suggests that the power outage information becomes more effective along with a decrease in the number of poles connected to the same feeder. In this paper, though it is assumed that a power company can identify a power outage range for every feeder, some power companies can identify the power outage within a subdivided range using a switch. In such a situation, the power outage information is more useful to improve the damage estimation accuracy.

Fig.10 also shows that the improvement effect based on the power outage information depends on the earthquake ground motion intensity level. For example, when the earthquake ground motion intensity under a target pole becomes about 6- to 6+ on the JMA seismic intensity scale, it is usually estimated that the damage probability without POI, which is evaluated by $P(a)$, P_i ($EPDE=1/EGM(a)=1$), becomes 0.001 to 0.01. When the damage probability without POI is from

0.001 to 0.01, there are significant differences in the damage probability with POI. On the other hand, when $P(a)$ exceeds 0.03, whose earthquake ground motion intensity becomes over 6+, there is a limited effect of power outage information on improving the damage estimation accuracy.

This result suggests that the power outage information is usually effective for improving the estimation accuracy. However, when one feeder, which is a unit to identify the power outage range, has over 50 high voltage poles, and over 6+ of the earthquake ground motion level strike target feeder, there is a possibility that the effect of the power outage information only slightly improves the damage estimation accuracy of the target equipment.



POI: Power Outage Information

Figure 8. Comparison of total number of damaged high voltage poles

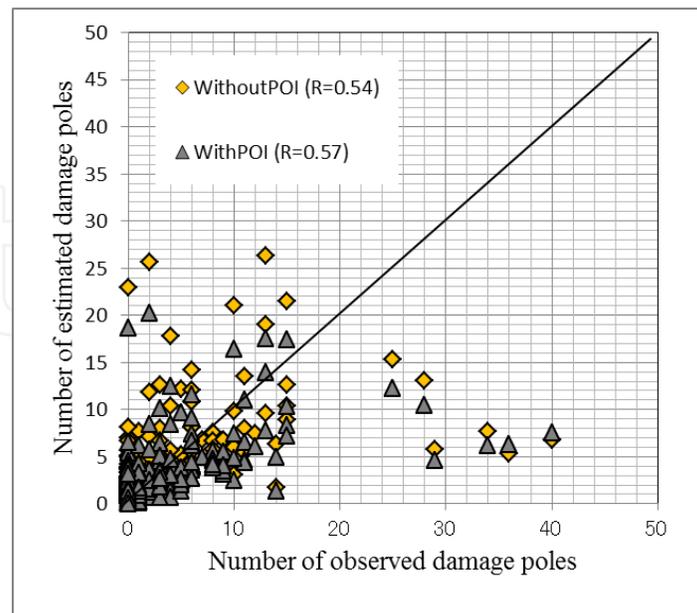


Figure 9. Comparison of the number of damaged poles for every third mesh (1kmx1km) among [Observed], [with POI], and [without POI].

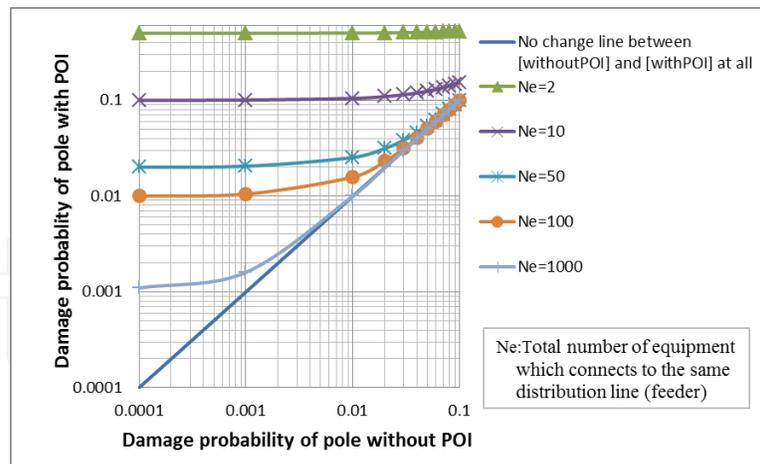


Figure 10. Effect of power outage information on the conditional damage probability of electric power distribution equipment

4.3. The effect on accuracy improvement by the damage inspection information

This section discusses the effect of the damage inspection information to improve the damage probability of the electric power distribution poles. In order to understand the effect of the inspection information on the improvement of the damage estimation accuracy, the damage probability of poles, P_i ($EPDE=1/EGM(a)=1$) is updated based on the different inspection rates. The inspection rate is evaluated as the number of inspected poles divided by the total number of poles (32,295 poles). In this simulation, it is assumed that actual damaged poles by the Chuetsu-Oki earthquake shown in Fig.7 are inspected based on an inspection priority. The inspection priority is determined as follows:

1. The target area is divided into the third mesh (1km×1km)
2. The third mesh (1km×1km) is also divided into the 16 fifth meshes (250m×250m).
3. The conditional damage probabilities, $P_i(EPDE=1/EGM(a)=1)$, for all poles are estimated based on table 1.
4. The averages of the estimated damage probabilities for every third mesh and for every fifth mesh are evaluated.
5. The differences in the average of all the estimated damage probabilities between the third meshes and the 16 fifth meshes of the same third mesh are evaluated as an inspection priority index.
6. The 16 fifth meshes are put in order based on the inspection priority index value. The smaller the priority index, the higher the priority level.

Fig.11 shows the allocated inspection districts of fifth meshes with a 29% inspection rate. The red square point shows the inspection point which is determined by the inspection priority index. The background chart with allocated third meshes is the estimated number of pole

damages for every third mesh based on the conditional damage probabilities of all poles, $P_i(EPDE=1/EGM(a)=1)$.

Fig.12 compares the number of estimated damaged poles evaluated by Equation (11) to that of the observed damage poles for every third mesh. Fig.13 also shows a comparison of the number of estimated damaged poles to that of the observed damage poles for every third mesh. The estimated values consist of two factors; i.e., the number of estimated damaged poles with 29% inspection information and that without any inspection information. The correlation coefficient R between the number of estimated damaged poles with 29 % inspection information and that of the observed one is 0.89 while R between that without inspection information and the observed one is 0.59. This result suggests that the estimation accuracy is highly improved by the 29% inspection information.

Fig.14 shows a sensitivity analysis between the inspection rate and the correlation coefficient. Fig.14 indicates that when the inspection rate exceeds 0.35, the correlation coefficient R becomes greater than 0.9. This result suggests that when a target correlation coefficient is assumed, the districts to be inspected for obtaining target damage estimation accuracy could be automatically determined in a target electric power distribution system. The proposed model enables us to rationalize the inspection during the initial and emergency restoration periods.

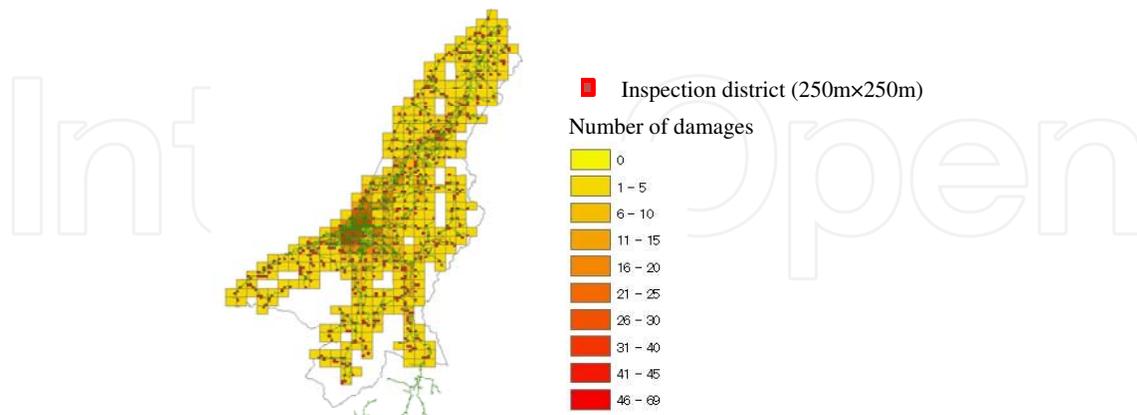


Figure 11. Effective inspection points for the damage estimation of a whole target area

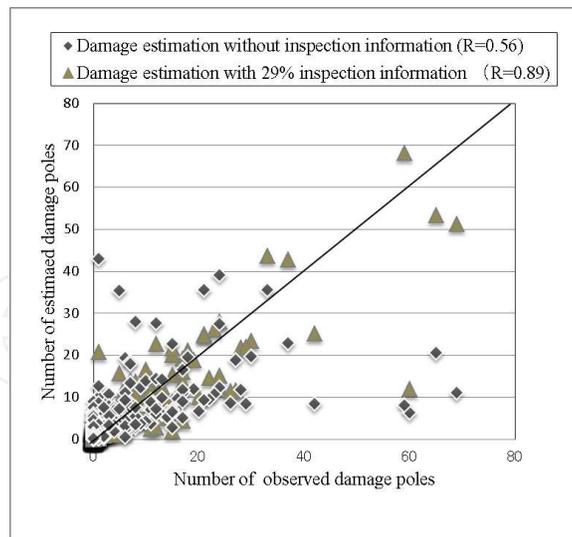


Figure 12. Comparison of estimation accuracies between the damage estimations with 29 % inspection information and without inspection information

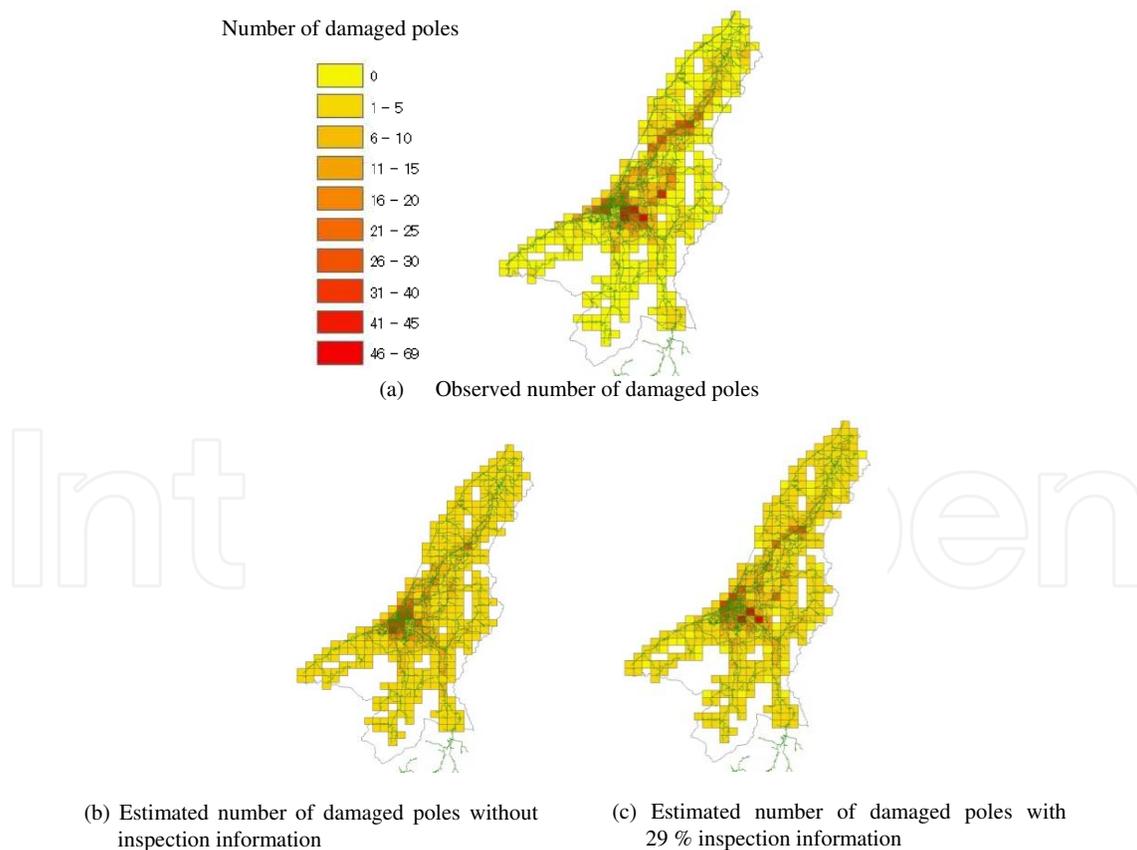


Figure 13. Comparison of the number of estimated damaged poles to that of observed damaged poles for every third mesh.

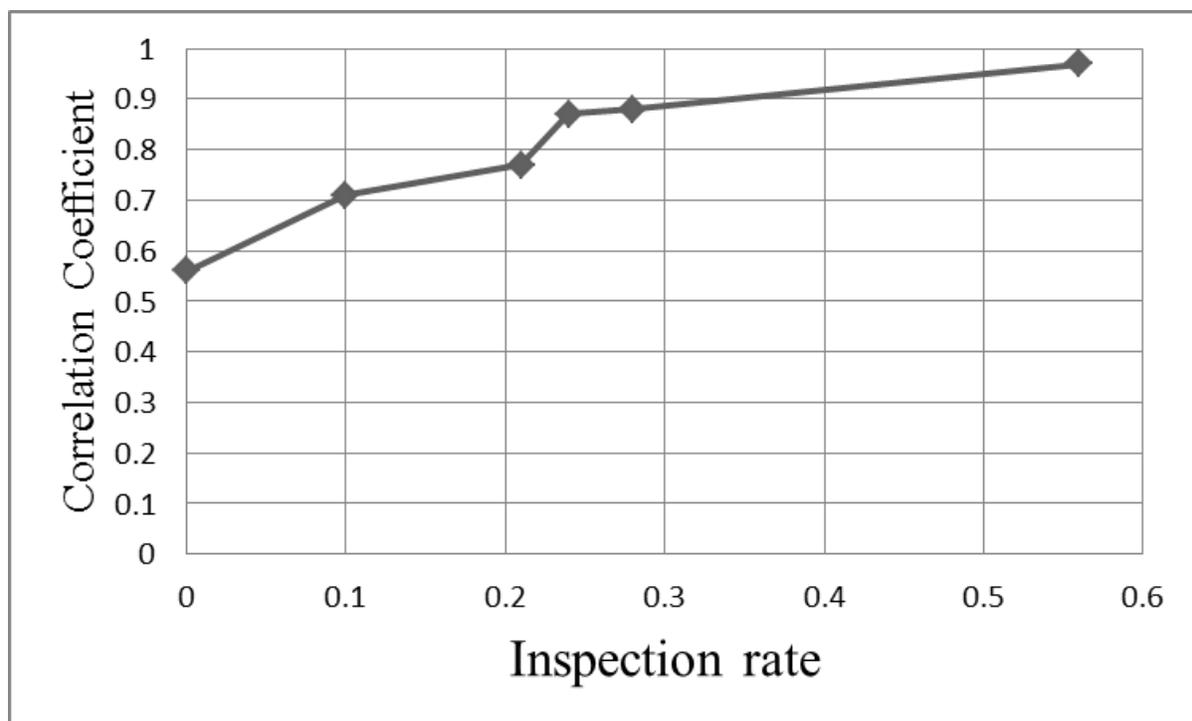


Figure 14. Relationship between the inspection rate and the correlation coefficient associated with the observed and estimation of damaged poles

5. Conclusion

This paper proposed a model to integrate multiple disaster information. The proposed model enables us to improve the damage estimation accuracy of electric power distribution equipment during the initial and emergency restoration periods after an earthquake. The research results are summarized as follows.

1. Information required for the emergency restoration work

The restoration process for an electric power distribution system after an earthquake is divided into three periods; i.e., initial, emergency, and permanent restoration periods. The necessary information and the information that was able to be collected within the three restoration periods were elucidated. As a result, it was clarified that the damage estimation technologies are very useful for actual restoration work under limited disaster information circumstances while the application of a seismic damage estimation system for electric power distribution equipment (RAMPER) to the actual restoration work after the 2011 earthquake off the Pacific coast of the Tōhoku is described.

2. Formulation of a sequential updated model for electric power distribution system

A basic model to integrate the sequentially updated disaster information was proposed based on a Bayesian network. The proposed model can effectively integrate multidimensional

disaster information, including earthquake ground motion, power outage and damage inspection information, to improve the estimation accuracy of seismic damaged electric power distribution poles.

3. Positive analysis based on the 2007 Niigata-Ken Chuetsu-Oki earthquake

The proposed model was applied to an actual electric power distribution system struck by the 2007 Niigataken Chuetsu-oki Earthquake, and the effect of the power outage and damage inspection information for improvement of the damage estimation accuracy was verified. As for the power outage information, it was clarified that under the installed conditions of the actual electric power distribution system, the damage estimation accuracy with power outage information was higher than that without power outage information. It was also realized that in order to effectively utilize the power outage information by the proposed model, the size of one feeder, which was related to a unit to identify the power outage range, and the earthquake ground motion level, which determined the damage probability level, were important parameters.

On the other hand, as for the inspection information, in order to effectively select the damage inspection point, the inspection priority of the actual electric power distribution poles was proposed. Based on the proposed inspection priority, the relationship between the inspection rate and the damage estimation accuracy was analyzed. As a result, it was also clarified that under the installed conditions of the actual electric power distribution system, the estimation accuracy is highly improved only by the 29% inspection information and when the inspection rate exceeds 0.35, the correlation coefficient R between the number of observed damaged poles and that of the estimated one becomes greater than 0.9.

In Japan, the occurrence of the Nankai Trough earthquake is feared. As mentioned in Chapter 2, the damage estimation system, RAMPER, in which the proposed model has already been installed, is operating in some areas that could be highly affected by the Nankai Trough earthquake. In such a high seismic area, it is expected that RAMPER will become a useful tool to support the restoration work after the earthquake. As future subjects, in order to improve the damage estimation accuracy of the proposed model, some remote sensing images will be integrated into the proposed model and the damage records due to the 2011 earthquake off the Pacific coast of Tohoku will be analyzed.

Appendix [A]

Equipment damage estimation model [4]

In this paper, based on reference [4], the seismic damage probability with the maximum earthquake ground motion a ($P_i(a)$) is evaluated as

$$P_i(a) = L_m \cdot C_i \cdot B_j \cdot T_k \cdot S_l \cdot f_c(z(a)) \quad (12)$$

where $f_c(z(a))$ is the seismic damage ratio of equipment i with seismic countermeasure C and seismic performance $z(a)$ assuming that the maximum ground motion a affects the target equipment. The seismic performance $z(a)$ is the seismic safety margin evaluated by the bending moment of the ground surface of the electric power distribution poles caused by the maximum ground motion a . S_l is the modification coefficient evaluated by the line connected type l . T_k is the modification coefficient for the land use condition k . B_j is the modification coefficient for the microtopography division j . C_i is the modification coefficient for the seismic countermeasure of equipment i . L_m is the modification coefficient for local region m . m is an electric power supply area covered by a business branch office.

Seismic performance $z(a)$ relative to the earthquake intensity a is evaluated as

$$z(a) = k_1 \cdot k_2 \cdot z_0(a) \tag{13}$$

where $z_0(a)$ is the safety margin relative to the maximum surface ground acceleration a (m/s^2), which defined as the ratio to the static earthquake force of the design collapse load (N). The static force is converted into the top concentration load of a distribution pole from the maximum surface ground acceleration.

According to the Japan Electric Technical Standards and Codes Committee (2007), $Z_0(a)$ is evaluated as

$$Z_0(e) = \left\{ \begin{array}{ll} \frac{K \cdot D_0 \cdot t^4}{120P(e) \cdot (H + t_0)^2} & \text{(without pole anchor)} \\ \frac{0.3K(D_0 \cdot Q \cdot t^4 + AJ)}{P(e) \cdot (H + t_0)^2} & \text{(with pole anchor)} \end{array} \right\} \tag{14}$$

K is a soil coefficient defined by the Japan Electric Technical Standards and Codes Committee (2007). K is divided into four types. The standard soil [A] is defined as 3.9×10^7 (N/m^4), which includes hardened soil, sand, gravel, and soil with small stones. The standard soil [B] is defined as 2.9×10^7 (N/m^4), which includes softer soil than [A]. Poor soil [C] is defined as 2.0×10^7 (N/m^4), which includes a kind of silt without soil. Poor soil [D] is defined as 0.8×10^7 (N/m^4), which includes moist clay and humid soil.

D_0 is the diameter on the ground surface of the distribution pole (m). t is the penetration depth of the distribution pole into the ground (m). H is the concentration load height from the ground surface (m).

$P(a)$ is the concentration load (kN) converted from the maximum surface ground acceleration a (m/s^2). $P(a)$ is evaluated as

$$P(a) = \frac{a}{H - 0.25} \times W_1 l_1 \tag{15}$$

where H is the height of the distribution pole from the ground surface (m), W_1 is mass of the upper ground part of the distribution pole (kg), l_1 is the height of the gravity center of the upper part of the distribution pole (m).

t_0 is the depth of the gyration center of the distribution pole from the ground surface, which is evaluated as

$$t_0 = \frac{2}{3}t \quad (\text{without pole anchor}) \quad (16)$$

$$t_0' = \frac{2}{3} \left(\frac{t^2 + 3nt_c^2}{t + 2nt_c} \right) \quad (\text{with pole anchor}) \quad (17)$$

$$n = \frac{A}{A_1} \quad (18)$$

where A is the area of the pole anchor. A_1 is the area of the base part of the distribution pole. A and A_1 are evaluated as

$$A = (L - D_0)d \quad (19)$$

$$A_1 = D_0t \quad (20)$$

where L is the length of the pole anchor (m), d is the width of the pole anchor (m).

Q and J are evaluated as

$$Q = \frac{1}{12}(6m^2 - 8m + 3), \quad m = \frac{t_0'}{t} \quad (21)$$

$$J = (t_0' - t_c)^2 t_c \quad (22)$$

where t_c is the depth of the center of the pole anchor from the ground surface (m).

k_1 is a modification coefficient considering the effects of the overhead wire including strung and joint use wires, and overhead equipment such as an overhead transformer.

Based on a preliminary analysis, $k1$ is evaluated as

$$k1 = \frac{1}{a1 \times \sum_{i=1}^4 w_i L_i + b1} \quad (23)$$

where $a1$ and $b1$ are recurrent coefficients evaluated by a preliminary analysis, and these values are assumed to be $a1$ is 0.000428, $b1$ is 1.0. Note that $i=1$: high voltage wire; $i=2$: low voltage wire; $i=3$: overhead transformer; $i=4$: joint use wire; w_i is the mass of I ; L_i is the height of the distribution pole from the ground surface.

$k2$ is a modification coefficient considering adjacent distribution poles. $k2$ is assumed to be

$k2=1.0$ (in the case where adjacent distribution poles have no overhead equipment), $k2=0.9$ (in the case where the number of adjacent distribution poles with overhead equipment is less than three), $k2 =0.85$ (in the case where the number of adjacent distribution poles with overhead equipment is more than four).

In Equation (A.1), the damage ratio is evaluated as

$$f_c(z(a)) = \frac{DP_c}{TP_c} \cdot \frac{\ln_c(z(a) / \lambda_d, \xi_d)}{\ln_c(z(a) / \lambda_{all}, \xi_{all})} \quad (24)$$

$$\ln_c(z(a) / \lambda_x, \xi_x) = \frac{1}{\sqrt{2\pi} \cdot \xi_x \cdot z(a)} \cdot \exp\left[-\frac{1}{2} \cdot \left(\frac{\ln(z(a)) - \lambda_x}{\xi_x}\right)^2\right] \quad (25)$$

$$x = \begin{cases} d & \text{(damaged equipment)} \\ all & \text{(all equipment)} \end{cases}$$

where, $f_c(z(a))$ is the seismic damage ratio function of equipment with seismic countermeasure c and equipment performance $z(a)$ assuming that the maximum ground surface acceleration a . DP_c is the total number of actual seismic damaged equipment with seismic countermeasure c , TP_c is the total number of equipment with seismic countermeasure c . When x is d , $\ln_c(z(a) / \lambda_{x=d}, \zeta_{x=d})$ is the log normal probability density function of the performance value $z(a)$ associated with damaged equipment with seismic countermeasure c due to a target earthquake. When x is d , $\lambda_{x=d}$ and $\zeta_{x=d}$ are the mean and standard deviation of $\ln(z(a))$ associated with the damaged equipment, respectively. When x is all , $\ln_l(z(a)); \lambda_{x=all}, \zeta_{x=all}$ is the log normal probability density function of the performance value $z(a)$ of all equipment with seismic countermeasure c . $\lambda_{x=all}$ and $\zeta_{x=all}$ are the mean and standard deviation of $\ln(z(a))$ for all equipment with seismic countermeasure c , respectively.

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