APPLICATION OF POWER DEMAND CHANGES TO EVALUATE BUILDING AND DWELLING DAMAGES DUE TO EARTHQUAKE

by

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ABSTRACT

Early earthquake damage evaluation is very important for the disaster-related organizations to take prompt action in order to minimize the hazard negative impact. This paper presents a methodology to evaluate the earthquake damage to buildings and dwellings using monitored power supply before and after the event. The electric power demand was used to evaluate regional characteristics and a high correlation was found between the demand changes and the earthquake damage. The proposed method allows a feasible real-time damage evaluation methodology that can be readily implemented with little investment and its applicability is not limited by the weather conditions or time.

INTRODUCTION

The accurate evaluation of earthquake damage is extremely important for disaster related organizations to efficiently plan their actions. After the 1995 Kobe Earthquake (Great Hanshin-Awaji Earthquake or Hyogo-ken Nambu Earthquake), several methodologies for quick disaster estimation have been developed (Noda and Meguro, 1995, Yamazaki et al, 1998). One of these techniques is the use of fragility curves. For this purpose, a dense seismometer network should be deployed at the target area to monitor the ground motion. Based on the structure and past earthquake damage databases, fragility curves are calculated. By combining this and the strong ground motion recorded during the event, damage estimation can be done. This method requires great amount of information, including ground motion data, soil properties, building characterization, etc. Furthermore, this method inherently has many uncertainties, such as the model for the strong ground motion calculation, the site conditions, soil properties, etc. In addition, there is still lively discussion regarding which is the most appropriate parameter to explain the earthquake damage. Peak ground acceleration, peak ground velocity, spectrum intensity and seismic intensity have been proposed by different researchers. Because of these reasons, the damage estimation by means of fragility curves is still not very accurate.

Another approach for the earthquake damage estimation is given by the remote sensing techniques (Takashima and Hayashi, 2000, Matsuoka et al, 2001). Satellite images and/or aerial photographs are used for this purpose. This methodology also presents several restrictions such as: the temporal resolution and satellite passage frequency, the satellite image resolution, the effects of the weather condition and time on the observation, etc. The accuracy attained by remote sensing techniques is still low.

As an alternative, the present study proposes a new methodology for earthquake damage evaluation using the power demand variation during and after the event. Power is permanently supplied to the users and its demand strongly reflects the people response or actions. During a disaster, the damage level of an area is directly reflected by the activities of the people there. Therefore, the power demand after the hazard occurrence strongly reflects the site damage situation.

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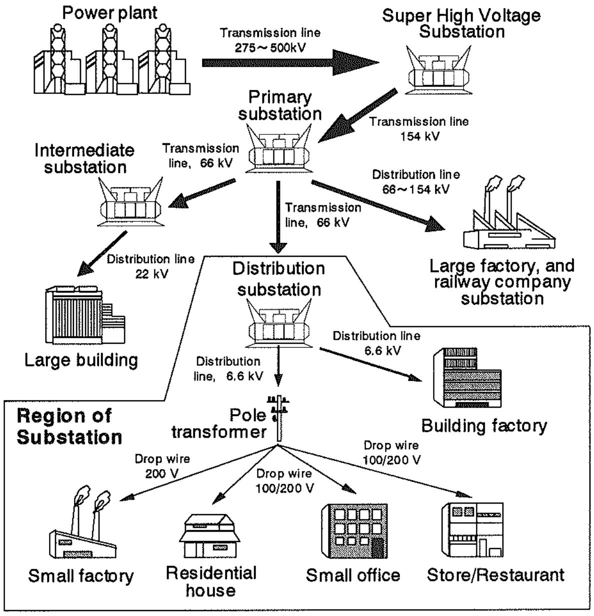


Fig. 1 Electric power supply system

The proposed methodology has several strong points. First, there is no need to develop new facilities to implement a power demand monitoring system. All the facilities are already available and provided by the power supply company. Second, a real time monitoring is possible. Third, there is no need to collect a database of the structure strength characteristics or to develop fragility curves before the event. Finally, the observation is not affected by weather conditions or time.

In this paper, the feasibility of the above mentioned methodology is explored. As a first approach, the power demand is monitored at a spatial unit denominated substation supply area. This unit consists of one substation for the transformation of the power for ordinary consumers (Fig. 1). At each substation, there are three transformers and approximately 20 distribution lines. Thus, from the system point of view, it is possible to reduce the spatial unit by monitoring the power demand at the distribution line level. However, at the present stage, the spatial unit is given by the substation supply area.

POWER DEMAND AND REGIONAL CHARACTERISTICS

The power demand and the substation supply area characteristics are strongly related. *Meguro et al* proposed a classification of a region according to its power demand. Four categories were defined: 1) residential type, 2) office type, 3) industrial (factory) type, and 4) entertainment (pubs and restaurant, etc.) type. By using a stochastic analysis, typical demand curves for each type according to the season were developed for Tokyo 23 wards. First, we assumed that power demand characteristics at Kobe area were the same as those in Tokyo and used demand curves obtained in Tokyo to calculate contribution rates of each type of demand curves in Kobe. However, the results were not good as the power demand characteristics strongly depend on the regional characteristics. Therefore, we calculated the typical demand curves using power demand data in Kobe.

Figures 2 and 3 show the distribution of the substation supply areas for Tokyo 23 wards and Hanshin region. The former consists of 314 spatial units whereas the latter has 69. Table 1 compares the characteristics of the Tokyo and Kobe spatial units. The average unit area is 1.78 km^2 and 4.78 km^2 for Tokyo and Kobe, respectively. Substations shown in Fig. 3 are managed by several controlling units as shown in Fig. 4 and the Kobe branch office of Kansai Power Corporation controls these units.

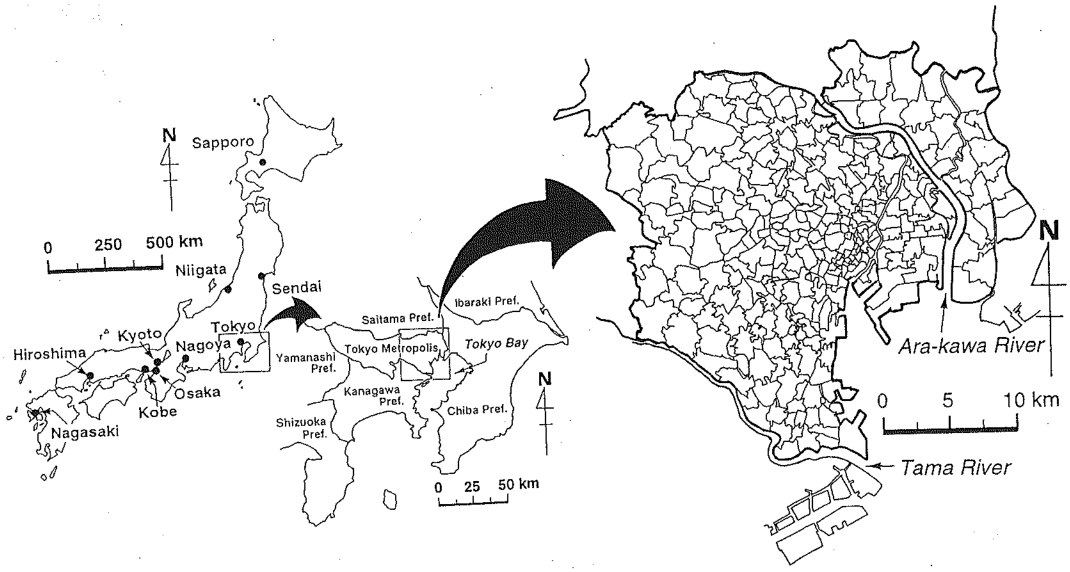


Fig. 2 Location map and distribution of substation areas in Tokyo

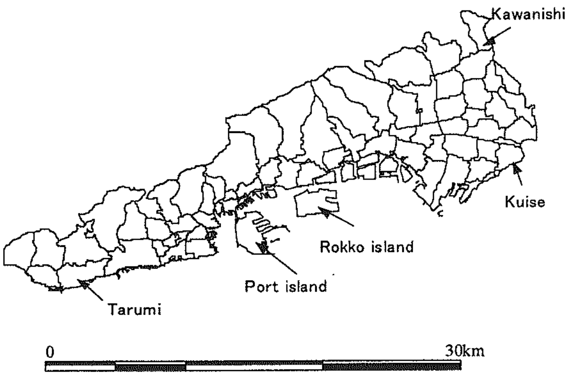


Fig. 3 Distribution of substation areas in Kobe

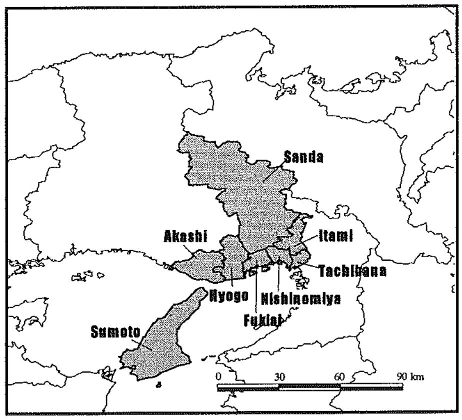


Fig. 4 Location map of the power supply controlling units, composed of substation areas, managed by Kobe branch office of Kansai Electric Power Corporation

Table 1 Comparison of characteristics between substation areas in Tokyo and affected regions in Kobe

	Area (Km^2)	No. of Households	Population	No. of companies	No. of workers
Tokyo (314 Substations)	1.78	10,726	25,470	2,018	22,836
Kobe (affected) (69 Substations)	4.78	12,569	33,285	1,854	15,343

Table 2 Dates and weather conditions of records

	Date of record	Weather	Temperature (Ave.)	Max. Temp Min. Temp	Humidity (Ave.)	Wind velocity (Ave.)
Tokyo	22 Jan. (Wed), 1992	Fine after Cloudy	7.3 ℃	11.7 ℃ 3.1 ℃	45 %	2.7 m/s
Kobe	11 Jan. (Wed), 1995	Cloudy and Occasionally Fine	4.0 ℃	7.3 ℃ 1.0 ℃	52 %	4.8 m/s

(1) Power demand database

The Kansai Power Company, which supplied power to the affected areas during the Kobe earthquake, provided data of the power demand before and after the earthquake. The database includes hourly records from January 9 to 24, from January 28 to February 3, i.e. approximately two weeks after the event, and from February 18 to 24, i.e. one month after the event.

(2) Calculation of the typical demand curves

The substation power supply area is composed of not only one of the categories defined in [1]. It is rather a combination of them. Thus, the power demand at each area can be evaluated as the summation of the contribution of each category. In order to calculate the typical demand curves, the used spatial unit was the substation area. We selected 69 substation areas in the affected region which were managed by Kobe branch office of the Kansai Power Company.

Assuming that the typical demand curves of a distribution area j are expressed as the combination of four elemental demand curves $x_i(t)$, the demand $y_j(t)$ at time t is expressed as:

$$y_i(t) = \sum_{i}^{4} \alpha_{ji} x_i(t)$$

where i corresponds to the four typical areas (i=1: residential, 2: office, 3: industrial, 4: entertainment) and α_{ji} is the contribution of component i to distribution area j. The parameter α_{ji} is obtained from the spatial unit regional characteristics and the optimum $x_i(t)$ were calculated by multiple regression analysis. Figure 5 shows a comparison between the typical load curves of the four demand areas for Tokyo and Kobe.

(3) Calculation of the contribution rate for each substation power supply area

Using the obtained elemental load curves, contribution rates for all substation areas were calculated. The contribution rate is the percentage of the power used in an area at peak-load time due to the residence, offices, factories or restaurant consumption. Figure 6 shows a comparison between the recorded power demand and the demand calculated using the concept of contribution rate. A good agreement is clear. Therefore, it can be concluded that the nature of the substation power demand can be accurately estimated by the contribution rate concept.

Figure 7 shows the map of contribution rates in Kobe area for the four typical demand areas. The dark zones correspond to the regions where the typical demand contribution is higher whereas the light zones show the areas where the contribution is less. The table on the bottom presents the number of spatial units for which the typical demand components are within the contribution ranges given. For instance, there are 9 substation areas out of 69 where the contribution of the residential component is between 81 and 100 percent.

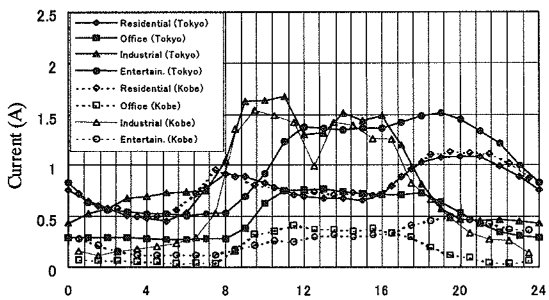


Fig. 5 Typical power demand curves for Tokyo and Kobe

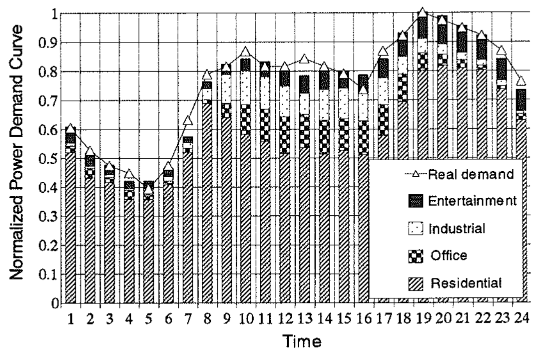
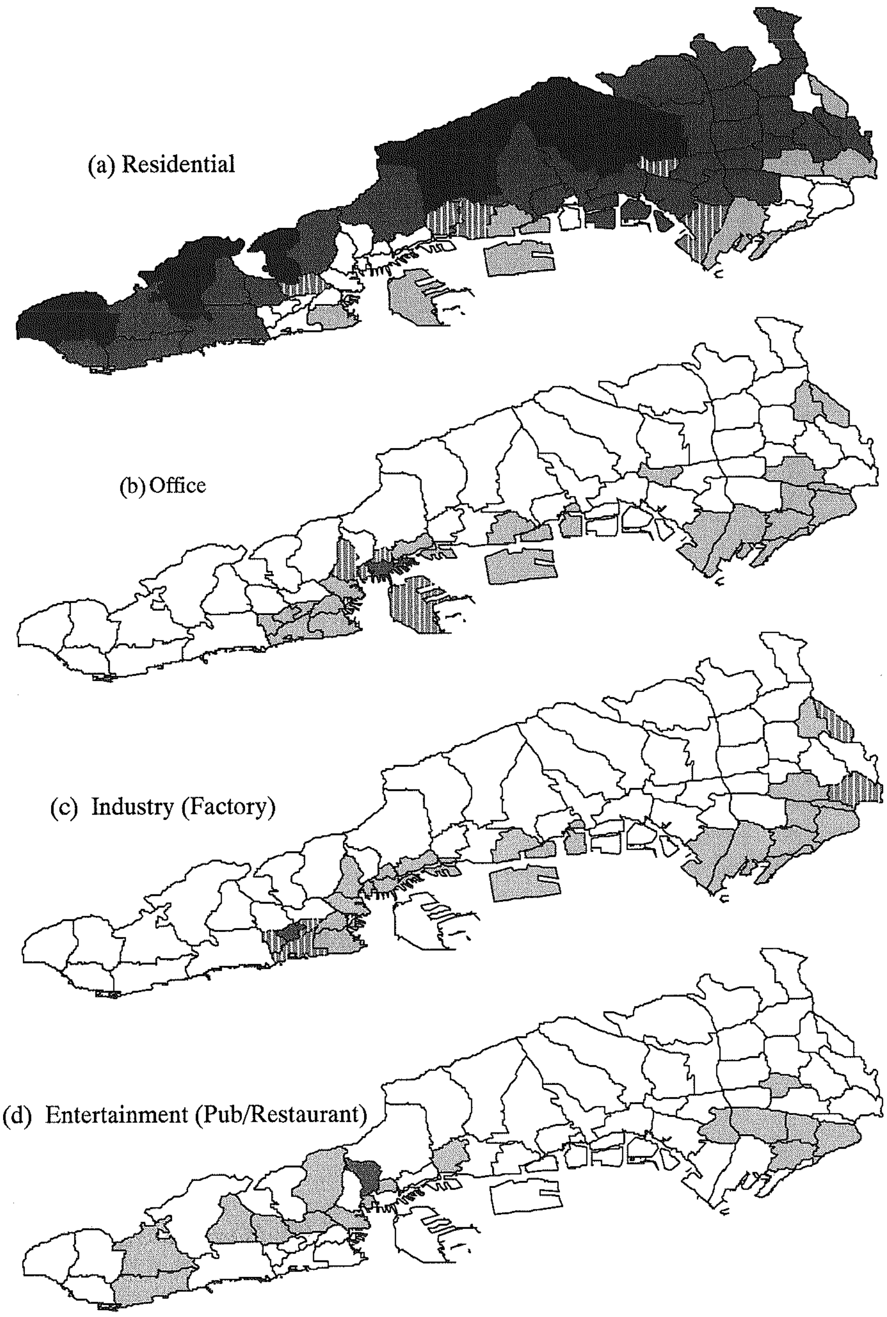


Fig. 6 Comparison between real power demand and simulated demand by contribution ratios



Contribution rate	(a) Residential	(b) Office	(c) Industry	(d) Entertainment
0 – 20	18 (26%)	42 (61%)	43 (62%)	52 (75%)
21– 40	9 (13%)	22 (32%)	20 (29%)	16 (23%)
41 – 60	5 (7%)	4 (6%)	5 (7%)	0 (0%)
61 – 80	28 (41%)	1 (1%)	1 (1%)	1 (1%)
81 –100	9 (13%)	0 (0%)	0 (0%)	0 (0%)

Fig. 7 Distribution of the contribution rate of each substation power supply unit

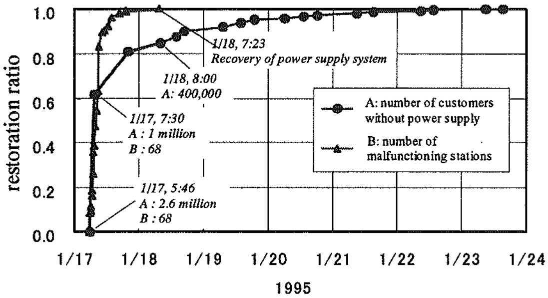


Fig. 8 Electric power recovery time after the Kobe earthquake

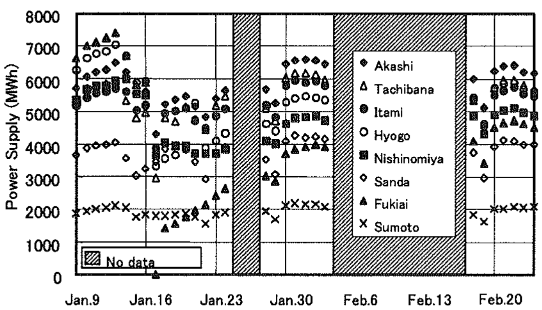


Fig. 10 Power supply variation with time

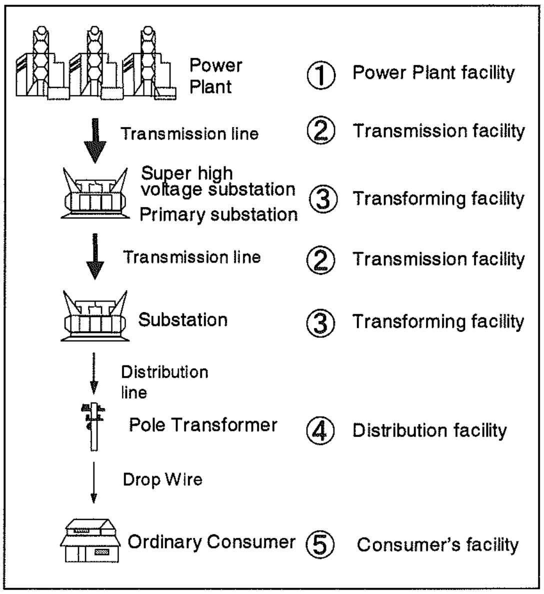


Fig. 9 Electric power supply system and facilities

CHANGES OF THE POWER DEMAND BEFORE AND AFTER THE KOBE EARTHQUAKE

(1) Over view of power outage due to the Kobe earthquake and its causes

As Fig. 8 shows, due to the Kobe earthquake, 260 million customers lost power just after the event and 169 substations including 106 stations of Kobe branch office got malfunction. Although it took about one week for all the costumiers to get power in the affected area, with the quick recovery response such as switching of supply network, 80 % of those substations recovered within 3 hours. Fukiai substation, whose malfunction time was the longest, could recover at 7:23 am on January 18 (about 26 hours after the earthquake). From that point in time, a discussion of the power demand changes can be done. There were about 400 thousand consumers without power even after all the substations' function recovered because of damage to facilities at level lower than substation. It can be argued that the demand might be affected by the falling of poles. This does not directly imply building damage. However, there is a strong correlation between the pole and building damage. A collapsed pole is an indication of the severity of the ground shake. Thus, the probability of building damage in the area next to a failed pole is very high.

There are several causes of power outage. Figure 9 shows the power distribution system scheme (1: power plant facility, 2: transmission facility, 3: transforming facility, 4: distribution facility, 5: final consumer's facility). In the present study, the unit of study is level 3.

(2) Changes of power demand before and after the earthquake at the level of controlling office unit

At first, the power demand changes are monitored at the controlling office or branch office level in order to observe the trends.

Figure 10 shows that the power demand decreased immediately after the earthquake. Due to the large area of the spatial unit as shown in Fig. 4, the demand drop is not so dramatic. The gap increases if a smaller area unit is taken into consideration. The main reason for considering a larger spatial unit at first is to discuss the effect of the weather conditions on the power demand change. It is likely that the temperature variation strongly affects the power demand. Therefore, before going further in the discussion of the relation between structural damage and power demand change, it is important to verify that the temperature does not have a strong influence in the demand change.

(3) Influences of weather conditions in power demand

Figure 11 shows the ratio of maximum and minimum temperature with respect to the average temperature from January 9 to 13, 1995. It is clear from the graph in Fig. 12 that the temperature changes were not important during this period. Thus, it can be concluded that temperature variation effect on the power demand change was minimum and can be mainly attributed to the structural damage.

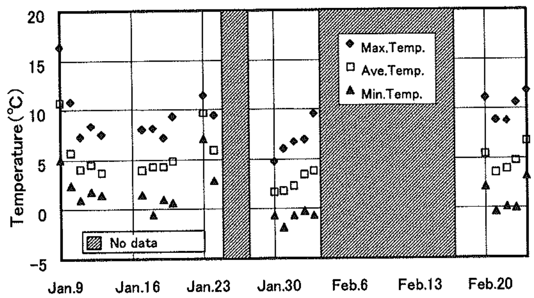
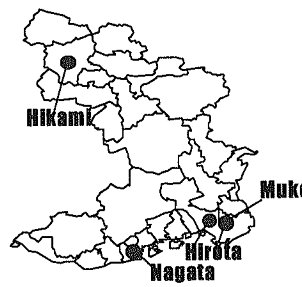


Fig. 11 Variation of maximum, minimum, and average temperature with time



(a) Location of substations

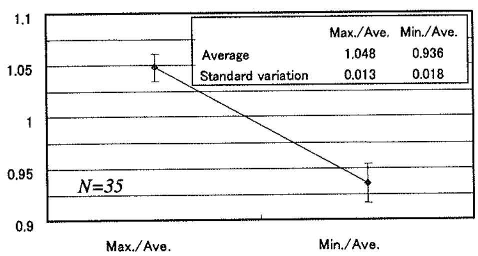
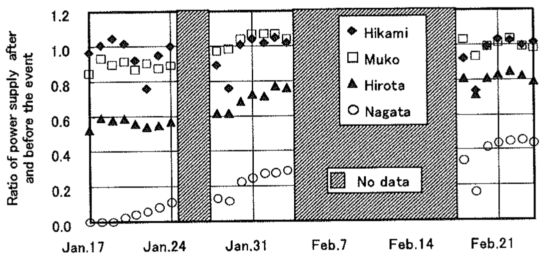
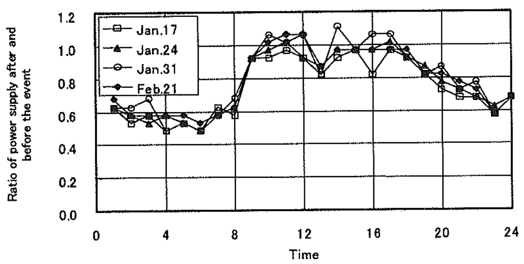


Fig. 12 Changes of power demand of the business days (from Jan. 9 to 13) before the earthquake in 35 substation areas in the coverage area of Hyogo and Hukiai power supply controlling offices

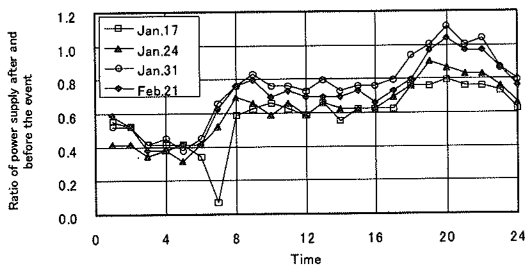


(b) Ratio of power after and before the earthquake

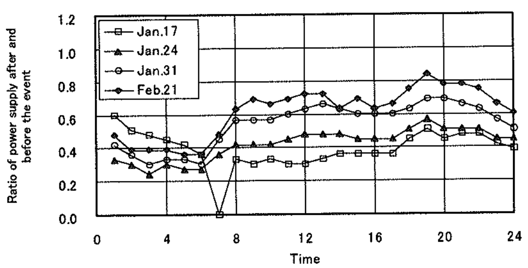
Fig. 13 Changes of power supply after the earthquake



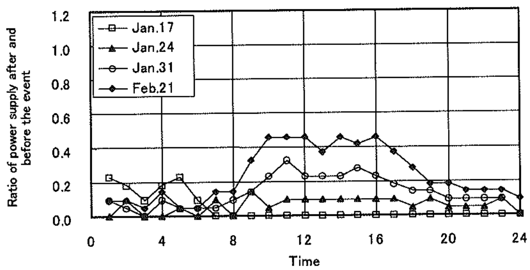
(a) Power supply curve at Hikami substation



(b) Power supply curve at Muko substation



(c) Power supply curve at Hirota substation



(d) Power supply curve at Nagata substation

Fig. 14 Changes of power supply after the earthquake at substations with different damage level

(4) Power demand changes at the substation unit level

The estimation of the power demand changes is the main tissue of the proposed methodology. Figure 13 shows the demand changes at Hikami, Muko, Hiroda, and Nagata substations. The first one is located far from the epicenter whereas the rest are located close to it. Muko did not exhibit extensive damage whereas Hiroda and Nagata suffered more, especially the latter, which was affected not only by the shake but also by fire.

Figure 14 shows the hourly distribution of power demand for January 17, 24, and 31 and February 21 at the above-mentioned substations normalized by the average demand in the week from January 9 to 16. At Hikami, no big demand variation is observed. At the earthquake time there is a drop in the demand at Muko. This is almost completely recovered as soon as the energy supply is restored. At Hiroda, the demand decreases at the time of the event. However, even after the supply is recovered, the demand does not reach the original and it is gradually recover as time passes. Finally, at Nagata, the most affected area, even one week after the supply is restored, the demand level is very low. Due to the extensive damage, there were no consumers in this area. One month after the event, the demand does not reach the original values yet.

Figure 15 shows the power demand variation on the day of the event, one and two weeks after and one month after for the 69 substations considered in the study. Figure 15(b) shows a white line surrounding the area where the seismic intensity was JMA7. The correlation between the power demand drop and the seismic intensity is very high.

DISCUSSION ON THE RELATION BETWEEN POWER DEMAND AND STRUCTURAL DAMAGE

Power demand can always be monitored. As time goes the peak value gradually increases until the original demand peak is reached. In order to analyze the relation between structural damage and power demand, the ratio of power demand with respect to the original demand and the damage ratio (collapsed or burned buildings) were plotted against each other. Figure 16 shows the graphs corresponding to the substations where a) the residential area component contribution is over 70%, b) the office component contribution is over 30%, c) the industrial component contribution is over 35%, and d) the entertainment component contribution is over 20%. Each graph shows four curves corresponding to four different times: 1) the day of the earthquake, 2) one week after, 3) two weeks after, and 4) one month after. If damage is 0%, the power demand should be 100%. On the other hand, if damage is 100%, the demand should be null. However, it is clear that even in the cases where the

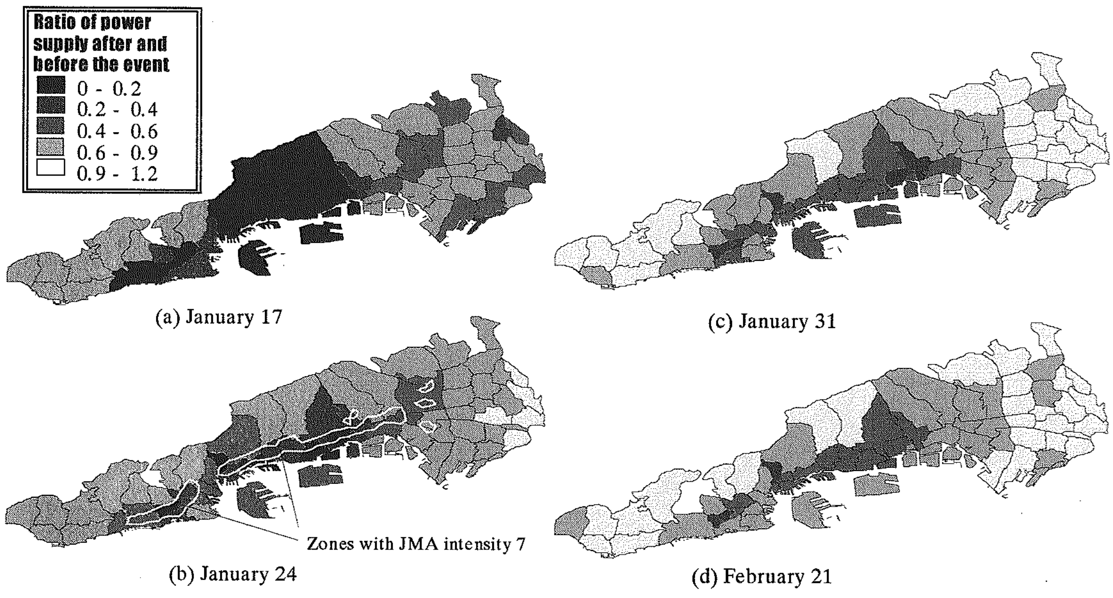
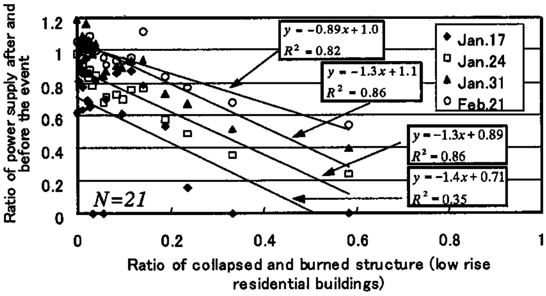
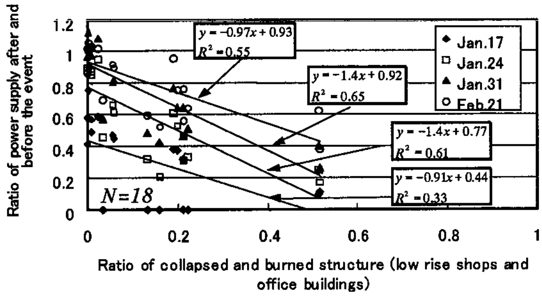


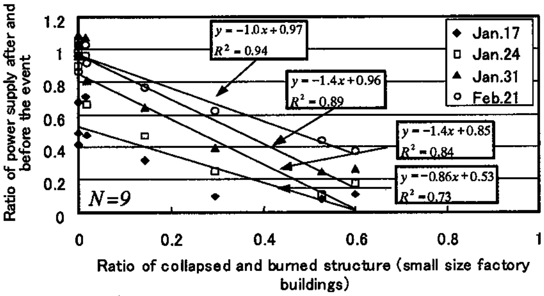
Fig. 15 Distribution of power supply ratio in the affected areas (on the day, one- and two-week, and one-month later the earthquake)



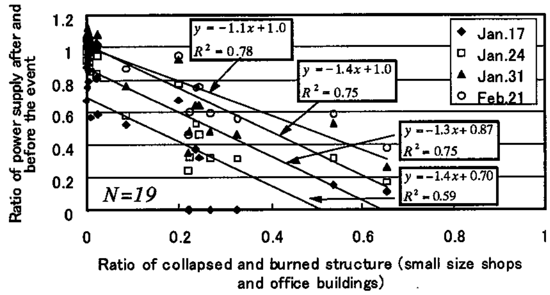
(a) Residential type substation areas
(contribution rate is more than 70%)



(b) Office type substation areas
(contribution rate is more than 30%)



(c) Industrial type substation areas
(contribution rate is more than 35%)



(c) Entertainment type substation areas
(contribution rate is more than 20%)

Fig. 16 Relation between damage level and power supply ratio

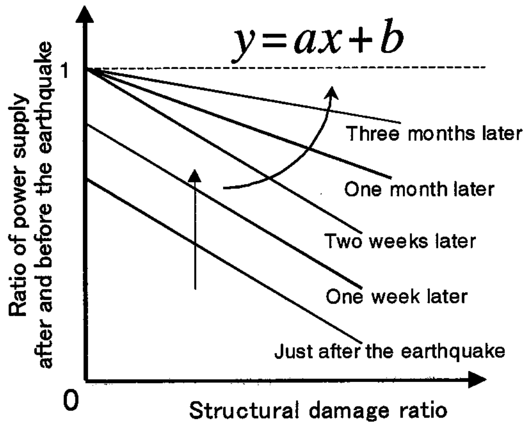


Fig. 17 Model for discussion of structural damage and power supply changes
(in case regional characteristics before and after the event are close to each other)

damage is zero, a drop in the demand can be observed. The reason for this is that even if the damage is small or inexistent at the spatial unit under consideration, the people activities change due to the damage in the surrounding areas. For instance, people cannot get to their offices or factories.

Figure 16 shows another interesting feature. In the four cases considered, the correlation between power demand and structural damage increases as time elapses from the earthquake occurrence time. On the day of the earthquake, the correlation is low. For instance, in the case of residential area, it is 0.35. This is mainly due to the presence of substations that are not supplying energy, i.e. power supply system failure, which are nevertheless considered for the calculation of the correlation. As time passes, the correlation dramatically increases. This allows the proposed method to achieve accuracy levels superior to other damage estimation methods.

A general trend of power demand recovery is observed for the four cases as shown in Figure 17. Shortly after the earthquake, the areas where the damage is minor rapidly recover the original levels of demand. The areas where damage is higher recover too but after longer time. Figure 17 depicts the mechanism of power demand recovery as a function of the damage ratio and time elapsed from the earthquake occurrence. At first, the regression line power demand versus damage ratio shifts until the original demand at the locations where damage is null is reached. After this the regression line slowly rotates until the entire region recovers the original demand level.

CONCLUSIONS

The present paper presents a new technique for structural damage estimation based on the observation of the power demand variations. This methodology has several advantages. First, there are not any limitations for the observation of the power demand such as weather conditions, time, etc. Second, there is no need to prepare new facilities such as airplanes or satellites for the observation. All the required facilities are already provided by the power supply company. Third, the data can be monitored in real time. Forth, the model is permanently updated since the power demand is permanently being observed, i.e. feedback is possible. Fifth, the proposed methodology is also useful to supervise the reconstruction progress by monitoring the power demand recovery. Even in case a certain area changes use, i.e. from an industrial use to a residential use, the expected power demand can be easily estimated from the model and recovery supervision is possible.

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