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MODELING IMPACT OF LIFELINE DISRUPTION ON THE INDUSTRIAL SECTOR IN EARTHQUAKE DISASTERS

N. Nojima[1], H. Shiratani[2] and M. Sugito[3]

ABSTRACT

An assessment method for the effects of lifeline disruption to the industrial sector is presented. First, post-earthquake levels of industrial production are evaluated for each individual pattern of disruption for three kinds of utility lifelines. Next, probabilistic estimation models of eight disruption patterns in terms of specific seismic intensity are combined to evaluate temporal variation of production levels. In consideration of the exposure to seismic intensity, the regional rate for satisfaction of industrial production is evaluated. Monetary losses are also assessed on the basis of reduced shipment values.

Introduction

The disruption of lifelines due to earthquakes seriously degrades industrial production, causing significant indirect losses. In Japan, intensive damage to lifeline facilities and the loss of urban functions during the 1995 Hyogoken-Nanbu (Kobe) earthquake gave rise to strong needs for estimating lifeline disruption and the resulting indirect losses. Business continuity planning (BCP) assuming lifeline disruption has become an important consideration in both private and public sectors. Self-reliance and mutual assistance to mitigate business interruptions are considered to be a key issue. Nevertheless, there are some challenges in the assessment of indirect losses induced by lifeline disruption. Estimation of post-earthquake serviceability of lifelines is not an easy task in itself because of the difficulty in physical damage estimation, complex causality between physical and functional damage, and also because of dependency on operational judgment that is essentially unknown until the actual event occurs. Therefore, especially in Japan, an appropriate method has not been established for evaluating business interruption caused by lifeline disruption and the resultant indirect losses.

With this background, a simple assessment method for the impact of lifeline disruption on the industrial sector is presented in this paper. Post-earthquake levels of industrial production, called "rate of satisfaction" in this study, are evaluated for individual patterns of the three utility lifeline systems: electric power, water delivery, and city gas supply systems. Time function of the rate of satisfaction is evaluated in consideration of the probabilistic restoration pathways of lifelines. The regional rate of satisfaction is evaluated for gross impact on regional industrial activities. Monetary losses are also evaluated on the basis of reduced shipment values. Numerical examples are shown for the industrial sector in central Japan confronting the imminent risk of off-shore huge earthquake, the hypothetical Tokai earthquake.

[1] Professor, Dept. of Civil Engineering, Gifu University, Gifu 501-1193, Japan
[2] Graduate Student, Graduate School of Civil Engineering, Gifu University, Gifu 501-1193, Japan
[3] Professor, River Basin Research Center, Gifu University, Gifu 501-1193, Japan

Definition of Rate of Satisfaction

In the U.S., the ATC-13 introduced "lifeline importance factors" for estimating the effects of lifeline disruption on various social functions in the event of earthquake disasters (ATC, 1985). The importance factors represent the extent to which each of the 35 social functions will be affected by the failure of eleven kinds of lifeline systems (water supply, waste water, electric power, natural gas, petroleum fuel, highway transportation, railway transportation, air transportation, water transportation, phone, radio & TV). The lifeline importance factors are evaluated as a value ranging from 0 to 1 on the basis of expert judgments. The modified estimates of "lifeline importance weights" are given in the ATC-25 (ATC, 1991). In order to develop the relationship between lifeline disruption and indirect economic losses, focus was placed on the economic sector comprised of 36 subsectors and the values were revised to better reflect economic impacts. Fig. 1 shows an example of lifeline importance weights for the food manufacture subsector. Obviously, the loss of electricity imposes the most significant effects on the capability of food manufacturing. Chang et al. (1996) defined the resiliency factor (RF) as the percent of remaining production in the event of complete lifeline outage, or equivalently, one minus the importance weight.

In the following sections, this study employs the resiliency factor; however, the factor is called "rate of satisfaction" for consistency with previous studies by the authors. Rate of satisfaction represents relative productivity normalized to pre-quake levels. The value of 0 corresponds to null productivity (complete loss) and the value of 1 corresponds to full productivity (intact state). Although the rate of satisfaction may be defined for the performance of a specific factory or plant, this study deals with the value as a collective and/or average performance of industrial subsectors rather than that of a specific one. Three kinds of utility lifelines (electric power supply, water supply, and city gas supply) comprise a combination of eight (=2^3) patterns of disruption. The rate of satisfaction of the subsector i is defined as:

$$R_i(\delta_E, \delta_W, \delta_G) = f(RF_i(E), RF_i(W), RF_i(G)) \qquad (1)$$

$f(\cdot)$: functions represented by Eqs.2 and 3
i : suffix indicating industrial subsector
δ_k : availability of lifeline k (unavailable: $\delta = 0$, available: $\delta = 1$)
k : suffix indicating E (electric power), W (water), G (city gas)

$$\left.\begin{aligned} &R_i(1,1,1) = 1 \\ &R_i(0,1,1) = RF_i(E) = 1 - LIW_i(E) \\ &R_i(1,0,1) = RF_i(W) = 1 - LIW_i(W) \\ &R_i(1,1,0) = RF_i(G) = 1 - LIW_i(G) \end{aligned}\right\} \qquad (2)$$

RF : resiliency factor
LIW : lifeline importance weight

As shown in Fig. 1, lifeline importance weights are given for each lifeline assuming independence among systems. In this study, joint effects of multiple disruptions of lifelines are tentatively considered as follows.

$$\left.\begin{aligned} &R_i(1,0,0) = \min[\quad RF_i(W), RF_i(G)] \\ &R_i(0,1,0) = \min[RF_i(E), \quad RF_i(G)] \\ &R_i(0,0,1) = \min[RF_i(E), RF_i(W) \quad] \\ &R_i(0,0,0) = \min[RF_i(E), RF_i(W), RF_i(G)] \end{aligned}\right\} \qquad (3)$$

Eq. 3 may underestimate the joint effects and is subject to change based on further research considering realistic impacts on productivity. Fig. 2 shows an example related to the food manufacture subsector for eight disruption patterns. Note that the relationship between Figs. 1 and 2 is represented by Eqs. 2 and 3.

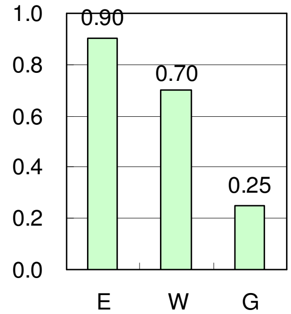


Figure 1. Lifeline importance weights for food manufacture subsector (ATC-25).

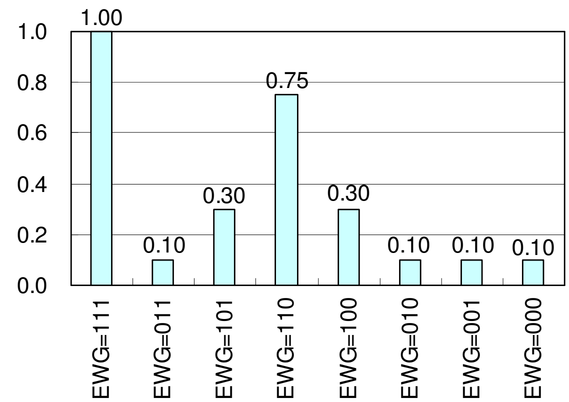


Figure 2. Rate of satisfaction $R_i(\delta_E, \delta_W, \delta_G)$ for eight disruption patterns for food manufacture subsector.

Time Function of Rate of Satisfaction

The availability of each lifeline, denoted δ_k, is regarded as non-decreasing time function after the event of earthquake. Therefore, the rate of satisfaction $R_i(\delta_E, \delta_W, \delta_G)$ is also a time function. Since the restoration of lifeline functions is event-dependent, site-dependent and therefore highly uncertain, the restoration path may be modeled only in a probabilistic manner. For this purpose, this section introduces a simple model of residual capacity curves as functions of seismic intensity. On this basis, time function of average rate of satisfaction is defined.

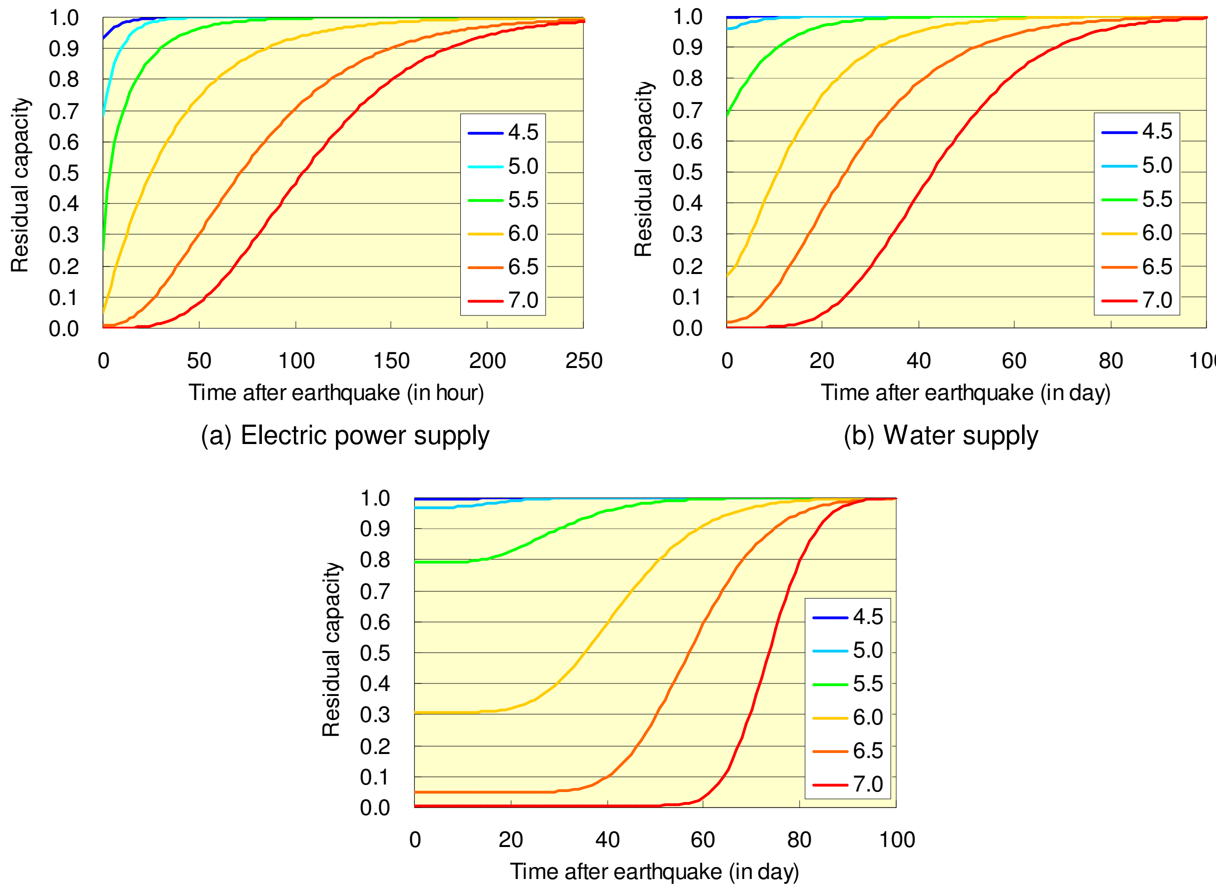
Time Function of Probability of Lifeline Availability

The authors (Nojima and Sugito, 2003, 2005) proposed a probabilistic model for assessment of post-earthquake residual capacity of the three utility lifeline systems. On the basis of data obtained in the 1995 Hyogoken-Nanbu earthquake, two kinds of empirical functions were derived; one is for the estimation of initial outage, and the other is for that of subsequent disruption as functions of seismic intensity on the Japan Meteorological Agency seismic intensity scale (JMA scale; see Appendix) and elapsed time after the earthquake. The two empirical functions were combined to construct the residual capacity estimation model for given seismic intensity.

$$P(I,t) = \{1 - p(I)\} + p(I) \cdot F(I \mid t) \tag{4}$$

I : JMA seismic intensity
t : elapsed time t after the earthquake (in hour for E; in day for W and G)
$P(I,t)$: probability of lifeline availability at I and t
$p(I)$: probability of initial outage at I
$F(I \mid t)$: probability of non-exceedance of required time t for restoration

Although the model provides a probable pathway of functional restoration of utility lifelines for a mass of customers at intensity I, the function is regarded as a probability of lifeline availability at I and t with respect to the application in this study. Fig. 3 shows the curves for the three utility lifelines. It is observed that the function of electric power supply is very susceptible to seismic intensity; however, its recovery is the most rapid of all. On the other hand, initial outage of city gas supply is relatively limited; however, its recovery process is very time-consuming. The function of water supply system indicates intermediate tendency between the two.



(a) Electric power supply

(b) Water supply

(c) City gas supply

Figure 3. Post-earthquake residual capacity curves.

Time Function of Eight Disruption Patterns

By combining the three time functions of probability of lifeline availability, appearance of each of eight disruption patterns is evaluated in a probabilistic manner.

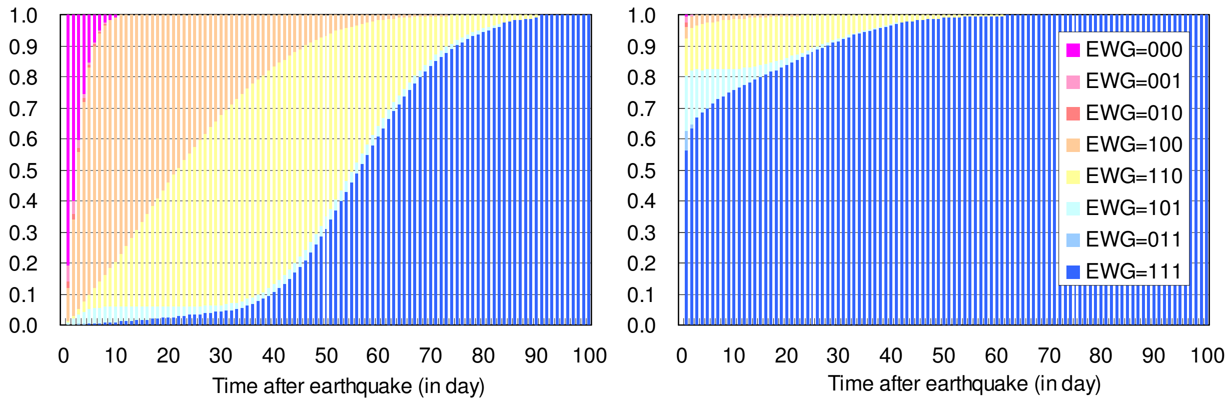
$$Q(\delta_E, \delta_W, \delta_G; I, t) = \prod_{k=E,W,G} P_k(I,t)^{\delta_k} \cdot \{1 - P_k(I,t)\}^{1-\delta_k} \tag{5}$$

$Q(\delta_E, \delta_W, \delta_G; I, t)$: probability of appearance of a disruption pattern $(\delta_E, \delta_W, \delta_G)$ at I and t

$P_k(I,t)$: probability of availability of lifeline k at I and t

Eq. 5 apparently assumes independence among restoration processes of the three utility lifelines. Both positive and negative correlation among lifelines may exist in reality. Spatial correlation generally observed in lifeline recovery process is such that recoveries of all lifeline systems in the area of light damage are rapid and those in the hardest-hit area are delayed. Such correlation due to the difference in the degree of damage is approximately attributed to the difference in seismic intensity, which is implicitly incorporated in the present model, because Eq.4 is already a function of seismic intensity. Therefore, Eq. 5 ignores dependencies due to other causes that are not attributed to seismic intensity.

Fig. 4 compares the results for two cases of different seismic intensities. In the case for $I = 6.5$, the probability of losing all services is approximately $Q(0,0,0;6.5,0) = 0.8$. In the course of recovery process, the patterns $(\delta_E, \delta_W, \delta_G) = (1,0,0)$ and $(1,1,0)$ sequentially become dominant. It is observed that complete restoration denoted $(1,1,1)$ requires very long period of time. The probabilities of appearance of the other four patterns, i.e., $(0,1,1)$, $(0,0,1)$, $(0,1,0)$ and $(1,0,1)$, are negligible. On the other hand, in the case for $I=5.5$, the probability of not experiencing any disruption is as much as $Q(1,1,1;5.5,0)=0.55$ and complete restoration is relatively rapid.



(a) $I=6.5$ (b) $I=5.5$

Figure 4. Probability of appearance of eight disruption patterns.

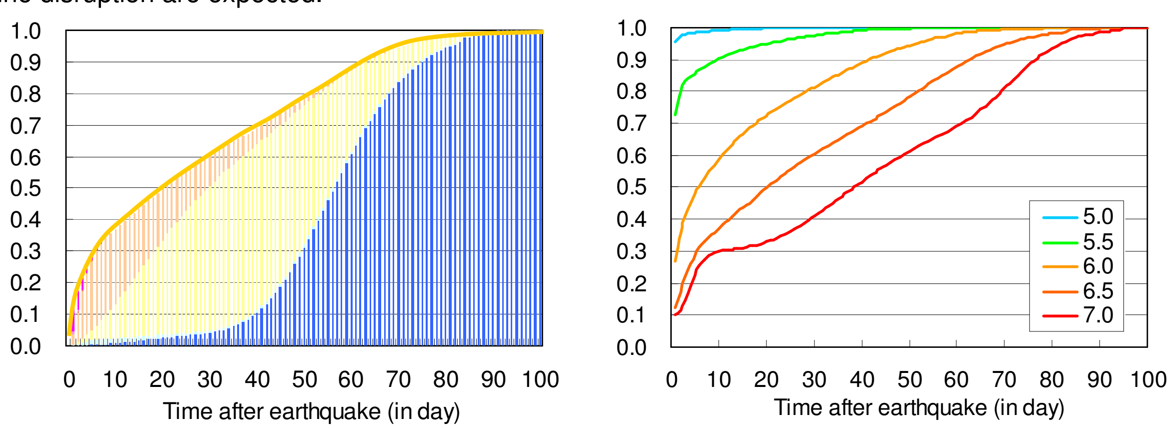
Time Function of Average Rate of Satisfaction

As shown in Eq. 1, the rate of satisfaction is defined as a function of the disruption pattern. Appearance of a disruption pattern $Q(\delta_E,\delta_W,\delta_G;I,t)$ at I and t is evaluated probabilistically using Eq.5 because of uncertainty in the restoration path. By combining these two terms, average rate of satisfaction can be evaluated as a weighted mean of $R_i(\delta_E,\delta_W,\delta_G)$ over all the probabilities of $Q(\delta_E,\delta_W,\delta_G;I,t)$.

$$\overline{R_i}(I,t)=\sum_{\mathrm{all}(\delta_E,\delta_W,\delta_G)} R_i(\delta_E,\delta_W,\delta_G)\cdot Q(\delta_E,\delta_W,\delta_G;I,t) \tag{6}$$

$\overline{R_i}(I,t)$: average rate of satisfaction for the subsector i at I and t

The solid line in Fig. 5(a) shows the time function of average rate of satisfaction of food manufacture subsector at $I=6.5$. Term-wise contributions are also shown in the figure. Fig. 5(b) shows the curves for various intensities I. For higher seismic intensity, more significant initial impact and longer duration of lifeline disruption are expected.



(a) $I=6.5$ (b) Various I

Figure 5. Time function of average rate of satisfaction of food manufacture subsector.

Estimation of Gross Impact of Lifeline Disruption on Regional Industrial Activities

In the previous section, the average rate of satisfaction is modeled as a function of seismic intensity I and time after the earthquake t on the assumption that availability of the three utility lifelines are primarily governed by the two independent variables. The evaluation is valid only for a specific site that experiences a specific seismic intensity. This section extends the model to evaluate the gross impact of lifeline disruption on regional industrial activities. Such evaluation requires the information of exposure distribution determined by the overlapping effect of two main contributors: the distribution of seismic intensity and that of industrial activity. Exposure distribution is evaluated in a very simple manner, which is described in the next section. The procedure is described along with numerical examples.

Distribution of Seismic Intensity

For description and demonstration of the evaluation procedure, examples for the hypothetical Tokai earthquake (moment magnitude M_w=8.0) are shown in this section. This particular event is a plate-boundary huge earthquake expected to occur in the near future in central Japan. Fig. 6 shows the seismic source region of the Tokai earthquake. Strong motion simulation for this scenario event was carried out (Kuse et al., 2003; Sugito, 2005). The distribution map of seismic intensity was obtained for the Tokai region and its surrounding area including Aichi, Gifu, Mie and Shizuoka prefectures. Grid cells equally distributed in the region were used for developing the map. The size of grid cell is NS15" by EW22.5" (approximately 500m by 500m), and approximately 116,000 grid cells cover the whole study area. Fig. 6 shows estimated distribution of JMA seismic intensity for the Tokai earthquake (see Appendix for the JMA scale).

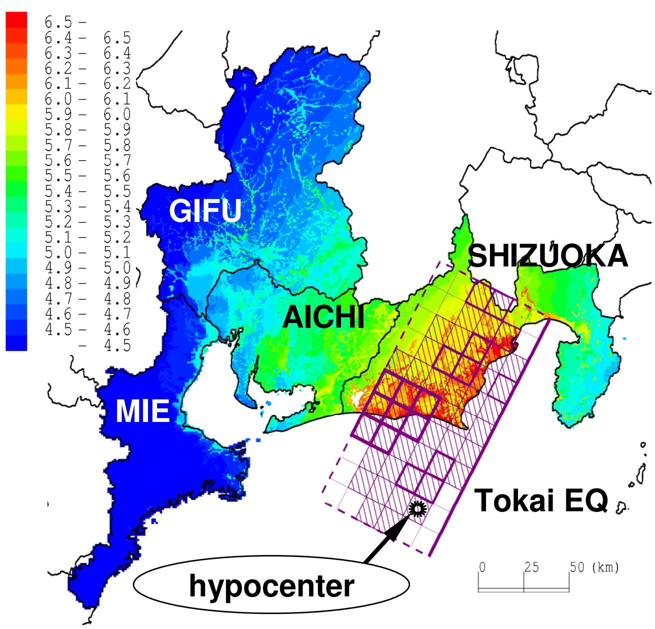


Figure 6. Estimated distribution of JMA seismic intensity for the hypothetical Tokai earthquake.

Distribution of Industrial Activities

For simplification, the distribution of industrial activities is approximated in terms of the number of employees of the industrial sector in each grid cell described above. Such approximation may be erroneous to some extent but enables one to perform quick assessment of wide-area impacts. The grid cell data of the number of employees for various economic sectors is available on commercial basis (MIC, 2006). The latest version is based on "The 2001 Establishment and Enterprise Census." The data for four prefectures was extracted from the nation-wide dataset. The total employees engaged in the industrial sector add up to 1,959,000 (949,000 in Aichi, 254,000 in Gifu, 219,000 in Mie, and 537,000 in Shizuoka). Fig. 7 shows an example for the food manufacture subsector; the number of employees in each grid-cell is summed up for four prefectures.

Population Exposure to Seismic Intensity

Population exposure to seismic intensity is defined as the number of people exposed to a certain level of seismic intensity I (Nojima et al., 2004). In this study, by overlaying the distribution map of seismic intensity and that of the number of employees, population exposure to seismic intensity, $PEX_i(I)$ is evaluated for each subsector i. Fig. 8 shows the estimated result for the food manufacture subsector, representing a breakdown of Fig. 7. Since the incremental value of seismic intensity was set to $\Delta I = 0.1$, the column of intensity I indicates number of people exposed to JMA intensity ranging from I to $I + \Delta I$ in each prefecture. Shizuoka prefecture is expected to go through extremely severe ground motion, since its major part is in the near-source region of the event under consideration.

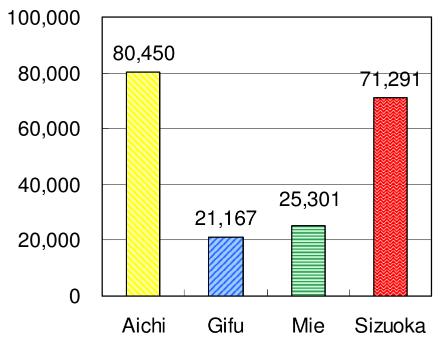


Figure 7. Number of employees engaged in food manufacture subsector.

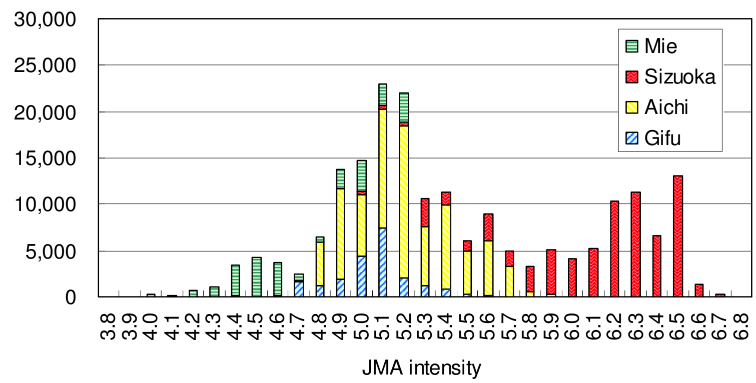


Figure 8. Population exposure to seismic intensity (The hypothetical Tokai earthquake).

Time Function of Regional Rate of Satisfaction

Next, the time function of the regional rate of satisfaction of industrial production is evaluated in consideration of the exposure distribution. In order to integrate the impact on individual sites into the that on overall production activities, the regional rate of satisfaction is defined as a weighted mean of the average rate of satisfaction $\overline{R_i}(I,t)$ at specific I over the contribution from all values of intensities using the population exposure.

$$S_i(t) = \frac{\sum_I PEX_i(I) \cdot \overline{R_i}(I,t)}{\sum_I PEX_i(I)} \tag{7}$$

$S_i(t)$: regional rate of satisfaction for the subsector i at t

$PEX_i(I)$: population exposure to seismic intensity I for the subsector i

Note that the regional rate of satisfaction $S_i(t)$ is not a function of intensity I any more. The value of $S_i(t)$ is normalized to the range between 0 and 1. Fig. 9 shows the estimated regional rate of satisfaction for the food manufacture subsector in four prefectures and that in the entire region. The productivity in Shizuoka prefecture drops to approximately 28% of the pre-quake level immediately after the earthquake, and it requires more than two months to get back to normal.

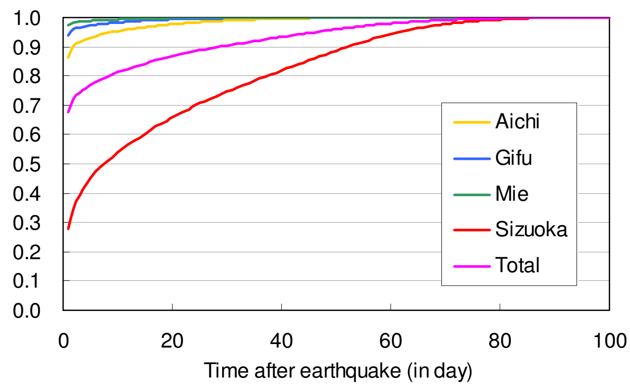


Figure 9. Regional rate of satisfaction for food manufacture subsector (The hypothetical Tokai earthquake).

Estimation of Economic Loss

Finally, economic loss induced by post-earthquake disruption of lifelines is evaluated. For this purpose, the time function of the regional rate of satisfaction is converted to monetary term on the basis of the shipment value. The data of annual value of manufactured goods shipments in four prefectures was extracted from "The 2001 Census of Manufactures" (METI, 2006). Fig. 10 shows an example for the food manufacture subsector. The pre-quake daily shipment value for the subsector i, denoted PR_i, was estimated by dividing the annual value by 365. Then, the time function of post-quake daily shipment value for the subsector i is evaluated by the following equation.

$$EC_i(t) = S_i(t) \cdot PR_i \tag{8}$$

$EC_i(t)$: post-quake daily shipment value at t for the subsector i
PR_i : pre-quake daily shipment value for the subsector i

Fig. 11 shows an example of the estimated time function of post-earthquake daily shipment value for the food manufacture subsector after the hypothetical Tokai earthquake. Cumulative losses evaluated as cumulative differences between the pre- and post-earthquake levels add up to 50.5 billion yen in Shizuoka, which is equivalent to 17.3 days' shipment value. On the other hand, the cumulative losses are 5.4 billion yen (1.3 days' equivalent) in Aichi, 340 million yen (0.5 days' equivalent) in Gifu, and 220 million yen (0.2 days' equivalent) in Mie. Fig. 12 compares the post-earthquake daily shipment values for various industrial subsectors in Shizuoka prefecture. The manufactures of transportation equipment, electrical equipment, and chemical product are found to be susceptible to lifeline disruption because of high concentration of industrial activities of these three subsectors in Shizuoka prefecture.

Concluding Remarks

This study has presented an assessment method for the impacts of utility lifeline disruption on the industrial sector. The method incorporates several dominant factors such as (i) concentration and distribution of industrial activities, (ii) dependencies on lifelines, (iii) resiliency against lifeline disruption, (vi) severity and distribution of both seismic intensity, and so on. In further studies, the applicability of the method will be examined. As mentioned earlier, the proposed method is based on many assumptions and simplifications, which may constrain the precision of estimation to some extent. The list of other contributors to the indirect impacts may include (1) damage to equipments and employees, (2) disruption of transportation lifelines, (3) short-term effects of the supply chain disruption, (4) long-term input-output effects, (5) interdependencies among lifelines, and so on. The future study with wider scope will cover the possibility to incorporate such secondary factors.

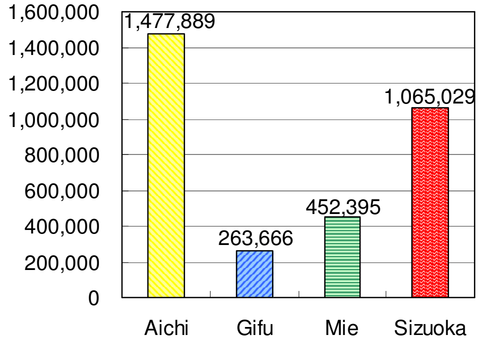


Figure 10. Annual shipment value for food manufacture subsector (in million yen).

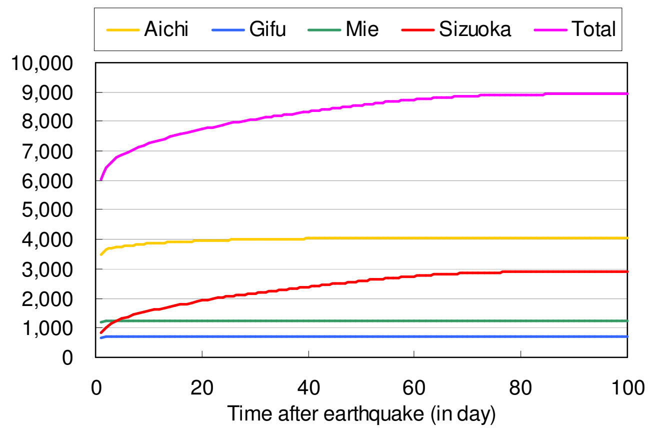


Figure 11. Post-earthquake daily shipment value (in million yen) for food manufacture subsector (The hypothetical Tokai earthquake).

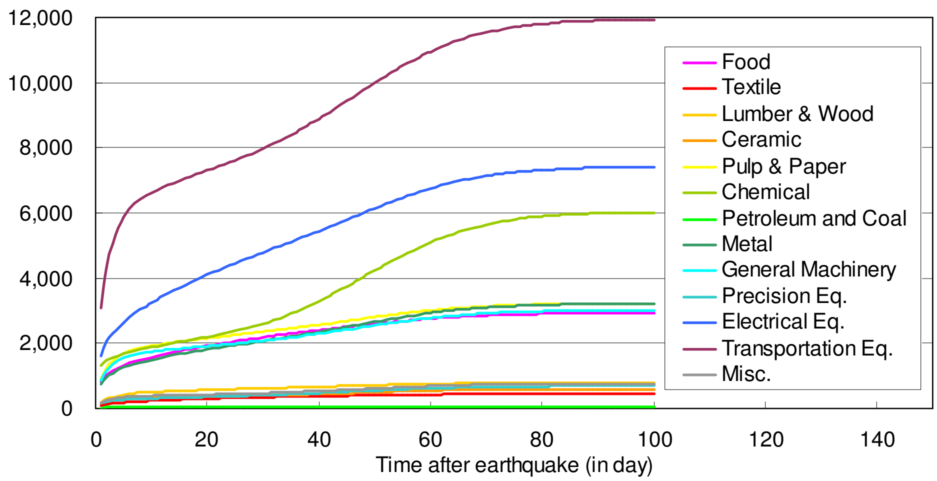


Figure 12. Post-earthquake daily shipment values (in million yen) for various industrial subsectors in Shizuoka prefecture (The hypothetical Tokai earthquake).

Appendix: JMA Seismic Intensity Scale

This study employs the continuous value of seismic intensity on the Japan Meteorological Agency scale which is calculated based on two horizontal and vertical components of strong motion accelerograms processed with the prescribed band-pass filter. Discrete ranks of the JMA seismic intensity are derived by rounding the continuous values into the 10-fold intensity scale ranging from 0 to VII. Fig. A1 compares the JMA seismic intensity scale and the MMI (Modified Mercalli intensity) scale. The relationship between those two is given by the following equation (Shabestari and Yamazaki, 1998).

$$I_{MM} = 1.81 I_{JMA} - 1.95 \tag{A1}$$

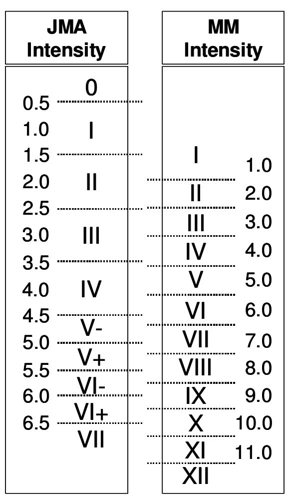


Figure A1. Relationship between JMA seismic intensity scale and Modified Mercalli intensity (MMI) scale.

References

Applied Technology Council, 1985. *Earthquake Damage Evaluation Data for California*, ATC-13, Redwood City, California.

Applied Technology Council, 1991. *Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous States*, ATC-25, Redwood City, California.

Chang, S. E., H. A. Seligson and R. T. Eguchi, 1996. Estimation of the economic impact of multiple lifeline disruption: Memphis Light, Gas and Water Division case study, Technical Report NCEER-96-0011.

Kuse, M., M. Sugito and N. Nojima, 2003. Estimation of seismic intensity distributions for the hypothetical earthquakes in the Nankai Trough region, *Journal of Japan Society for Natural Disaster Science*, Vol.22, No.1, pp. 87-99. (in Japanese)

Ministry of Economy, Trade and Industry (METI), 2006. Statistics Report, http://www.meti.go.jp/english/statistics/h_main.html

Ministry of Internal Affairs and Communications (MIC), Statistics Bureau, 2006. Establishment and Enterprise Census, http://www.stat.go.jp/english/data/jigyou/index.htm

Nojima, N. and M. Sugito, 2003. Development of a probabilistic assessment model for post-earthquake residual capacity of utility lifeline systems, *Proc. of the 6th U.S. Conference on Lifeline Earthquake Engineering*, *TCLEE/ASCE Monograph*, No.25, Long Beach, CA, USA, pp.707-716.

Nojima, N. and M. Sugito, 2005. Probabilistic assessment model for post-earthquake serviceability of utility lifelines and its practical application, *Proc. of the 9th International Conference on Structural Safety and Reliability* (ICOSSAR 2005), Rome, Italy, Millpress, pp.279-287. (on CD-ROM)

Nojima, N., M. Sugito and M. Kuse, 2004. Macroscopic assessment of seismic disaster potential in terms of population exposure to seismic intensity, *Proc. of the Third Taiwan-Japan Workshop on Lifeline Performance and Disaster Mitigation*, Taipei, Taiwan, pp.251-258.

Shabestari, K. T. and F. Yamazaki, 1998. A proposal of new seismic intensity scale compatible with MMI evaluated from seismic records, *Proc. of the 11th European Conference on Earthquake Engineering*, pp.121-127.

Sugito, M., 2005. Comprehensive forecast of destructiveness for huge earthquakes in subduction zone of Japan, *Proc. of the EE-21C*, IZIIS, Ohrid, Macedonia, Keynote Lecture TS3 (on CD-ROM).