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MODELING POST-EARTHQUAKE SERVICEABILITY OF RAILWAY SYSTEMS BASED ON THE DATABASE OF THE GREAT EAST JAPAN EARTHQUAKE DISASTER

N. Nojima [(1)], H. Kato [(2)]

[(1)] *Professor, Department of Civil Engineering, Gifu University, Gifu, Japan, nojima@gifu-u.ac.jp*
[(2)] *Academic Research Assistant, Department of Civil Engineering, Gifu University, Gifu, Japan, kato_hir@gifu-u.ac.jp*

Abstract

In Japan, railway service plays an essential role for every aspect of socio-economic activities, especially in urban regions. Therefore, estimation of possibility and duration of suspension of railway service is an important issue in order to enhance social resiliency in case of loss of service as well as to prevent and mitigate significant degradation of the whole transportation systems. In this study, statistical analyses have been carried out for evaluation of post-earthquake serviceability of railway systems in the 2011 Great East Japan Earthquake Disaster on the basis of JMA seismic intensity. By following the two-step evaluation model for serviceability of utility lifelines proposed by the authors, an empirical model has been statistically-derived to predict railway service suspension in anticipate earthquake scenarios.

Firstly, a GIS database was compiled with regard to railway lines, railway stations and service suspension caused by ground shaking and tsunami inundation. Maps of shaking intensity distribution in terms Japan Meteorological Agency (JMA) seismic intensity scale and those of tsunami inundation area along the coastal regions of Pacific Ocean were also compiled. Secondly, the relationship between the incidence of railway service suspension and shaking intensity was evaluated. On this basis, a logit model was fitted to predict the probability of occurrence of service suspension as a function of shaking intensity. Thirdly, the relationship between the duration of suspension and shaking intensity was evaluated and gamma distribution was fitted to predict the duration of suspension under the condition that service suspension occurs. By combining these two sub-models describing the probability and duration of railway service suspension, a prototype of post-earthquake serviceability curve for railway systems was derived in terms of JMA seismic intensity. Although there remains a need for improvement of model accuracy, the prototype enables one to perform an easy evaluation of post-earthquake serviceability of railway systems.

Keywords: Railway service suspension; Initial outage and duration; The Great East Japan Earthquake Disaster

1. Introduction

In Japan, railway service plays an essential role for daily lives and socio-economic activities as public transportation for both short and long distance. When railway service is delayed and/or suspended due to safety inspection and/or damage to facilities, significant difficulties to commute, to attend school and to travel home, etc. occur. In order to accommodate unsatisfied traffic demands, alternative means such as private cars, buses and airlines must be prepared. In the Great East Japan Earthquake Disaster, which was caused by the 2011 off the Pacific Coast of Tohoku Earthquake, Japan (Mw9.0), extensive and prolonged suspension of railway service caused serious effects inside and outside of the disaster-stricken areas [1, 2]. Estimation of duration of railway suspension is an important issue in order to best operate the whole transportation systems in post-earthquake situation and to enhance social resiliency thereby. In previous studies, estimation models for duration of suspension due to safety inspection and restoration of damaged facilities [3, 4] were proposed. Vulnerability functions of railway facilities [5, 6] and risk assessment method considering duration of suspension corresponding to damage situation [7] were also proposed.

With regard to the Great East Japan Earthquake Disaster, substantial amount of damage data have been published [1, 2, 8-11]. Analysis of such data, however, has not been conducted enough to model the duration of railway service suspension. Although the Cabinet Office published damage estimation for the Anticipated Nankai Megathrust Earthquake [12], estimation is limited to the number of damaged structures as for railway damages. The authors proposed the evaluation model for serviceability of utility lifelines, i.e., electric power, water supply and city gas supply, on the basis of damage statistics and shaking intensity distribution of the 1995 Hyogoken-Nambu earthquake, Japan [13]. The original model has been modified in the light of the progress of disaster mitigation measures achieved to date. The modified model was applied to the Great East Japan Earthquake Disaster, and reasonable agreement has been found between the estimation and observation on prefectural level [14].

This study aims to construct an evaluation model for post-earthquake serviceability of railway service by following the same approach as the model for utility lifelines; probability of occurrence of service suspension and the duration of suspension are statistically derived as function of shaking intensity and combined with each other to represent time-dependent serviceability curves. In chapter 2, the occurrence and duration of railway service suspension and the Japan Meteorological Agency (JMA) seismic intensity in the Great East Japan Earthquake Disaster are compiled. On the basis of their relationship, in chapter 3, the functional fragility curve and the conditional duration curve are derived in terms of JMA seismic intensity. By combining those two, a prototype of post-earthquake serviceability curve for railway service is derived. Suspension of railway service directly caused by tsunami was excluded from this study.

2. The relationship between railway service suspension and shaking JMA seismic intensity in the Great East Japan Earthquake Disaster

2.1 Database on suspension of railway service

A GIS database was compiled with regard to railway lines and stations by using “railways (line data) FY2011” from National Land Numerical Information Download [15] serviced by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), National and Regional Policy Bureau. The name of railway lines and stations are based on “Railway Catalog” [16]. Information of initial suspension and restoration status until June 30, 2013, i.e., up to 842 days after the earthquake, was compiled from the references [1, 8-11]. The subject of this study is passenger stations of each railway company: East JR (Japan Railway) Japan (Shinkansen lines and conventional lines), Central JR (conventional lines), Hokkaido Railway Company, private railways, third-sector and municipal railways. Suspensions due to planned power outage, lack of fuels, resuspension causes by congestion of platforms at railway stations were excluded.

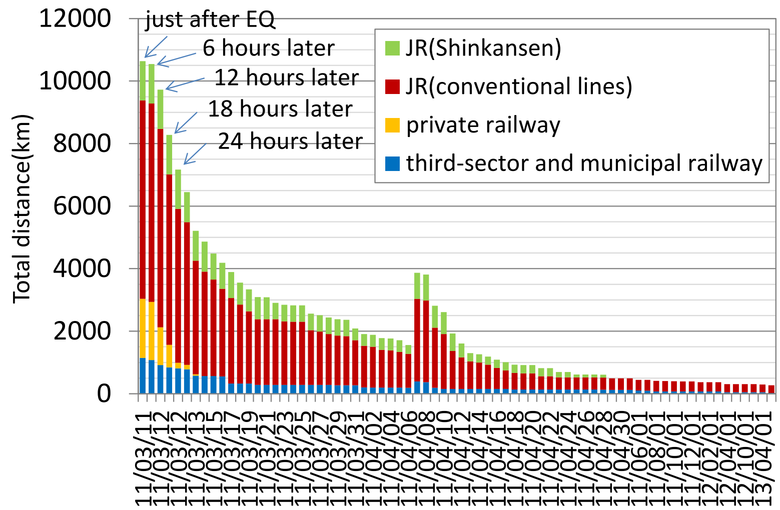


Fig. 1 – Decreasing process of total distance out of railway service (March 11, 2011 through June 30, 2013)

Figure 1 shows the decreasing process of total distance out of railway service. The distances between stations were based on track length compiled by “Railway Catalog” [16]. Additional information was obtained from the reference [17]. Immediately after the occurrence of the 2011 off the Pacific Coast of Tohoku Earthquake (main shock, March 11 14:46, Mw=9.0), suspension of service exceeded 10,000 km. One month after, suspension decreased to 20% of the initial distance. During this period of time, the aftershock of Miyagiken-oki (April 7, 23:32, M_{JMA}=7.1) caused additional service suspension. This study deals with the effect of main shock only. In case where service was restored before the aftershock, additional suspension was not considered. In case where it was difficult to separate the effect of the aftershock from that of the main shock, suspension was considered to be caused by the main shock only.

Suspension of railway service by the main shock occurred to 201 lines including 3,365 sections between neighboring stations in total. Railway stations with initial suspension are shown by red solid circles in Fig.2. In the Tokyo metropolitan area, duration of suspension was given in terms of minutes from the occurrence of main shock at 14:46 of March 12, 2011. In the other area, duration was given in terms of days from March 11, 2011. In this study, duration of suspension was rounded in the following way:

Resume operation on March 11 : 0.5 day

Resume operation on March 12 : 1 day

Resume operation on March 13 or later : 2 days, 3 days, and so on

Figure 3 shows the distribution of duration of suspension. Tsunami-devastated lines along the coastal area of the Pacific Ocean in Iwate, Miyagi and Fukushima Prefecture had not been restored as of June 30, 2013. In its surrounding area, it required one month or longer time for service restoration. Duration becomes shorter with increasing distance from the Pacific Ocean. On the other hand, railway operation resumed relatively quickly in the Tokyo metropolitan area and its surrounding area by March 12, 2011.

2.2 The relationship between occurrence of railway service suspension and JMA seismic intensity

In this study, the distribution map of JMA seismic intensity were obtained from “QuiQuake: Quick estimation system for earthquake map triggered by observed records” [18] by National Institute of Advanced Industrial Science and Technology (AIST). Figure 4 shows the estimated JMA seismic intensity distribution by the main shock. JMA seismic intensity at each railway station was extracted and shown in Fig.5. Almost the entire study area was exposed to JMA seismic intensity 3.5 or greater (intensity scale IV).

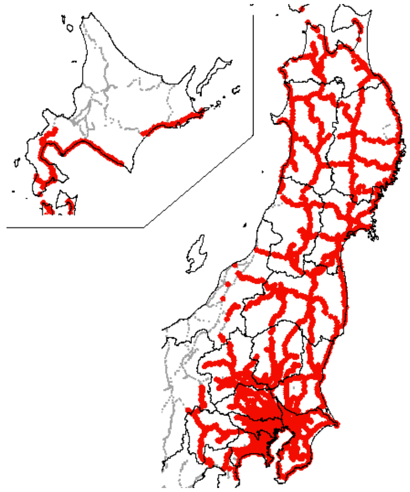


Fig. 2 – Location of railway stations with initial suspension

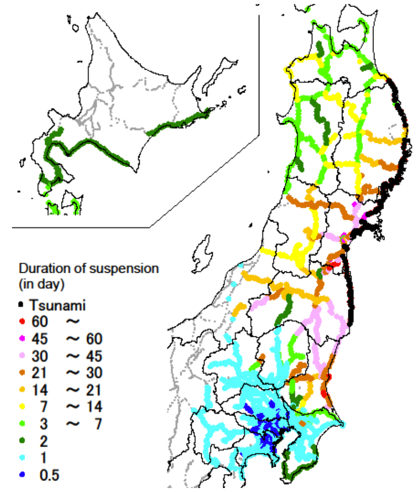


Fig. 3 – Duration of suspension

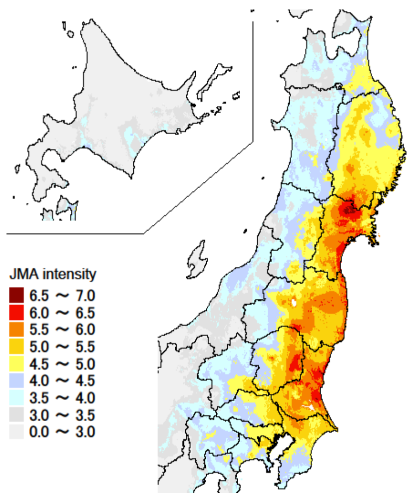


Fig. 4 – Estimated JMA seismic intensity distribution in the 2011 off the Pacific Coast of Tohoku Earthquake. (Based on QuiQuake [18])

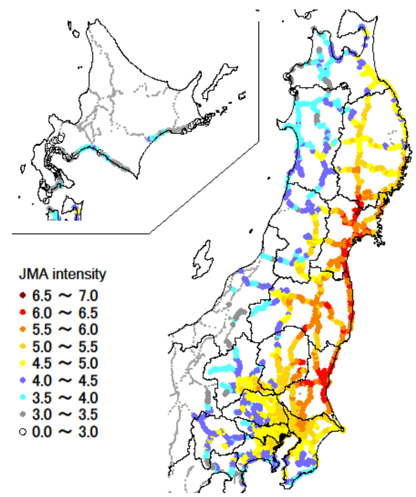
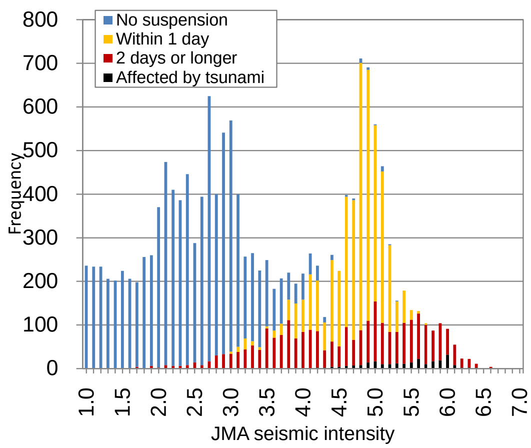


Fig. 5 – Estimated JMA seismic intensity at railway stations in the 2011 off the Pacific Coast of Tohoku Earthquake.

The database of service suspension was overlaid upon the JMA seismic intensity map. Figure 6 shows the histogram of railway service suspension categorized into four. Both ends of each station represent the section between the two, therefore, the number of data, 17,650, is almost twice of the total stations; the breakdown is "no suspension": 10,930, "(restored) within 1 day": 3,906, "(restored in) 2 days or longer": 2,579, and "affected by tsunami": 235. Although overlapped, "No suspension" is obviously distributed in lower intensity range than the others, On the other hand, "Within 1 day" and "2 days or longer" are not separable. According to Fig.3, the Tokyo metropolitan area and its surrounding area were exposed to JMA seismic intensity ranging from 4.5 to 5.5, where many lines were restored within one day. On the other hand, in the western part of Tohoku region and Hokkaido region, it took "2 days or longer" for service restoration in spite of seismic intensity ranging from 2.5 to 3.5. "Affected by tsunami" is distributed over seismic intensity ranging from 4.5 to 6.0. Suspension ratios calculated from the results are shown in Fig.7. Red solid rectangles are for "Case 1" and open rectangles are for "Case 2", which are explained in section 3.1.

For readers' convenience, Fig. A1 in the appendix shows description of JMA seismic intensity scale and Fig. A2 in the appendix shows prefectures in Hokkaido, Tohoku and Kanto regions.



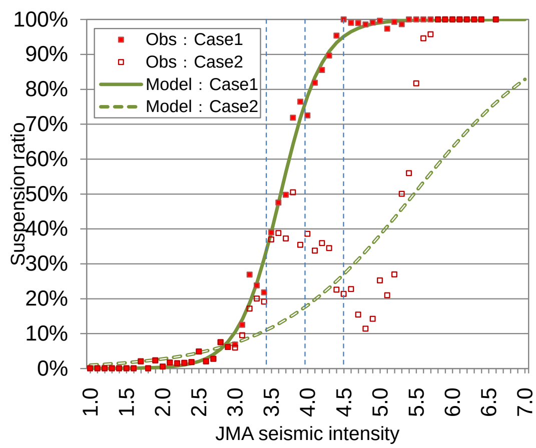


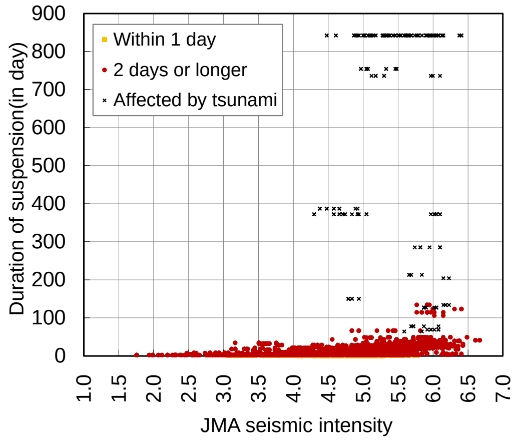
Fig. 6 – Histogram of duration of suspension in terms of JMA seismic intensity in the Great East Japan Earthquake Disaster.

Fig. 7 – Relationship between JMA seismic intensity and suspension ratio (red solid/open rectangles: observed ratio, light green line: logit model, Case 1: all data (excluding tsunami damage), Case 2: excluding suspension within 1 day and tsunami damage, blue dashed lines: seismic intensities corresponding to SI values 3, 6 and 12kine for seismic operation control in East Japan Railway Co.).

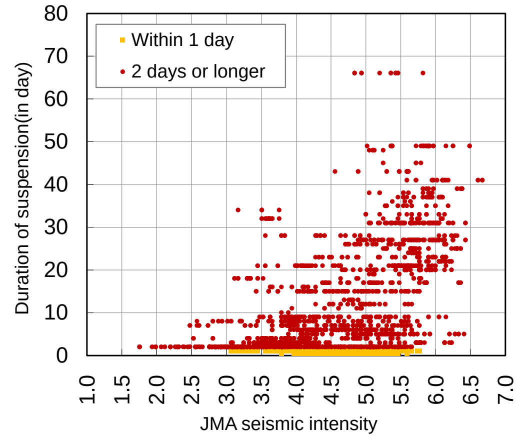
2.3 The relationship between the duration of suspension and JMA seismic intensity

The scattergram representing the relationship between JMA seismic intensity and duration of suspension is shown in Fig.8(a). Maximum days required for restoration is 842 days; those lines were suspended as of June 30, 2013. It is obvious that tsunami-affected sections took remarkably long time to resume operation. If the effects of tsunami are excluded, maximum duration of suspension is 134 days. Figure 8(b) focuses on the first 80 days in order to look into the effects of shaking intensity in detail. In low seismic intensity range, durations of suspension are generally short and their variability is small. On the contrary, in high seismic intensity range, durations are generally long while variability becomes large. Such trends are similar to the relationship between the duration of restoration of utility lifelines and JMA seismic intensity [13]. This suggests that the duration can be modeled as a function of JMA seismic intensity and the uncertainty can be expressed using probability distribution.

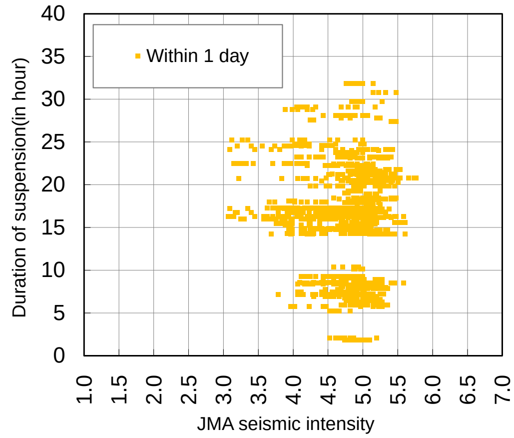
Figure 8(c) focuses on the relatively short duration of suspension within one day mainly in Tokyo metropolitan area. The data, measured in terms of minutes, show no correlation with JMA seismic intensity. In this area, only safety inspection was required for service restoration because of no damage to facilities; or at most, restoration was very quick because of slight damage. The duration of service restoration depends on the process of safety inspection and/or restoration rather than JMA seismic intensity. It is appropriate to model this aspect separately.



(a) All data



(b) Data with suspension less than 80 days



(c) Data with suspension within 1 day

Fig. 8 – Relationship between JMA seismic intensity and duration of suspension in the Great East Japan Earthquake Disaster.

3. Statistical analysis of post-earthquake serviceability of railway systems

The authors proposed the evaluation model for serviceability of utility lifelines based on 1995 Hyogoken-Nambu earthquake, Japan [13, 14]. In this study, by following the method, probability of occurrence of suspension and its duration are statistically analyzed for the evaluation of post-earthquake serviceability of railways. Tsunami-devastated sections shown in Fig.3 are excluded from the analysis.

3.1 Analysis of incidence of railway service suspension (The first step)

The first step of the evaluation model [13, 14] predicts occurrence of railway service suspension as “functional fragility function”. While “fragility curve” generally represents probability of physical damage to structures in terms of input ground motion intensity, “functional fragility function” represents probability of loss of serviceability.

Suspension of railway service is regarded as a binomial response; dummy binomial variable X=1 denotes occurrence of suspension and X=0 denotes no suspension, Outage probability $p(I)$ is evaluated as a logit model represented by Eq.(1) below with parameters b_0 and b_1.

$$p(I)=\frac{\exp[b_0+b_1\cdot I]}{1+\exp[b_0+b_1\cdot I]} \tag{1}$$

On the basis of Fig.6, two cases below are considered; Case 1: whether there was suspension or not, Case 2: whether there was suspension with 2 days or longer. Converged values of parameter b_0 and b_1 were derived using maximum likelihood estimation method and the Newton-Raphson method. The results of parameters are shown in Table 1, and the functional fragility functions are shown in Fig.7. In Case 1, suspension of railway service appears at JMA seismic intensity around 2.5. The suspension ratio reaches 50% at intensity 3.63 and almost 100% at intensity 4.7. As for goodness-of-fit of the model, likelihood ratio ρ^2 is 0.76 and hit-ratio is 0.94, which suggests that observed and estimated values are compatible.

Table 1 – Logit model parameters and goodness of fit.

		Case 1 (All data excluding tsunami damage)	Case 2 (Suspension of 2 days or longer)
Eq.(1)	b_0	-12.42	-5.61
	b_1	3.42	1.03
	Average	3.63	5.47
	Std. deviation	0.53	1.77
	MacFadden ρ^2	0.76	0.52
	Hit ratio	0.94	0.88

East JR prescribes two levels of regulation for train operation control [19, 20]. One is “reduction of speed”; the motorman reduces train speed and conducts inspection at low speed until the train catches up with the preceding one. The other is “emergency stop”; the motorman stops train and engineers conduct facilities and equipment on foot. East JR adopts SI (Spectral Intensity) values [kine=cm/s] for judgement of regulation [19]. For mountainous sections, SI=3 and 6 kine are set for “reduction of speed” and “emergency stop”. On the other hand, those values for general sections other than mountainous ones are SI=6 and 12 kine, respectively. According to the conversion formula [19], SI=3, 6 and 9 kine correspond to JMA seismic intensity=3.42, 3.96 and 4.50, respectively. Blue dashed lines in Fig.7 represent these values.

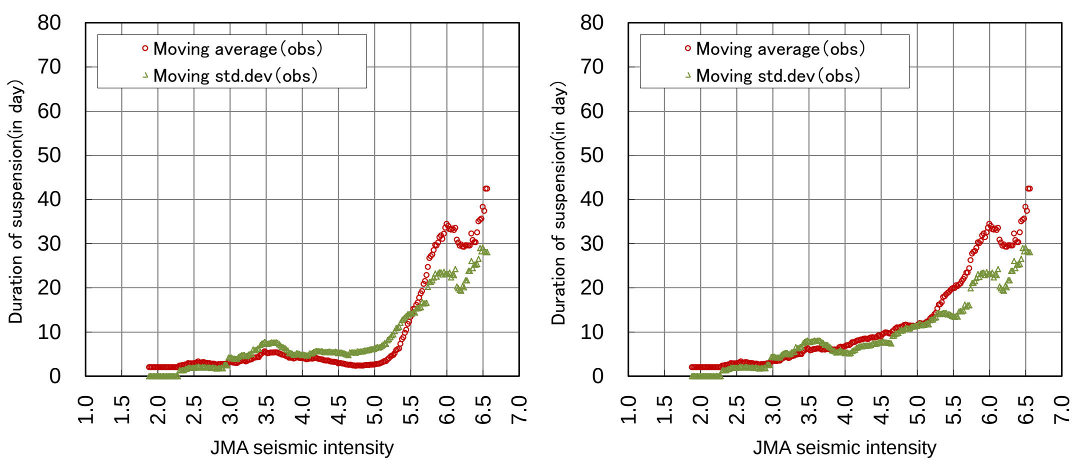
The functional fragility function for Case 1 tends to increase drastically around the three regulatory thresholds. Although other railway companies individually have their own regulations for train operation control based on JMA seismic intensity or peak ground acceleration, conventional lines of East JR occupies 50% of lines of this analysis (5321.2 km out of the subject line extension 10639.6 km). Therefore the tendency for Case 1 agrees well with regulations of East JR. In detail, there is a slight shift of the functional fragility function for Case 1 to lower seismic intensity of the three regulatory thresholds. The reason is considered to be service suspension because of tsunami warning in the region of low seismic intensity centered on the coastal area of Hokkaido.

On the other hand, observed values for Case 2 appear at JMA seismic intensity 2.5 as well as Case 1. Suspension ratio is about 35% from JMA seismic intensity 3.5 to 4.5. However, suspension ratio decreases to around 20% in the range of intensity 4.5 to 5.0 and increases again rapidly to almost 100% at intensity 6.0. The reason of such fluctuation is that the Tokyo metropolitan area, where the spatial density of train stations is very high, restoration of railway service was within one day in JMA seismic intensity 4.5 to 5.5. The functional fragility function for Case 2 does not fit well because of such fluctuation. Also the curve for Case 2 is higher than that for Case 1 in the range of intensity 2.8 or less, which is theoretically irrational. There remains a room for improvement of the models.

3.2 Analysis of the duration of railway service suspension (The second step)

The second step of the evaluation model [13, 14] derives a restoration curve under the condition that suspension of service occurs as a function of JMA seismic intensity I. Data of durations of suspension shown in Fig.8 excluding those related to tsunami-devastation were used. By following the previous study on utility lifelines [13], moving window with width 0.4, i.e., window ranging of [I-0.2, I+0.2] for intensity I, was applied to Fig.8. Moving average and moving standard deviation within the window were calculated to obtain the trend component and variability of duration of suspension as shown in Fig.9.

Figure 9(a) shows the result for Case 1. Moving average of duration of suspension obviously shows increasing tendency with increasing JMA seismic intensity from 5.0 to 6.0. Relatively long duration of suspension from intensity from 3.0 to 4.5 is due to suspension in the western part of Tohoku region and Hokkaido region. On the other hand, the dip around intensity 5.0 is due to relatively short suspension in the Tokyo metropolitan area. Moving standard deviation is almost comparable to moving average, which means that the variation is quite large. Figure 9(b) shows the result for Case 2. Moving average is larger than Fig.9(a), but increase tendency is also clearer. Moving standard deviation is equivalent to moving average, therefore the coefficient of variation is almost 100%.



(a) Case 1 (b) Case 2

Fig. 9 – Moving average and moving standard deviation of duration of suspension in terms of JMA seismic intensity.

Although large variation is seen in both cases, this study aims to incorporate and quantify such uncertainty and construct a probabilistic model for evaluation of suspension of service. This study employs probability density function (PDF) of gamma distribution for this purpose, since gamma distribution was found to be suitable for both convex and S-shape forms which are commonly seen as the shape of restoration curves [21].

$$f(t \mid I) = \frac{t^{\alpha(I)-1} \exp\left(-\frac{t}{\beta(I)}\right)}{\beta(I)^{\alpha(I)} \Gamma(\alpha(I))} \tag{2}$$

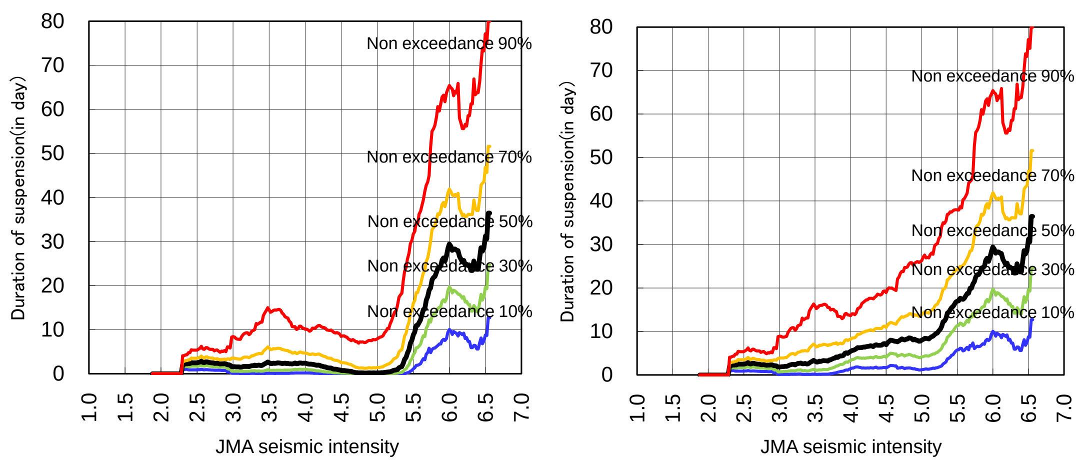
Two parameters α(*I*) and β(*I*) are calculated by applying the moment method:

$$\alpha(I)=\left(\frac{\mu(I)}{\sigma(I)}\right)^2, \quad \beta(I)=\frac{\sigma^2(I)}{\mu(I)} \tag{3}$$

The duration of suspension of non-exceedance probability was calculated from its cumulative distribution function (CDF).

$$F(t\,|\,I)=\int_0^t f(\tau\,|\,I)d\tau \tag{4}$$

Figure 10 shows statistical model of duration of suspension represented by gamma distribution in terms of JMA seismic intensity. Five lines correspond to duration of suspension with non-exceedance probability from 10, 30, 50, 70 and 90% for arbitrary values of JMA seismic intensity. Visually, the overall trend is better reflected in Fig.10(b) rather than Fig.10(a). There remains a room to improve the model; overestimation in low seismic intensity range and fluctuation of moving average and moving standard should be reduced.



(a) Case 1 (b) Case 2

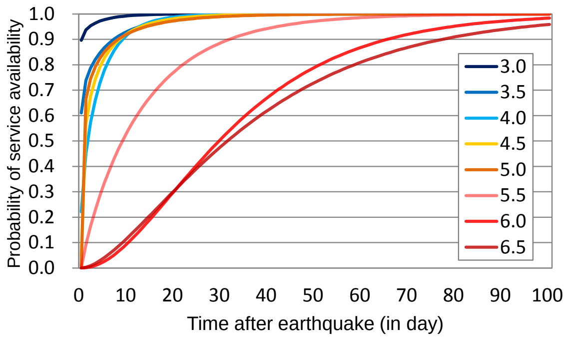
Fig. 10 – Statistical model of duration of suspension represented by gamma distribution in terms of JMA seismic intensity.

3.3 A prototype of post-earthquake serviceability curves of railways for various JMA intensities.

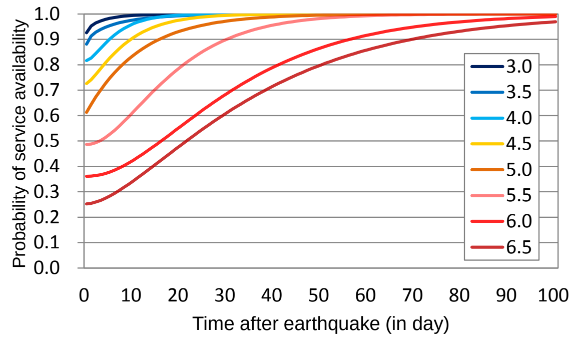
Equation (4) also serves as the conditional restoration curve. By combining Eq.(1) and Eq.(4), namely, Fig.7 and Fig.10, post-earthquake serviceability curve for railway was derived

$$P(I,t)=\left\{1-p\left(I\right)\right\}+p\left(I\right)\cdot F\left(t\middle|I\right) \tag{5}$$

Fig.11 shows the curves for JMA seismic intensity ranging from 3.5 to 6.5 with an increment of 0.5. The curves represent the probability of service availability at arbitrary time period. Because of the fluctuation of data shown in Fig.9 and Fig.10, some irregular tendency can be seen. This study excluded data related to physical damage caused by tsunami only. Factors which are not incorporated in the present model are: lack of energy, i.e., interruption of electric service and lack of fuels in the non-electrified section, tsunami warning, the process of evacuation of passengers, the process of inspection and restoration facilities, inter-connection of railway routes operated by different railway companies, judgement of operation of inter-connected routes as a whole system, weather conditions such as snowfall, etc. For improving the model, further analysis is needed to consider those factors and incorporate appropriate explanatory variables.



(a) Case 1



(b) Case 2

Fig. 11 – Prototype of post-earthquake serviceability curves of railways for various JMA intensities.

4. Conclusions and future developments

In this study, the method of the two-step evaluation model for serviceability of utility lifelines [13, 14] was applied to railway service, and the relationship between the duration of suspension and seismic intensity was statistically analyzed. Those sections devastated by tsunami were excluded from the dataset.

1) On the basis of the relationship between occurrence of railway service suspension and JMA seismic intensity, functional fragility functions were derived for two cases: Case 1: “whether there was suspension or not,” and Case 2: “whether there was suspension with 2 days or longer.” Case 1 showed high goodness-of-fit, although suspension ratio is too high at low seismic intensity. On the contrary, Case 2 showed low goodness-of-fit.

2) The relationship between the duration of suspension and JMA seismic intensity. Case 1 showed clear tendency of increasing duration of suspension with increasing intensity in the range from 5.0 to 6.0. Case 2 showed such increasing tendency for wider range of intensity. For both cases, the coefficients of variation were as large as almost 100%. Therefore, gamma distribution was fitted to predict the duration of suspension under the condition that service suspension occurs.

3) By combining those sub-models, a prototype of post-earthquake serviceability curve for railway systems was derived in term of JMA seismic intensity. Because of the statistical fluctuation of parameters, some irregular tendency can be seen, which should be eliminated in the model for practical use. For improving the model, further analysis is needed to consider additional factors and incorporate appropriate explanatory variables.

In the Tokyo metropolitan area, it is known that additional factors other than shaking intensity significantly affected the occurrence of service suspension and the process until the operation was resumed. Those factors are, for instance, the locations where trains halted in emergency, whether trains could reach the nearest stations or not, the process of evacuation of passengers, the process of inspection and restoration of facilities, inter-connection of railway routes operated by different railway companies. The effect of those factors on service suspension will be discussed in future study.

5. Acknowledgements

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6. Appendix

Figure A1 compares the JMA seismic intensity scale and the MMI (Modified Mercalli 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.

Figure A2 shows the locations and the names of a prefecture in Hokkaido region, six prefectures in Tohoku region and seven prefectures in Kanto region.

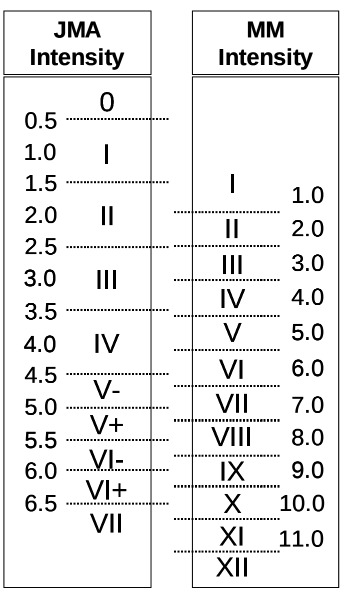

Fig. A1 – Relationship between JMA and MM intensity (after Shabestari and Yamazaki [22])

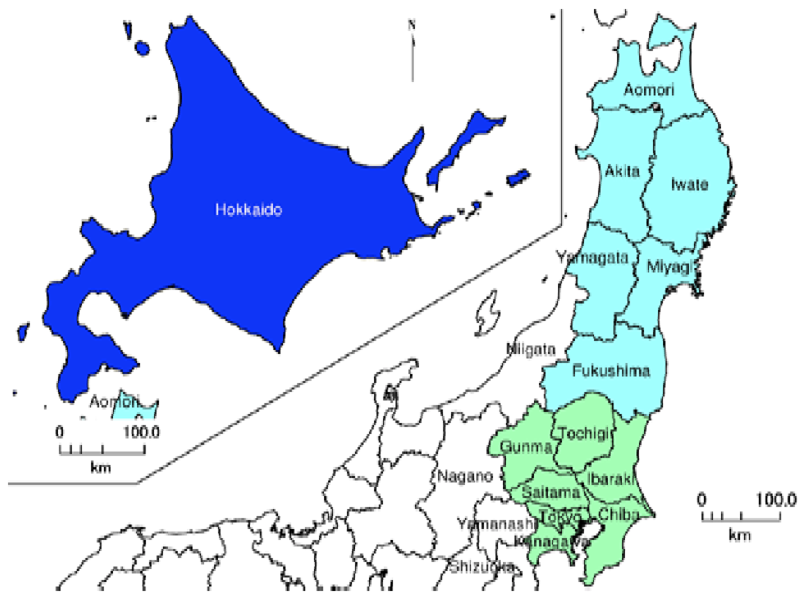

Fig. A2 – Prefectures in Hokkaido region shaded blue, Tohoku region shaded light blue and Kanto region shaded light green.

7. References

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