DEVELOPMENT OF FRAGILITY CURVES FOR HIGHWAY EMBANKMENT BASED ON DAMAGE DATA FROM RECENT EARTHQUAKES IN JAPAN

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ABSTRACT :

Many major and minor damages were caused to various structures in the recent earthquakes in Japan. Among them, the embankments of expressways were severely damaged. Using both the actual damage data and estimated spatial distribution of seismic intensity, this study conducts the statistical analysis on the relationship between the damage ratio of expressway embankment and seismic intensity. Based on the results, the fragility curves of expressway embankment are constructed. The actual damage datasets used in this study were compiled for the 2003 Northern-Miyagi earthquake and the 2003 Tokachi-oki earthquake. Based on the obtained results, major damages affecting the traffic are found to occur in the area where the JMA instrumental seismic intensity is larger than 5.3. Slight damages are also found to occur when JMA seismic intensity exceeds 4.8. The fragility curves constructed in this study may be helpful to predict the damage distribution in the expressway at an early stage of an earthquake occurrence so as to make an efficient traffic control and a rapid disaster response.

KEYWORDS: fragility curve, expressway embankment, peak ground velocity, weighted least squares method

1. INTRODUCTION

The expressway structures were severely damaged in some recent earthquakes in Japan. Expressway networks serve as vital trunk lines of transportation and they are also important for the restoration of stricken areas. Hence, it is expected that the damaged sections of expressways are estimated at an early stage.

The damages were mainly found in the embankment sections in the 2004 Mid-Niigata earthquake. Three large-scale collapses of expressway embankments were caused in the areas subjected to severe seismic motion [Maruyama *et al.*, 2006]. In order to conduct a rapid disaster response and a proper traffic control just after an earthquake, it is important to estimate the damage distribution in the expressway network at an early stage. Yamazaki *et al.* (2000) proposed fragility curves for bridge structures based on the damage data in the 1995 Kobe earthquake. Maruyama *et al.* (2007) constructed fragility curves for embankment of expressways based on the damage data in the 2004 Mid-Niigata earthquakes.

In order to improve the accuracy of fragility curves proposed by Maruyama *et al.* (2007), the expressway damage data due to other recent earthquakes are considered in this study. The additional damage datasets are compiled for the 2003 Northern-Miyagi earthquake and the 2003 Tokachi-oki earthquake. The relationship between the peak ground velocity (PGV) and expressway damages are evaluated, and then the statistical analysis is performed to construct embankment fragility curves.

2. ESTIMATION OF PEAK GROUND VELOCITY ALONG THE EXPRESSWAY

In order to evaluate the relationship between the seismic motion and the expressway damages, the intensity of the seismic motion at the site where the damage was caused should be properly considered. Hence, the spatial distribution of the PGV was obtained in this study. Simple Kriging, a method of stochastic interpolation [Cressie 1993], was employed to draw the spatial distribution. In Kriging, observed values are realized at observation points. Between the observation points, stochastic interpolation consisting of the trend and random components gives an estimation of the spatial distribution [Shabestari *et al.*, 2004].

The effects of site conditions, which affect the magnitudes of strong motion records, should be eliminated to conduct the spatial interpolation of seismic indices. Wakamatsu *et al.* (2004) proposed the engineering geomorphologic map of Japan. This map consists of about 380,000 grid cells with size of 1 × 1 km. The grid cells are categorized by geomorphologic characteristics into 19 classes. The more detailed engineering geomorphologic map, which consists of grid cells with the size of 250 × 250 m, is recently provided [Wakamatsu, 2008]. Matsuoka *et al.* (2006) estimated the distribution of the average shear-wave velocity in the upper 30m (AVS30) throughout Japan using the engineering geomorphologic map. Fujimoto and Midorikawa (2006) constructed the relationship between the amplification factor of PGV and AVS30. In the relationship, the amplification factor is defined with respect to the outcrop base whose shear wave velocity is equal to 600 m/s. Based on these results, the map of PGV amplification factor consisting of the 250 × 250 m sized grid cells is illustrated (Fig. 1).

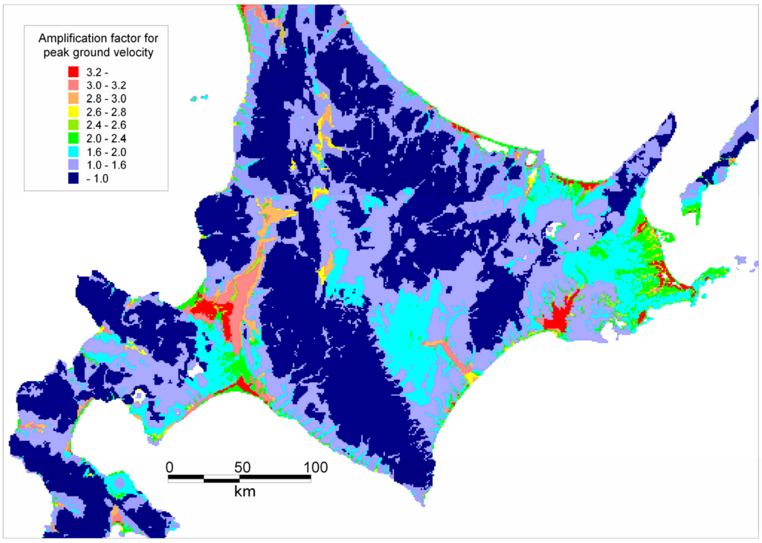


Figure 1 Amplification factors of the peak ground velocity in Hokkaido, Japan

Figure 2 shows the schematic figure for the interpolation performed by Maruyama *et al.* (2007). First, the recorded PGV is deconvoluted to the outcrop base. Using the PGV at the outcrop base, the attenuation relationship (Fig. 3) is constructed. The attenuation relationship is used as a trend component in Kriging. Lastly, the interpolated values are convoluted to the ground surface by multiplying the PGV amplification factors. It should be noted that the amplification factor at a K-NET accelerometer was determined using the station coefficient, *c*, proposed by Shabestari and Yamazaki (1999) and the relationship between the average shear wave velocity and the station coefficient by Tamura *et al.* (2000). Based on the results, the amplification factor at K-NET station with respected to the outcrop base whose shear wave velocity is equal to 600m/s can be described as $10^{c+0.23}$.

The distribution of the PGV in the 2003 Tokachi-oki earthquake was estimated as is mentioned above. As for the 2003 Northern-Miyagi earthquake, the Sanriku expressway, where many damages were found after the earthquake, lies near the epicenter, and the number of seismic observation stations was not large enough to follow the same methodology. Therefore, the attenuation relationship of PGV at ground surface (Fig. 3(a)) was used as a trend component of Kriging, and then the interpolation was carried out without considering the amplification factor. Figure 4 shows the distribution of PGV for the two events estimated in this study.

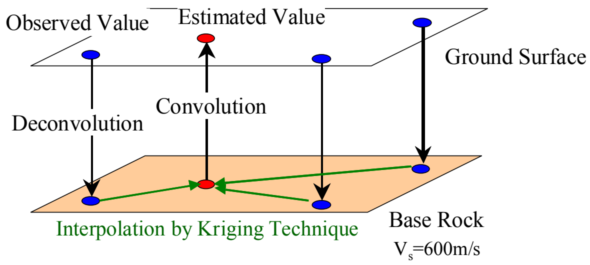
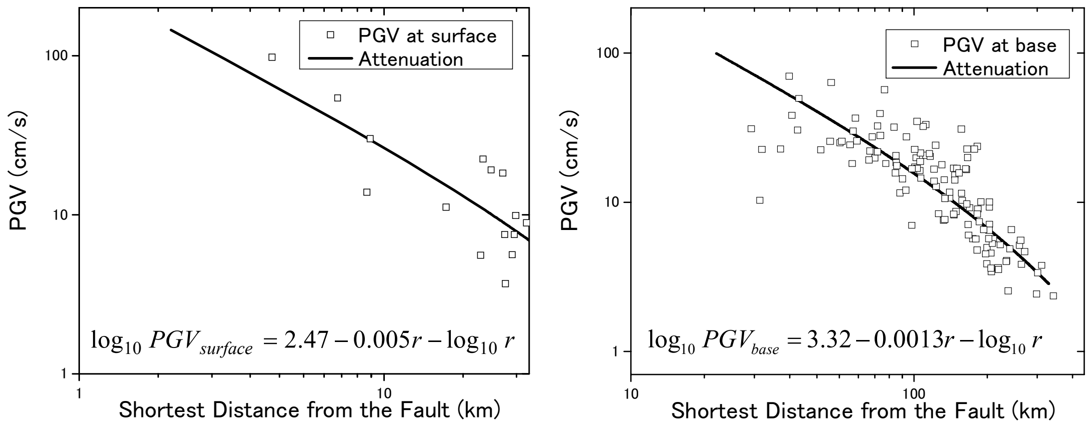
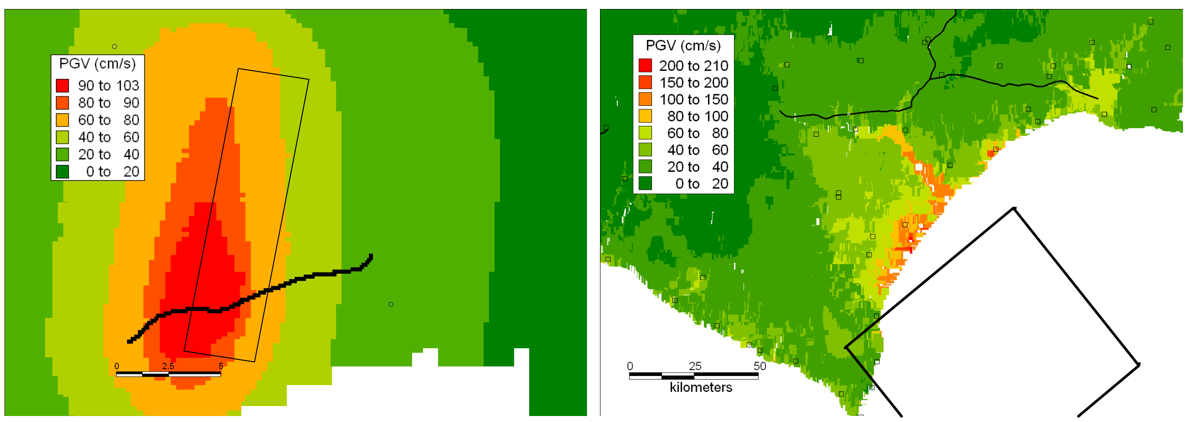


Figure 2 Schematic figure for interpolation of the peak ground velocity



(a) (b)

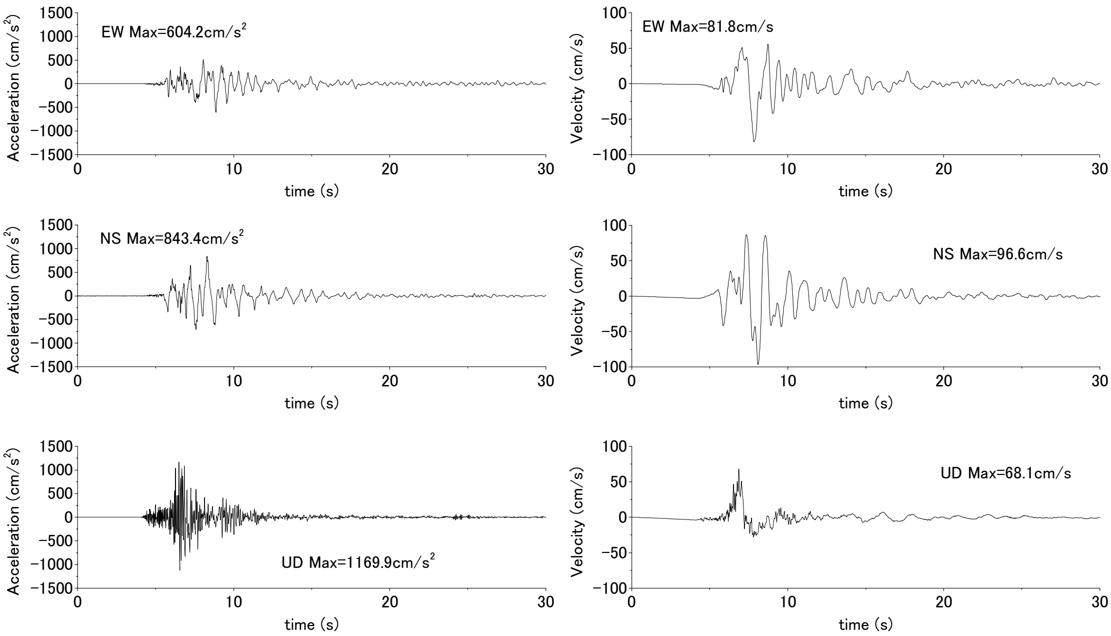
Figure 3 Attenuation relationship of PGV in (a) the 2003 Northern-Miyagi earthquake and (b) the 2003 Tokachi-oki earthquake



(a) (b)

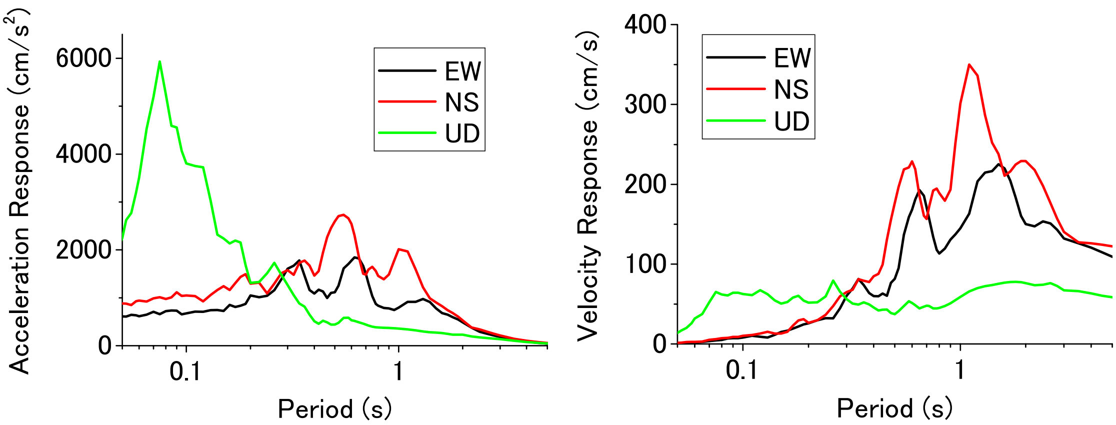
Figure 4 Estimated distribution of the peak ground velocity in (a) the 2003 Northern-Miyagi earthquake and (b) the 2003 Tokachi-oki earthquake

As shown in Fig. 4(a), the fault plane of the 2003 Northern-Miyagi earthquake is located near the Sanriku expressway. An accelerometer is deployed at Yamoto interchange (IC) and the seismic ground motion was recorded during the earthquake. Figure 5 shows the acceleration and velocity time histories for 3 components at Yamoto IC. Response acceleration spectra and response velocity spectra with 5% damping ratio are also illustrated in Fig. 6. Since the accelerometer was located almost immediately above the fault of the earthquake, the amplitude of acceleration of vertical component is the largest of the three. It should be noted that the JMA instrumental seismic intensity at Yamoto IC is 6.52 (7), which indicates the maximum rank in the JMA seismic intensity scale.



(a) (b)

Figure 5 (a) Acceleration and (b) velocity time histories recorded at Yamoto IC during the 2003 Northern-Miyagi earthquake



(a) (b)

Figure 6 (a) Acceleration response spectra and (b) velocity response spectra with 5% damping ratio at Yamoto IC during the 2003 Northern-Miyagi earthquake

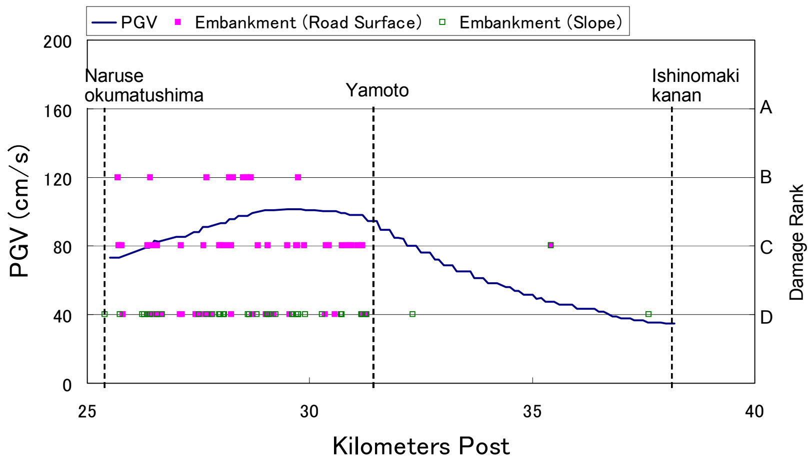
3. RELATIONSHIP BETWEEN DAMAGE OF EXPRESSWAY EMBANKMENT AND PEAK GROUND VELOCITY

The detailed damage data of expressway due to recent earthquakes were complied by Nippon Expressway Research Institute Co., Ltd. Each damage location is counted at every 10 m span along the expressway and the severity of damage is also labeled as the damage rank. The damage rank is classified into four levels, i.e. A (severe damage), B (moderate damage), C (small damage), and D (minor damage). The damage ranks A and B are considered to disturb an ordinary traffic on expressways.

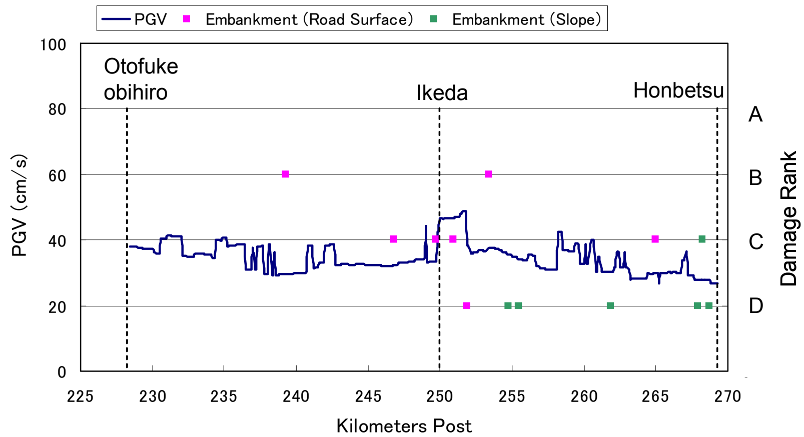
Figure 7 shows the relationship between the PGV and damages of expressway embankment in the 2003 Northern-Miyagi earthquake and the 2003 Tokachi-oki earthquake. The symbols of embankment damages are marked with respect to damage rank. In the Sanriku expressway, the damages mainly located between Naruse-Okumatsushima IC and Yamoto IC. Almost all the damages were found in the area where the PGV was larger than 70.0 cm/s expect for some cases. Particularly, the damages categorizes as ranks A and B were mainly found in the area where the PGV was larger than 80.0 cm/s. In the Douto expressway, the estimated PGV is not so large because the epicenter of this earthquake is far away from the expressway. Hence, the number of damages in the 2003 Tokachi-oki earthquake was smaller than that in the 2003 Northern-Miyagi earthquake.

Combining the results obtained in this study with that of the 2004 Mid-Nigata earthquake by Maruyama *et al.* (2007), the fragility curves of the expressway embankment are constructed. To construct fragility curves, the damage ratio of the expressway embankment, P, is assumed to follow Eq. (1).

$$P = C\Phi\left(\left(\ln PGV - \lambda\right)/\zeta\right) \quad (1)$$



(a)



(b)

Figure 7 Relationship between the peak ground velocity and damages of expressway embankment for (a) the Sanriku expressway and (b) the Douto expressway embankment

Table 1 Parameters of fragility curves constructed in this study

damages of expressway embankment	ζ	λ	C
≥B (Major damages)	0.29	4.09	2.25
≥D (All damages)	0.52	4.45	30.0

where $\Phi(x)$ is the standard normal distribution. λ, ζ and C are the constants determined by regression analysis (Table 1). The damage ratio was defined as a ratio between the number of damages and the length of expressway embankment sections. The three parameters in Eq. (1) were determined by a weighted least squares method with the weight of length.

Figure 8 shows the fragility curves of expressway embankment constructed in this study. The curve for major damages looks similar to that constructed by Maruyama *et al.* (2007). The curve for all damages gives larger number of damages than that constructed by Maruyama *et al.* (2007) when the PGV is larger than about 70 cm/s. According to the figure, the major damage with ranks A and B may be caused when the PGV is larger than about 35.0 cm/s. When the PGV is larger than about 25.0 cm/s, there may occur some minor damages.

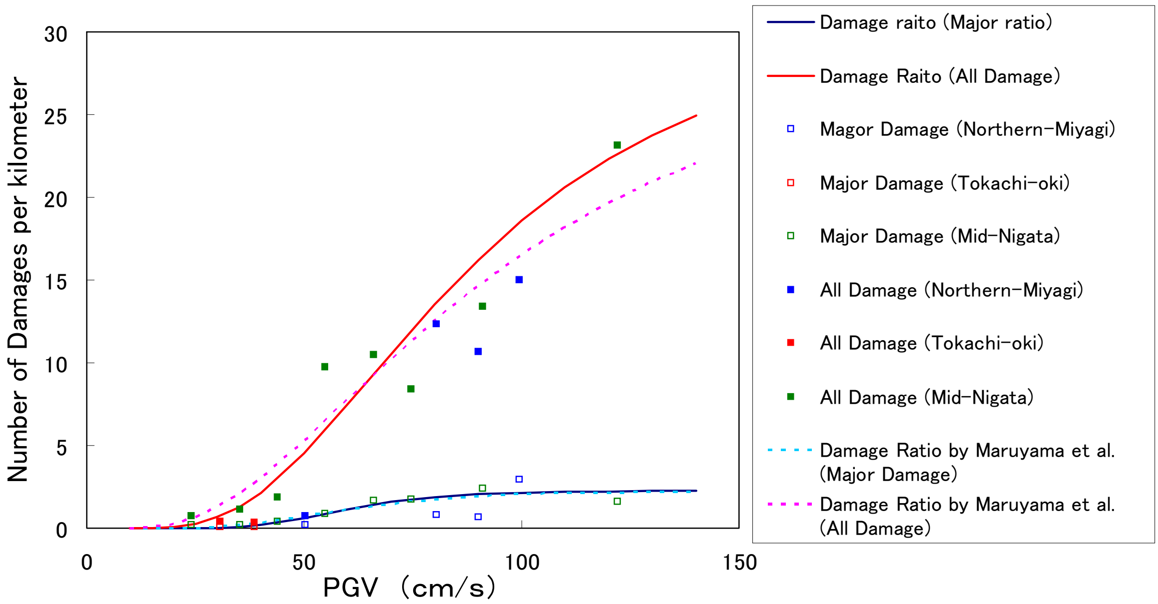


Figure 8 Fragility curves of expressway embankment with respect to the peak ground velocity

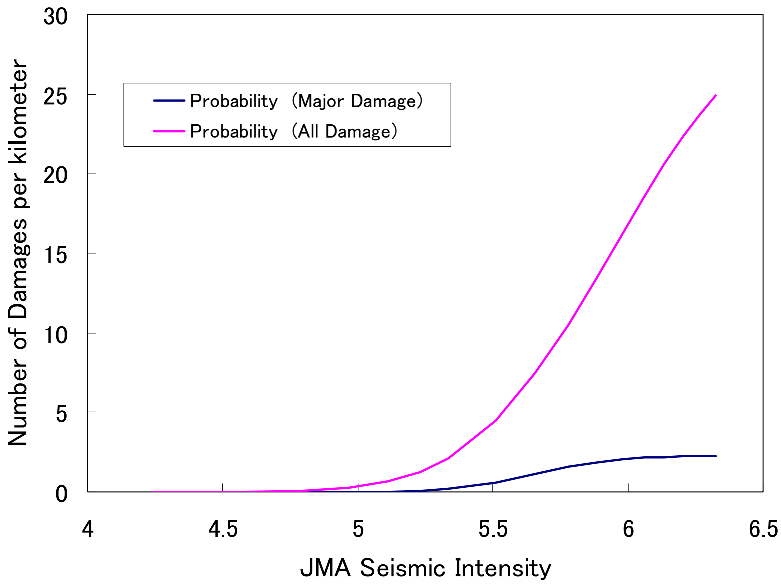


Figure 9 Fragility curves of expressway embankment with respect to JMA seismic indensity

The constructed fragility curves of expressway embankment are expressed with respect to the PGV. The JMA instrumental seismic intensity (I) can be estimated from the PGV using Eq. (2) [Karim and Yamazaki. 2002].

$$I = 2.42 + 1.82 \log_{10} PGV \quad (2)$$

The JMA seismic intensity is the seismic index to determine a traffic control in expressways just after an earthquake. Figure 9 shows the fragility curves constructed in this study with respect to the JMA instrumental seismic intensity. According to the figure, major damages that affect the expressway serviceability are found in the areas where JMA seismic intensity is larger than 5.3. Slight damages are found when JMA seismic intensity becomes lager than 4.8.

4. CONCLUSIONS

In this study, the fragility curves of the expressway embankment were constructed using the actual damage data from the recent three earthquakes in Japan. To achieve the objectives, the detailed distributions of the peak ground velocity were estimated based on simple Kriging.

According to the fragility curves, major damages that disturb an ordinary traffic on expressways may be caused when the JMA seismic intensity becomes larger than about 5.3. The fragility curves constructed in this study is helpful to predict the damage distribution on expressways at an early stage of an earthquake occurrence so as to make an efficient traffic control and a rapid disaster response.

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