A study on the seismic segmentation method of levee using the natural frequency of multiple layers

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ABSTRACT

The Levees of Shinano River were subjected to many damages at Niigata Chuetsu Earthquake in 2004 as well as Tohoku-Pacific Ocean Earthquake in 2011. The damage of levees depends not only on the distance from the epicenter, but also on the soil profile of levee and its foundation. In this study, we classified the damage of levee into five types, and investigated the relationship the geological categorization and the seismic characteristics of the levee with the damage types. The natural frequency for multiple layers and the shape of transfer function were adopted as the seismic index, because the natural frequency can be express the seismic stiffness of levee. To obtain natural frequency of multiple layers, we carried out the linear elastic analysis based on multiple reflection theory using the results of standard penetration and laboratory soil tests. Those investigations of levee have already performed at each 1 km, for every main rivers managed by MLIT, therefore the new investigations are not required. However, the interval of 1 km is not enough for management length in Japan sea side region, because of its geological complexity compared with the Pacific Ocean side. To specify the representative levee length for one borehole logging, the geomorphologic data was considered. To estimate the damage rank, the influences of magnitude of ground motion should be considered. In this study, the multiple linear regression analysis, which the base acceleration, the natural frequency and the shape index of transfer function were adopted as dependent variables, and its explaining variable was damage rank, was performed to prediction of damage rank.

Keywords: river levee, estimation of damage, earthquake, natural frequency, multiple reflection theory

1 INTRODUCTION

At the Tohoku-Pacific Ocean Earthquake in 2011, the total of 1195 river levee damages, managed by Tohoku Regional Development Bureau of MLIT, were observed. About 80 percent of all damages concentrated into Miyagi Prefecture and 12.5% for Iwate, 6.6% for Fukushima and 1.1% for Aomori. The maximum acceleration or S.I. value were not so different between Fukushima, Miyagi and Iwate, but the number of damages in levee were quite different. It seemed that those differences were caused by geological variation. Some of damages might be caused by liquefaction; however, the evidences around river mouth were washed out by Tsunami.

Meanwhile, the Niigata Chuetsu Earthquake of inland earthquake occurred on 23rd Oct. 2004, its magnitude was 6.8 and the depth of seismic fault was 13km. The maximum acceleration of main shock was 818 gal and three big aftershocks took place within 40 minutes after the main shock. The magnitudes of aftershocks were 6.3, 6.0 and 6.5.

The levees along the Shinano River and the Uono River were widely damaged at the earthquake. There were 137 damages in total, and 120 places (88%) were minor faults. The other 17 places were suffered from serious damages. The serious damages were occurred at 40km from epicentre, the maximum acceleration was not so large. This suggests that the geological differences or levee material variations are related to the damage level. In Shinano river area, there are enough geological and levee material's information, then we have used these information to estimate the damage type of levee.

2 GEOLOGICAL FEATURES AROUND SHINANO RIVER

The levee foundation along Shinano and Uono Rivers can be categorized into the five regions in geologically, which are named as First and Second Floodplain Area, Alluvial Fan Area, Inclosed Meander Area of the Shinano River and Alluvial Fan Area of the Uono River located on foot-wall of the active fault, as shown in Figure 1 and Figure 2. The geological profile along Shinano River to Uono River is shown in Figure .

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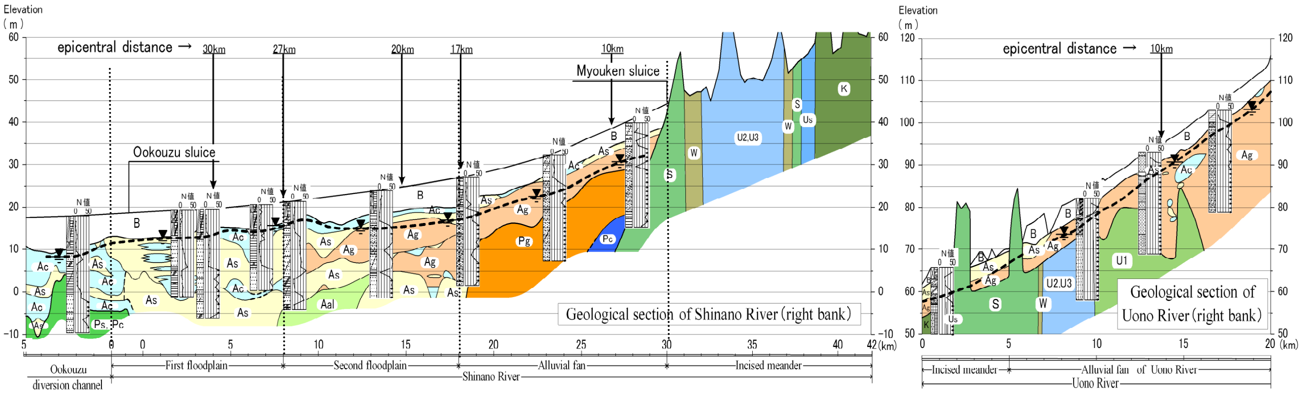


Fig. 1. Longitudinal geological profile along Shinano River to Uono River.

Table 1. Legend of geological symbols

Geochronologic division		Geological classification	symbol
Recent		banking	B
Quaternary	Holocene	cohesive soil	Ac
		sandy soil	As
		gravelly soil	Ag
		alternation of strata sand and clay	Aal
	Pleistocene	silt・sand・gravel	U2,U3
		mudstone	Pc
		gravelly soil	Pg
		mudstone and sandstone	Pc,Ps
Neogene	Pliocene	gravel・silt・sand	U1
		sandstone	W
		sandy mudstone・argillaceous sandstone	S
		blocky mudstone	Us
		alternation of strata sandstone and mudstone	K

1 and its legend is shown in Table 1.

The locations of damaged levees by main shock are shown in Figure 2. The damage ranks of levees were classified into four types as shown in the legend of Figure . 2. The blue lines show Rank 1 (R1) which have shallow cracks on the levees, and the green lines are Rank 2 (R2) which have cracks on the levee reached over 50cm. The sliding failure of embankment is occurred in Rank 3 (R3) shown as yellow lines, and the deep failure of embankment due to settlement of foundation is defined to Rank 4 (R4) shown as red lines. The Rank 5 (R5) shown as light blue line means the damage of structure. The Rank is larger; the damage size is also getting serious, except for the Rank 5.

First Floodplain region is placed around the downstream area from 8 km kilo-post of Shinano River, and the catastrophic failures R4 occurred as well as R2 with deep cracks as displayed in Figure 2, although the most distant area from the epicenter and estimated fault model. The deep cracks may be related that the thick sand layer with high ground water level. That is, the saturated sand layer induced the liquefaction at the earthquake. And the R4 damage was occurred on the reclaimed ground.

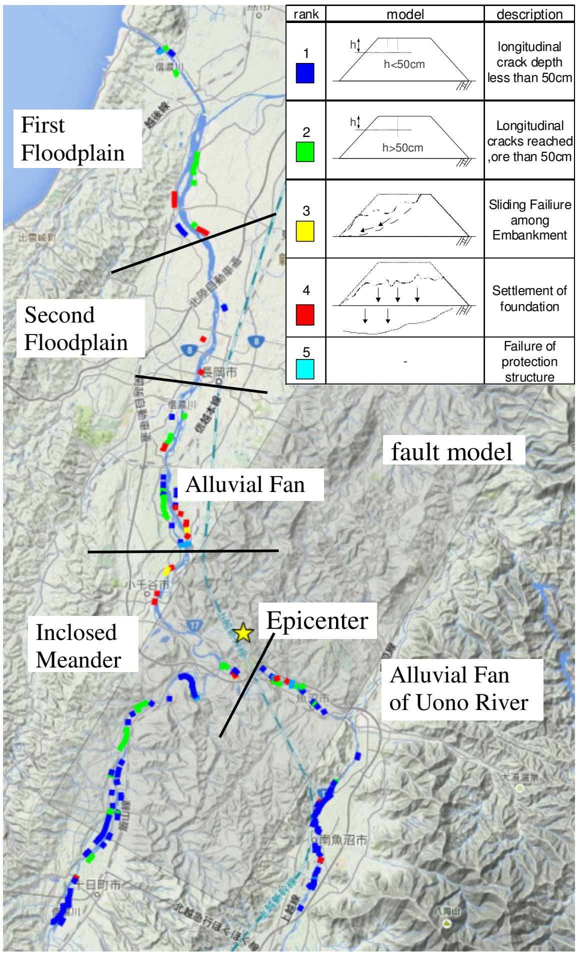


Fig. 2. Location of damaged places by main shock (map by Google Earth)

In the Second Floodplain region, most of the levees had no damages, because the sand layer is very thin and not saturated. At the third region, Alluvial Fan Area, almost levees had insignificant damages, the foundation bellow the levee consists of the thick gravel with the enough strength. However, several short section levees, which are on the former river channel or near small channel, were suffered from significant damage. Therefore, the geologically weakness may have caused the serious damages at the earthquake.

Around the forth and fifth regions, where are near the epicenter, have stiff foundation such as bedrock. Therefore, almost damaged levees in these areas had suffered only small cracks. The ground displacement in up-down direction was observed in the forth region called Inclosed Meander Area, so the embankment protections made of concrete were damaged.

The fifth region of Alluvial Fan of Uono River is situated on bottom side of fault, and there were few ground displacement, then the levees and protection structures had only insignificant cracks.

3 NATURAL FREQUENCY OF MULTIPLE LAYERS AND ITS TRANSFER FUNCTION

The theoretical natural frequency, fm, is obtained from transfer function. The horizontal displacement, ui(zi,t), in each layer as shown in Figure .3, is expressed by Eq. 1.

$$u_i(z_i,t)=\left(A_i e^{I\lambda_i z_i}+B_i e^{-I\lambda_i z_i}\right)e^{I\omega t} \qquad (1)$$

where, *I*: imaginary unit, *i*: layer number, ω: angular frequency, z_i: depth at local coordination, *t*: time. The *A* and *B* should be determined by following boundary conditions.

1. Shear stress is zero at surface.
2. Displacement and shear stress is same at boundary of neighbor elements.

And λ_i is shown as following equation.

$$\lambda_i=\omega\sqrt{\frac{\rho_i}{G'_i}} \qquad (2)$$

where, ρ is wet density, and *G'* is complex shear modulus as shown in Eq. 3.

$$G'=G(1+2Ih) \qquad (3)$$

where *G* is real shear modulus, *h* is damping ratio.

The variables, A_i and B_i are specified by following recurrence equation.

$$\begin{cases}2A_{i+1}=A_i(1+\alpha_i)e^{I\lambda_i H_i}+B_i(1-\alpha_i)e^{-I\lambda_i H_i}\\ 2B_{i+1}=A_i(1-\alpha_i)e^{I\lambda_i H_i}+B_i(1+\alpha_i)e^{-I\lambda_i H_i}\end{cases} \qquad (4)$$

Where $\alpha_i=\dfrac{G'_i\lambda_i}{G'_{i+1}\lambda_{i+1}}$. The transfer function, *Z*(ω), and its spectrum, *R*(ω) are determined as shown in Eq. 5.

$$Z(\omega)=\frac{2A_1}{2A_n} \quad , \quad R(\omega)=\left|Z(\omega)\right| \qquad (5)$$

The example of spectrum of transfer function is shown in Figure 4. The x-axis value of transfer function's peak shows the natural frequency, f_m. The height of the peak shows amplification ratio. When the whole ground including embankment become stiffer, the natural frequency of multiple layers also is getting higher as shown in Figure 4. Therefore, we can estimate the strength of levee at earthquake.

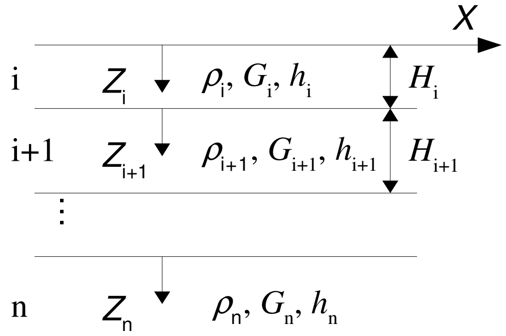


Fig. 3. Stratification ground model and local coordination.

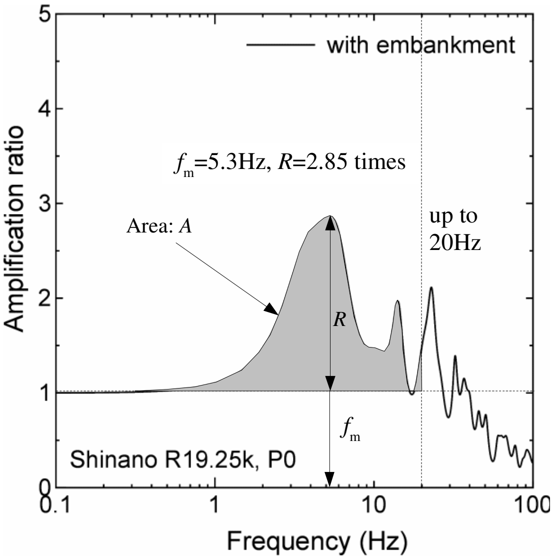


Fig. 4. Example of transfer function spectrum.

However, the response can be calculated by multiplying the transfer function and Fourier transfer function of input wave. This means the area, *A*, shown in Fig. 4, in transfer function is also important as well as the natural frequency, because the wide rage seismic waves, except for the wave has the natural frequency, are also amplified on surface in case of the wide area: *A*.

Although the amplification ratio, *R*, is depend on damping ratio, the determination of the damping ratio is very difficult. To eliminate the influence of the height of damping ratio and consider the area, *A*, the shape index of transfer function, *R*/*A*, is adopted.

4 DIVIDING METHOD OF LEVEE USING GEOMORPHOLOGY

The levees are usually managed by kilo-posts, which are located each 200 m, and detail investigations have been carried out each 1 km. The standard penetration test and hydraulic analysis etc. are performed in the detail investigation.

Therefore, the managed unit length, assumed that they have same properties, is 1 km, and the properties are obtained by the result of the detail investigations.

However, the geological conditions are not same within a managed 1 km length as shown in Figure . 5. So, the detail investigation can not be representative during the 1 km length.

In this study, the length of managed section was changed according to the geomorphology as shown in Figure .5. Therefore, some sectioned levees have no investigation results and seismic features, such as natural frequency or shape index of transfer function. To reduce no information sections, it is assumed that the same geomorphologic classifications within the same geological area mentioned in Chapter 2, will have same seismic features.

5 ESTIMATION DAMAGE RANK BY MULTIPLE LINEAR REGRESSION ANALYSIS

The distribution of Peak Ground Acceleration (PGA) in Niigata Chuetsu Earthquake is shown in Figure 6. This PGA data was referenced from Konagai et. al. 2005~2007. As shown in Figure .6, the maximum acceleration is not same against whole levee. To estimate the damage rank against any earthquake from these actual damages in Niigata Chuetsu Earthquake, we have to normalize the influences of seismic motion. To eliminate the influences of seismic motion, the base maximum accelerations were calculated from base velocity waves also calculated by Konagai et al., 2005~2007 as shown in Figure 7., because the ground surface acceleration, such as PGA, is not independent from the natural frequency which is influenced by their soil structures of ground and embankment. The provided area of the base velocity waves is smaller than PGA area as shown in Figure 6 and Figure 7.

In Multiple Linear Regression Analysis, the explanatory variable was damage rank, *r*, and the independent variables were natural frequency of multiple layers, fm, the shape index of transfer function, *R*/*A* in Figure .4, the common logarithm of base maximum acceleration, log(accb), and the dummy variable. The obtained regression curve is shown in Eq. 6, and the results of regression analysis are indicated in Table 2. The numbers of sample which can be used for this analysis are only 27 damages as shown in Table 3.

$$r = 4.103 - 3.613\frac{R}{A} - 0.079 f_m + 0.258\log(acc_b) \qquad (6)$$

The comparison of the actual all damages including aftershock and the estimated damage ranks by using Eq. 6 is shown in Figures 8 (a), (b), respectively. Although the estimation overestimates the damages, especially in Second Floodplain and Alluvial Fan, the estimated R4 places are similar with actual R4 damage places. In this estimation, the influences of ground water level can not be considered.

For prediction of damages in earthquake, the base maximum acceleration should be constant, because the location of actual fault can not be predicted in the present. In this study, the base maximum acceleration was set to 70 gal, which observed around Shinano River midstream area in Figure 7. The proper value of base maximum acceleration should be considered again, in advanced investigation of levee damages in another earthquake. The result of prediction is shown in Figure 9. It was found that the more damages might have occurred around the First Floodplain Area, when the base acceleration was slightly lager than actual acceleration. On the other hand, the many damages around Inclosed Meander Area of Alluvial Fan of Uono River were seemed to be caused by large acceleration.

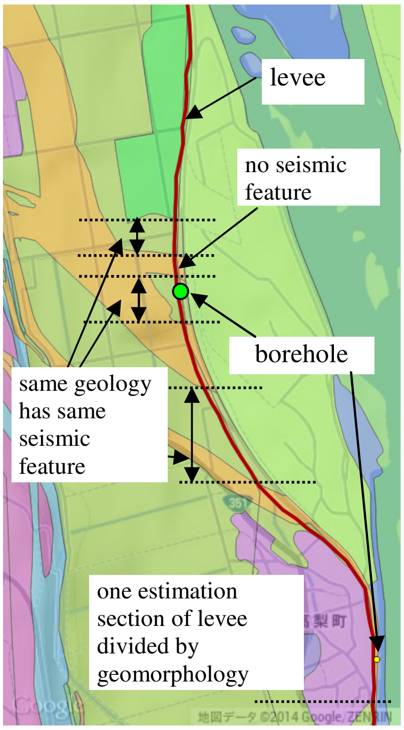


Fig. 5. Division of levee by geomorphology.

Table 2. Results of multiple regression analysis

Independent variables	partial regression coefficient	standardized partial regression coefficient
R/A	-3.613	-0.389
f_m	-0.079	-0.646
$\log(acc_b)$	0.258	0.249
dummy	4.103	0

multiple correlation coefficient 0.57

Table 3. Number of analyzed samples

rank	sample
1	7
2	10
3	0
4	10
5	3

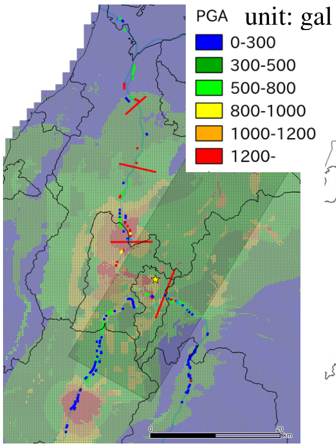


Fig. 6. Distribution of PGA.

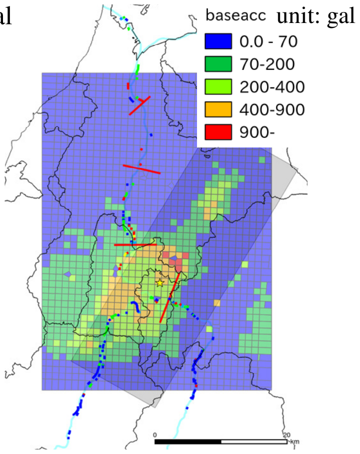


Fig. 7. Calculated base acceleration.

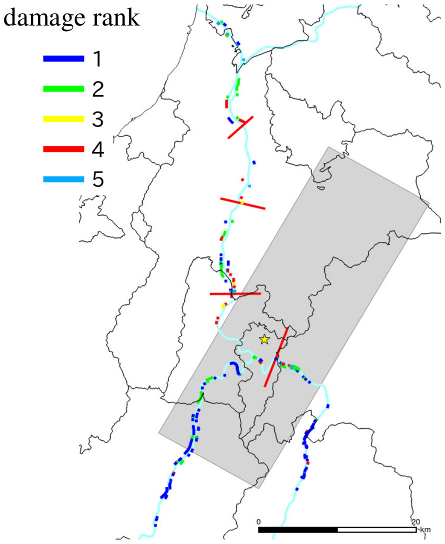


Fig. 8(a). Actual all damages of levee

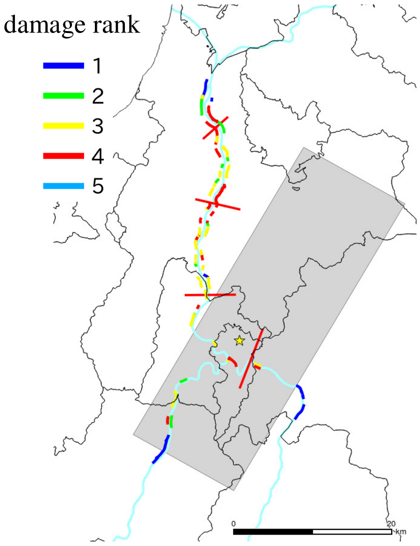
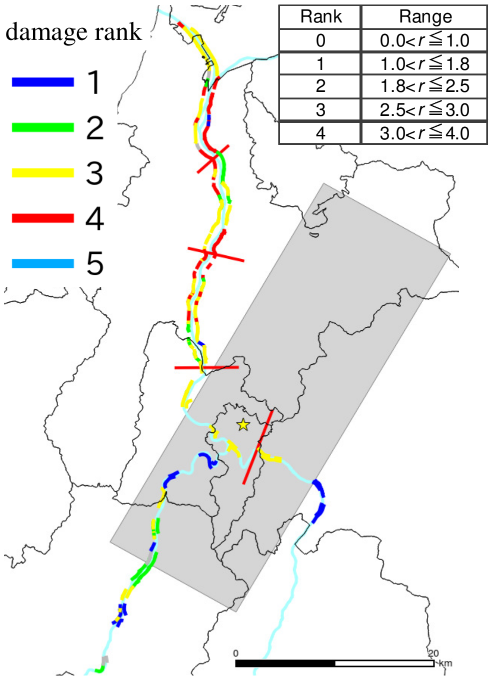


Fig. 8(b). Estimated damages by regression analysis

6 CONCLUSIONS

A prediction equation of river levee damage rank is proposed by using multiple linear regression analysis.



Rank	Range
0	$0.0<r\leqq 1.0$
1	$1.0<r\leqq 1.8$
2	$1.8<r\leqq 2.5$
3	$2.5<r\leqq 3.0$
4	$3.0<r\leqq 4.0$

Fig. 9. Prediction of levee damages in condition of 70 gal as base maximum acceleration.

In previous other studies, the prediction equations were derived only from geological information. However, by adopting both of the seismic features obtained from transfer function and the geological features, the accuracy of prediction method becomes better than the past methods. Although further inspection is required to consider the influences of ground water level or the dominant frequency of earthquake, the proposed prediction equation will be useful for first screening in the extraction of the potential damage levees.

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