RELATIONSHIP BETWEEN EARTHQUAKE DAMAGE TYPES OF LEVEES AND SEISMIC CHARACTERISTICS OF THEIR FOUNDATION

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At the Niigata Chuetsu Earthquake in 2004, the levees along the Shinano River and the Uono River were widely damaged. The damage of levees depends not only on the distance from the epicenter but also on the foundation stratum of levee. In this study, we classified the degree of the damage of the levee situated 2 to 50km from the epicenter, and compared these damages with the geological categorization of the levee foundation. To make clear the seismic characteristics of each geological category, we carried out the linear elastic analysis based on multiple reflection theory using results of standard penetration and laboratory soil tests. We compared damage type with the dominant frequency by multiple reflection theory and averaged layers.

Key Words : *Levee, Earthquake, Seismic Characteristics, Dominant Frequency, Multiple Reflection Theory*

1. INTRODUCTION

Niigata Chuetsu Earthquake of inland strong earthquake occurred on 23rd Oct. 2004, its magnitude is 6.8 and depth of seismic center is 13km. The maximum magnitude of acceleration of main shock is 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 and the damages of levee observed at 137 places in total. Eighty eight percent (120 places) of stricken levees were minor faults, Other 17 places were suffered from serious damage. The serious damages were distributed to 40km from epicenter.

The preliminary study[1)] suggests that the damage of levees depends not only on the distance from the epicenter, but also the foundation stratum of levee. In this study, we classified the degree of the damage into four patterns, and compared these damages with the five geological categorizations of the levee foundation. As mentioned before, the geological features may concerned with damage pattern at earthquake[1),2)], however, the stochastic studies does not supply sufficient relationship. This means only geology is not enough for explanation of damage properties, then we calculated the dominant frequency of each damaged levee using detail inspection results performed by MLIT.

2. Geology around Shinano River and damage types

The foundation stratum along Shinano and Uono Rivers are categorized into the five regions in geologically, which are named 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 footwall of the active fault. The geological profile along

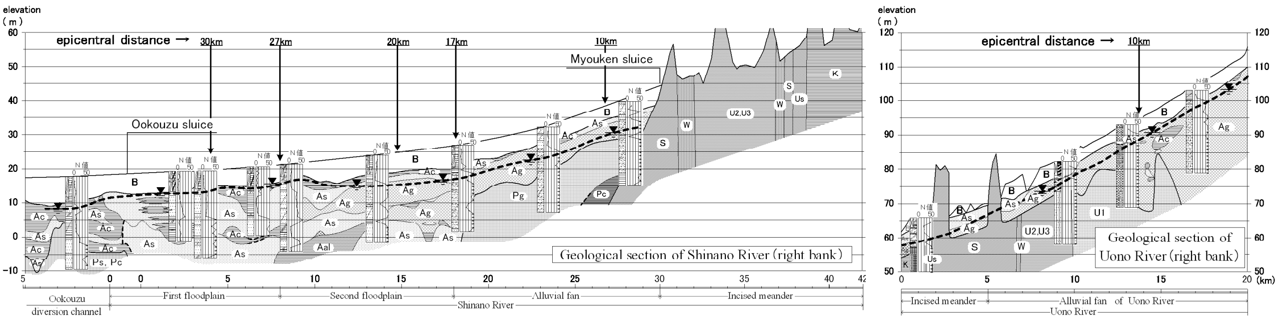


Fig.1 Longitudinal geological profile along Shinano River to Uono River.

Table 1 Legend of geological symbols In Fig. 1.

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

Shinano River to Uono River is shown in Fig. 1 and its legend is shown in table 1.

The damaged and non damaged levees, which were adopted as calculation points, are shown in Fig. 2. The damage types in the 17 serious damaged levee were patterned into four types as shown in Table 2. The symbols of white circle show non damaged levees in the following figures. The half solid triangle in Fig. 2 shows pattern P1, solid triangle is pattern P2, and half solid circle is pattern P3, solid circle is pattern P4 and double circle is pattern P5, respectively. The pattern P1 means insignificant longitudinal cracks above H. W. L., and the pattern P2 shows significant longitudinal cracks reached H. W. L. as shown in Table 2. The sliding failure of embankment is occurred in the pattern P3, the settlement of embankment due to settlement of foundation is defined as pattern P4.

First Floodplain region is placed on the downstream from 18 kilo-post of Shinano River, and the catastrophic failures P4 of the levee occurred as displayed in Fig. 2, although the most distant area from the epicenter. It 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.

In the Second Floodplain region, most of the levee has suffered no damages. It may be reason that the sand layer is very thin and is not saturated.

At the third region, Alluvial Fan Area, almost levees have insignificant damages, the foundation

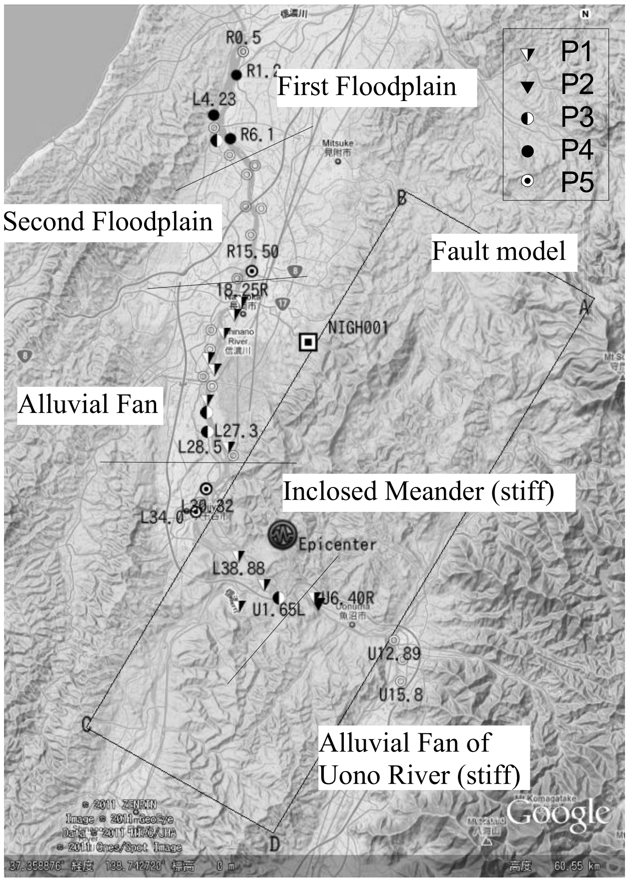
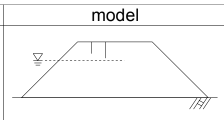
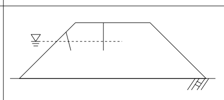
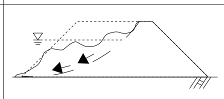
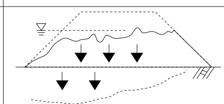


Fig.2 Location of intended damaged, non damaged levee and plan view of fault model. (map by Google Earth)

Table 2 Classification of damage types of levee.

pattern	model	description	total length (m)
P1		longitudinal cracks above H. W. L.	6,997
P2		Longitudinal cracks reached H. W. L.	449
P3		Sliding Failiure among Embankment	8,659
P4		Settlement of foundation	2,871
P5	-	Failure of protection structure	-

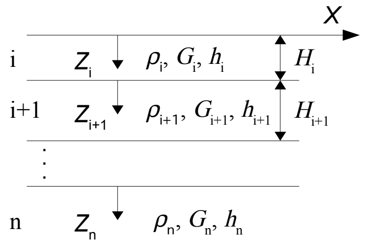


Fig.3 Multiple layers.

bellow the levee consists of the thick gravel with the enough strength. However, a few levees, which are on the former river channel or small reservoir, were suffered from significant damage. Such the geologically weak area may have caused the damage at the earthquake.

Around the forth and fifth regions where are near the epicenter have stiff foundation such as bedrock. Therefore, levees in these area 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. SEISMIC PROPERTIES OF FIVE GEOLOGICAL REGIONS

To obtain the seismic properties for five geological regions, two methods were compared. One is average dominant frequency, f_G, using one forth wave length law, such as the reciprocal of T_G in Specification of Highway Bridge. The other is dominant frequency, f_m, based on multiple reflection theory, it can be consider the undulation of stiffness distribution for multiple layers, though the ground is assumed as elastic material.

The average dominant frequency, f_G, is obtained by following equations on multiple layers as shown in Fig. 3.

$$f_G = \frac{1}{4\sum_{i=1}^{n} \frac{H_i}{V_{si}}} \tag{1a}$$

$$V_{si} = \sqrt{\frac{G_i}{\rho_i}} \tag{1b}$$

Where, H_i is depth of i th layer, G_i is shear modulus, ρ_i is wet density, h_i is damping constant and V_{si} is shear wave velocity.

The theoretical dominant frequency, f_m, is obtained from transfer function. The horizontal displacement, $u_i(z_i,t)$, in each layer are shown in Eq. (2a).

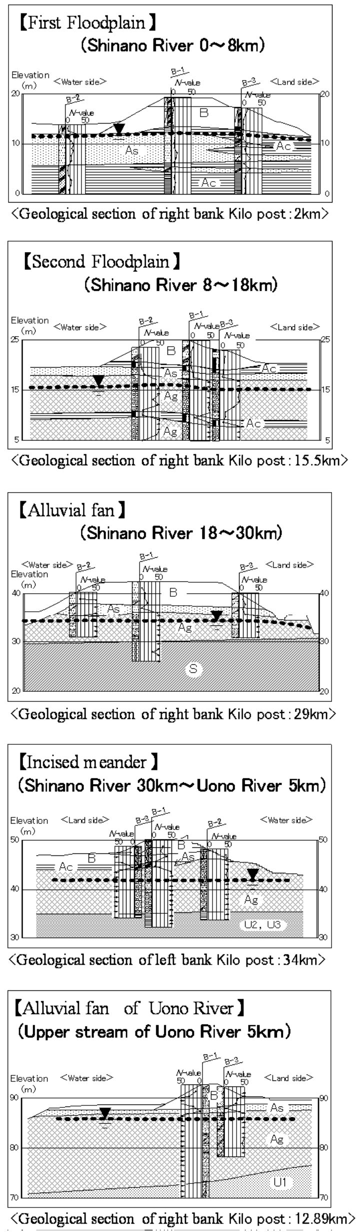


Fig.4 Typical soil profile for each geological regions.

$$\begin{aligned} u_i(z_i, t) &= U_i(z)\,\mathrm{e}^{I\omega t} \\ &= \left(A_i \mathrm{e}^{I\lambda_i z_i} + B_i \mathrm{e}^{-I\lambda_i z_i}\right)\mathrm{e}^{I\omega t} \end{aligned} \tag{2a}$$

where I is imaginary unit, A_i and B_i are unknown constant. λ_i is expressed in Eq. (2b).

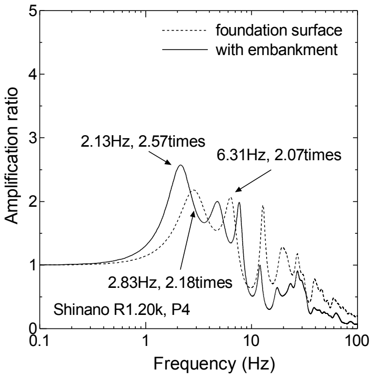
$$\lambda_i = \omega\sqrt{\frac{\rho_i}{G'_i}} \tag{2b}$$

where G'_i is called complex stiffness and defined as following formula.

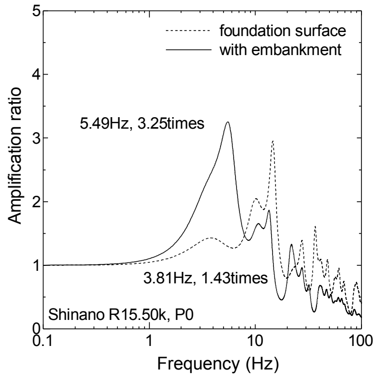
$$G'_i = \left\{1 - 2h_i^2 + 2Ih_i\sqrt{1-h_i^2}\right\} G_i \tag{2c}$$

Equation (2c) is used so as to obtain same amplitude in hysteresis curvature.

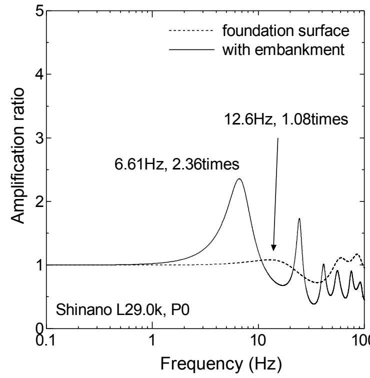
The boundary conditions of layer boundary continuity and zero shear stress on surface is substituted into Eq. (2a), then we obtained unknown constant A_i and B_i are expressed in recursive equation as follows.



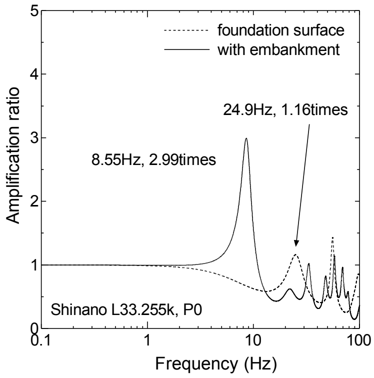
(a) First Floodplain.



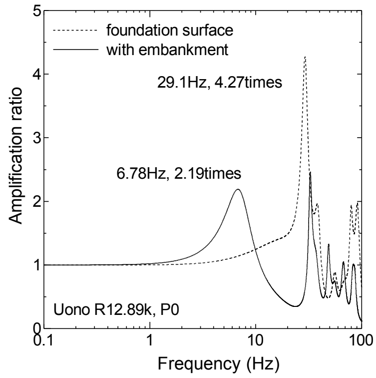
(b) Second Floodplain.



(c) Alluvial Fan.



(d) Inclosed Meander.



(e) Alluvial Fan of Uono River.

Figs.5 (a)-(e) Sample of transfer function for each geological region.

$$\begin{cases} A_{i+1}=\frac{1}{2}A_i(1+\alpha_i)e^{I\lambda_i H_i}+\frac{1}{2}B_i(1-\alpha_i)e^{-I\lambda_i H_i} \\ B_{i+1}=\frac{1}{2}A_i(1-\alpha_i)e^{I\lambda_i H_i}+\frac{1}{2}B_i(1+\alpha_i)e^{-I\lambda_i H_i} \end{cases} \quad (3a)$$

where α_i is defined in Eq. (3b).

$$\alpha_i=\frac{G'_i\lambda_i}{G'_{i+1}\lambda_{i+1}} \quad (3b)$$

The amplification ratio, $R(\omega)$, of ascending waves such as 2E/2E is expressed as in Eq. (3c).

$$R(\omega)=\left|\frac{2A_1}{2A_n}\right| \quad (3c)$$

The typical soil profiles for each region , which are classified in geological aspects, are shown in Fig. 4. The parameters for each layer were determined using results of standard penetration and laboratory soil tests. The average depth of calculation is about 25m from top of the embankment. Though it is difficult to determine the damping constant, the damping constant is estimated by observed data at NIGH01 of KiK-net, so as to fit the calculated surface response to observed acceleration wave. The estimated damping constant is shown in Table 3.

The densities of unmeasured layers are estimated with reference to measured density as shown in Table 4. The soil type is determined by soil profile in detail inspection of levee, although the stratum thickness of calculation model is not based on soil type. The thickness of each layer is one meter adapted to standard penetration test.

Table 3 Definition of damping constant.

V_s (m/s)	sand	clay
0～100	0.04	0.05
100～200	0.03	0.04
200～400	0.02	0.03
400～	0.01	0.02

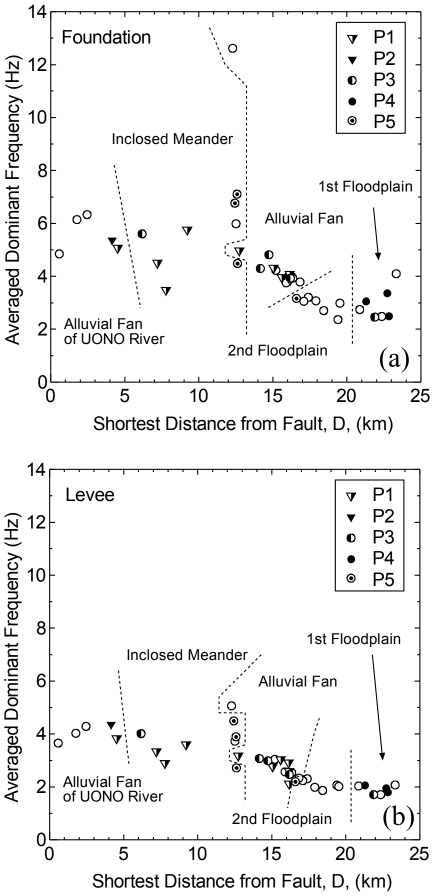
Table 4 Estimation of density which is unmeasured.

N-Value	sand(g/cm^3)	clay(g/cm^3)
0～3	1.4	1.3
3～10	1.6	1.5
10～20	1.7	1.6
20～30	1.8	1.7
over 30	2.0	1.9
min. over 20m depth	1.8	1.7

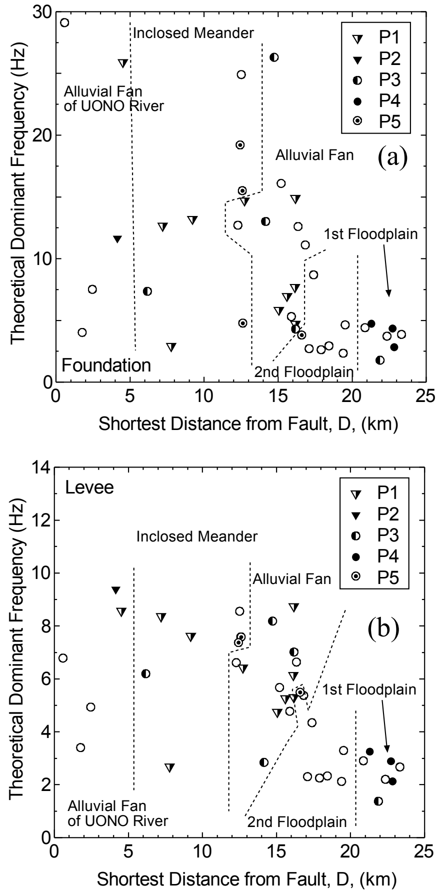
The samples of transfer function for the five geological region are shown in Fig. 5 (a)-(e). The dotted line shows the amplification ratio of foundation surface without embankment, and the solid line shows transfer function at the top of embankment. The first dominant frequency at embankment surface is smaller than the foundation among almost calculated points, this means embankment is weak compared with its foundation stratum.

(1) Averaged dominant frequency using one forth wave length law

The calculated dominant frequency, f_G, using Eq. (1a), which is assumed as some averaged value, are



Figs.6 (a),(b) Averaged dominant frequency: (a) up to foundation, (b) including levee.



Figs.7 (a),(b) Theoretical dominant frequency: (a) up to foundation, (b) including levee.

shown in Figs. 6 (a), (b) for foundation and embankment surface, respectively. The horizontal axis shows shortest distance from fault model in three dimension, not distance from epicenter. The symbols indicate the damage patterns (P1 to P5) as defined in Fig. 2 and Table 2. The average dominant frequency tends to decrease with increasing distance from fault in both of foundation and levee.

According to average dominant frequency, the levee involved its foundation is weaken with distance from fault, however, there is few relationship between damage type and average dominant frequency.

(2) Dominant frequency based on multiple reflection theory

The theoretical dominant frequency, considering distribution of stiffness, against distance from fault is shown in Figs. 7 (a), (b). It seems that there are no tendencies with distance from fault in f_m of foundation in Fig. 7 (a), though the points in First Floodplain shows always small dominant frequency. In Fig.7 (b), the dominant frequency decreases with distance from fault. This tendency is same as Fig. 6 (b), however, the correlation is much lower compared with average dominant frequency.

In any case, the theoretical dominant frequency has also no relation with damage pattern.

The theoretical dominant frequency, f_m, is larger and scattered compared with the average dominant frequency, f_G. There is a possibility that the ground stiffness is underestimated in using average dominant frequency.

Even in the theoretical frequency, the dominant frequency of levee is decreasing with increasing the distance from fault. It means that the embankment material is getting weak toward downstream.

Although the theoretical dominant frequency is varied in foundation results, it shows that the influences of stiffness distribution in actual ground are estimated appropriately, such as former river channel or reservoir.
However, it is difficult to estimate damage type using raw dominant frequency.

4. NORMALIZED DOMINANT FREQUENCY BY PEAK AREA OF TRANSFER FUNCTION

(1) Method for normalization

The dominant frequency is determined by peak position of transfer function, however, there are plural peaks and the amplification ratio is also

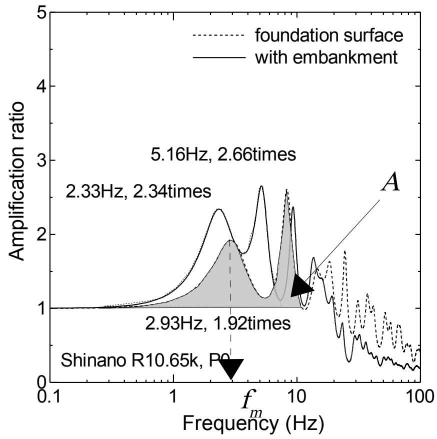


Fig.8 Peak area of transfer function

important in actual response. Even the dominant frequency is not so high, when the amplification ratio is very small, the response will be not so large. Therefore, to reflect these influences, the area around peak of transfer function as shown in Fig. 8 is considered.

The dominant frequency of foundation in Fig.8 is f_m=2.93(Hz), and the area around peak is shown as grayed hatch, the area is A=5.57. The proposing normalized dominant frequency, f_n, is expressed in Eq. (4).

$$f_n = \frac{f_m}{\sqrt{A}} \tag{4}$$

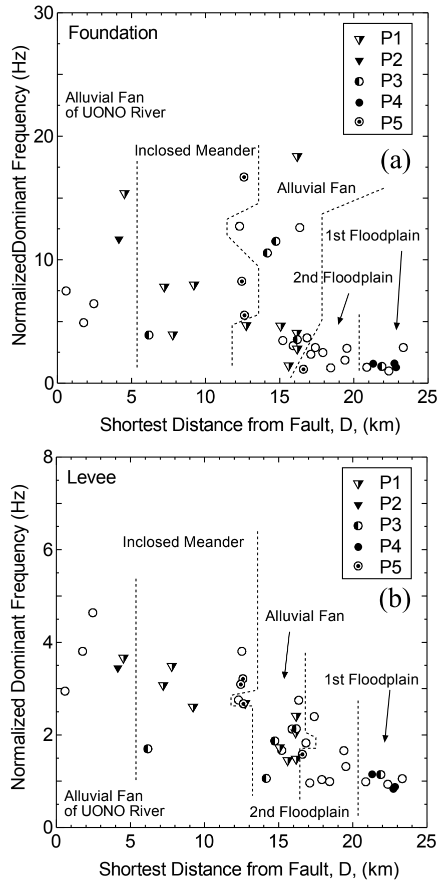
For example, the normalized dominant frequency of foundation in Fig. 8, f_n=1.24 (Hz)

(2) Proposed normalization dominant frequency

The normalized theoretical dominant frequencies for foundation and levee surface are shown in Figs. 9 (a), (b), respectively. The variation becomes small compared Fig. 9 (a) with Fig. 8 (a) to some extent. It is seemed that the scattered dominant frequencies express the ground variation.

It is noted that the normalized dominant frequency for levee can express the damage type as shown in Fig. 9 (b). The pattern P4 and P3, solid and half-solid circle, indicate serious damage, and its normalized dominant frequency are small obviously.

At Inclosed Meander Area, the levees and river protection structure were damaged, though the normalized dominant frequency is high. In this area, ground displacement about 70cm upward was observed, it seems to cause the damages.



Figs.9 (a),(b) Normalized dominant frequency by transfer function's area: (a) up to foundation, (b) including levee

5. CONCLUSIONS

In this study, we investigated the relationship between the damaged type of levee, geological classification and seismic properties using some dominant frequencies. It is revealed that both of average frequency, such as T_G in national specification, and geological classification are not enough for expression of seismic properties. On the other hand, there is possibility that the normalized dominant frequency is able to estimate the damage type of levee. It is seemed that the levee has high risk against serious damage, when the normalized frequency, f_n, is under 2Hz.

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REFERENCES

1) Sugimoto, T.: Relationship between Earthquake Damage of Embankment and Their Foundation, *Geotechnical Engineering Magazine*, Vol.59, No.2 Ser.No. 637, PP.20-23, 2011

2) Shi, H. and Midorikawa, S.: New Attenuation Relationships for Peak Ground Acceleration and Velocity Considering Effects of Fault Type and Site Condition, *Journal of Structural and Construction Engineering.*, Vol.523, pp.63-70, 1999.

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