Proceedings of the 8th U.S. National Conference on Earthquake Engineering
April 18-22, 2006, San Francisco, California, USA
Paper No. 802

EVALUATION OF SEISMIC CAPACITY OF RIVER DIKES IN URBAN AREAS DURING A LARGE TSUNAMI-EARTHQUAKE

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ABSTRACT

Seismic capacity of existing river dikes is analyzed by a finite element deformation method, which is found to be efficient. The seismic capacity of river dikes has been evaluated by an empirical methodology based on damage to dikes from past earthquakes in Japan. However, the application of this method for evaluating the settlement of river dikes results in overestimation. We employed a new method to evaluate a seismic capacity evaluation of existing river dikes in order to obtain a more accurate evaluation by considering time histories of the earthquake motion and degree of liquefaction. Two scenario earthquakes are used; a subduction earthquake and a nearby fault earthquake. The earthquake response analysis is carried out first, then the maximum shear stress and shear stress time histories are used to evaluate the resistant factor against liquefaction in the liquefiable layers by the Design Specifications of Highway Bridges (DSHB) and by the cumulative damage concept (CDC), respectively. Then post liquefaction stiffness is evaluated from the resistant factor against liquefaction based on the empirical formula. A switch-on-gravity analysis gives residual deformation pattern. In the case of the subduction earthquake, the calculated deformation using the CDC method, is larger than the deformation obtained by the DSHG method. In the case of the nearby-fault earthquake, both methods yield a similar deformation. The deformations obtained from the CDC and DSHB methods are much smaller than the deformations obtained by the empirical method; therefore, the use of our seismic evaluation methodology can be applied to estimate a more rational and low cost reinforcement design of the existing river dikes.

Introduction

The 2004 Sumatra earthquake affected many countries across the Indian Ocean and killed over 240,000 people. Japan is also exposed to a large Tsunami hazard because subduction earthquakes along the Pacific coast are expected within the next 30 years with a high probability.

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Therefore, disaster reduction from tsunami has become a very important issue in recent years.

An embankment is a flexible structure which easily deforms under a strong ground motion, but the deformation is not generally associated to a complete collapse. Moreover, the embankment can be easily repaired, even when damaged. Because of these reasons most of the embankments such as road embankments and river dikes were not seismically designed in Japan. On the other hand when seismic criteria are considered for design of embankments, only very simplified procedures such as a stability criteria by means of a circular arc method were employed. This contrasts with the use of advances design techniques such as performance based design for other civil structures. Damage to embankments, for example, may induce subsequent severe disasters such as the derailment of super express trains and the flooding of lowland urban areas.

In recent years several government agencies investigated the safety of river dikes against earthquakes. Their studies concluded that nearly 1,000 km among the 300,000 km of total river dike length in Japan requires seismic reinforcement. Considering the huge length of existing river dikes in Japan, a screening procedure based on empirical observations was employed. Details of the method are given in a section below. However, since the method largely overestimates the deformation as we will describe in the subsequent section, a more accurate method is desired. In this study, we evaluate the seismic capacity of actual river dikes using a finite element approach, and evaluate efficiency of this method.

Methodology

Evaluation Based on Empirical Method

Seismic capacity of river dikes in Japan has been evaluated by an empirical method because it is not efficient to use complicated deformation analysis for a large amount of structures. The empirical method estimates the vertical settlement of the river dike from the empirical relationships between the safety factor against the seismic stability and the settlement ratio against the height of the structure. These relationships were elaborated from the deformations of the existing river dikes under several large-scale earthquakes in Japan (Fig. 1). The safety factor calculated by the circular arc method, selecting the minimum value obtained from the following procedures; in the first one the safety factor is applying a static seismic load without considering liquefaction. In the second one the safety factor is computed by using an excess pore water pressure of liquefiable soil layer without considering seismic inertia force. For details refer to the Inspection manual for earthquake resistance of river dikes in Japan (River Bureau, Ministry of Construction Government of Japan 1995).

The settlement ratio for seismic design is defined as the upper limit of the actual damaged dikes, as shown in Fig. 1. Therefore, we can easily recognize that the structure designed by this method underestimates its seismic capability.

Evaluation Based on FEM Deformation Analysis

As mentioned in the previous section, the evaluation of the displacement from the empirical method leads to underestimation of the seismic capacity of embankments, which is far from sufficient for rational seismic design. We propose to use the FEM based deformation evaluation. The method we use in this paper combines the dynamic response and the static flow

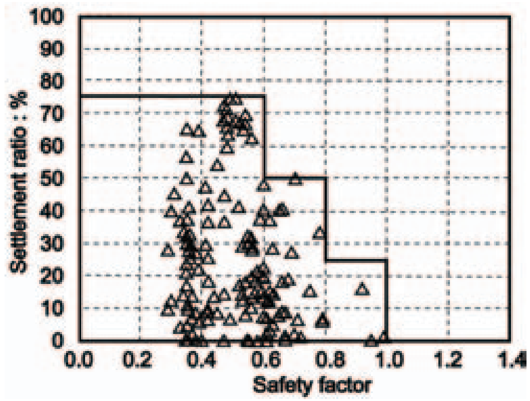


Figure 1. Relationships between the safety factor and the settlement ratio defined as settlement over height of dike (Japan Institute of Construction Engineering, 2002). The triangles are past damage and the solid line is the relationship used in evaluating the settlement from the safety factor.

analyses. The effective stress analysis may be an ideal method, but we do not use it because it usually requires a huge amount of information regarding material properties that is difficult to obtain. To minimize this in convenience we use the dynamic response analysis code FLUSH (Lysmer et al. 1975) to obtain the maximum shear stresses of liquefiable layers, and used the static analysis computer code ALID (Yasuda et al. 1999) in order to evaluate liquefaction-induced flow. The post liquefaction shear rigidities use within the ALID code are obtained from an empirical equation with respect to the resistant factor against liquefaction F_L (Yasuda et al. 2005), and the deformation after liquefaction-induced flow is evaluated by a self-weight analysis.

The resistant factor against liquefaction F_L is computed by two methods. The first method is an extended use of the Design Specifications of Highway Bridges, DSHB (Japan Road Association 2002), which is a widely used method in Japan;

$$F_L=R/L \tag{1}$$

$$R=C_w\, R_L \tag{2}$$

Where, R denotes liquefaction strength ratio, and L a maximum shear stress ratio computed by FLUSH. R_L is a cyclic stress ratio under which liquefaction occurs at 20 cycles of loading. In this study, this parameter is evaluated from SPT N-values (N_{SPT}) and the fines component. C_w is a correction factor depending on the type of earthquake and takes a value between 1 and 2.

The second method is based on the cumulative damage concept, CDC (Valera and Donovan 1976, Tatsuoka and Silver 1981 and Ohkawa et al. 1987). It can consider effect of duration and irregularity of the earthquake motion. The outline of the method is briefly described in the following.

Number of cycles equivalent to constant stress amplitude loading N_i under the amplitude of stress ratio L_i under irregular loading such as earthquake is evaluated from the relationships between stress ratio (S_R) and number of loading cycles at initial liquefaction under constant stress amplitude loading (N_c). Then the damage DM_i caused by a half cycle of loading under the amplitude of stress ratio L_i is computed by

$$DM_i=1/2N_i \tag{3}$$

The total cumulative damage due to the entire irregular loading pattern yields

$$DM = \sum (DM_i) = \sum (1/2N_i) \tag{4}$$

The value of DM exceeds unity, if liquefaction occurs in the meantime of the earthquake. We can compute the scaled shear stress time history under which DM becomes unity. Then inverse of scaling factor becomes F_L value. To estimate the liquefaction curve we use the relationship between the shear stress ratio (S_R) and the number of cycles at liquefaction (N_{liq}), (Tatsuoka 1980);

$$S_R = R_L (N_{liq} / 20)^{-0.10-0.10\log_{10} DA}. \tag{5}$$

where DA denotes double amplitude axial strain and is assumed to be 5 %.

Numerical Analysis

Model Structure

Aichi Prefecture has been surveying seismic capacities of river dikes whose damage can induce sever flooding disaster of lowland urban areas. Their study, which based on an empirical method suggested that an important number of river dikes such as those around the Nikko river could experience large settlements under future earthquakes (River Works Office of Aichi Prefecture 2003). We evaluate seismic capacity of eight river dikes within Nikko river based on a finite element analysis described in a precious section. Figure 2 shows the location of the analyzed river dikes; Figs. 3 and 4 the soil profiles of the left bank and the cross section at point 3K400. There are very soft Holocene clay layers (Ac_1 and Ac_2), beneath the dike and the Holocene sand layer (As_2). Judging from the fines contents and the plastic index of the soils from data of the Aichi prefecture report, Ac_1, As_1 and the upper part of Ac_2 are judged to be liquefiable layers.

The River Bureau of the Ministry of Construction Government of Japan (1995) requests that crest height of dikes should be at least 1.0m higher than the expected water level during and after an earthquake. The seismic performance of the dikes in compiled in Table 1. Figure 5

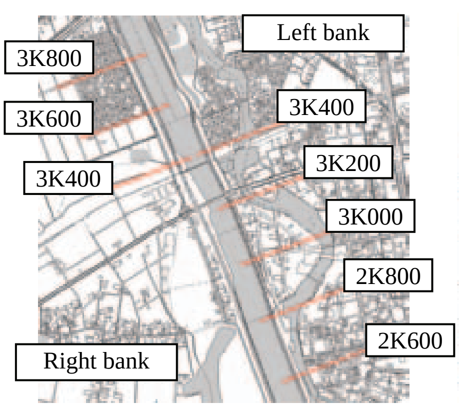


Figure 2. Location of the analyzed river dikes

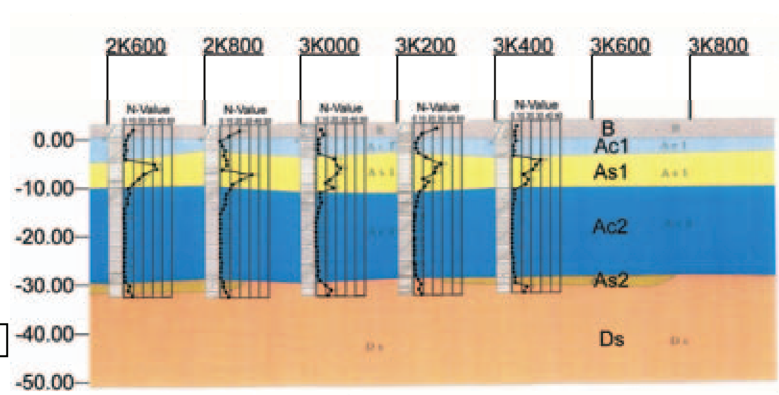


Figure 3. Soil profile along the left bank (River Works Office of Aichi Prefecture 2003)

shows the cross-section of the river dike (3K000 Left bank in Fig. 2) where the settlement is largest.

Input Earthquake Motion

We estimate the seismic performance of the river dikes under two types of seismic input motions. The first motion comes from a subduction earthquake and the second motion from a nearby-fault earthquake. Ground motions from both scenario earthquakes are obtained by a 3-D FDM considering the deep under-ground structure at each site (Research Study Group on Aichi

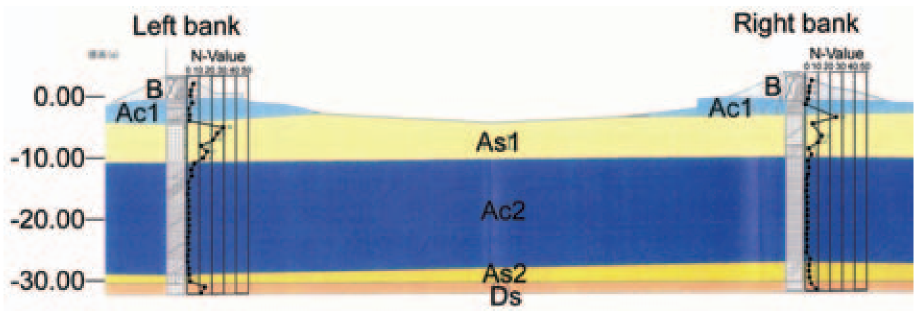


Figure 4. Soil profile at the 3K400 (River Works Office of Aichi Prefecture 2003)

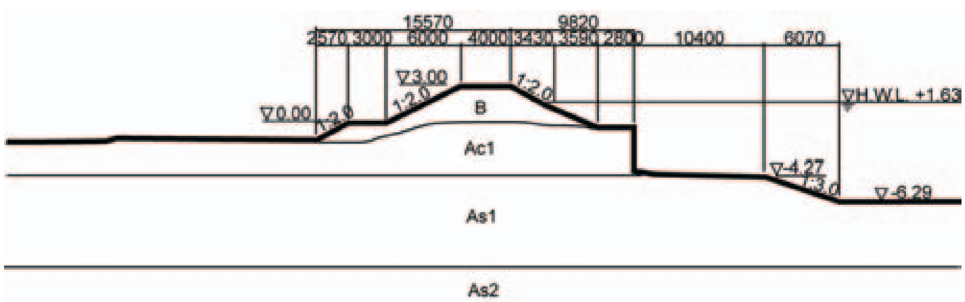
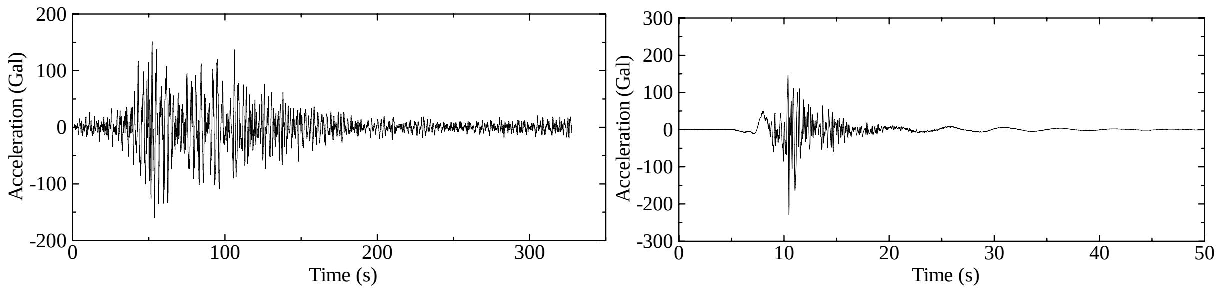


Figure 5. Outline of the river dike structure at the 3K000 Left bank.

Table 1: Seismic evaluation results for the river dikes by the empirical method. Not acceptable means an evaluated top level below the demanded level. (River Works Office of Aichi Prefecture 2003)

		top level (m)	evaluated top level (m)	demanded level (m)	seismic capacity
left side	2k600	3.00	1.44	0.70	OK
	2k700		-1.40		Not acceptable
	2k800		-0.93		Not acceptable
	2k900		-0.85		Not acceptable
	3k000		-1.16		Not acceptable
	3k100		-1.24		Not acceptable
	3k200		-1.10		Not acceptable
	3k300		-0.86		Not acceptable
	3k400		0.30		Not acceptable
right side	3k400	3.20	-1.57	0.70	Not acceptable
	3k500		-1.62		Not acceptable
	3k600		-1.65		Not acceptable
	3k700		-0.04		Not acceptable
	3k800		-0.03		Not acceptable



(a) Subduction earthquake (Shin-Tokai, Sannomaru-EW-wave) (b) Nearby-fault earthquake (Nagoya shallow, Tomita-EW-wave)

Figure 6. Calculated incident waves at the upper side of the Ds at the site.

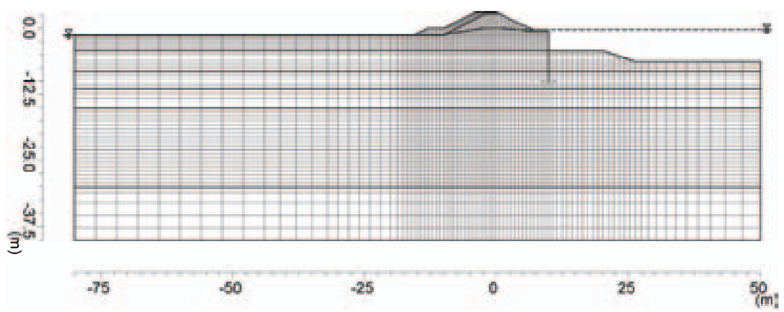


Figure 7. Analyzed FE mesh (3K000 Left bank).

Prefecture Design Seismic Motion 2003). We computed the input earthquake motions at the engineering seismic base layer by 1-dimensional equivalent-linear earthquake response analysis code, DYNEQ (Yoshida and Suetomi 1996). Empirical equations reported by the Public Works Research Institute (Iwasaki et al. 1977, Iwasaki et al. 1980, Yokota and Tatsuoka 1982) are used for the dynamic deformation characteristics of soil in the analysis. The simulated input waves are shown in Fig. 6.

Method of river dike seismic capacity analysis

We show a typical FE mesh used for our analyses in Figure 7. We used this mesh for both the earthquake response analysis and the liquefaction-induced flow analysis. For the earthquake response analysis, we used energy transmitting boundaries at the both sides and a viscous boundary at the bottom. We use the same dynamic deformation characteristics of soils as in the case of the 1-D earthquake response analysis. The results of the Public Works Research Institute (Iwasaki et al. 1977, Iwasaki et al. 1980, Yokota and Tatsuoka 1982) are also referred for the dynamic deformation characteristics of soils.

For the liquefaction-induced flow analysis, we extend the land-side boundary by 10 meshes with 5 m width to model the half space towards inland direction, and use the same material properties of the contact mesh layers. Vertical rollers are arranged at the river side boundary because of the symmetry of the problem along this vertical axis. The difference of treatment of lateral boundaries is that we expect half space toward inland direction whereas another dike exists in the river direction. We use a rigid boundary at the bottom. Regarding the soil characteristics, we calculate the resistant factor against liquefaction F_L using the equations of CDHB, and use the relationship between the reduced shear rigidity ratio and F_L shown in Fig. 8. (Yasuda et al. 2005)

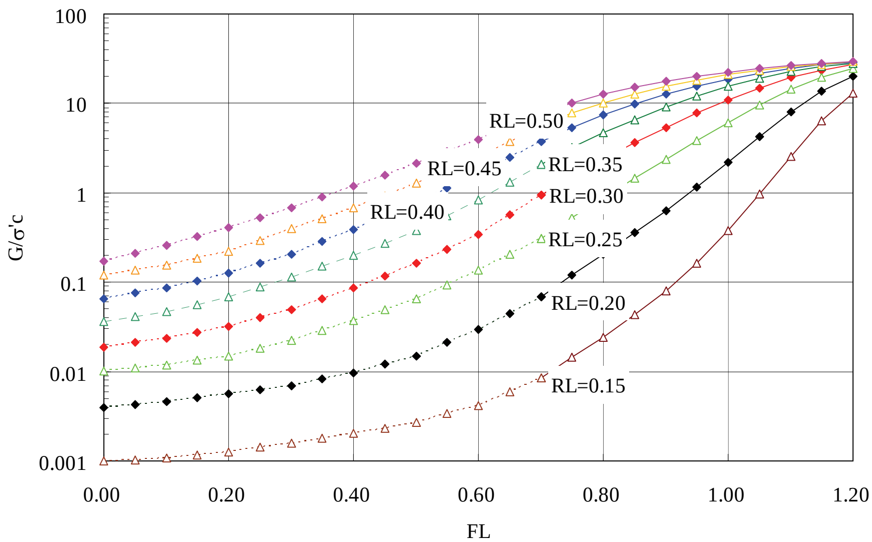
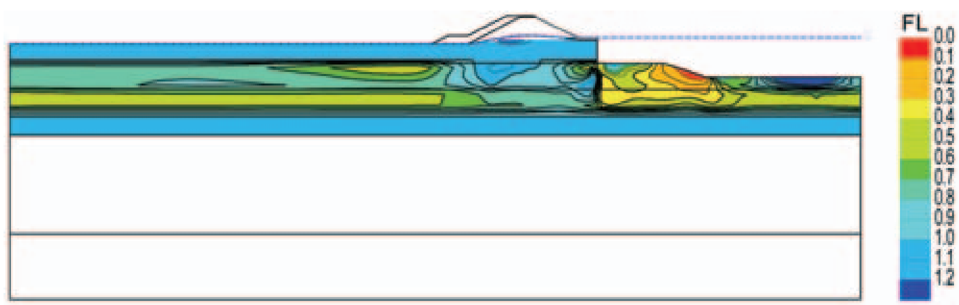
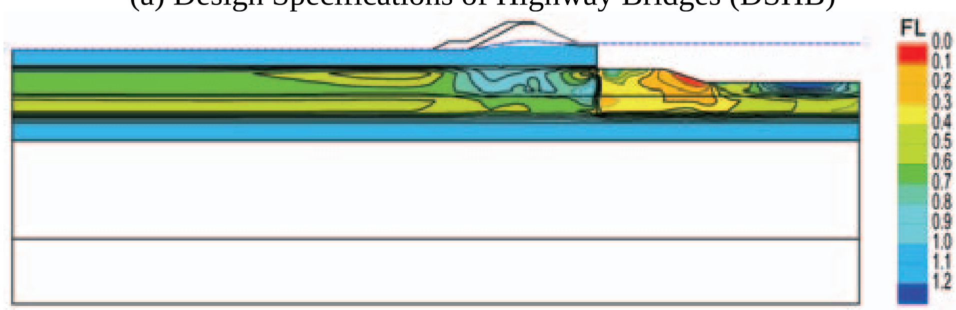


Figure 8. Relationship between the reduced shear rigidity ratio and the resistant factor against liquefaction (Yasuda et. al. 2005).



(a) Design Specifications of Highway Bridges (DSHB)



(b) Cumulative damage concept (CDC)

Figure 9. Distribution of the resistant factor against liquefaction F_L. (Subduction earthquake, 3K000 Left bank)

Results

Earthquake response and liquefaction-induced flow analyses

We calculated the deformation of eight river dikes. Settlement of the 3K000 Left bank was the largest for the subduction type earthquake. Distributions of F_L calculated by two methods are shown in Fig. 9. Liquefaction-induced flow based on CDC is shown in Fig. 10.

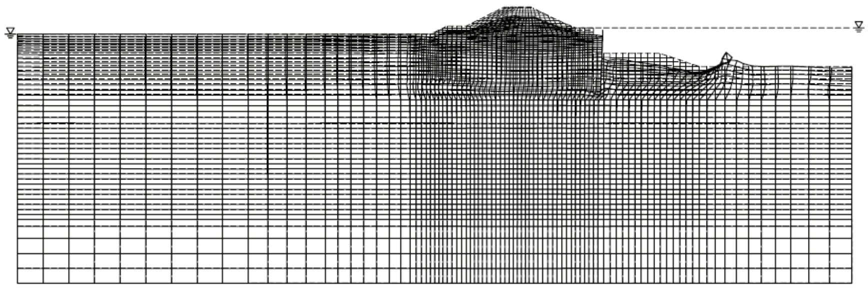


Figure 10. Deformation based on the liquefaction-induced flow analysis (Subduction earthquake, 3K000 Left bank).

Table 2 Seismic evaluation results for the river dikes by the scenario of subduction earthquake. Not acceptable means an evaluated top level below the demanded level.

		top level (m)	demanded level (m)	Empirical method	Design Specification of Highway Bridge		Cumulative damage concept	
				seismic capacity	evaluated top level (m)	seismic capacity	evaluated top level (m)	seismic capacity
left side	2K600	3.00	0.70	OK	2.66	OK	2.52	OK
	2K800			Not acceptable	2.50	OK	2.32	OK
	3K000			Not acceptable	1.86	OK	1.48	OK
	3K200			Not acceptable	2.35	OK	2.08	OK
	3K400			Not acceptable	2.62	OK	2.37	OK
right side	3K400	3.20	0.70	Not acceptable	2.85	OK	2.72	OK
	3K600			Not acceptable	2.87	OK	2.79	OK
	3K800			Not acceptable	2.93	OK	2.90	OK

Table 3 Seismic evaluation results for the river dikes by the scenario of nearby-fault earthquake. Not acceptable means an evaluated top level below the demanded level

		top level (m)	demanded level(m)	Empirical method	Design Specification of Highway Bridge		Cumulative damage concept	
				seismic capacity	evaluated top level (m)	seismic capacity	evaluated top level (m)	seismic capacity
left side	2K600	3.00	0.70	OK	2.99	OK	2.99	OK
	2K800			Not acceptable	2.71	OK	2.73	OK
	3K000			Not acceptable	2.95	OK	2.98	OK
	3K200			Not acceptable	3.00	OK	3.00	OK
	3K400			Not acceptable	3.00	OK	3.00	OK
right side	3K400	3.20	0.70	Not acceptable	3.08	OK	3.18	OK
	3K600			Not acceptable	3.16	OK	3.19	OK
	3K800			Not acceptable	3.19	OK	3.20	OK

The As_1 and the upper part of Ac_2 layers have potential for severe liquefaction. The F_L values based on DSHB are generally larger than the ones based on CDC (Fig. 9). The areas with large settlement agree with the areas with low F_L value (Fig. 10).

Estimation of seismic capacity

We estimated the seismic capacity of the eight river dikes under two types of earthquake; the results are summarized in Tables 2 and 3. We obtained that the settlements of the river dikes under the scenario subduction earthquake are larger than those under the nearby-fault earthquake.

In the case of the subduction earthquake, the calculated settlement by using the CDC method is larger than the settlement obtained from the DSHB. In the case of the nearby-fault earthquake, we obtained the opposite result; the settlement by using the CDC method is slightly smaller than the one based on DSHB. The settlements obtained from DSHB and CDC methods are much smaller than the ones based on the empirical method. We obtained that none of the river dikes need reinforcement. Moreover, even if we introduce a safety factor of 2, the resulting residual displacement is still small and reinforcement is not required for all dikes except one dike estimated with the CDC. In general, the cost for reinforcement directly managed by the Ministry of Land, Infrastructure and Transport Government of Japan is more than one million yen per meter. Our results show that the seismic estimation by using FE deformation analysis could result in an enormous reduction in cost for the reinforcement of the dike compared with an assessment by the empirical method.

Concluding Remarks

We evaluated the seismic performance of the river dikes classified as vulnerable by the Aichi prefecture government office during a subduction and a nearby-fault earthquake by using a two-step finite element deformation analysis; an earthquake response analysis to calculate the degrading stiffness and the degree of liquefaction combined with a liquefaction-induced flow analysis. Two design specifications were used for evaluating F_L values. The effect of the input ground motion was also investigated. We obtained that the calculated settlement by using the cumulative damage concept (CDC), is larger than the settlement obtained from the Design Specification of Highway Bridge (DSHB) in the case of the subduction earthquake. In the case of the nearby-fault earthquake, the settlement by using the CDC method is slightly smaller than the one based on DSHB. The settlements obtained from DSHB and CDC methods are much smaller than the ones based on the conventional method. The reinforcement is not necessary for all studied river dikes. Even if the analytical safety factor of 2 for the settlement is introduced, only one dike structure evaluated with the cumulative damage concept would require reinforcement. The top levels of the river dikes estimated by FE deformation analysis are higher than the ones by the empirical method. Our results show that the seismic estimation by using FE deformation analyses could result in an enormous reduction in cost for the reinforcement of the dike compared with an assessment by the empirical method.

Acknowledgments

This study is a part of the activities of the Earth Structure Working Group of the Special Committee for Great Earthquake Disaster, JSCE (Japan Society of Civil Engineering). We would like express our gratitude to the members of the working group for their kind advises. The soil and structural profiles used in our study were provided by the Aichi prefecture. Input ground motions of scenario earthquakes were obtained by the Research Study Group on Aichi Prefecture Design Seismic Motion. We wish to extend our gratitude to the all persons concerned.

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