DEVELOPMENT OF SEISMIC DESIGN CRITERIA FOR RIVER FACILITIES AGAINST LARGE EARTHQUAKES

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ABSTRACT
This paper introduces the fundamental concept of seismic design of river facilities against large-scale earthquakes described in the “Performance-based Seismic Design Criteria for River Facilities (Draft)” recently compiled by the Ministry of Land, Infrastructure and Transportation (MLIT) on 2007.3. River facilities include levees, self-supporting structural levees, sluiceways, water gates, weirs and drainage pumping station. As background, characteristics of damage induced in river facilities by past earthquakes, and the history of revision of the “Technical Criteria for River Works and Sabo Works (Draft) Volume of Design” are also briefly reported.

KEYWORDS:
Earthquake Damage, Large Earthquake, River Facilities, Seismic Design Criteria

1. INTRODUCTION

River facilities are divided into earth structures such as general levees and high-standard levees, and structures consists of reinforced concrete and steel components. The latter structures are further classified into works attached to levees or to river beds, such as revetments, dikes, and groundsills, and into structural groups such as sluiceways, water gates, weirs, and drainage pumping stations. The seismic design of these various structures basically conforms to the “Technical Criteria for River Works and Sabo Works (Draft) Volume of Design, 1997, the Ministry of Construction”. However, since only the Level 1 (moderate-scale) earthquake ground motion was taken into account in the criteria, seismic design procedure against Level 2 (large-scale) earthquake ground motion had been urgently required. Under the circumstances, the MLIT (Ministry of Land, Infrastructure and Transport) established and carried a “Committee for countermeasures against large earthquakes of River Facilities” during 2004 to 2007, and compiled the “Performance-based Seismic Design Criteria for River Facilities (Draft)” in March 2007.

This paper presents fundamentals of the “Performance-based Seismic Design Criteria for River Facilities (Draft)”. And as a background, characteristics of damage induced in river facilities by past earthquakes, and the history of revision of the “Technical Criteria for River Works and Sabo Works (Draft) Volume of Design” are also briefly described.

2. EARTHQUAKE DAMAGE FEATURES

The relationship between levee height and levee crown settlement in cases of earthquake damage induced by major earthquakes after the 1981 Nobi Earthquake is summarized in **Figure 1**. General river levees have been suffered damage such as settlements, longitudinal and transversal cracks, or sliding destruction reputedly. It can be said that the seismic resistance of levees is based on the condition of foundation ground, since obvious damage has occurred on soft ground. Furthermore, since sand boiling phenomena have been found in most cases, soil liquefaction of foundation is considered to be the main factor of the damage. Cases of damage are rarely found in soft cohesive soils.

Although the amount of levee crown settlement changes according to the foundation condition or the scale of the seismic motion, those difference conditions are not considered in summarizing **Figure 1**. According to this figure, the amount of levee crown settlement is generally about 75% of the levee height at most.

Table 1 shows cases of earthquake damage induced in river structures consist of reinforced concrete and steel components after the 1964 Niigata Earthquake. Since there are not enough remaining records from the very old days, the data from **Figure 1** cannot be directly compared with that in **Table 1**. According to **Table 1**, however, the number of seismic damage to structures is obviously small compared with the number of damage events to river levee. The reason for this is thought to be because the moderate-scale ground motion has been taken into the seismic design for river structures of reinforced concrete and steel components from years ago. In cases of damage, considerable sluiceway box culvert damage has been reported. This is because, unlike with the design of the sluiceway gate column, seismic-resistant design considering seismic load has not been applied in the case of the sluiceway box culvert. If the levee is largely deformed, then only the joints set between each box culvert cannot absolves the deformation of the surrounding ground. That causes joint separation, cracks of box culvert and breakage of supporting pile foundation.

Although cases of damage to water gates or weirs are rarely found, the Myoken weir suffered extensive damage by the 2006 Mid-Niigata Earthquake as shown in **Picture 1**. The strong-motion accelerograph installed at the Myoken Weir control office measured the maximum value of the acceleration time-history waveform as more than 1500 gals, and the acceleration response spectrum exceeded the ground motion observed at the Kobe Marine Observatory on the occasion of the 1995 Kobe Earthquake especially in the short natural period range. This fact indicates that even river structures consisted with reinforced concrete and steel components may suffer severe damage when strong ground motion greatly exceeds the design seismic load (moderate-scale ground motion) developed at the site.

3. HYSTORY OF SEISMIC DESIGN

The “Technical Criteria for River Works and Sabo Works (draft)” was first published in 1958 in order to compile the technologies for the construction river works and sabo works at that time. The criteria were divided into five volumes in 1972, i.e. survey, plan, design, construction and maintenance in order to correspond to the rapid economic growth and social changes that began around 1955. In the 1985 revision of the criteria, the seismic load equivalent to the moderate-scale of earthquake ground motion was first introduced into the design of river structures consists of reinforced concrete and steel components.

In the 1995 Kobe Earthquake, levees located downstream of Yodo-river was settled approx. 3m. The fact endorsed recognition of seismic strength of levees that had low-lying areas behind them. The Ministry of Construction (at that time) established a “Committee for seismic strengthening of levees (chairman: Prof. Kazuya Yamamura of Nihon Univ.)” soon after the earthquake and proposed the fundamental policy for the seismic strengthening of levees located zero-meter area (area below sea level). In the 1997 revision of the criteria, seismic design of levees was introduced taking into account the proposal. Since the revision of criteria, seismic inspection and seismic strengthening has been initiated across the nation.

The settlement of levee has been estimated based on the experimental relationship between the settlement and safety factor derived from the seismic coefficient method as shown in **Table 2**. This is because a theoretical method to estimate the seismic deformation, i.e. the finite element method was not yet well prepared at that time. In the criteria, design seismic coefficient has been given as between 0.10 and 0.18 according to the regional classification and the levee scale, whereas large-scale earthquake ground motion is not considered. Behind the decision of seismic coefficient, political circumstances are taken into account, i.e. restoration of earth structures is generally easy, and countermeasure against heavy rain is prior to the measures against large-scale earthquake from the frequency point of view.

4. CRITERIA AGAINST LARGE-SCALE EQ

In recent, technical review of the probability and damage scenarios of large-scale earthquake such as Miyagiken-oki Earthquake, Tokyo inland Earthquake, Tokai Earthquake, Tonankai Earthquake and Nankai Earthquake has been conducted by the Central Disaster Prevention Council of Government. However, as mentioned before, only moderate-scale earthquake ground motion is considered in the conventional criteria. Therefore, it was urgently required to prepare new criteria that include counter earthquake measures for river facilities against large-scale earthquake. Under these circumstances, the MLIT established and carried the "Committee for countermeasures against large earthquakes of river facilities (chairman: Prof. Yasushi Sasaki of Hiroshima Univ.)" during 2004 to 2007 and compiled the "Performance-based Seismic Design Criteria for River Facilities (draft)" in March 2007. The criteria covers moderate-scale (Level 1) and large-scale (Level 2) earthquake ground motion.

4.1 Contents

The criteria shall be applied to check the seismic performance of river facilities including levee, self-supporting structural levee, water gate, sluiceway, weir and drainage pumping station. Contents of the draft criteria are shown in **Table 3**. Among river structures that could affect flood control or water utilization due to their earthquake damage, inverted siphons and underground tunnel river shall be treated in accordance with the technical guidelines for similar structures such as roads and sewage systems.

4.2 Basic Policy to Check Seismic Performance

In checking the seismic performance of river facilities, required seismic performance and earthquake ground motion shall be appropriately determined and seismic analysis method shall be appropriately adopted. The seismic analysis method can be classified into the dynamic response analysis method and static analysis method. The dynamic response analysis generally requires precise modeling of actual dynamic phenomena, detailed input data and technically difficult decisions. On the other hand, the static analysis method can be conducted more easily by simplifying the actual dynamic phenomena. In the draft criteria, mainly specify the static analysis method considering its practical use, however seismic performance check shall be appropriately conducted considering the response characteristic of the structure and required analysis accuracy.

The water level for checking the seismic performance of river facilities shall be, in principle, the highest daily water level under usual condition. The water level was defined in accordance with the water level that has been considered for the seismic inspection practice and seismic strengthening practice supposing that the earthquake and heavy rain would not occur simultaneously from the statistic point of view. Around the river mouth area, the highest tidal water level and the amount of wind wave shall be considered. Furthermore, tsunami supposed to be occurred following the earthquake, estimated tsunami height shall be considered in addition.

4.3 Earthquake Effect

As the effect of the earthquake, the inertia force caused by the structure's weight, earthquake ground deformation, earthquake earth pressure, dynamic water pressure and the effect of soil liquefaction shall be considered. There are many kinds of structures, including earth structure such as levee, aboveground structure such as water gate or weir, and structures installed in the ground such as drainage pumping station. Some structural components may contact surrounding soil or water. The effect of the earthquake shall be appropriately considered depending on each structure and each structural component.

4.4 Earthquake Ground Motion

Level 1 earthquake ground motion and Level 2 earthquake ground motion shall be considered in the checking of the seismic performance. Definition of the Level 1 earthquake ground motion is the ground motion occurs with high probability during its service period. Level 1 earthquake ground motion was determined to follow the ground motion that has been adopted in the conventional seismic design according to the seismic coefficient method.

Definition of the Level 2 earthquake ground motion is the maximum credible ground motion at each site from the present to the future. As the Level 2 earthquake ground motion, Level 2-1 ground motion which assumes a large-scale earthquake occurs at the plate boundary and Level 2-2 ground motion which assumes an inland earthquake shall be considered. Level 2 earthquake ground motion was determined by referring the “Draft Guideline for the Seismic Design of Civil Structures, Japan Society of Civil Engineering, 2001.9” and the “Design Fundamentals for Constructing Civil Structures and Architectural Structures, MLIT, 2002.10”. Level 2-1 ground motion is characterized as a repeated motion with large amplitude for a long duration time, whereas Level 2-2 ground motion is characterized as a motion with extremely large amplitude for a short duration time. Above mentioned two types of ground motion shall be considered to check the seismic performance of river facilities, because the dynamic response of structure is affected by the characteristics of amplitude, natural period, duration time and repetition.

4.5 Required Seismic Performance Level

Required seismic performance level of various river facilities and various structural components were defined according to the flowchart shown in **Fig. 2**. In the flowchart, emphasis is placed on whether or not the structure is important for the water utilization or flood control, whether or not the structural component is one of the major components that consists the structural flame, and whether or not an alternative measures are available when the component lose its function.

Here, three kinds of seismic performance level were defined. Seismic performance level 1 means that the structure or component does not loose the soundness as a river facility. Seismic performance level 2 means that retains the function as a river facility against the water level defined in the criteria for checking the seismic performance. And seismic performance level 3 means that the earthquake damage is limited and the recover of the damage can be made within a short time.

Table 4 shows the required seismic performance for each river facility. **Table 5** shows the required seismic performance for each structural component of the structure that is important for the water utilization and flood control.

5. SEISMIC PERFORMANCE OF LEVEE

5.1 Basic Policy to Check Seismic Performance

Levees are constructed to prevent running water from overflowing. In the zero-meter area much settlement of levee may induce flood disaster. On the other hand, it is not necessarily rational that development of any settlement of levee is not allowed after a large-scale earthquake. Based on these characteristic of earth structure, therefore, required seismic performance of levee was defined as level 2 that means levee retains its function against the water level defined for checking seismic performance although some amount of settlement may be developed.

In the checking of seismic performance of levee, soil liquefaction shall be considered as the earthquake effect. This is because severe damages of levee in the past earthquake were induced by the soil liquefaction of their foundation ground.

5.2 Analysis Method

The static analysis method can be adopted to check the seismic performance of levee because it is relatively simple structure. For the checking of seismic performance of levee by the static analysis method, first seismic coefficient in the horizontal direction shall be determined, and then probability of soil liquefaction at sandy layer shall be checked. Next, seismic deformation of the levee shall be estimated in proportion to the degree of soil liquefaction, and check whether or not the levee height after the earthquake will exceed the water level defined in the criteria for checking the seismic performance. As a simple and precise static analysis method to estimate the seismic deformation of the levee, the finite element method assuming that the levee deforms in cooperation to the reduction of shear stiffness can be adopted. Also, the estimation method of fluidic deformation of the levee assuming that the liquefied soil layer is a viscous fluid can be adopted.

5.3 An Example of Static Analysis by FEM

As an example, static analysis of levee using the above-mentioned finite element method is shown in here. The levee specifications and a sectional view are shown in **Fig. 3** and **Table 6**.

Ground conditions of the levee are supposed to be horizontally laminated. From the surface, the ground consists of sandy soil with approx. 2m thickness, alluvial sandy soil As1 with approx. 6-7m thickness which shows 1-11 N-value, soft clay soil Ac1 with approx. 14m thickness which shows 1-5 N-value, and alluvial sandy soil As2 with approx. 4m thickness which shows 11-20. Below the As2, alluvial clay soil Ac2 and gravel soil is accumulated. According to the boring data, the ground of river side and protected side are both classified soil type III. On the basis of the soil type, the design horizontal seismic coefficient for Level 2-1 and Level 2-2 ground motion are determined 0.40 and 0.60, respectively. As the result of checking the probability of soil liquefaction against two kinds of seismic coefficient, all the alluvial sandy layer As1 is found to be liquefied.

The analysis method estimates the deformation of levee by assuming that the levee deforms in accordance with the reduction of shear stiffness due to soil liquefaction. In this case study, reduction of shear stiffness in the liquefied layer was determined based on the relationship between the liquefaction resistant ratio F_L, cyclic triaxial strength ratio R_L and the degree of reduced shear stiffness. The averaged cyclic triaxial strength ratio was adopted for the R_L. Here, it is necessary to consider the settlement associated with the volume compression separately from the analytical solution. This is because the analysis method does not consider the settlement of levee associated with the volume compression induced by the propagation of excess pore water pressure generated in the liquefied layer during the earthquake.

In this case study, both Level 2-1 and Level 2-2 ground motion were considered. In the case of Level 2-1 ground motion, the analytical solution was 163.0cm, settlement associated with volume compression was 38.3cm, and the total settlement of levee crown was estimated as 201.3cm. In the case of Level 2-2 ground motion, the analytical solution was 171.4cm, settlement associated with volume compression was 38.3cm, and the total settlement of levee crown was 209.7cm. **Fig. 4** shows the deformation of the levee against Level 2-2 ground motion.

6. CONCLUDING REMARKS

The fundamentals of the "Performance-based Seismic Design Criteria for River Facilities (Draft)" were introduced briefly. From the fiscal year of 2007, new structures will be constructed based on the criteria. Seismic inspection will be conducted in nationwide and seismic upgrading of existing structures which have insufficient seismic performance will be carried out one by one from the viewpoint of importance for flood control and water utilization.

7. REFERENCES

1. Committee on Earthquake Countermeasure for River Facilities: *Committee Report*, 1996
2. Full criteria (in Japanese)can be download through
   http://www.mlit.go.jp/river/shishin_guideline/bousai/wf_environment/structure/index.html

Table 1 Major Cases of Damage to River Structures by Past Earthquakes

Earthquake	Structure	Damage
1964 Niigata EQ	Structural Levee	Gap of Joint
I978 Miyagi offshore EQ	Weir	Deformation of Gate
	Sluiceway	Damage of Column
	Weir	Deformation of Gate
1983 Mid Nihonkai EQ	Sluiceway	Crack of Culvert
	Sluiceway	Crack of Culvert
	Sluiceway	Spread of Joint
	Sluiceway	Spread of Joint
	Water Gate	Tilting of Retaining Wall
1997 Kushiro offshore EQ	Sluiceway	Spread of Joint
	Sluiceway	Spread of Joint Damage of Drainage Inlet
1993 Hokkaido Nansei-oki EQ	Sluiceway	Spread of Joint Breakage of Culvert
1995 Hyogoken Nanbu EQ	Structural Levee	Tilting of Retaining Wall, Damage of Pile Foundation
	Water Gate	Damage of Column
	Weir	Deformation of Gate
	Tunnel River	Breakage of Joint Crack of Culvert
	Tunnel River	Crack of Lining
2003 Tokachi offshore EQ	Sluiceway	Tilting of Column
2004 Mid Niigata EQ	Weir	Damage of Column
	Sluiceway	Spread of Joint
	Pump Station	Damage of Flexible Joint

Table 2 Relationship between Levee Settlement and Seismic Safety Factor

Safety Ratio F_{sd}		Settlement (maximum)
$F_{sd}(kh)$	$F_{sd}(\Delta u)$	
$1.0 < F_{sd}$		0
$0.8 < F_{sd} \leqq 1.0$		(Levee Height) ×0.25
$F_{sd} \leqq 0.8$	$0.6 \leqq F_{sd} \leqq 0.8$	(Levee Height) ×0.50
—	$F_{sd} \leqq 0.6$	(Levee Height) ×0.75

Table 3 Contents of Draft Criteria

Volume	Contents
Common	Basic Principle of seismic performance design, Common Items such as Design Load
Levee	Seismic Performance Design of Levee*
Self-supporting Structural Levee	〃 Self-supporting Structural Levee
Water Gate, Sluiceway and Weir	〃 Water Gate, Sluiceway and Weir
Drainage Pumping Station	〃 Drainage Pumping Station

*High-standard levees are not included in this draft principle, since they are at present separately reviewed

Table 4 Required Seismic Performances for Facilities

Structure	Type	Importance Classification	Earthquake Ground Motion	
			Level 1	Level 2
Levee		※	Not Required	Level 2
		Other Area	Not Required	Not Required
Self-supported Structural Levee	RC Retaining Wall	※	Level 1	Level 2
		Other Area	Level 1	Level 3
	Sheet Pile	※	Not Required	Level 2
		Other Area	Not Required	Level 3
Weir	Flip-top Gate	Very Important	Level 1	Level 2
		Others	Level 1	Level 3
	Steel Reverse Gate	Very Important	Level 1	Level 2
		Others	Level 1	Level 3
Water Gate Sluiceway		Very Important	Level 1	Level 2
		Others	Level 1	Level 3
Drainage Pumping Station		Very Important	Level 1	Level 2
		Others	Level 1	Level 3

※ Area that the ground level is lower than the water level defined in the seismic design criteria for checking the seismic performance

Table 5 Required Performances for components

Structure	Type	Component	Earthquake Ground Motion	
			Level 1	Level 2
Levee		Main Body	Not Req.	Level 2
Self-supported Structural Levee	Retaining Wall	Main Body, Foundation	Level 1	Level 2
	Sheet Pile	Main Body	Not Req.	Level 2
Weir	Flip-top Gate	Slab, Weir Column, Gate Column, Foundation, Gate Beam	Level 1	Level 2
		Gate, Operation Room, Maintenance Deck	Level 1	Level 2*
		Apron, Liner Facility, Revetment, Fish Way, Others	Not Req.	Not Req.
	Steel Reverse Gate	Slab, Weir Column, Foundation, Gate	Level 1	Level 2*
		Apron, Liner Facility, Revetment, Fish Way, Others	Not Req.	Not Req.
Water Gate Sluiceway		Slab, Weir Column, Gate Column, Foundation, Gate Beam, Culvert	Level 1	Level 2
		Gate, Operation Room, Maintenance Deck	Level 1	Level 2*
		Apron, Liner Facility, Revetment, Fish Way, Parapet Wall, Others	Not Req.	Not Req.
Drainage Pumping Station		Pump, Foundation	Level 1	Level 2
		Pump Rated Device, Building	Level 1	Level 2*
		Others	Not Req.	Not Req.

* Alternative Measures are Available in order to Secure Structural Function

Table 6 Analyzed Levee Specifications

Levee Height (River Side)	Levee Height (opposite)	Width of Levee Crown	Width of Levee
6.9m	5.2m	9.0m	55.4m
Slope (River Side)	Slope (Opposite)	Altitude of Levee Crown	Highest tidal Water Level
1:1.6	1:2.0	AP+8.7m	AP+2.1m

Picture 1 Damaged Gate Column of Myoken weir by 2004 Mid-Niigata Earthquake

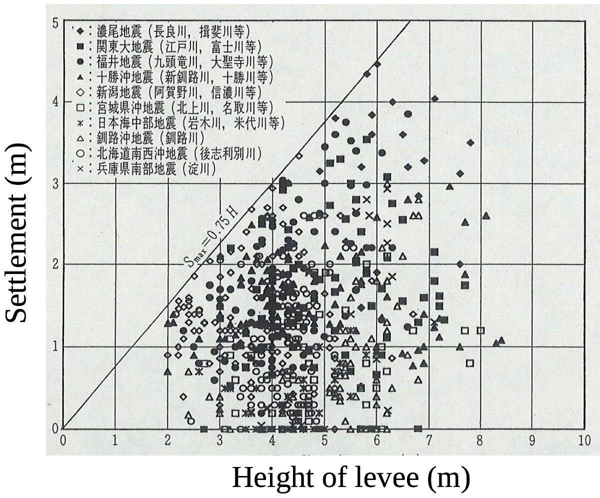


Figure 1 Relationship between Levee Height and Settlement of Crown in Past Earthquake[1)]

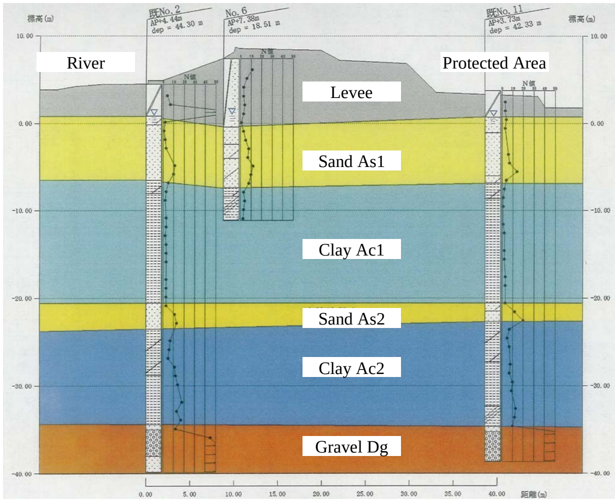
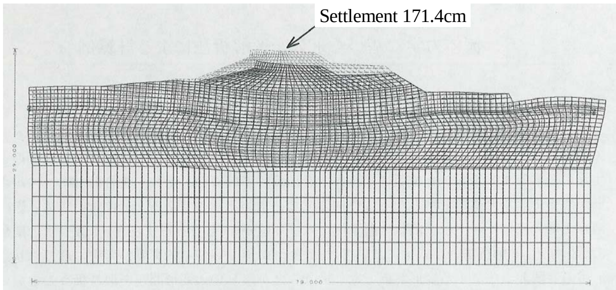
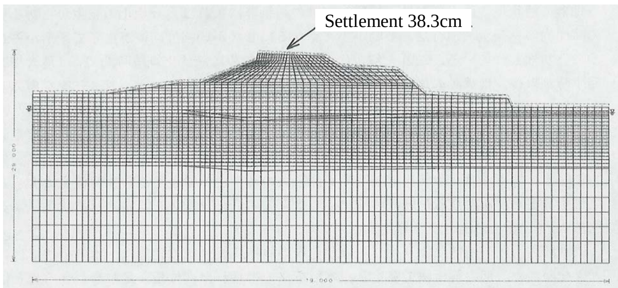


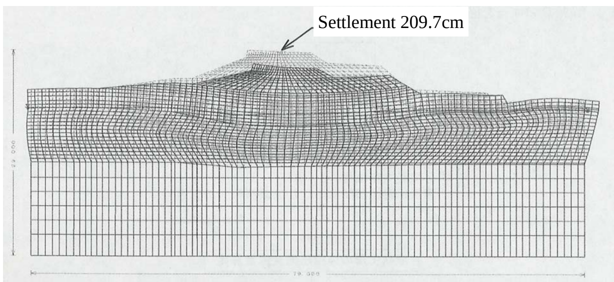
Fig. 3 Sectional Area of Analyzed Levee



(a) Solution of Finite Element Method

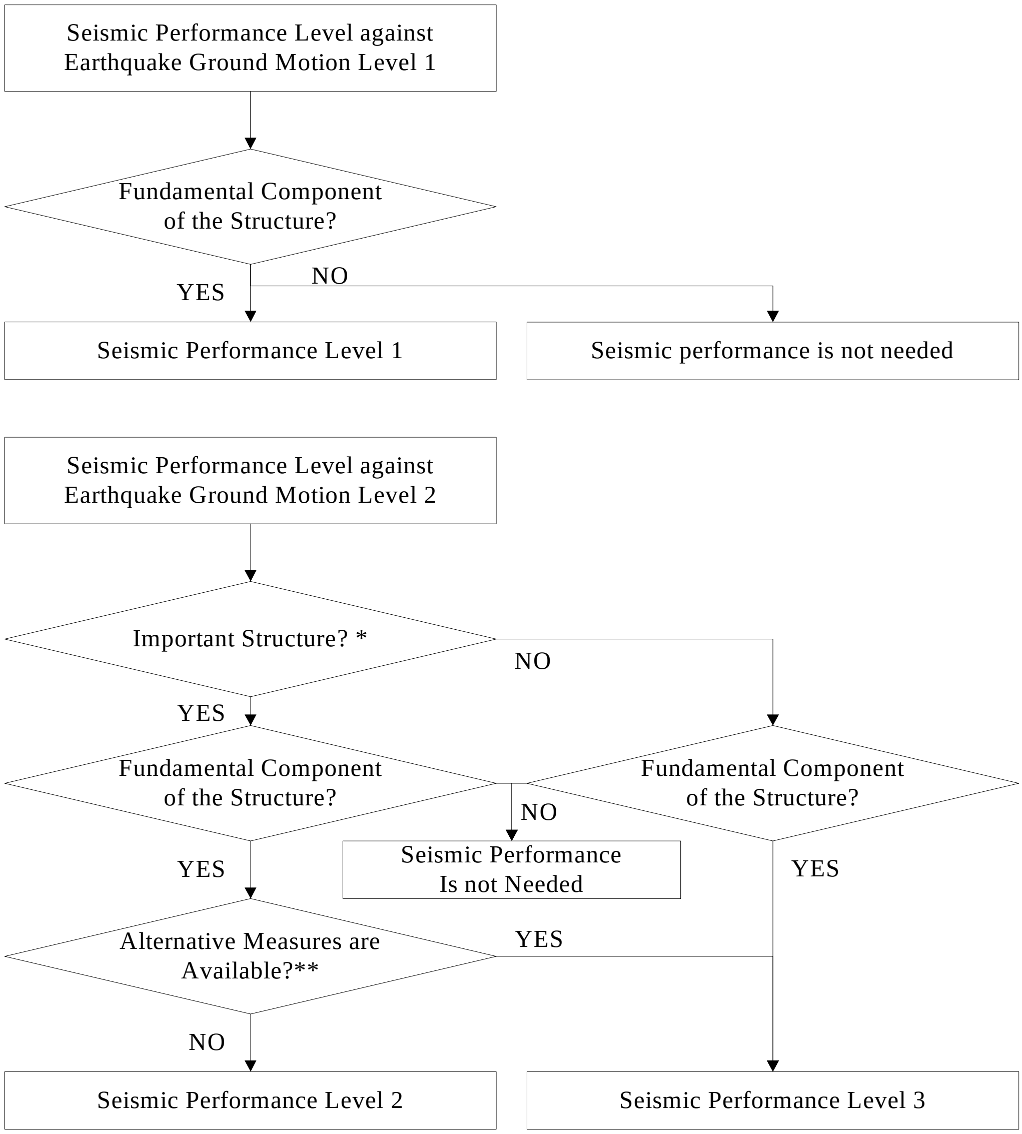


(b) Volume Compression of Liquefied Layer



(c) Total Deformation

Fig. 4 Deformation of Levee against L2-2 EQ



*Important Structure :	Important for flood control or water utilization. 1) When the structure lose control, flood damage may be induced by the water level defined in the seismic design criteria for checking the seismic performance. 2) When the structure lose control, difficulty of water utilization may be induced by the water level defined in the seismic design criteria for checking the seismic performance.
** Alternative Measures are Available	1) When the structure lose control, weir , water gate and sluiceway can be closed by supplemental gate or using square timbers. 2) When the structure lose control, the drainage pump can be replaced by supplemental handy pump in the drainage pumping station

Fig.2 Determination of Required Seismic Performance