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FAILURE MODE OF EMBANKMENTS DUE TO RECENT EARTHQUAKES IN JAPAN

Yasushi SASAKI [1], and Kei-ichi TAMURA [2]

ABSTRACT

After the Hyogo-ken Nanbu earthquake, in order to prepare against a great earthquake, it is needed to introduce the performance-based seismic design for river facilities in place of the allowable stress design used long in the conventional seismic design. For this purpose, efforts are being made from various directions which include modelling of constitutive law of post liquefaction state of soils, and development of numerical analysis method. Although it is required to evaluate the amount of deformation of an embankment during an earthquake for its performance-based design, however, the evaluation criterion for embankment, specially for river dikes is not yet fully established.
By reviewing the seismic damage to river dikes at sites during recent earthquakes, the direction of the technical development needed to evaluate the seismic performance of river dikes is discussed.

Keywords: *River Dikes, Seismic Failure, Soil Liquefaction, Seismic Performance of river dike*

INTRODUCTION

As Japan is an earthquake prone country, it has suffered seismic damage for many times since past. In 1964, the Niigata Earthquake caused failure of dikes near river-mouths of the Agano and Kyu-Shinano Rivers, and the part of the Niigata city was inundated by water boiled from ground due to soil liquefaction and brought in water by tsunami.
The damage by the Hyogoken-Nanbu Earthquake in 1995 forced the revision of seismic design standards of the engineering structures in Japan so that they should be withstand against extremely strong earthquakes, therefore, two levels of design earthquakes and the performance-based design are being adopted in various technical manuals for seismic design of many structures.
Not only against earthquakes, in view of the flood damage of hurricane Katrina in 2005, prevention of the flood disaster at the low flat region is recognized to be an urgent and important subject in Japan.
Since the river dikes in Japan have been constructed on the basis of fulfilling the mandatory standard cross sections which have been defined for each section from experience gained in long history, the rational seismic design is expected to be introduced in accord with the progress of the technology.
The river facilities are basically being constructed and maintained following the “Technical Standards for River and Sabo Facilities” which was enacted in 1958 and revised for 6 times since then and relating technical manuals for river dikes. Though, it is hard to say that the descriptive content about the triggering mechanism of seismic failure of dikes is enough in these standards.
Considering the accumulation of knowledge about the seismic failure of river dike and the increasing demand of preparedness of river facilities against extremely big earthquake, the Ministry of Land, Infrastructure and Transport (MLIT, formerly MOC) of Japanese Government is now preparing a "Design guideline for river facilities against L2 earthquake".

[1] Professor Emeritus, Hiroshima University, Executive Advisor, Japan Institute of Construction Engineering, Email: 8sasaki@jice.or.jp
[2] Research Coordinator for Earthquake Disaster Prevention, Disaster Management Center, National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure and Transport.

Although it was revealed that the intense failure of dikes during earthquakes was caused by soil liquefaction, however, as the liquefaction consequences are very complicated phenomena and is still not fully solved problem, so it is thought necessary to continue efforts both in laboratory and fields so that the Guideline will be brushed up to more advanced one. Keeping this in mind, after briefly introducing the history of mitigating efforts on earthquake inducing failure of river dikes in Japan, then this paper discusses about the research direction needed to increase the rationality of current design method.

HISTORY OF MITIGATATION OF SEISMIC DAMAGE TO RIVER DIKES IN JAPAN

Efforts to mitigate seismic damage to soil structures in Japan in the past are classified into three categories: Damage study based on the results gained from field reconnaissance, Diagnosis of existing structures, and Remediation of structures. Diagnosis and Remediation are to be based on the proper methods to estimate its performance against earthquake based on validated theories. How far those efforts were made is shown below.

Damage investigation

Investigation by field engineers on damage to embankment due to earthquakes had been conducted primarily for diagnosing the residual performance of damaged sections, for prioritizing the sections for which emergency treatment should be taken for preventing secondary disaster and for selecting the proper restoration works if necessary. The investigated results gave also precious bases for clarifying the cause and mechanism of the damage which could be utilized to revise technologies to mitigate seismic damage.

Problems concerning damage investigation are the lack of experts and tools. As the ordinary engineers at field hardly happen to face earthquakes, and they do not know what kind of quantities should be looked into and what technique is proper to measure the residual performances. However the experiences of treating seismic damage of embankments are being disseminated among field engineers through such materials like a “Manual for repair methods of the civil engineering structures damaged by earthquakes” (PWRI, 1986), “Guideline for rehabilitation work for seismic damage of river facilities” (River Bureau, 1994) or reports of the investigated results on damage and rehabilitation activities published from the construction offices.

In the above Manual, embankment failure due to earthquakes is classified into 4 fundamental modes as shown in Figure 1 in accord with their occurrence portion of failure (Sasaki, 1980). Type 1 and 2 in this Figure are the failure in the embankment, type 3 is intense deformation of embankment due to soil liquefaction in foundation ground, and type 4 is crest settlement without apparent deformation of whole embankment.

Figure 2 shows an alternative classification of a failure mode of damaged dike written in the above Guideline, which is slightly different from the one in the Manual. This alternative classification which has been often used for selecting restoration works during rehabilitation period focuses on the residual ability of dike in flood protection performance in comparison with HWL. Figure 2 is the case of the Shinano River dike damaged by the Niigata-ken Chuetsu earthquake (Oshiki & Sasaki, 2006). Transverse crack is included as a type of failure in Figure 2, though it is not included in Figure 1.

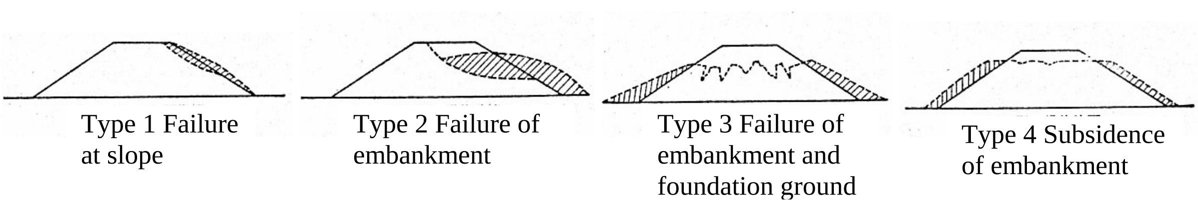


Figure 1. Classification of damage modes of failed dikes

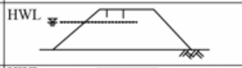
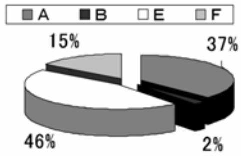
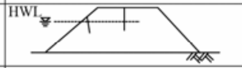
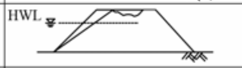
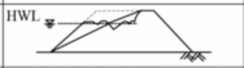
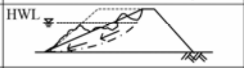
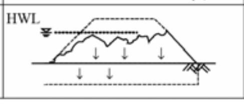
type	failure mode	features	places	distance (m)	
A		longitudinal cracks (shallower than H.W.L)	8	6,997	percentage of distance 
B		longitudinal cracks (deeper than H.W.L)	1	449	
C		transverse cracks (shallower than H.W.L)	–	–	
D		transverse cracks (deeper than H.W.L)	–	–	
E		slide of slope (failure of crest)	5	8,659	
F		total collapse of crest no original shape remaining (liquefaction of foundation)	3	2,871	
			17	18,976	

Figure 2 Classification of damaged dikes during the 2004 Niigata-ken Chuetsu Earthquake

Rehabilitation work after disaster

Financing System for disaster rehabilitation of infrastructure facilities in Japan had not basically allowed strengthening restoration, but only adopted the investment for recovering the damaged structures as it had been before the disaster.

In 1993, the river dike sections controlled by the central government were seriously damaged at the Tokachi River and the Kushiro River in Hokkaido due to the strong shaking of the Kushiro-oki earthquake. The Ministry of Finance (MOF) at that time accepted including the cost for additional strengthening against future earthquakes in the restoration budget for these damaged dike sections for the first place in the history of restoration works in Japan as described in a paper (Sasaki et al., 2004). After this event, it became common to take measures for strengthening against soil liquefaction at seriously damaged sections of river dike. For damaged sections by Kushiro-oki Earthquake, SCP treatment was conducted at particular sections where the failure mode of dike was serious; solidification technique was used for the rehabilitation of seriously damaged Yodo River dike due to the Hyogo-ken Nanbu Earthquake; and similarly at the occasion during succeeding earthquakes thereafter.

Estimating method of seismic deformation of embankments for Diagnosis /Remediation

Late in the 1970's, the national committee for disaster prevention of Japanese Government started to estimate potential damage caused by an earthquake anticipated its occurrence in southern Kanto area. Corresponding to this movement, a study to establish countermeasure for existing river dikes against earthquake was started by the Kanto Regional Bureau of Construction, MOC.

A simplified method to screen out the potentially dangerous section against earthquake from existing long dikes was firstly proposed in place of a diagnosing method, so-called "Flood control Div. method" developed several years prior to this study. This method named "Cs method" was proposed in 1978 (Kanto Regional Bureau, 1978). In this method, dangerous section is to be selected by the Rank allocated to a targeted section of dike. The Rank is to be given from the value of Cs calculated from the score on various items such as the location of the section in view of tidal change influence, inclination of the side slope, size of the cross section, soil classification of embankment materials, soil classification of subsoil layer, seismic coefficient, and the liquefaction susceptibility.

The liquefaction susceptibility in this method is to be evaluated by F_L through the method used in the Highway Bridge Specification at that time.

And it should be noted that the attitude of thus obtaining stability of dike by a method stated in "Cs method" is a reflection of basic concept in behind that both the inertia force due to shaking and the soil liquefaction acting at the same time are direct causes of dike failure.

Second-grade Simplified method of screening

Later in 1985, the "Cs method" was modified to a next grade simplified screening method which judges the seismic stability and crest settlement by the safety factor obtained from conventional stability analysis.

In this method, the safety factor is examined by considering the inertia force due to earthquake shaking by seismic coefficient, or by considering the decrease of shear strength in liquefiable layers separately. And the smaller one of the obtained safety factor is selected as the safety factor for this embankment. The reason why the safety factors against the inertia force and against the liquefaction are calculated separately is come from the concept in behind that the instability of dike due to the liquefaction is regarded to be brought about after the cease of shaking.

The decrease of the shear strength is usually calculated from the susceptibility to liquefaction of the subsoil layer, since it is known that the F_L value obtained from the evaluation of the susceptibility of liquefaction is correlated to the increase of the pore water pressure (Japan Road Association, 1986).

Though the conventional stability analysis is based on the limit equilibrium concept and deformation is not obtained, however, it is experienced that the deformation of an embankment becomes larger as the safety factor becomes smaller. Therefore the safety factor has been used for predicting the dike settlement based on this experience because there was no other simple and reliable method to estimate the dike settlements.

Figure 3a shows the chart to estimate the excess pore water pressure ratio and Figure 3b shows the empirical correlation between crest settlement and safety factor (River Bureau 1995).

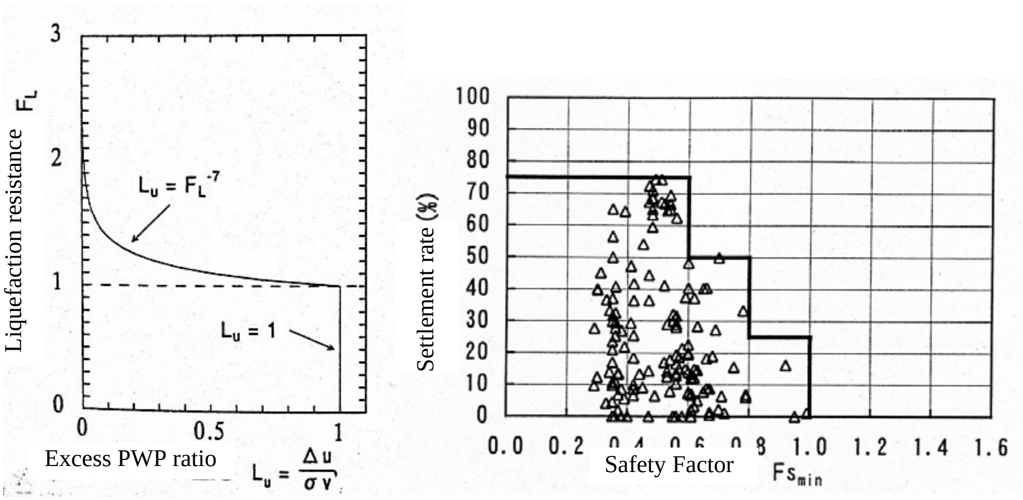
This modified screening method had been used in practice until recently. And in 1995-96, whole length of river dikes in Japan controlled by central government was diagnosed by this method against L1 earthquake, the biggest earthquake which may take place during life cycle of considered structures.

By the screening diagnosis on dikes at flat lowland area in 1995 after the Hyogo-ken Nanbu earthquake, it was found that about 513 km sections out of examined 1400 km long sections of dikes needed precise diagnosis. The screening diagnosis was conducted by using estimated ground condition and on the contrary, the precise diagnosis was conducted by using soil data obtained from soil investigation at each subjected section. And it was also found from the succeeding precise diagnosis that about 350 km long sections needed remediation against earthquakes.

It should be noted that this diagnosis was conducted in view of the necessary altitude of dike crest as the evaluating point of seismic performance of river dike.

Numerical analysis

Apart from the practice, research and development on mitigating technology was proceeded by academic or research organizations. Those include a development of advanced method to estimate



(a) L_u-F_L **(b) S/H-F_s**

Figure 3. Charts used for estimating the dike settlement

seismic deformation of embankments from various directions.
It became generally recognized that the crest settlement of river dikes on liquefiable deposit due to seismic effect is composed of the subsidence of the bottom boundary and the deformation of the dike. The subsidence of the bottom boundary is due to the large deformation of the liquefied subsoil layer. The subsoil deformation includes the deformation due to the liquefaction during the shaking in an undrained condition followed by the deformation due to the dissipation of the raised pore water pressure, namely by consolidation after the shaking.
Following this recognition, several types of analysis method to estimate the large deformation of ground due to soil liquefaction are developed and used in comparatively widely in Japan. Those methods are divided into two groups: one is rigorous method based on effective stress analysis and the other is a simplified method. Rigorous method is so called dynamic analysis along the time history of input motion, and the simplified method simulate the deformation process in static condition where the mechanical properties of liquefied soil is replaced by proper ones representing the liquefaction consequences can be expressed. Two different concepts on constitutive model of liquefied soil are used in simplified methods in practice. One model treats the liquefied soil as a softened solid, and the other model as a viscous liquid.
A technical committee organized by the Japan Institute of Construction Engineering (JICE) examined the efficiency of these numerical methods (Japan Institute of Construction Engineering 2002).
The committee picked up an empirical approach and four numerical analysis methods. The numerical analysis methods are: a computer code named ALID for static analysis using softened soil concept: the Towhata method, a static approach using the viscous liquid concept: a computer code named LIQCA using coupled effective stress analysis, and a computer code named FLIP using an uncoupled analysis, both in category of rigorous method. Computed deformations were compared with the dike settlements observed during the Hokkaido-nansei-oki Earthquake and the Hyogo-ken Nanbu Earthquake.
Estimated dike settlements by the numerical analysis methods mentioned above were compared to the observed settlement during the Hokkaido-nansei-oki earthquake and the Kobe earthquake.
Figure 4 shows the comparison between the calculated dike settlements and the observed settlements.
As seen in this figure, the predicted settlements by numerical analysis methods agree fairly well, but the empirical method by the conventional stability analysis predicts always larger settlements than the observed ones. This too conservative prediction by the conventional stability analysis arises from the use of the step-wise relationship between the calculated safety factor and the settlement (see Figure 3b), which envelopes the maximum settlement.

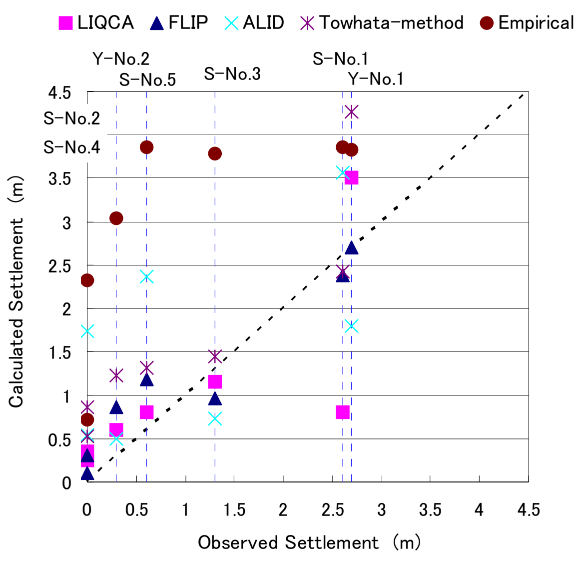


Figure 4. Comparison between calculated and observed settlements

Simplified method to evaluate the effectiveness of remediation

In order to establish proper method to evaluate the efficiency of remedial treatment of soil liquefaction for river dikes, PWRI has conducted a research project. As a result of this project, they proposed a manual on the evaluation of the effectiveness of remediation works by simplified method (PWRI, 2003). Two types of remediation are considered in this manual. One is densification of liquefied layer beneath dikes and the other is solidification to prevent the subsoil liquefaction. They consider only the cases that both of them are executed at limited area near embankment toes, since it is not practical to treat whole width of foundation ground beneath the existing dikes. They divided the crest settlement of river dikes during earthquake into three components illustrated in Figure 5 (PWRI, 2003)

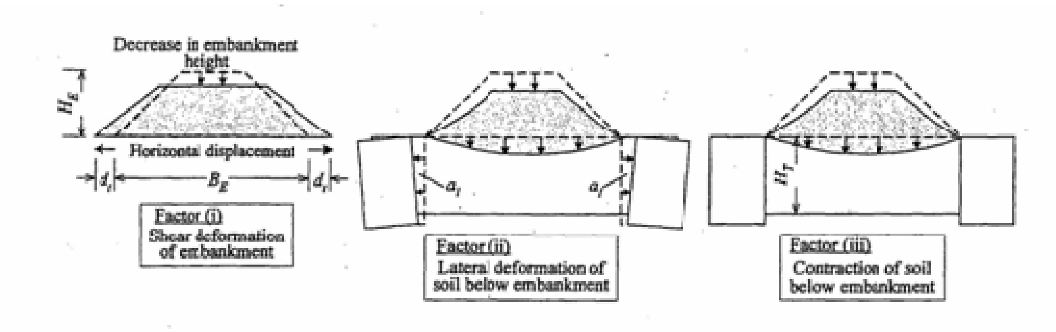


Figure 5. Three components of settlement

Crest subsidence due to shear deformation of embankment (S_1) is to be calculated from horizontal elongation ($2d_1$) of the dike bottom width (B_E) by a following equation, where H_E is embankment height:

$$S_1 = c_1 \bullet 2d_1 / B_E \bullet H_E \qquad (1)$$

Crest settlement due to subsoil deformation (S_2) is to be calculated from the displacement of the side boundary of the subsoil beneath embankment due to lateral spread by following concept, where $2a_1$ is increased area of subsoil layer:

$$S_2 = c_2 \bullet 2a_1 / B_E \qquad (2)$$

c_1 and c_2 in above equations are constants.

And they consider that the displacement of the side boundary of the subsoil is to be caused by the increased lateral earth pressure due to soil liquefaction and the inertia force of earthquake shaking.

It should be noticed that the PWRI method mentioned above is based on following concepts; firstly, liquefied ground is regarded to behave in easy-to-deform manner as very soft material like liquid, so it follows the change of boundary shape, secondary, the boundary shape change is induced by the accumulation of displacement/deformation in treated portion of ground by the application of cyclic force due to shaking. By this treatment, without accurately modelling the post liquefaction properties of soil, it became easy to treat the very complicated phenomena.

Design guideline against L2 earthquake

Utilizing the recent progress of analytical methods to predict the deformation of river dikes during earthquakes mentioned above, MLIT is editing a “Design guideline for river facilities against L2 earthquake”. Since the river facilities consists of various structures other than dike, which include sluice gate, sluice pipe, and pumping station, this guideline has to describe evaluating methods of seismic performance of various facilities.

Outline of the contents concerning river dike in this guideline is as follows:

Design Earthquake

Two grades of seismic motion are assigned as design earthquake: one is the Level 1 earthquake, and the other is the Level 2 earthquake. The Level 1 earthquake is set as an earthquake which may take place during life cycle of considered structures, and the Level 2 earthquake is assigned as a maximum earthquake which might occur without regarding the frequency. The Level 2 earthquake motion is set considering an earthquake caused by plate activity at subduction zone and near fault causing earthquake around the site. Figure 6 shows the response spectrum of these earthquake motions.

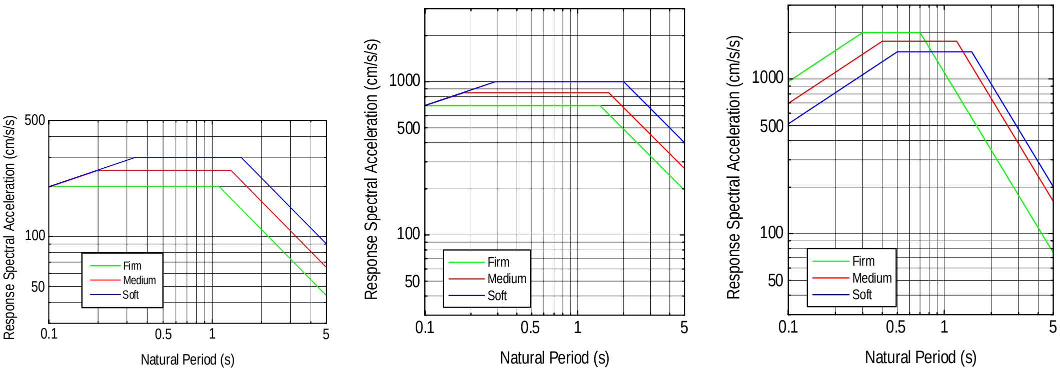


Figure 6. Design motion of earthquake

Evaluating method of seismic performance of dikes

Performance of dike in flood protecting ability even after an earthquake is to be evaluated by the crest height of dike after an earthquake.

Post earthquake height of the subjected dike is evaluated from the comparison between the results of deformation analysis and required altitude needed for this dike section to protect land behind dike. This Guideline recommends proper numerical analysis be used to estimate the residual height, and it says that the evaluation of the seismic performance by using static type analysis, ALID or Towhata Method, is regarded to have satisfied the requirement by this Guideline.

RIVER DIKE FAILURE DURING RECENT EARTHQUAKES

Table 2 shows recent earthquakes occurred in Japan since 1993. Not short lengths of river dike sections were caused to fail during these earthquakes. It was noticed that some remarkable failure modes of dike were mingled among the damaged sections.

Table 1 Damaging earthquakes which caused river dike failure

Year	Earthquake	M	Damaged length	Remarkable failure mode
1993	Kushiro-oki Earthquake	7.8	Kushiro R. 28places, 10.1km Tokachi R. 20 places, 9.2 km	Liquefaction inside embankments, 3-d response of dike
1993	Hokkaido Nansei-oki Earthquake	7.8	Shiribeshi-Toshibetsu R. 18 places 6.6 km	Crest cave-in along diagonal slip plane
1995	Hyogo-ken Nanbu Earthquake	7.2	Yodo R. 18 places 5.7 km	Separation into blocks, submerged into liquefied subsoil layer
2000	Tottori-ken Seibu Earthquake	7.3	Naka-umi lakefront 32 places 20.7 km	Bend of dike bottom, transverse cracks at a curvilinear part
2003	Miyagi-ken Hokubu Earthquake	6.4	Naruse R 66 places	Flow-like deformation
2003	Tokachi-oki Earthquake	8.0	Tokachi R. 26 places 16km	Elongation of sluice gate length
2004	Niigata-ken Chuetsu Earthquake	6.8	Shinano R. 17 places 19km	(usually seen type of failure mode)

Feature of the earthquakes

The features of the earthquakes shown in Table 2 are summarised as follows:

a) There were earthquakes which induced stronger ground motion than that by the design earthquake (the Hyogo-ken Nanbu earthquake, the 2004 Tokachi-oki earthquake)
b) There were earthquakes on which occasion, comparatively big aftershock followed repeatedly within a short time from the main shock (the 2003 Miyagi-ken Hokubu earthquake, 2004 Niigata-ken Chuetsu earthquake).
c) There were earthquakes on which occasion, influential rain dropped at the time of the occurrence of an earthquake or just before the event (the 2003 Miyagi-ken Hokubu earthquake, 2004 Niigata-ken Chuetsu earthquake).
d) There were earthquakes which attacked the same location of dike sections damaged during preceding damaging earthquakes, though they did not brought about severe damage to those rehabilitated sections in some cases (the 1994 Hokkaido Toho-oki earthquake after the 1993 Kushiro-oki earthquake, the 2003 Tokachi-oki earthquake after the 1993 Kushiro-Oki earthquake).
e) There were earthquakes on which occasion, well documented reports on damage were left which were considered to be useful for clarifying the deformation mechanism.
f) Crest subsidence of dikes during these earthquakes were within the values observed during past cases.

Crest settlement

It had been found that the crest settlement of river dikes did not exceed 75% of original heights. It is also noticed that the crest settlements by these earthquakes shown in Table 2 scattered in the range below S=0.75 H line.

However, it should be noted that the difference of the altitude which can secure as much width as before at the crest and the original crest altitude was taken as an amount of the crest settlement as shown in Figure 8. Further, since the survey on dike shape is not conducted frequently in general, so, it is not rare that the accurate altitude before an earthquake was unknown. This means that it is not avoidable somewhat amount of error be included in recorded crest settlements.

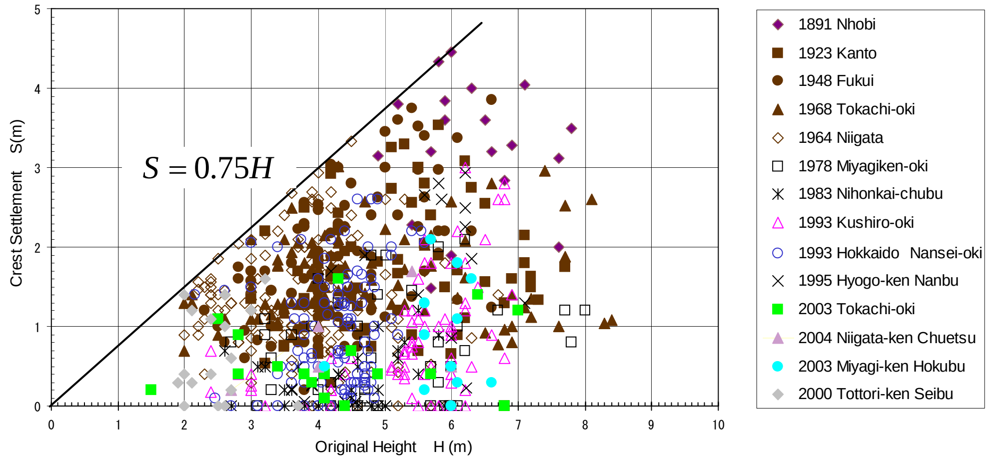


Figure 7. Settlement of river dikes during past earthquakes

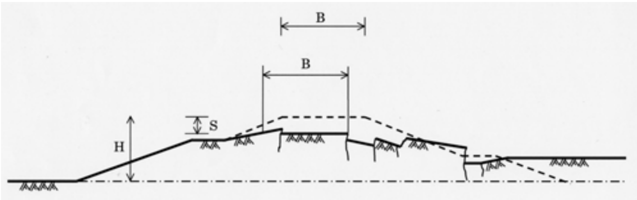


Figure 8. Settlement amount

Failure mode

It is shown in Figure 2 that seismic damage of embankment in the past could be classified into four failure modes, and it is well known that those damaged sections were found to be generally accompanied with longitudinal cracks though they are not clearly expressed in Figure 2.

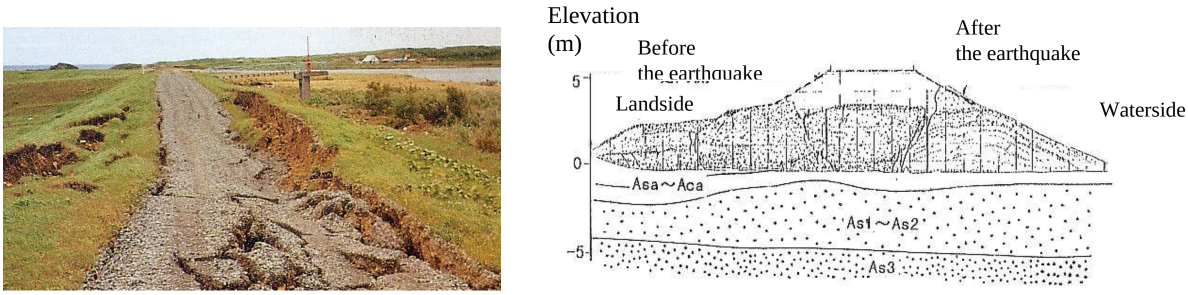
Other than those ordinary types of failure mode, "Remarkable failure mode" was found during the earthquakes in Table 2. Brief descriptions about these failure modes are shown below.

Liquefaction inside embankment due to the Kushiro-oki Earthquake in 1993

The intense deformation of river dikes seen in the case of the Kushiro-oki earthquake was caused by the soil liquefaction inside the river dike embankment. It was caused by the liquefaction in the dike constructed on heavily compressible layer. So it should be carefully treated when the bottom of embankment is easily submerged due to consolidation of subsoil layer (Sasaki et al. 1993). This finding is being reflected in the L2 guideline.

Crest depression due to the Hokkaido Nansei-oki Earthquake in 1993

Diagonal slip surface was found at the failed section of the Shiribeshi-Toshibetsu River dike in 1993. This case implied the process of depression type of deformation to embankment. It should be noted that this type of deformation mode can take place without any deformation of foundation ground. Only the loss of frictional stress between foundation ground and the embankment bottom induces this type of deformation mode (Sasaki and Ohbayashi, 1997a).



(a) External appearance **(b) Sketch from trench-cut surface**

Figure 9. Damage to the Shiribeshi-Toshibetsu River dike

Separation into blocks due to the Hyogo-ken Nanbu Earthquake in 1995

It was found from the post earthquake investigation that the Torishima section of the Yodo River dike had settled into the subsoil layer. It was reported that the dike was separated into blocks subsiding into the sand layer which was originally forming horizontal surface of foundation ground (Sasaki & Shimada, 1997b). This implied that the liquefied layer behaved as if it were liquid.

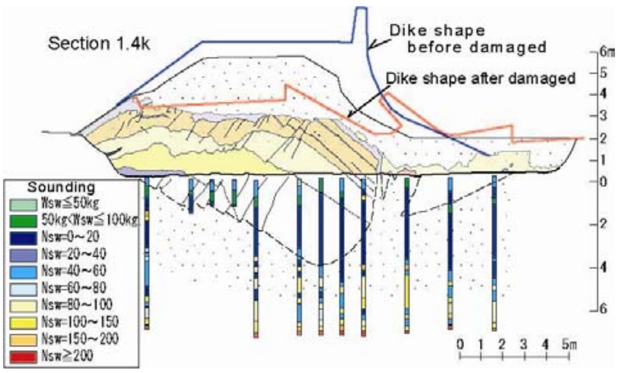


Figure 10. Torishima section of the Yodo River dike

Bend of dike bottom due to the Tottori-ken Seibu Earthquake in 2000

In case of strengthened against stretching like the dike of the Naka-umi lakeshore, bent mode of deformation without generating separation or longitudinal cracks was seen (Sasaki et al., 2004a).

This might be similar mode of deformation of dike resting on non-liquefiable deposit underlain by liquefiable deposit.

Flow-like mode of deformation due to the Miyagi-ken Hokubu Earthquake in 2003
In the case of heavily wet dike case at the time of occurrence of earthquake, failed mass of dike deformed in flow-like mode as described in a paper (Nakayama et al., 2006). This case evidences that the seismic deformation is influenced by the moist condition of embankments. Although usually the seismic effects are independently considered without duplicating other source of natural disaster like flood, heavy rain, except for sea side dikes threatened against Tsunami attack, it is considered necessary to evaluate quantitatively the effect of moisture content condition on its deformation.
Elongation of sluice gate length due to the Tokachi-oki Earthquake in 2003
It was found that the Ohtsu-shigai sluice was elongated at the flexible joints of concrete segments at a location where no visible damage was detected to the dike after the Tokachi-oki Earthquake in 2003 (Kawai et al. 2006). It was thought that the subsoil liquefaction was the cause of this damage to sluice structure from the evidences of concrete pile damage and the shear planes found in the subsoil layer. This case shows that even at sections where the damage degree of embankment is less, subsoil liquefaction may cause stretch mode of deformation of embankment.

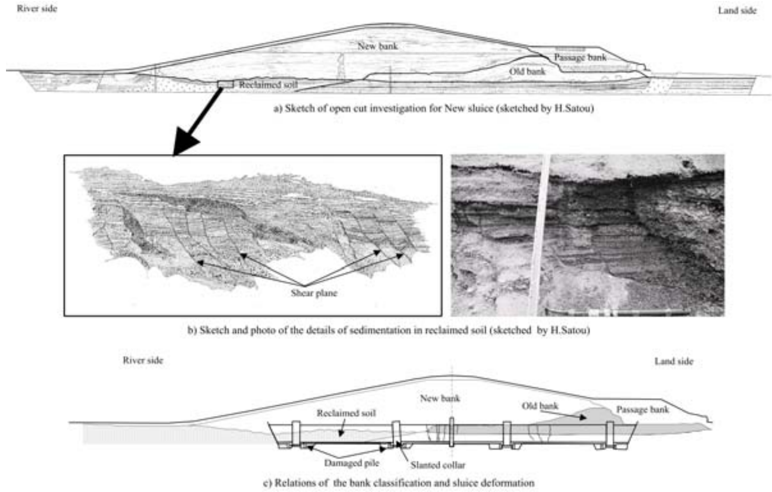


Figure 11. Sluice elongation during the 2003 Tokachi0oki Earthquake

Three dimensional response due to the Kushiro-oki earthquake in 1993
During the Kushiro-oki earthquake, it was found that the damaged sections were located periodically from each other although the dike size and the foundation conditions were the same (Sasaki et al. 2004a). This finding implies that further study should be made on the 3-D response of the river dike and the governing conditions on which 3-D response be considered.

DISCUSSION ON THE FAILURE MODE OF RIVER DIKES DURING EARTHQUAKE

Summary of failure mode of river dikes seen at sites

Table 2 shows the summary of failure mode seen in the previous chapter except for the case during the 1983 Nihonkai Chubu Earthquake. Inclusion of this case will be mentioned below. It was shown from the cases during recent earthquakes that the failure mode of embankment is not as simple as classified in Figure 1 or 2.

Table 2. Summary of deformation mode

Deformation mode	Earthquake	Suspected Liquefaction	Occurrence timing
Sliding	1993 Kushiro	Dike bottom	During shaking?
Sliding	2003 Miyagi	Dike bottom/Shallow subsoil	?
Stretch of embankment	1983 Nihonkai	Subsoil/thick	After shaking?
Stretch of embankment	1993 Nansei-oki	Shallow subsoil	?
Stretch of embankment	2003 Tokachi	Shallow subsoil	?
Bend of dike bottom	2000 Tottori	Subsoil	?
Separation into block	1995 Hyogo-ken	Subsoil/thick	?

Failure process

As damage records at site are only gained from the residual state after the event, there is no evidential record to know about failure process which is believed inevitable to know the true factors to trigger embankment failure during earthquakes. Test results from a series of shaking table tests show that about 90 % of the total amount of the crest settlement of embankments was induced by the deformation of subsoil layer during shaking (Sasaki et al. 2004b).

However, on the contrary to this simulation, there remain records that the deformation should have induced after the cease of shaking. Figure 12 is an example among them (Sasaki, 2003). The deformed U type concrete gutter in this Figure shows that the deformation of this embankment was believed to be induced after the cease of shaking; otherwise this much unstable state of gutter could not be left. Furthermore, delayed subsidence of footing model after shaking in a centrifuge test was reported (Kawasaki et al., 1998).

Those evidences together with the test result that the depression type of deformation mode could be reproduced by reducing the horizontal stress at embankment bottom, but not deformation of boundary shape at its bottom imply that the reduction of confining stress due to propagation of built up pore water pressure may statically cause non-negligible residual strain to soil where initial shear stress acted. In other words, in order to clarify the mechanism of this kind of deformation, it is required to study more in deep on strain accumulation by the reduction of confining stress of soil.


Figure 12. Longitudinal cracks and uplifted gutter seen at the Hachirogata dike in 1983

Generation of cracks

From this review on the deformation process, it is considered inevitable to brush up the simulation technique to estimate liquefaction induced deformation mode of embankment so that the generation of cracks and the deformed shape of failed embankment could be analyzed.

CONCLUSION

Technical history of mitigating seismic damage to river dikes in Japan and the failure modes seen during recent earthquakes were briefly introduced.

This review tells that the insight of actual performance is inevitable to lead a technical progress. Damage study revealed that most of the disastrous deformation of dikes was caused by the occurrence of soil liquefaction in foundation ground and/or saturated bottom part of embankment as well. Remediation of dikes against liquefiable soil layer showed its efficiency during succeeding earthquake occasions though much of them were not mentioned in this paper due to the lack of spaces.

It was also shown that the recent progress of analytical method of prediction can give more accurate amount of the liquefaction inducing deformation of embankments than in the past, this means that the technical progress can save the necessary cost for remediation.

Although the numerical analysis methods can simulate well in general the deformation of river dike damage by past earthquakes, it was also shown from the review of past cases observed at field that there are some deformation which can not be reproduced by ordinary numerical analysis. Further, the really required seismic performance of river dikes is still in the mist.

It is considered important for gaining the solution of these problems to accumulate the actual cases in the field and to draw out the real mechanism of failure from a deep insight of failure mode.

Authors consider that the main points of the advance urgently expected in this field are as follows.
Firstly, it is considered necessary to revise the predicting methods of dike deformation so that they can predict the generation of cracks and separation potential.
Secondary, the three dimensional response of dikes during earthquake shaking should be studied.
Finally, criteria on flood protection performance of dike should be established.

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