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# DEFORMATION OF A RIVER DIKE DUE TO THE MIYAGI-KEN HOKUBU EARTHQUAKE

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## ABSTRACT

The Miyagi-ken Hokubu Earthquake occurred in July 2004 caused severe damage to the Naruse River dike. It could be pointed out that the damage to the Naruse River dike was different from other past cases in Japan in following points. Aftershocks registering 6 on the seismic intensity of JMA scale occurred three times in one day. And the dike was wet and the water level of the Naruse River channel was high since there had been prolonged rainfall before the earthquake.

This paper reports the seismic damage to the Naruse River dike that was damaged by the Miyagi-ken Hokubu Earthquake. The wet state of the dike when the earthquake occurred is studied by using the saturated and non-saturated seepage analysis, and the deformation modes possible in such a circumstances are also examined using dynamic analysis. From these results, the influence of the wet state of a soil upon the deformation of the dike during earthquakes is discussed.

Keywords: Miyagi-ken Hokubu Earthquake, River dikes, Seepage analysis, Deformation modes

## INTRODUCTION

Continuous earthquake activity with its epicenter in the northern area of Miyagi Prefecture occurred on July 26, 2003. The resulting damage was tremendous; 675 people were injured and 5,000 houses were totally or partially destroyed. The Naruse River, which runs near the epicenter, faced significant damage including subsidence and deformation of its dike. Quake-prone Japan has endured many instances of dike damage due to earthquake. However, the damage of the Naruse River dike caused by this earthquake was peculiar in the following respects:

1) Earthquake activity registering 6-strong on the JMA scale occurred three times in one day.
2) Since there had been prolonged rainfall in the days prior to the earthquake, the dike was wet.
3) Flooding due to the prolonged rainfall caused the water level in the channel to rise above ground level.

This report focuses on the Naruse River dike that was damaged by the earthquake. The wet state of the dike at the time of the earthquake was simulated using saturation and non-saturation seepage flow analysis, and the amount and pattern of deformation of dike was examined using seismic response

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analysis and residual deformation analysis. The influence of the wet state of the dike upon the dike deformation as well as the mechanism of deformation is also discussed. The main results are summarized below.

1) The dike was wet due to rainfall prior to the earthquake, and the underground water level was higher than ordinary situation.
2) No significant deformation was caused by the foreshock registering 6- on the JMA intensity scale, but liquefaction occurred in the dike partially at sandy-soil region below groundwater level and the $A_{s1}$ layer in the foundation ground. The pore-water pressure rose and dike integrity lowered.
3) The liquefaction area in the lower part of the dike and the $A_{s1}$ layer expanded due to the main shock registering 6+ shaking that occurred seven hours after the foreshock, further reducing the rigidity and integrity of these layers. Dike stability was lost, resulting in large deformation.

## OUTLINE OF EARTHQUAKE

Data on the earthquake event is shown in Table 1. Earthquake shaking registering 6+ occurred three times in one day, and shaking registering 5 or more occurred five times in one day. The Miyagi-ken Hokubu Earthquake was the first earthquake in the history of seismic observation to record such high seismic intensity with such high frequency.

**Table 1 Main Feature of the Earthquake**

| Category of earthquake | Date and time | M | Maximum seismic intensity | Maximum acceleration ($cm/s^2$)※ | Duration (NS component) ※ |
|---|---|---|---|---|---|
| 1) Foreshock | July 26, 2003<br>00:13 a.m. | 5.5 | 6- | NS=560<br>EW=482<br>UD=258 | 50 gal or more<br>6.29 s<br>100 gal or more<br>2.54 s |
| 2) Main shock | July 26<br>7:13 a.m. | 6.2 | 6+ | NS=580<br>EW=424<br>UD=403 | 50 gal or more<br>10.41 s<br>100 gal or more<br>7.84 s |
| 3) Aftershock | July 26<br>10:22 a.m. | 4.8 | 5- | | |
| 4) Aftershock | July 26<br>4:56 p.m. | 5.3 | 6- | NS=26<br>EW=46<br>UD=21 | 50 gal or more<br>0.01 s |
| 5) Aftershock | July 28<br>4:08 a.m. | 5.0 | 5- | | |

※ Maximum acceleration and duration were read from the waveform data of the Nakashimo Observation Station of the Ministry of Land, Infrastructure and Transport.

Distinct characteristics of this earthquake include a short time interval (7 hr) between the foreshock and main shock, and a nearly equal maximum acceleration, but the duration at 100 gal or more was as long as 8 sec in the main shock, which is three times longer than the duration of the aftershock. Figure 1 shows strong motion records of the foreshock and main shock observed by the Nakashimo Observation Station at the lower reach of the Naruse River.

Foreshock 0:13 a.m. on July 26

Main shock 7:13 a.m. on July 26

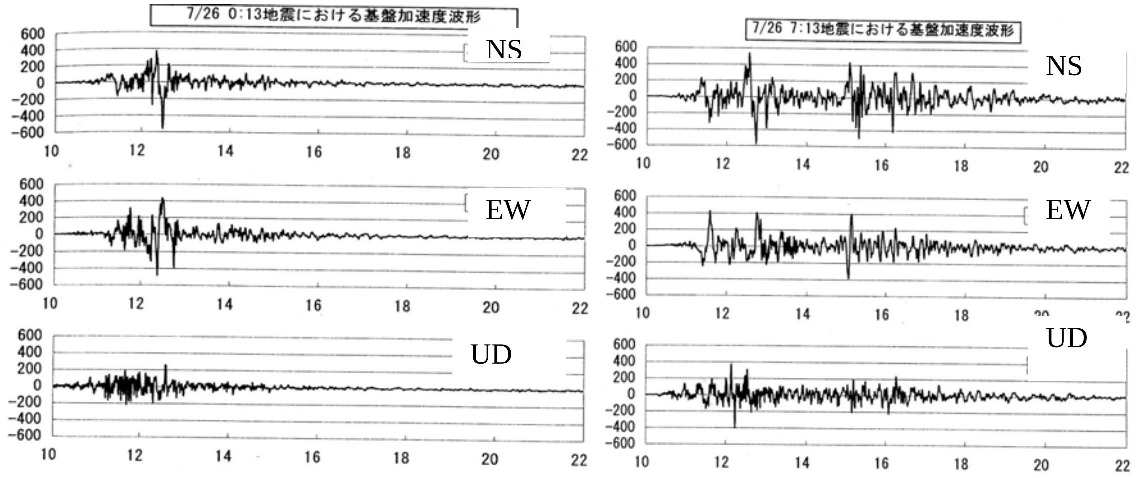



**Figure 2. Seismic vibration records (Nakashimo Vibration Observation Station)**

## DAMAGE TO RIVER DIKE

There are 66 places in the Kitakami River and Naruse River where the dikes were damaged, many of which are concentrated at the Naruse River near the epicenter. Severely damaged sections (indicated by the arrow in Fig. 2) are concentrated at the dike 8 to 17 km from the mouth of the river.

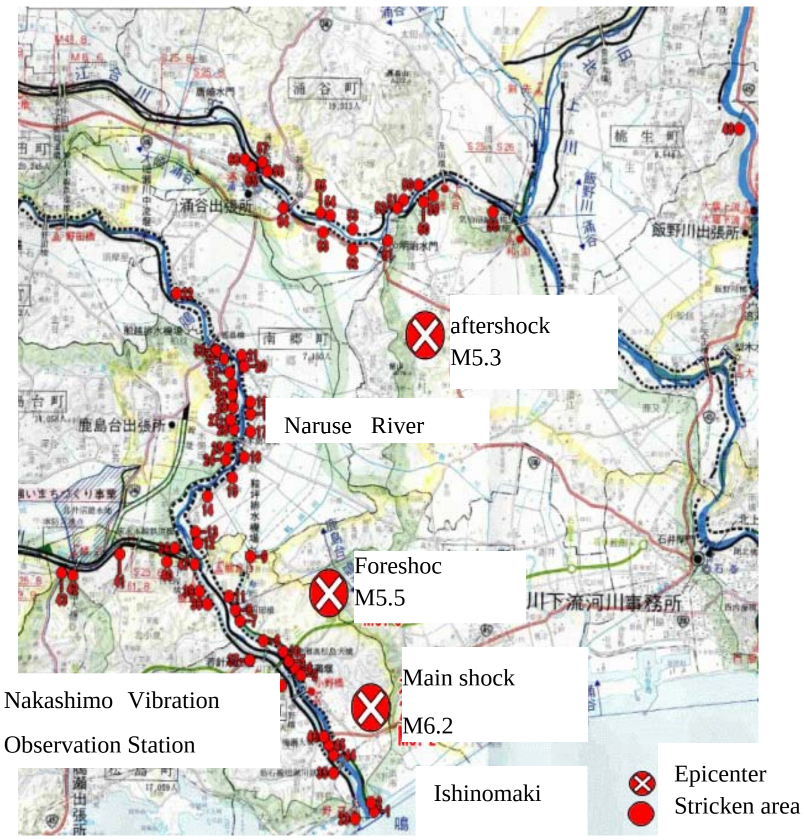



**Figure 2. Damaged spots of dike**

Figure 3 shows the state of damage to the right bank of the middle reaches of the Naruse River in the Kimazuka District. A large difference in level occurred at the dike crest, and deformation whereby mass of soil was pushed out toward the land side can be confirmed.

The difference in level at the dike crown is about 3.5 m in height (Figure 4.), and a crack about 100 m long runs in a longitudinal direction. The depth of the crack is about 2 m (Figure 5.), and it was confirmed that water, presumably from underground, is present in the crack.

The back slope pushed-out flow was about 5 m wide (Figure 6.), and it buried a road running parallel to the dike. The moisture content was so high that the soil was muddy. Water had oozed from the edge of sediments immediately after the earthquake occurred.

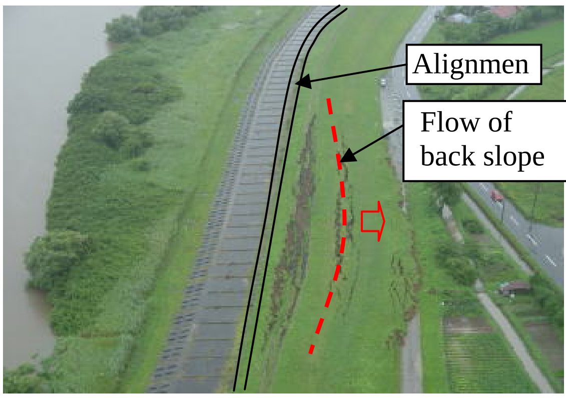



**Figure 3. State of damage to dike (Naruse River right bank 13.0 k, Kimazuka)**


**Figure 4. Difference in level at Kimazuka**

**Figure 5. Crack on land side at Kimazuka**


**Figure 6. Flow of sediment on land side at Kimazuka**

## RAINFALL AND WATER LEVEL OF RIVER PRIOR TO EARTHQUAKE

### State of Rainfall

Figure 7 shows the state of rainfall for the month preceding the earthquake. It rained intermittently during the month and rainfall was 78 mm on July 24, immediately before the occurrence of the earthquake. The accumulated rainfall up to the time of the earthquake was 356 mm, so quite a lot of water is considered to have permeated the dike body.

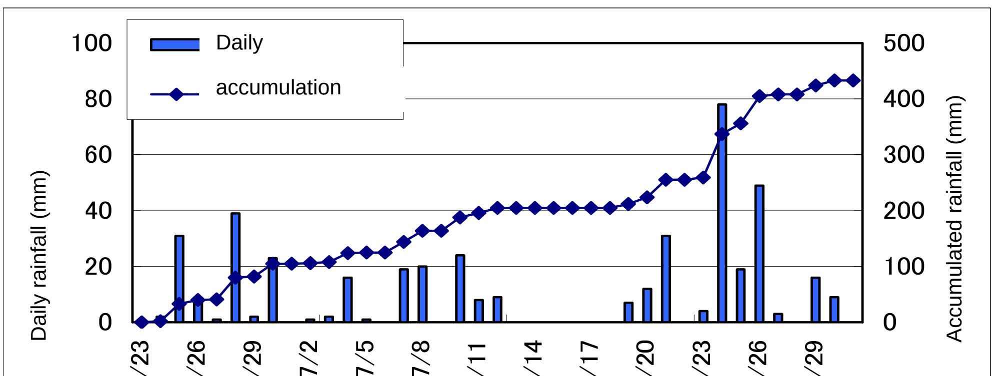
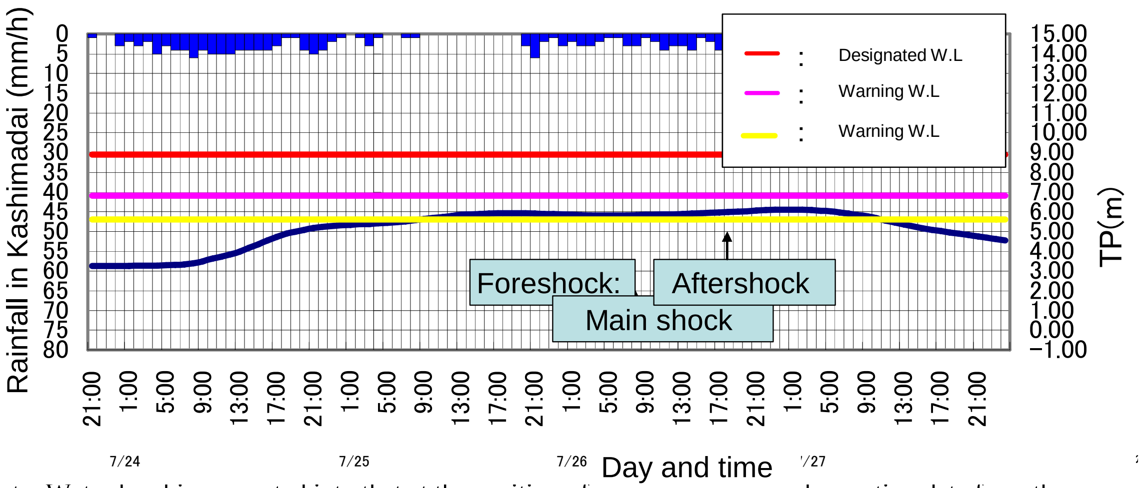


**Fig. 7 Rainfall before and after earthquake (Accumulated rainfall from June 23, recorded at the Kashimadai Rainfall Station of the Sendai District Meteorological Observatory of the Meteorological Agency)**

### Water Level of River

A flood warning was issued for the Ishinomaki District at 5:20 a.m. on July 26 due to prolonged rainfall that started in the Naruse River basin on the evening of July 23. At the Kashimadai Rainfall Station, the Naruse River rose above the preparatory water level for flood-fighting activities at 1:00 p.m. on July 25. Three earthquakes registering 6- or more occurred during this state. Meanwhile, the ground height behind dike was now only a little lower than the water level.



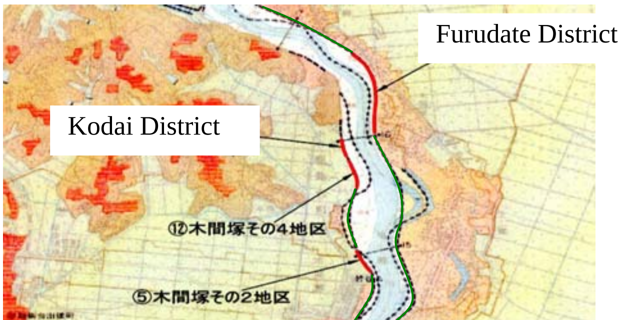

Note: Water level is converted into that at the position of 13.0 km based on observation data from the monitoring stations at Noda-bashi and Kashimadai.

**Figure 8. Water level at the 13.0 km position of the Naruse River**

## FOUNDATION GROUND AND DIKE STRUCTURE

### Geomorphology of Foundation Ground

Locations of the severely damaged sections of dike are shown on the geomorphology classification map/for flood control of the Naruse River. Earthquake damage to dikes is generally represented by liquefaction of foundation ground, and damage tends to occur in old river courses(Sasaki et al.,1997), but in the case of the Northern Miyagi Prefecture Earthquake, no clear relationship is found between the old river courses and damaged sections/damage degree, and severely damaged sections belong to the hinterland marshes of geomorphology classification.



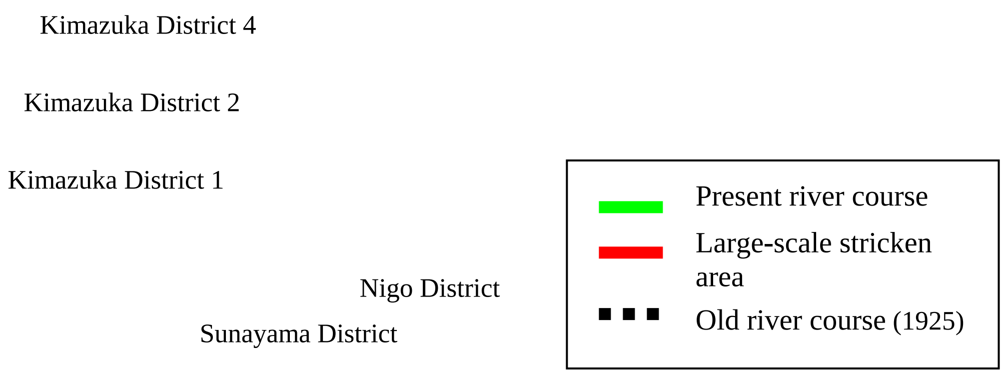



**Figure 9. Geomorphology near the severely damaged sections**

**History of Dike Improvement**

The embankment history of the Naruse River dike is summarized in this section with the use of topographic maps, embankment records and results obtained by surveying a cross section of the dike. The original embankment dates back to the 1910s, after which the dike was raised and widened two or three times, resulting in the present dike.

From the embankment history, past soil examinations and results obtained from boring after the damage due to the event, it was found that the dike at the middle and lower reaches of the Naruse River was mainly composed of cohesive soil or sandy soil as shown in Figure 10 and that the soil of the dike body was of a one- to two-layer structure. The dike in which intense deformation occurred is old and either originally composed of cohesive soil and widened by sandy soil, or originally composed of sandy soil and widened by cohesive soil.

Furthermore, there is considerable foundation ground where a loose sand layer having an N-value of 10 or less , susceptible to liquefy, is distributed at surface underlain by weak cohesive soil having an N-value of 3 or less depositing about 40 m.

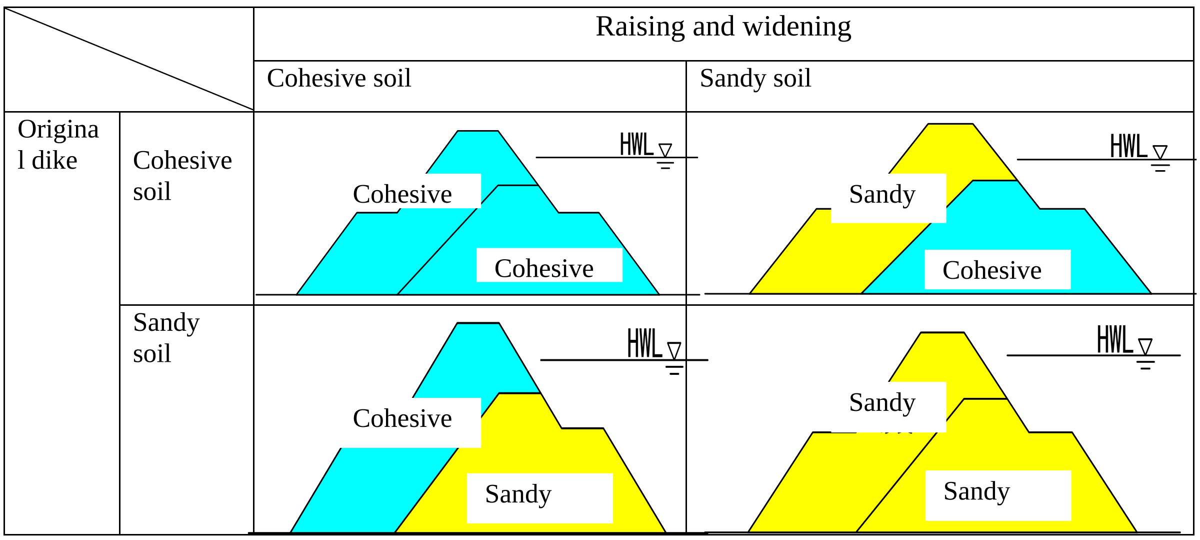
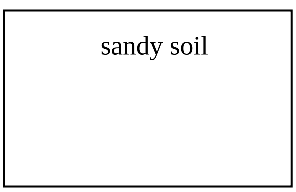



**Figure 10. Classification of dike by material soil and structure**

**Excavation Examination**

A dike excavation examination was carried out at severely damaged sections. The results confirmed that the slip plane of the dike failure caused by the earthquake exists near the outside boundary of the original dike. A sand chain considered to be derived from the foundation ground beneath the dike was also confirmed.



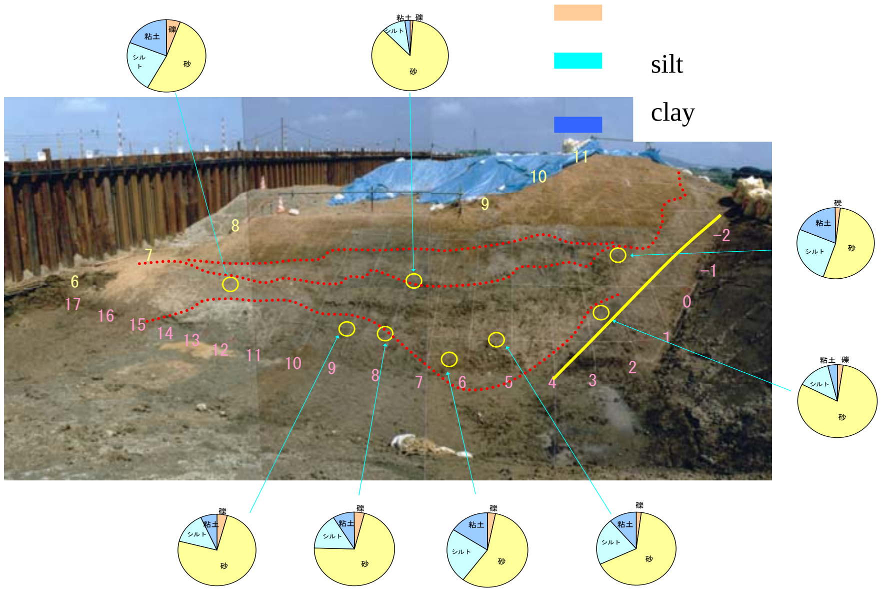



**Figure 11. Excavation examination (Kimazuka Section)**


**Figure 12. Sand chain (Nigo Section)**

## MECHANISM OF DAMAGE TO DIKE

### Reproduction of Wet State of Dike

The dike in the Kimazuka Section where significant failure occurred was modeled based on the results of the soil investigation and excavation examination (Figure 13). Two-dimensional saturation and non-saturation seepage flow analysis (Akai et al., 1977) was performed using the records of rainfall (Figure 7) and water level at river side as boundary condition (Figure 8) to calculate a seepage line in the dike. Meanwhile, since sheet piling and revetment were provided on the river side of the dike, and as there was no damage caused by the earthquake, the sheet piling and revetment were also modeled in performing seepage flow analysis. The analysis results indicate that the groundwater level, which is believed to be about 50 cm below the ground surface before the rainfall, rose by about 2 m due to rainwater infiltration, and saturated zone had been formed in the dike body before the earthquake as shown in Figure 14.

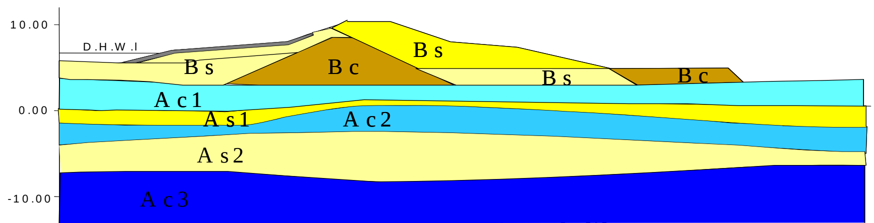



**Figure 13. Modeling of dike**

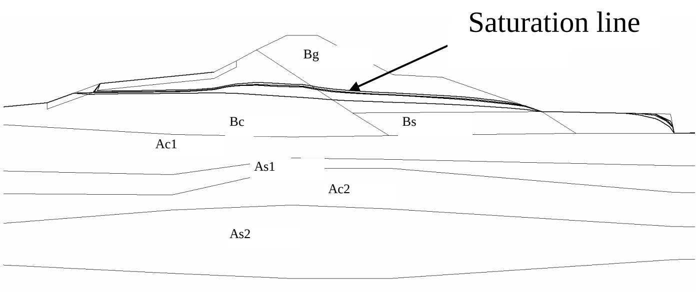


**Figure 14. Analysis results of infiltration flow**

This height almost matches the water level observed through the boring implemented immediately after the earthquake and the level of the water surface found in Figure 5. Presumably, the water level in the dike rose when the earthquake occurred, and the degree of saturation in the dike also increased.

**Behavior of Dike**

Two-dimensional response analysis (Lysmer et al.,1974) of the Kimazuka dike was performed using the observed records at the Nakashimo Observation Station in the lower reaches of the Naruse River shown in Figure 2 as input motion. Figure 15 shows the presumed results of maximum acceleration distribution. A similar acceleration distribution is shown during both the foreshock and main shock, but the maximum acceleration value is larger during the foreshock as is the case with the actual earthquake. Meanwhile, soil constants of the dike and foundation ground at the points of analysis are shown in Table 2. The constants are determined based on geophysical logging and laboratory soil test data.

**Table 2 Soil constants of the dike and foundation ground**

| | $\gamma$ t(t/m$^3$) | c(kN/m$^2$) | $\phi$(°) | k(cm/sec) | Vs(m/sec) |
|---|---|---|---|---|---|
| Bs | 1.75 | 18.0 | 15.0 | 1×10$^{-3}$ | 130 |
| Bc | 1.53 | 27.0 | 0.0 | 1×10$^{-4}$ | 130 |
| Ac1 | 1.71 | 40.0 | 0.0 | 1×10$^{-5}$ | 130 |
| As1 | 1.75 | 0.0 | 38.0 | 8×10$^{-3}$ | 130 |
| Ac2 | 1.55 | 37.0 | 0.0 | 1×10$^{-5}$ | 130 |
| As2 | 1.80 | 0.0 | 38.0 | 8×10$^{-3}$ | 160 |
| Ac3 | 1.53 | 50.0 | 0.0 | 1×10$^{-5}$ | 120 |
| As3-1 | 1.95 | 69.0 | 35.0 | 1×10$^{-3}$ | 200 |
| As3-2 | 1.95 | 63.0 | 35.0 | 1×10$^{-3}$ | 360 |
| Dc | 2.00 | - | - | 1×10$^{-5}$ | 240 |
| Ss | 2.10 | - | - | 1×10$^{-5}$ | 600 |

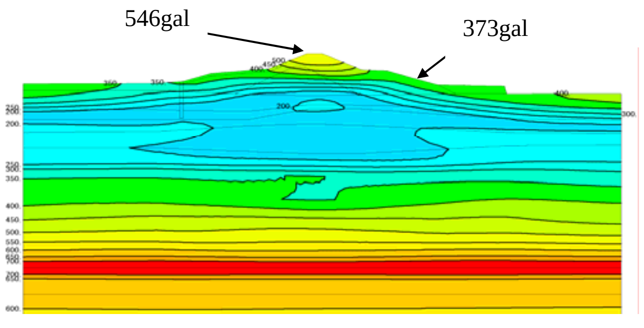



**Figure 15 (1) Distribution of maximum acceleration (During foreshock)**

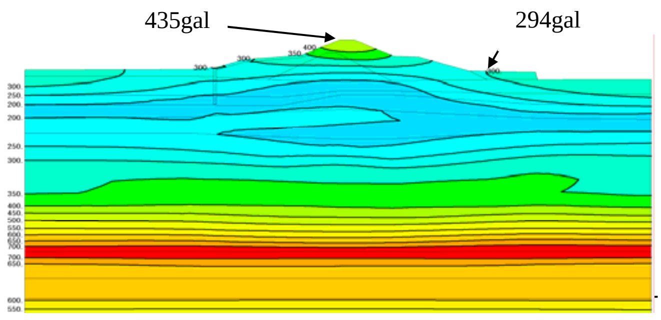


**Figure 15 (2) Distribution of maximum acceleration (During main shock)**

## Simulation of Dike Deformation

The state of liquefaction when the main shock occurred was presumed based on the Highway Bridge Specification method(Japan Road Association,2002) with the use of the maximum acceleration distribution obtained by the above two-dimensional response analysis. Figure 16 shows an $F_L$ distribution when the main shock occurred, and it is known that liquefied zone of $F_L < 1.0$ spreads widely in the dike.

Furthermore, the amount of deformation and deformation mode of the dike at the Kimazuka section when the main shock occurred were analyzed using a static deformation analysis technique (ALID) (Yasuda et al., 1999). Figure 17 shows a deformation of the dike obtained from ALID analysis, and Fig. 18 shows displacement vectors. The amount of horizontal displacement on the land side is about 1.2 m, smaller than the actual phenomenon, and the deformation pattern, whereby the dike is pushed out toward the land side, was reproduced.

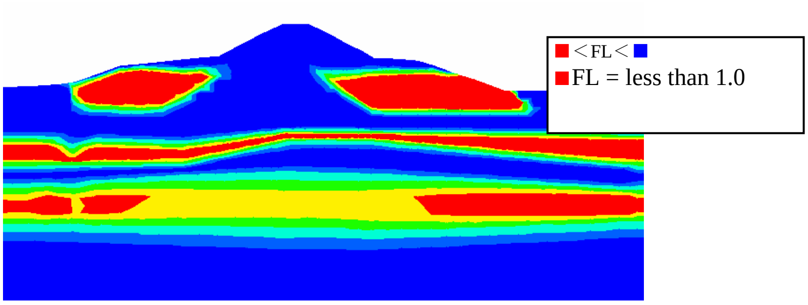
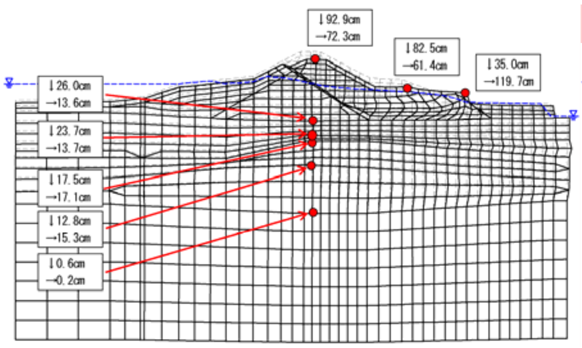



**Figure 16. Distribution of $F_L$ value (during main shock)**



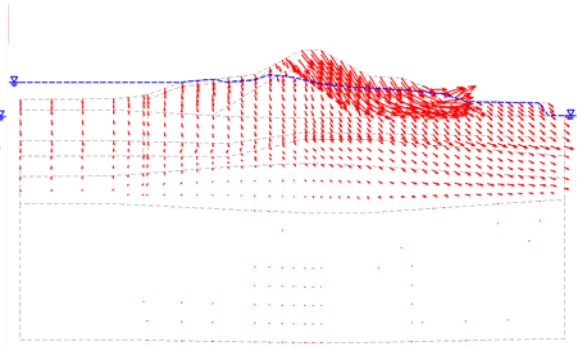



**Figure 17. Deformation of the dike at Kimazuka section** **Figure 18. Displacement vector map**

## Damage Mechanism

The damage mechanism of the dike at the Kimazuka section was tried to be revealed based on the results of the studies described above.

*State of dike prior to earthquake*

1) Composition of dike and foundation ground (see Figure 19)

a) The dike was raised and widened toward the land side by using sandy soil as construction material from the original dike mainly composed of cohesive soil. There is banking for road mainly composed of cohesive soil along the toe of land side slope. Cohesive soil ($A_{c1}$) is distributed as the surface layer of the foundation ground underlain by a sandy layer ($A_{s1}$).

b) Revetment is provided on the river side, and impervious sheet piling forms the basis of revetment.

2) State of dike prior to earthquake (see Figure 19)

The water level in the river channel rose due to prolonged rainfall, but its permeation into the dike was presumably suppressed by the sheet piling and revetment. However, the saturation degree and saturation line in the dike is considered to have risen due to rainwater infiltration and the integrity of the dike was reduced accordingly.

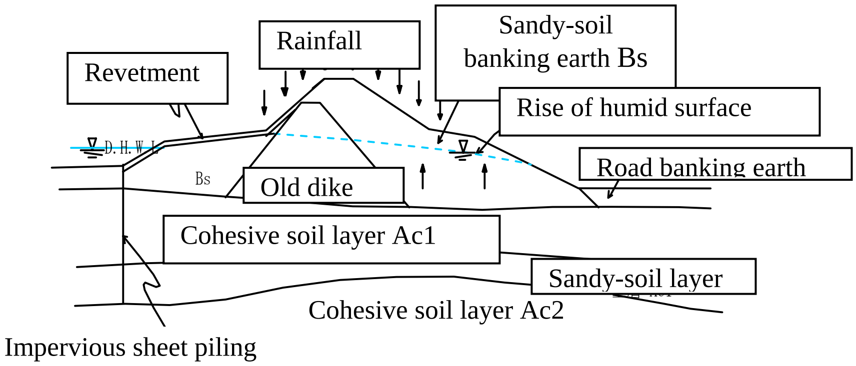



**Figure 19. State of dike prior to earthquake**

3) State of dike during earthquake (see Figure 20)

a) Liquefaction presumably occurred in part of the $A_{s1}$ layer and below the saturation line of the sandy soil in the dike (groundwater level) due to the foreshock of the earthquake, causing the pore-water pressure to rise and the integrity of the dike to lower. However, at that point, no significant deformation or crack was found in emergency checkups carried out immediately after the foreshock, indicating that deformation of the dike was nil or small.

b) Liquefaction of the lower part of the dike and the $A_{s1}$ layer presumably expanded due to the main shock that occurred seven hours after the foreshock, causing further reduction in the rigidity and integrity of these layers.

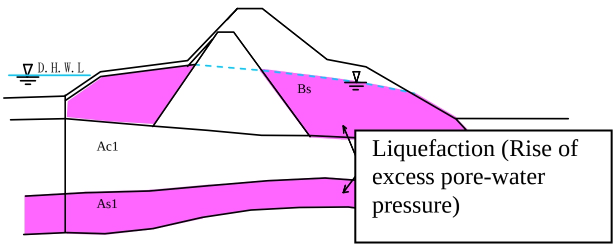
The peak ground acceleration of the foreshock was larger than that of the main shock, but since there was no damage when the foreshock occurred, duration (see Table 1) having larger acceleration than a specific one would have had a significant influence on the deformation of the dike.

4) Presumed damage factors (see Figure 20)

a) As a result, the stability of the dike was lost, and sliding failure, which pushed out the failed mass of soil to the land side along the border of the original dike (cohesive soil), presumably occurred.

b) On the other hand, no deformation was found on the water side. Since impervious sheet piling and revetment had been provided on the water side, they are considered to have effectively suppressed deformation.

c) Settlement presumably occurred as well in accordance with the liquefaction of the $A_{s1}$ layer. However, since traces of sand boiling could not be found in or around the dike, it is considered that the $A_{c1}$ layer above the $A_{s1}$ layer was not destroyed.



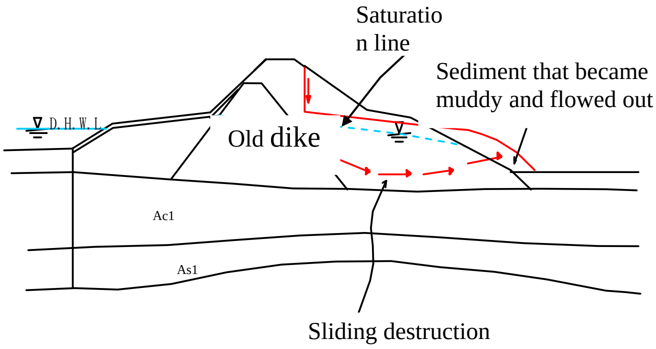




**Figure 20. State of dike during earthquake** **Figure 21. State of dike when damage occurred**

## ANALYSIS ON INFLUENCE OF RAINWATER PERMEATION

The rise of the saturation line in the dike due to rainfall prior to the earthquake event is considered to have greatly affected the degree of damage. To investigate the difference in deformation amount, earthquake inducing deformation analysis was conducted based on the supposition that the saturation line of the dike did not rise, namely, the state in which there was little preceding rainfall. Shown in Figure 22 are the results of ALID deformation analysis for the state in which there was no pre-rainfall. Table 3 shows the difference in deformation amount for both the dike crown and the toe of the land side slope depending upon the presence or absence of pre-rainfall.
When there was no preceding rainfall, the deformation amount at the dike crest was 40.7 cm maximum, which is half or less compared with the case in which there was preceding rainfall. On the land side, the amount of horizontal displacement toward inland was 17.4 cm, which is only 1/7 compared to the case in which there was pre-rainfall.
A comparison of displacement vectors reveals that when rainwater permeated into dike, movement followed such as failed mass of soil pushing out the dike toward the land side, but when rainwater did not permeate the dike, such movement did not occur, and the displacement was small.

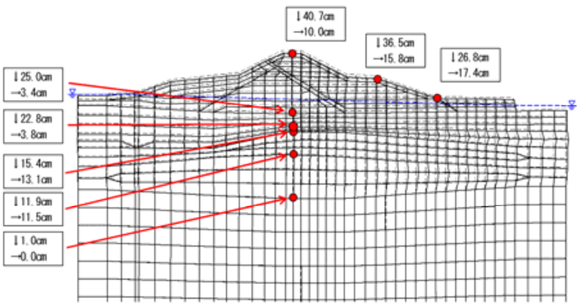



**Figure 22. Deformation of the dike )**
**(No rainwater permeation)**

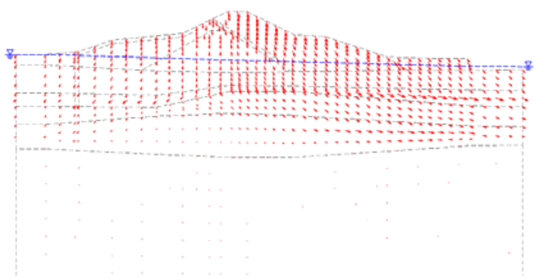


**Figure 23. Displacement vectors**
**(No rainwater permeation)**

**Table 3 Test Calculation Comparison**

| Consideration of rainfall effect | Yes | No |
|---|---|---|
| Settlement amount (cm) of dike crown | 92.9 | 40.7 |
| Horizontal displacement amount (cm) of land-side base | 119.7 | 17.4 |

## CONCLUSION

In quake-prone Japan where earthquakes often cause extensive damage, various hardware and software measures have been taken to strengthen earthquake-proof structures and to minimize damage. The damage to the Naruse River dike caused by the Miyagi-ken Hokubu Earthquake differed in that the saturation degree of the dike was high due to large amounts of rainfall in the days prior to the earthquake, and the groundwater level rose forming the saturation line in the dike.

Concerning the influence of the wet state of the dike upon the dike deformation when the earthquake occurred, the state could be reproduced on the whole by combining the saturation and non-saturation seepage flow analysis and the static deformation-during-earthquake analysis. The results clarified that when the dike was wet due to rainfall, the amount of deformation during earthquake increased.

Various measures for improving a weak sand layer that is susceptible to liquefaction have been taken as measures against earthquake damage. However, taking into consideration the results obtained by this research, the following methods implemented as rainwater permeation countermeasures are considered to be an effective supplement.

1) To strictly carry out the compaction of a dike and to cover the surface layer of a dike with material(s) impervious to water so that rainwater or river water does not easily permeate the dike.
2) To install a drain, etc. at the toe of a land side slope so that the saturation line in a dike does not easily rise

## REFERENCES


Akai, K.,. Ohnishi, Y.and Nishigaki,M. Analysis of Saturation and Non-saturation Seepage Flow by finite element method, Proceedings of Civil Engineering Society of Japan, No. 264, pp. 87-96, 1977

Japan Road Association. Road and Bridge Specifications (V-Earthquake-Proof Design Edition), and Explanation of same, pp. 349-362, 2002

Lysmer, J., Udaka, T., Seed, H.B. and Hwang, R. LUSH, A Computer Program for Complex Response Analysis of Soil Structure System, Report No.EERC 74-4, Univ. of California, Berkeley, 1974.

Sasaki,Y., Moriwaki,T., Obayashi,J ., Yamada,Y .and Kato,M. Interpretation of Deformation and Failure Mechanism of Embankments due to Soil Liquefaction, Ground and Construction Vol.15, No.1, pp.81-90, 1997.

Yasuda, S., Yoshida,N., Adachi, K., Kiku,H. andGose ,S. A simplified analysis of liquefaction-induced residual deformation, 2nd International Conference on Earthquake Geotechnical Engineering, pp.555-560, 1999.