Topographic and Geological Features Involved in Water Leakage at Levee Foundations and in Levee Body Deformation by Piping on the Kakehashi River

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ABSTRACT

This study aims to estimate the locations of levee collapse resulting from the piping in foundations, and the mechanism behind such collapse. First, topographic and geological features were investigated on the Kakehashi River. Based on the interpretation of aerial photos taken by the US military in 1947, levee leakage occurred where the present river crosses the former river channel. In the geologic profile along the levee, there was a gravel layer distributed in the foundation. Field investigations quantitatively demonstrated that the seepage conditions there were determined by the relationship between the surface soil thickness and the permeability coefficient of permeable layers. We found that leakage occurred at locations where the surface soil thickness was 3m or less and the permeability coefficient was greater than 10^{-4}m/s. It was also demonstrated that levee deformation from piping in the foundation was mainly controlled by the grain size distribution, thickness and distribution depth of the permeable layers and the embankment load.

Key words: seepage, piping, sand boil, levee failure, abandoned river

1. INTRODUCTION

The authors investigated on the Kakehashi River (Ishikawa Pref., Hokuriku District, Japan) and found water leakage at the levee foundation were observed near the former river channel. Thus, the water leakage at the levee foundation was closely related to the location of the former river channel. However, such water leakage does not always occur at a place where a levee and a former river channel cross, so it is critical to accurately predict vulnerable places in a levee so that monitoring can focus on these places. Tabata et al., (2017) proposed a levee vulnerability index which is useful for risk management and levee management. However, its accuracy needs to be improved, and for that purpose, the distribution of former river channels and the relationship between the longitudinal distribution of foundation ground soils and the water leakage at levee foundations should be analyzed.

Cui et al., (2017), Saito et al., (2016), Ueno et al., (2017), and Sasaoka et al., (2017) conducted model experiments to analyze the relationship between levee body deformation (due to piping and water leakage at levee foundations) and the soil properties and soil composition of the foundation ground/levee body. The present study compares the data from these model experiments to data on observed soil properties and soil compositions of the levee where deformation occurred on the Kakehashi River in order to improve the accuracy of a method for identifying vulnerable locations in a levee.

2. METHOD

Aerial photos taken by the U.S. military (Geospatial Information Authority of Japan, 1946&1947) were chiefly used for identifying the former river channels of the Kakehashi River by using a stereoscope (magnification x3; field of view: 70mm). Plan views (MLIT, 1902) of the river improvement work in the Meiji Era (1868-1912) owned by the Kanazawa River and National Highway Office (Ministry of Land, Infrastructure, Transport and Tourism, Japan (MLIT)) were available for identifying the locations of the former river channel, and such locations and the aerial photos were used to develop a distribution map of the former river channels. Based on the map of the former river channels and a longitudinal geological profile, the relationship between the locations of water leakage (Table 1) and their foundation ground soil properties was summarized. The results of the model experiments show that it is important to understand the soil composition of the surface layer at the toe of the levee landside slope so that levee body deformation due to water leakage can be accurately predicted at the early stage of water leakage. Thus, for each cross-sectional surface where boring survey was conducted, the soil properties and the thickness of the surface layer up to 3m thick near the toe were investigated. These and the permeability coefficient (hereinafter: "$\boldsymbol{k}$") of the underlying gravel bed (the permeable layer) are summarized in a schematic. Locations of water leakage were analyzed in relation to the thickness of the surface layer and $\boldsymbol{k}$ of the permeable layer. The particle size composition of the surface layer was also analyzed toward understanding its association with types of water leakage.

Table 1. Records of levee water leakage on the Kakehashi River

Month and year of flooding	District	Left/right bank	Location (closest KP)	Water leakage type	Water leakage situations
Jul. 2006	Kawabe	Right bank	KP5.0	Leakage at levee body	Sand boil
Jul. 2006	Shirae	Left bank	KP6.6	Leakage at levee foundation	Sand boil
Jul. 2006	Kanaya	Left bank	KP6.8	Leakage at levee body	Sand boil
Jul. 2006	Sendai	Right bank	KP7.6	Leakage at levee foundation	Leakage only
Jul. 2013	Kofu	Right bank	KP8.6	Leakage at levee foundation	Sand boil, sliding failure
Sept. 2013	Arakida	Left bank	KP9.5	Leakage at levee foundation	Leakage only

3. RESULTS

3.1 The relationship between water leakage at the levee foundation and the topographic/geological features of the levees on the Kakehashi River

The Kakehashi River is a gently sloping river running through the City of Komatsu, Ishikawa Prefecture. The bed slope gradient of the river section under the control of the national government is 1/690～1/4,500. On this river section, water leakage occurred in the districts shown in Table 1 due to floods in August 2006, July 2013, and September 2013 (Photos 1 and 2).

Photo 1. Water leakage (with sand boil) in the Shirae district (KP6.6 on the left bank) (MLIT, 2007)

Photo 2. Water leakage in the Arakida district (KP9.5 on the left bank) (MLIT, 2014)

In the Shirae district (KP6.6 on the left bank) shown in Photo 1, sand boils took place near the toe of the levee landside slope and in crop fields protected by the levee. Flood-fighting activities were conducted in that district by “hooping.” In this method, sandbags are piled up in a semi-circular arrangement to prevent the spread of water leakage when water begins to leak at the back of the levee. In the Arakida district (KP9.5 on the left bank) shown in Photo 2, water leakage occurred in paddy fields protected by the levee. There were no sand boils, as shown in the enlarged photo. Figure 1 shows a distribution map of the former river channels which were identified by using U.S. military aerial photos taken after the Pacific War and survey maps of 1902 created by the Kanazawa Construction Office of the former Ministry of Construction. In the Shirae, Sendai, Kofu, and Arakida districts, where water leakage at the levee foundation occurred, the water leaked near where the levee crossed the former river channel and in areas bordered by the former river channel and the levee.

The basin at the lower reaches of the Kakehashi River has long been a damp area, and it has frequently flooded. In 1869, the section of the Kakehashi River between the Haccho River and the Nabetani River was straightened by the cutting off of large meander river channels. From 1911 through 1923, the Kakehashi River was improved by the cutting off of a large southward meander river channel downstream of Komatsu Castle and the shortening of the river channel there into a 1.1km-long section. The aerial photos taken by the U.S. military after the war show that most of the former river channels had been converted to paddy fields. The bed slope gradient of the former river channel between the river mouth and the Kakehashi River’s confluence with the Nabetani River is 1/4,500. The former river channel was serpentine, and the meander belt had a constant amplitude. The former river channel was joined by the Haccho River, largely bent southward near Komatsu Temmangu Shrine, and was joined by the Mae River before flowing into the Sea of Japan. In the former river section upstream of the Nabetani River, the meander amplitude was smaller than at the lower reaches, and the meander width was restricted by the surrounding hills. Water leakage at the levee foundation occurred immediately upstream and downstream of the Kakehashi River's confluence with the Nabetani River. The bed slope gradient changes at the confluence.

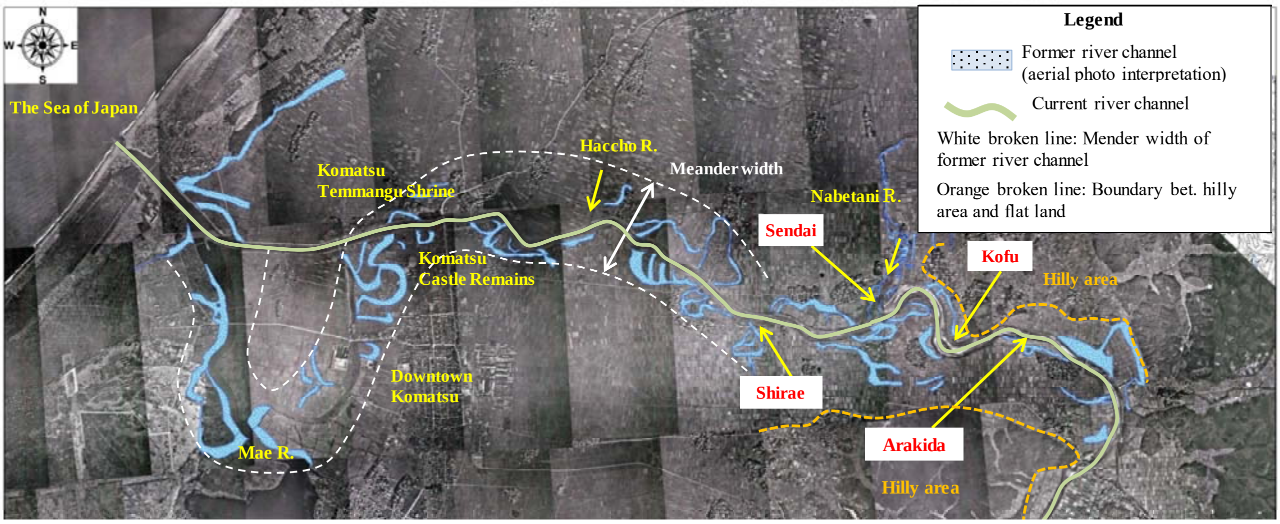

Figure 1. The former river channels of the Kakehashi River identified in U.S. military aerial photos, and places of water leakage (MLIT, 2008)

Figure 2 shows the longitudinal geological profile along the levee on the right bank of the Kakehashi River. The surface-layer soil distribution characteristics reflect the topographic features. Sandy soil is distributed from near the ground surface in the area downstream of the place near Kokatsu Temmangu Shrine where the Kakehashi River bends southward. In the area upstream of the shrine toward the Haccho River, there is a thick layer of cohesive soil near the ground surface, and the cultivated land in that area is used for paddy fields. In the river section between the Haccho River and the Nabetani River, the former channel of the Kakehashi River meanders widely, and natural levees were developed along the former channel. On that river section, sandy soil is chiefly distributed in the surface layer. In the river section upstream of the confluence with the Nabetani River, where the bed slope gradient changes, the meander amplitude of the former channel is smaller than at the lower reaches and gravel is distributed in the surface layer. Water leakage took place on the river section upstream of the Haccho River. On that section, a bed of highly permeable gravel is distributed in the foundation layer. The geology of the foundation ground in the Kakehashi River can be summarized as follows: Gravel is chiefly distributed at the upper reaches, with the particle size decreasing toward the lower reaches, where sand is chiefly distributed. The transition of soil layers follows the sediment deposition of rivers.

Regarding the permeable layer (sand or gravel), which is a causal factor in water leakage at the levee foundation, Figure 3 shows the relationship between the distance from the river mouth (the x-axis) and *k* of the permeable layer (the y-axis). The value of *k* tends to decrease toward the lower reaches and to increase toward the upper reaches, consistent with the geological layers shown in the longitudinal geological profile.

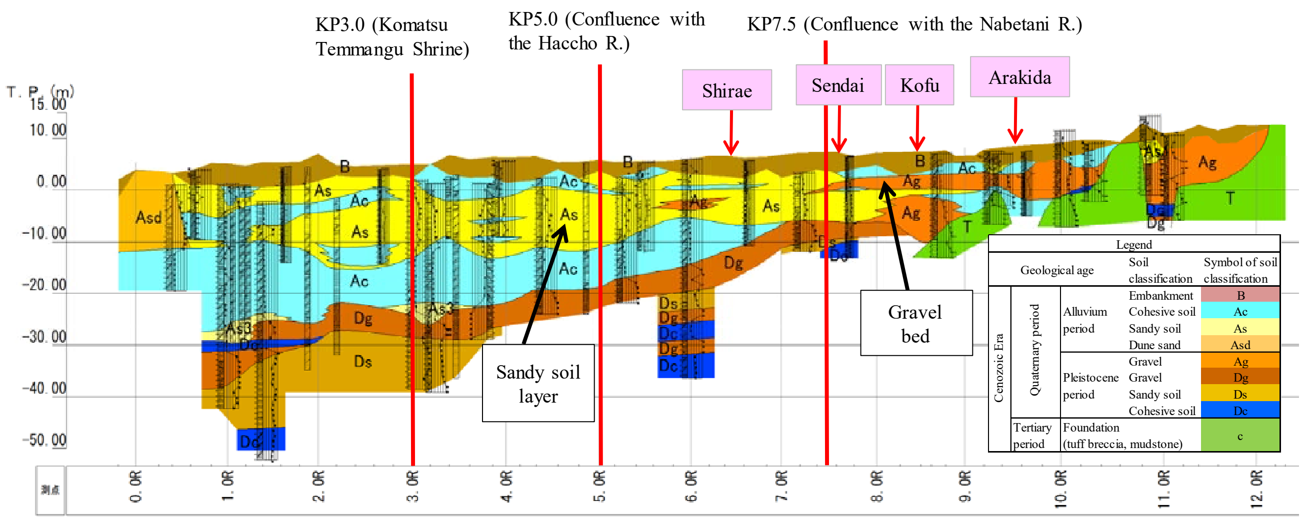

Figure 2. Longitudinal geological profile along the levee on the right bank of the Kakehashi River (MLIT, 2014)

The datum in the black square in Figure 3 is the value for homogeneous dune sand, and the order of k is 10^{-4}m/s. The data in the blue square in Figure 3 are k of the gravel layer deposited in the valley bottom plain, and the orders of the values of k are 10^{-4}~10^{-5}m/s. The sediment in the valley bottom plain consists of soil from the surrounding mountains, and the matrix of the gravel layer has a high content of fine-grained fraction. Thus, the values of k are low.

By using the cross-sectional geological profile (MLIT, 2014) created on the basis of detailed surveys of the levee, the diagrams shown in Figure 4 were developed. These diagrams show the thickness of the surface layer near the toe of the levee landside slope on the right bank and k of the permeable layers below the surface layer. The thickness of the surface layer and k are factors that directly affect the occurrence of piping. The permeable layers are ‘As’ layers and ‘Ag’ layers, which are continuously distributed from the river mouth to KP10.5 in Figure 2. Based on these diagrams, Figure 5 shows the relationship between k of the permeable layer (the x-axis) and the thickness of the surface layer (the y-axis). Figure 5 indicates that water leakage occurred at places where cohesive soil is distributed near the ground surface, the surface layer is 1~3m thick, and the k of the permeable layer is at least 10^{-4}m/s. Water leakage did not occur in the region within the green square in Figure 5. The region contains a sand dune and a valley bottom plain. Regarding the places where water leakage occurred, causal relationships between water leakage and factors such as a change in the bed slope gradient and topographic features (such as the former river channel) need to be analyzed.

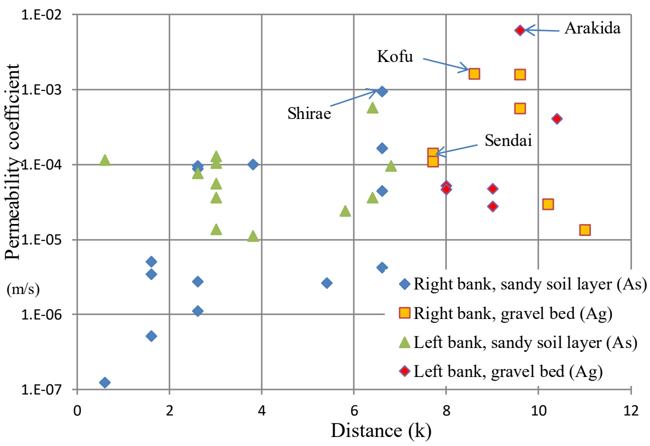

Figure 3. Permeability coefficient of the permeable layer in the foundation ground in the river longitudinal direction

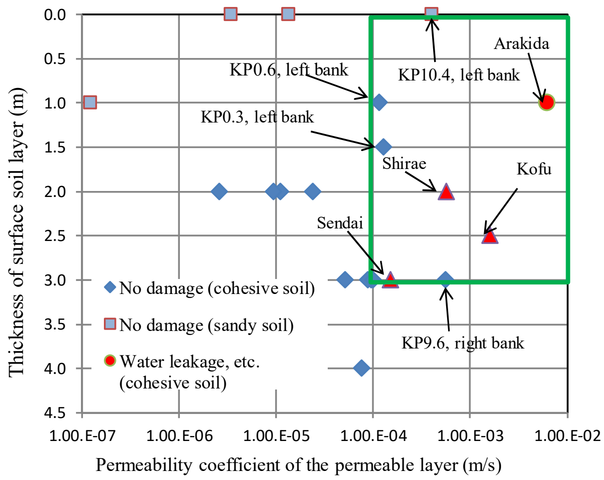

Figure 5. Relationship between the permeability coefficient of the permeable layer and the thickness of the surface layer

					Thickness of layer	Permeability coefficient	
Left bank Shirae	KP6.4	Levee body soil classification	Silty sand				Sand boil
		Surface layer soil classification	Sand		2m	3.57.E-05	
		Permeable layer	Sand		-	5.64.E-04	

					Thickness of layer		
Right bank	KP6.6	Levee body soil classification	Silty sand				
		Surface layer soil classification	Silty sand		1m	3.53.E-05	
			Cohesive soil		1m	-	
		Permeable layer	Sand		-	9.45.E-06	

					Thickness of layer	Permeability coefficient	
Left bank Kanaya	KP6.8	Levee body soil classification	Silty sand				Leakage at levee body
		Surface layer soil classification	Cohesive soil		3m	-	
		Permeable layer	Sand		-	9.61.E-05	

					Thickness of layer	Permeability coefficient	
Right bank Sendai	KP7.7	Levee body soil classification	Cohesive soil				Leakage only
		Surface layer soil classification	Silty sand		3m	3.95.E-05	
		Permeable layer	Gravel		-	1.50.E-04	

					Thickness of layer	Permeability coefficient	
Left bank	KP8.0	Levee body soil classification	Silty sand				
		Surface layer soil classification	Cohesive soil		3m	-	
		Permeable layer	Gravel		-	5.13.E-05	

					Thickness of layer	Permeability coefficient	
Right bank Kofu	KP8.4	Levee body soil classification	Silty sand				Sand boil, sliding failure
		Surface layer soil classification	Cohesive soil		0.5m	-	
			Sand		2m	1.84.E-06	
		Permeable layer	Gravel		-	1.60.E-03	

					Thickness of layer	Permeability coefficient	
Left bank Arakida	KP9.6	Levee body soil classification	Cohesive soil				Leakage only
		Surface layer soil classification	Cohesive soil		1m	-	
		Permeable layer	Gravel				

					Thickness of layer	Permeability coefficient	
Right bank	KP9.6	Levee body soil classification	Cohesive soil				
		Surface layer soil classification	Cohesive soil		3m	-	
		Permeable layer	Gravel		-	5.57.E-04	

					Thickness of layer	Permeability coefficient	
Left bank	KP10.4	Levee body soil classification	Gravel				
		Permeable layer	Gravel		-	4.02.E-04	

					Thickness of layer	Permeability coefficient	
Right bank	KP11.0	Levee body soil classification	Gravel				
		Permeable layer	Gravel		-	1.34.E-05	

Unit of permeability coefficient: m/s

Figure 4. Soil property composition diagram near the toe of the levee landside slope on the right bank

3.2 Mechanism of levee body deformation due to piping

Figure 6 shows the locations of water leakage due to the flood in the Kofu district in July 2013 and the distribution of the former river channels. Photo 3 shows KP8.4, where sliding failure occurred at the levee due to water leakage at the levee foundation. Sand boils also occurred in the area protected by the levee. At KP8.6, sand boils occurred and the levee crown cracked (Photo 4). Sand boils also occurred at KP8.2. The soil properties and the levee conditions at these sites are summarized in Tables 2 and 3. Table 2 shows the following: levee height (H); gradient of the levee landside slope (gradient of the line connecting the shoulder and the toe of the slope); piping value, G/W, calculated on the basis of non-stationary saturated and unsaturated seepage analysis that utilizes external forces of rainfall and the record of river water level (MLIT, 2014) and on the basis of stability calculation (the total stress method); safety factor against circular failure on the landside slope (Fs)(Japan Institute of Country-ology and Engineering, 2012); and disaster type.

Photo 3. Site of sliding failure near KP8.4 on the right bank (MLIT, 2014)

Photo 4. Sand boils near KP8.6 on the right bank (MLIT, 2007)

Table 2. Data on the sites where piping occurred, and the consequences of piping

Analysed cross-section	Levee height H [m]	Slope gradient	Piping judgement	Back slope sliding failure	Soil classification and location of circular sliding surface	Damage situations
			G/W	Min. factor of safety, Fs		
KP8.2	3.8	1 : 1.40	3.178	1.469	Cohesive soil layer (Levee body)	Sand boil
KP8.4	4.3	1 : 1.17	0.233	1.046	Sandy soil layer (Foundation ground)	Sand boil Sliding failure
KP8.6	4.0	1 : 1.35	0.438	1.311	Sandy soil layer (Levee body)	Large amount of boiling sand

Table 3. Soil parameters used for calculating the data in Table 2

Use	Symbol of soil layer	Soil classification	Saturated unit weight (kN/m^3)	Unsaturated unit weight (kN/m^3)	Internal friction angle (degree)	Cohesive strength (kN/m^3)	Permeability coefficient (m/s)
Levee body	Bs1	Sandy soil	16.8	14.9	9.5	20.7	5.3E-06
	Bs2	Sandy soil	16.9	16.3	9.9	12.5	2.9E-06
	Bs3	Sandy soil	20.0	19.0	30.0	1.0	9.1E-06
Foundation ground	Ac1-1	Cohesive soil	17.3	16.7	0.0	29.4	1.0E-07
	As1-1	Sandy soil	-	17.0	27.2	0.0	1.8E-06
	Ag1-1	Gravel	-	19.0	34.6	0.0	1.6E-03

Because KP8.2 on the right bank is close to where the bank merges with the former river channel, the soil properties are the same as those of the former river channel. Near the toe of the levee landside slope, a cohesive soil layer with a thickness of up to 3.5m is distributed. At the same place, the piping value (G/W=3.178) is higher than 1. Water leakage did not occur at the toe of the landside slope. The water leakage and sand boils that occurred in the paddy fields protected by the levee were probably a result of the cohesive soil layer there being thin. The minimum safety factor against circular failure (Fs) is 1.469, a value higher than at other sites, and levee body deformation did not occur at this site (Figure 7.)

At KP8.4 on the right bank, sand boils occurred in a footpath between rice paddies. The cause is likely to have been the reduction in the inland water levels near the inside of the levee. At this site, the cohesive soil layer in the surface layer is 0.5m thick, which is thinner than at other sites, and the piping value is 0.233, which is much lower than 1. The sand layer beneath the cohesive soil layer is up to 2m thick. The circular sliding surface given by the calculation of the minimum safety factor extends through the sand layer. The minimum safety factor is 1.046, which is higher than 1; thus, sliding failure did not occur (Figure 8.)

In the levee body deformation at KP8.4 on the right bank, the canal at the foot of the levee near the toe of the landside slope moved horizontally and upward. The soil of the foundation ground seems to have moved, too. Because water was retained in the canal at the foot of the levee upstream of where the levee collapsed, it is likely that the collapse occurred when the inland water level decreased to ground level around the canal. Sand boils occurred in a footpath between paddies, followed by sliding failure. A portable cone penetration test conducted after the levee failure (Figure9.) indicates that part of the sand layer in the foundation ground is relatively weak. Because the location, shape and the dimensions of the weak part are consistent with those of the calculated circular sliding surface, it is possible that the sliding failure was due to a decrease in the effective stress caused by an increase in hydrostatic pressure. At the same time, because the gabion walls sank significantly, the levee body deformation might have been caused by subsidence that followed the hollowing of the foundation ground due to piping and the movement of soil particles, as were simulated in model experiments by Ueno et al., (2017) and Sasaoka et al., (2017).

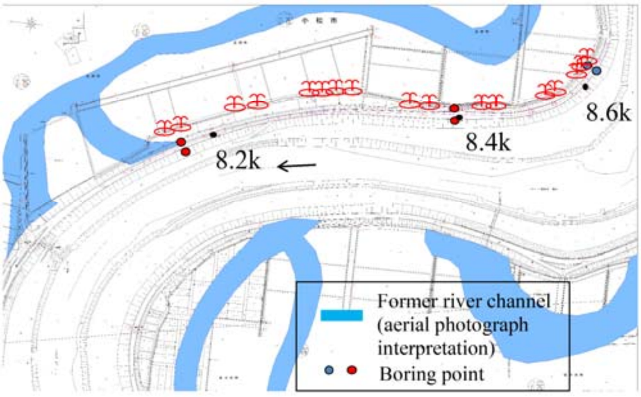

Figure 6. Site of water leakage in the Kofu district (MLIT, 2014)

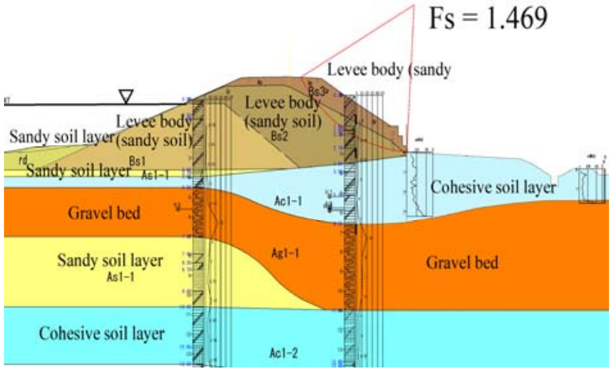

Figure 7. Geological profile at KP8.2 on the right bank (MLIT, 2014)

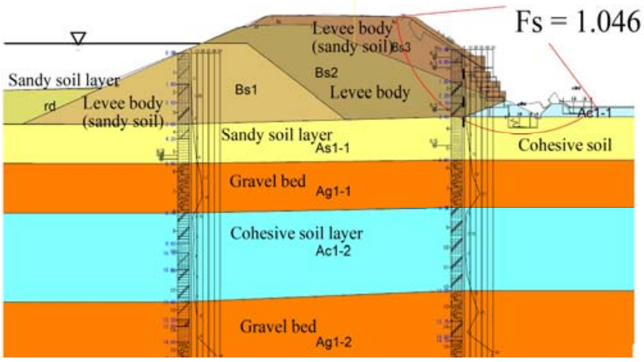

Figure 8. Geological profile at KP8.4 on the right bank (MLIT, 2014)

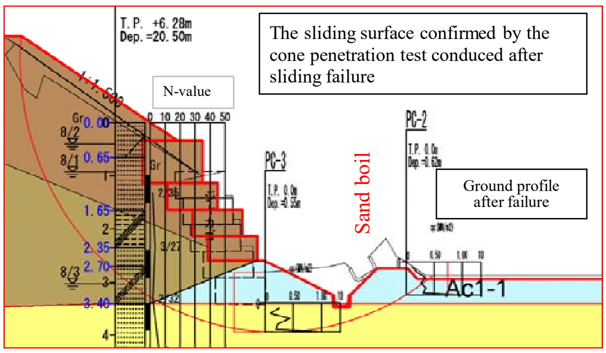

Figure 9. Portable cone test results for KP8.4 on the right bank (MLIT, 2014)

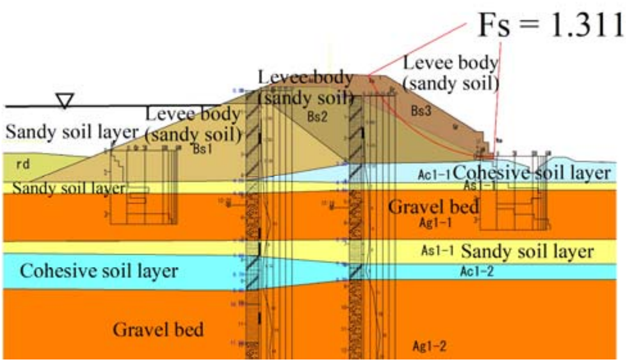

Figure 10. Geological profile at KP8.6 on the right bank (MLIT, 2014)

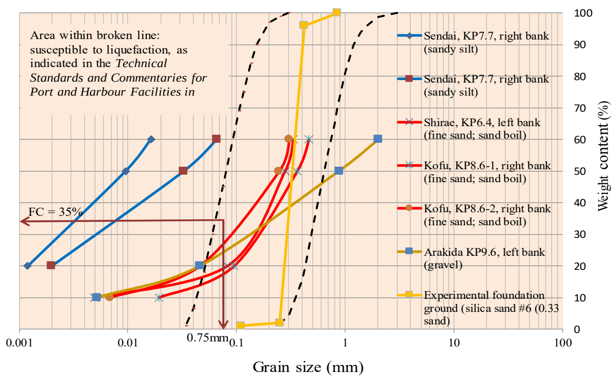

Figure 11. Grading curves for the soil of sand boil sites

At KP8.4 on the right bank where sliding failure occurred, the levee was higher and the landside slope gradient was steeper than at other sites. Consequently, the safety factor against circular failure was lower than at the other sites, being close to 1.

At KP8.6 on the right bank, large-scale sand boils occurred in the canal at the foot of the levee near the toe of the landside slope, but sliding failure of the levee did not occur. At this site, the cohesive soil layer in the surface layer was as thin as 1.0m, and the piping value was 0.438, a value higher than at KP8.4. There was no relationship between the sand boils and the piping value. The minimum safety factor against circular failure is as high as 1.311. The circular sliding path given by the calculation of the minimum safety factor extended through the levee body (Figure 10.) Sand particles but no gravel particles spurted to the ground surface; thus, it is likely that the soil particles moved in the sand layer on the gravel bed. Even when the strength of the sand layer decreases because of failure due to piping (on the assumption that the angle of shear resistance φ=0), the safety factor is 1.149. A safety factor higher than 1 means that sliding failure does not occur.

Figure 11 shows the particle size composition of the sand layer where sand boils occurred (or where soil particles moved). The particle size composition is based on the soil test data from Results of Soil Tests at River Levees (River Division, National Institute for Land and Infrastructure Management, 2012). According to the Japanese Geotechnical Society, the coefficient of uniformity is D60/D10, but because D10 cannot always be obtained in soil that is high in fine fraction content, D60/D20 was used in this study.

Judging from the particle size composition, the boiling sand in the Shirae district was sand distributed in the surface layer (Photo 1). The coefficient of uniformity of that sand is 10 or less, and the fine fraction content is 35% or lower. Values greater than these indicate a high likelihood of liquefaction, according to the Specifications for Highway Bridges (Japan Road Association, 2012). Water leakage alone took place in the Sendai district. The surface layer consists of silt and sand, and the fine fraction content is 50%. The boiling sand in the Kofu district (Photos 3 and 4) is sand distributed in the surface layer, as in the case of the Shirae district. The surface layer in the Arakida district consists of cohesive soil. Consequently, there were no sand boils, and only water leakage occurred (Photo 2). A grading curve of the permeable layer that makes up a gravel bed is shown in Figure 11. This curve is on the right of the grading curve of boiling sand. The coefficient of uniformity is 44, which is quite high, and the curve is gentle.

In Figure 11, the area between the two broken lines corresponds to a range of particle sizes that are especially susceptible to liquefaction, as indicated in the Technical Standards and Commentaries for Port and Harbour Facilities in Japan (The Overseas Coastal Area Development Institute of Japan, 2008). This suggests that the type of soil that is prone to sand boils due to piping has the same range of particle sizes as the type of sand that is likely to undergo liquefaction.

Figure 11 also shows a grading curve for the type of soil used by Ueno et al., (2017) in a model experiment. The grading of the silica sand #6 (0.33mm) used in the upper layer of the foundation ground of the model experiment is similar to the grading of sand ejected at the sand boils on the Kakehashi River. From the model experiment, it was reported that when the upper layer and lower layer of the foundation ground were made the silica sand #6 and silica sand #3, respectively, and a levee was built with bentonite-mixed soil (an impermeable material with ***k***=4.1×10-9), not only was the sand in the foundation ground discharged, but so were portions of the soil in the bentonite-mixed levee body, and that rapid subsidence caused the levee body to collapse.

Even when the levee body consists of an impermeable material, soil particles move at the boundary between the bottom of the levee body and the top layer of the foundation ground if the top layer is sand that is susceptible to piping and whose particle size distribution is within a certain range. The movement of soil particles causes erosion at the boundary, which leads to the settlement and deformation of the levee body. The soil of the levee body in the Kofu district had a higher fine fraction content and had a different particle size composition than the impermeable material used in the experiment. In the sliding failure of the levee in the Kofu district, the effective stress decreased due to the boiling of sand in the foundation ground. Consequently, the balance between the foundation ground and the load of the levee body was lost, which resulted in deformation similar to the circular failure of the levee body.

4. DISCUSSION

Water leakage at the levee foundation occurred where the levee crossed the former river channel. To identify sites susceptible to water leakage, it is important to develop a map of former river channels on the basis of old maps and aerial photos. Not all water leakage sites were at places where the levee crossed the former river channel, but many were. It is critical to understand the soil properties of the surface layer to the depth of 3m as well as the *k* of the underlying permeable layer. Based on the relationship between the thickness of the surface layer and the *k* of the permeable layer, it was confirmed that water leakage occurred at places where the thickness of the surface layer was less than 3m and the *k* of the permeable layer was at least 10^{-4}m/s. It is likely that the difference between the river water level and the level of the ground at the toe of the levee landside slope was among the causal factors in water leakage. A causal relationship between the difference of these two levels and water leakage needs to be investigated.

Only water leakage occurred when the surface layer consisted of cohesive soil, and both water leakage and sand boils took place when sand of a uniform particle size was distributed in the surface layer. Thus, the type of water leakage varies depending on the soil properties of the surface layer.

The thickness of the sand layer and the length of a circular sliding path affect the occurrence of sliding failure. Thus, it is important to determine the geometry and dimensions of the circular sliding surface according to the load exerted by the levee. From laboratory model experiments, it is known that when seepage failure progresses, soil masses in the foundation ground begin to move at some point in time and sliding failure occurs. The relationship between the duration of seepage and sliding failure needs to be analyzed for different soil properties of the surface layer.

5. CONCLUSIONS

The relationship between water leakage at the levee foundation and levee body and the topographic/geological features was analyzed for the sites where water leakage occurred at levees on the Kakehashi River due to flooding. The analysis results are as follows.

1. Judging from the configuration of the former river channels identified in aerial photos, water leakage at the levee foundation took place at the boundaries between meander channels on floodplains and braided channels on alluvial fans or valley bottom plains.
2. An analysis of longitudinal geological profiles along levees indicated the following: Water leakage occurred on river sections where the values of k were high (10^{-4}m/s or higher for the Kakehashi River) in sand or gravel layers that were continuously distributed in the foundation ground along the river, and water leakage occurred where the surface layer thickness was between roughly 1m and 3m.
3. The particle size composition of soil susceptible to sand boils is in the range of particle sizes associated with liquefaction. Water leakage alone took place in soil consisting of particle sizes outside that range.
4. Regarding the levee body deformation at KP8.4, because the soil particle size for the levee was outside the range of particle sizes associated with sand boils, it is likely that the circular failure occurred due to a decrease in shear resistance caused by soil particle movement in the sand layer of the foundation ground.

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