Evaluating the Saturated Permeability Coefficients of River Embankments via Field Permeability Tests

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Abstract. The authors conducted field permeability tests on numerous river embankments using a Marriott siphon in 30-cm test holes to obtain their saturated permeability coefficients. The results revealed that the field-obtained saturated permeability coefficients were larger than those obtained as a result of the laboratory permeability test conducted on the undisturbed specimens sampled from the same location. Regarding embankments constituted by fine-grained soils, there are cases in which the field-obtained coefficients are several orders of magnitude larger than those obtained under laboratory conditions. These results suggest that the field permeability coefficient obtained by the Marriott siphon with large-diameter test holes evaluates the macroscopic permeability, including in situ heterogeneity and anisotropy. In this study, the results of the field permeability tests at two embankments of the Oda and Kano Rivers are shown. In addition, the results of the laboratory permeability test for the undisturbed specimens sampled at each field site are shown. In each survey, the field permeability coefficients were larger than both the laboratory permeability coefficients and the estimated value from particle size, as in the case of other embankments investigated so far.

Keywords: river embankment, permeability, field permeability test, laboratory permeability test

1 Introduction

In the qualitative inspection of river embankments, it is crucial to evaluate the permeability coefficient of embankments. The authors conducted field permeability tests on old river embankments [1]–[3] or banks damaged by floods [4] using a Marriott siphon with 30-cm test holes to obtain their saturated permeability coefficients. Previous studies confirmed that the saturated permeability coefficients obtained at the field are generally larger than those obtained as a result of laboratory permeability tests conducted on undisturbed specimens sampled at the same location. Regarding embankments constituted by fine-grained soils, there are cases in which the field-obtained coefficients are several orders of magnitude larger compared to those obtained under laboratory conditions. These results suggest that the field permeability coefficient obtained by the Marriott siphon with large-diameter test holes evaluates macroscopic permeability, including in situ heterogeneity and anisotropy.

In this study, the results of the field permeability tests conducted at two embankments of the Oda and Kano Rivers are presented. An open-cut investigation was conducted on the collapsed banks of the Oda River, which was damaged by heavy rain in July 2018. At that time, a field permeability test was conducted using a Marriott siphon at multiple points on the embankment. Furthermore, a field survey was conducted in December 2020 on the embankment excavation section of Kano River. In addition, the results of the laboratory permeability test conducted using undisturbed specimens sampled at each field site are presented. In each survey, the field permeability coefficients were larger than both the laboratory-obtained permeability coefficients and values estimated from particle size; a similar trend has been observed in the other embankments investigated so far. In this study, we demonstrate how to conduct such a field permeability test easily using a water meter and show its usefulness.

2 Field investigation at Oda River embankments

2.1 Field permeability test

The field permeability test was conducted at two breach locations (3.4km point, hereafter just 3.4k, on the left bank and 6.4k on the left bank) and two slip failure locations (0.6k on the right bank and 4.2k on the left bank) of the Oda River. At each site, open-cut investigations at the embankments were conducted to determine the causes of Dyke failures. Fig. 1 shows the cross-sectional view of the open-cut investigation conducted at the 3.4k on the left bank and locations where the field permeability test was conducted. The photograph framed in red shows the operational conditions of the field permeability test. The numbers ① to ③ in white located at the execution positions correspond to the results reported in Table 1. Figs. 2 and 3 show the locations of the field permeability tests conducted during open-cut investigations at 6.4k on the left bank and 0.6k on the right bank. The white numbers in Fig. 1 correspond to the results in Table 1. The left bank result obtained at 4.2k is omitted owing to space limitations.

Table 1 summarizes the results of the field permeability tests starting from the downstream side. As mentioned above, the numbers ① to ⑥ in the table indicate the locations where field permeability tests were conducted on the cross-sections investigated in Figs. 1 to 3, respectively. The saturated coefficient of permeability obtained from the field permeability test is presented in the middle column of the table. The soil properties near each test hole are also shown; however, note that they do not necessarily denote the same point. In addition, the coefficient of permeability estimated by Crager's method with a 20 % grain size, namely D_{20}, of these soil samples is presented as well.

0.6 km point on the right bank corresponds to an embankment composed mainly of cohesive soil; however, thin sand and gravel layers exist in places [5]. Consequently, the field coefficient of permeability is high, which is very different from that of cohesive soil. In the test conducted at 0.6k ① on the right bank, the steady state was maintained for a while. Subsequently, the coefficient of permeability, shown in Table 1, was obtained. However, the surrounding cohesive soil collapsed owing to water seepage into the narrow gravel layer; therefore, the field test could not be continued. At other locations, although no noticeable inhomogeneity was observed near the permeability test points, the values obtained in the field permeability tests were generally larger than those estimated from the grain size, approximately three orders of magnitude higher. This tendency is remarkable in an embankment containing a large number of fine grains. Conversely, the evaluation of coarse-grained embankment soil, such as gravel sand, was consistent with the field permeability test results. However, in the case of the 6.4k upstream cross-section, the difference between the value estimated from the grain size and field test result appears to be large when there is a large amount of fine grains, even if gravel is sufficiently mixed.

Fig. 1. Process locations and conditions of filed permeability tests during open-cut investigations conducted at the breach location on the left bank at 3.4k.

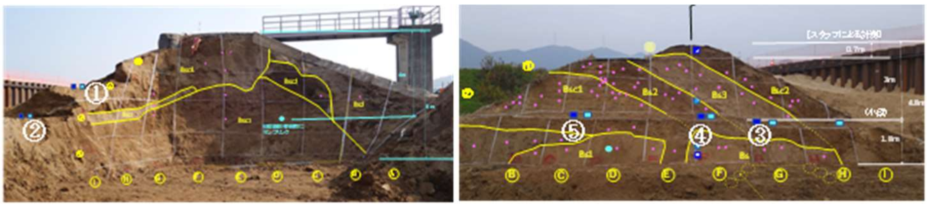

Fig. 2. Location of field permeability test during open-cut investigations at 6.4k breach location on the left bank. (Left Fig: Downstream location and Right Fig: Upstream location)

Fig. 3. Location of field permeability test during open-cut investigations at 0.6k slip failure locations on the right bank. (Left Fig: Upstream location and Right Fig: Downstream location)

Table 1. Field permeability test results, soil classification, and estimated coefficients of permeability at each location.

Investigations of embankments	Open-cut (stream)	Test point		Permeability (m/s)	Permeability of test point		Crager's (m/s)
		Detail	Photo		Classification	D_{20} (mm)	
Right bank 0.6k	Down-stream	Upper step	①	1.6×10^{-4}	(CLS)	–	–
		Downer step	②	3.1×10^{-5}	(FS)	0.0016	–
	Up-stream	Upper step (Outfield)	③	4.6×10^{-5}	(CLS)	–	–
		Upper step (Infield)	④	2.3×10^{-5}	(CLS)	–	–
		Downer step (Outfield)	⑤	1.9×10^{-5}	(CLS)	–	–
		Downer step (Infield)	⑥	6.4×10^{-5}	(SC)	0.0046	3.0×10^{-8}
Left bank 3.4k	Down-stream	Outfield	①	3.2×10^{-6}	(FS)	0.0013	–
		Infield (Inside)	②	3.7×10^{-4}	(SP-G)	0.4130	4.8×10^{-4}
		Infield (Outside)	③	1.1×10^{-4}	(SP-G)	0.3257	2.7×10^{-4}
Left bank 4.2k	Down-stream	Upper step	–	2.5×10^{-4}	(SG-F)	0.3700	2.5×10^{-4}
		Downer step	–	3.1×10^{-5}	(SF)	0.0400	1.8×10^{-6}
	Up-stream	Infield (Inside)	–	9.2×10^{-5}	(SF)	0.0780	8.5×10^{-6}
		Infield (Outside)	–	4.6×10^{-5}	(S-FG)	0.2000	8.9×10^{-5}
Left bank 6.4k	Down-stream	Upper step	①	6.2×10^{-5}	(SC)	–	–
		Downer step	②	6.9×10^{-6}	(SC)	–	–
	Up-stream	Outfield	③	6.2×10^{-5}	(SF-G)	0.0106	1.1×10^{-7}
		Center	④	5.4×10^{-4}	(SF-G)	0.0074	6.6×10^{-8}
		Infield	⑤	1.4×10^{-4}	(SFG)	0.0098	1.0×10^{-7}

2.2 Laboratory permeability test

For the laboratory permeability test, samples taken from the open-cut section downstream at 3.4k on the left bank (see Fig. 1) and samples taken from the open-cut section upstream at 4.2k on the left bank were used. These samples were collected using a simple sampling method [6] near the test hole where the field permeability tests were conducted. Specifically, a 10-cm simple sampler, which is a 19-cm-high polyvinyl chloride (PVC) pipe with a cutting edge on one side, was carefully pushed into the ground. Subsequently, the soil around the sampler was excavated and removed for sampling. Fig. 4 illustrates the excavation process. The collected samples were temporarily frozen and maintained in PVC pipes. Then, they were cut and shaved into specimens for laboratory permeability tests. Accordingly, to investigate the anisotropy of permeability at a specimen level, two specimens were formed from one PVC pipe in the vertical and horizontal directions, as shown in Fig. 5. Fig. 6 illustrates this procedure. First, the PVC pipe around the specimen was cut, and the frozen sample was carefully removed. Frozen samples were cut 12 cm from the tip and divided into two groups. Using a specially processed specimen forming lathe, each specimen was rotated and shaved with a sharp bit to form a cylindrical specimen with a diameter of 5 cm and height of 9 cm.

Fig. 4. Excavated situation

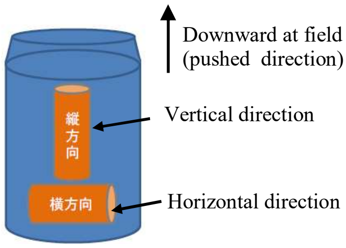

Fig. 5. Form image

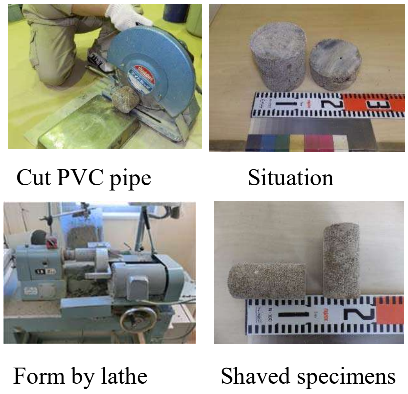

Fig. 6. Specimen forming procedure

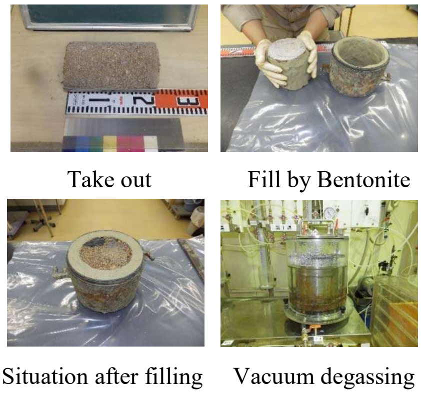

Fig. 7. Laboratory permeability test procedure

Since several samples were collected from the same location, when vertical and horizontal specimens were formed as described above, a laboratory permeability test using a single PVC pipe frozen sample was also conducted for comparison. At that time, only the end surface was formed, without cutting the peripheral surface. In addition, since there is a risk of damaging the sample collected at locations with a large amount of gravel during specimen formation, the frozen sample was not cut or shaved to be used as a single specimen for the permeability test. A laboratory permeability test was conducted by placing the frozen specimen in a mold with a diameter of 15 cm. Since there was a large gap between the mold and specimen, the circumference of the specimen was filled with bentonite, a material with low permeability. Fig. 7 shows an example of the test procedure using a single PVC pipe specimen. The procedure is the same for lateral and vertical specimens with a diameter of 5 cm; only the amount of bentonite to be filled increases. Fig. 1 shows the state of the field permeability test, as well as the state of specimen formation during the laboratory tests, which were collected near the test holes. In Figs. 1 and 5, the cutting edge of each sampler is illustrated upward; however, the samples are collected upside down.

Table 2 summarizes the laboratory permeability test results. At 3.4k on the left bank, a total of 13 specimens were tested with samples collected at three points. Moreover, at 4.2k on the left bank, a total of seven specimens were tested at four points. The table also reports the wet density immediately after formation in the frozen state for each specimen. Variations in wet density were observed, even for specimens collected from the same sampling point.

Table 2 lists the coefficients of permeability obtained from the field permeability tests mentioned earlier. Comparing the coefficients of permeability obtained from both tests, observe that the coefficients of permeability obtained from the laboratory test are generally smaller than those obtained from the field test. A similar trend has been observed in previous studies [1]. In positions where fine grains are considered abundant, there is a difference of one to two orders of magnitude, or even more, in some cases.

Compared with the coefficient of permeability estimated from the grain size, the estimated value appears to be close to the coefficient of permeability obtained by the field test conducted at positions with rich gravel content and high permeability. Meanwhile, the estimated value appears to be close to the coefficient of permeability obtained from the laboratory test conducted at positions with rich fine grains content and low permeability.

Regarding the evaluation of anisotropy, the horizontal coefficient of permeability was approximately 10 times larger than the vertical one conducted at 3.4k downstream of the left bank (outside) ③. However, in this case, a clear difference cannot be observed, partly because the wet density of the specimen in the vertical direction is slightly higher. However, the field permeability test itself can be interpreted as an evaluation that includes horizontal permeability anisotropy, which appears to be largely different from the laboratory test. Therefore, it is necessary to separately verify the permeable scale effect inside the levee body.

Table 2. Laboratory permeability test results, soil classification, estimated coefficient, field permeability coefficient.

Investigations of embankments	Open-cut (stream)	Test point	Test method	Direction	Laboratory permeability(m/s)		Test hole			Field permeability (m/s)
		Detail			Vertical direction	Horizontal direction	Classification	D_{20} (mm)	Crager's (m/s)	
Left bank 3.4k	Down-stream	Outfield ①	Falling head	Vertical	8.4×10^{-9} (1.93)		(FS)	0.001	Impossible to estimate	3.2×10^{-6}
			Falling head	Vertical & horizontal	1.6×10^{-8} (1.93)	7.5×10^{-8} (2.01)				
			Falling head	Vertical & horizontal	8.8×10^{-9} (2.00)	6.9×10^{-9} (2.00)				
		Infield (Inside) ②	Constant head	Vertical	4.2×10^{-5} (1.99)		(SP-G)	0.413	4.8×10^{-4}	3.7×10^{-4}
			Constant head	Vertical	7.0×10^{-5} (1.95)					
			Constant head	Vertical	5.8×10^{-5} (1.95)					
		Infield (Outside) ③	Falling head	Vertical	2.3×10^{-7} (1.90)		(SP-G)	0.326	2.7×10^{-4}	1.1×10^{-4}
			Falling head	Vertical & horizontal	5.7×10^{-7} (1.78)	9.7×10^{-6} (1.67)				
			Falling head	Vertical & horizontal	8.6×10^{-7} (1.76)	8.9×10^{-6} (1.71)				
Left bank 4.2k	Down-stream	Upper step	Falling head	Vertical & horizontal	7.7×10^{-7} (1.65)	2.2×10^{-6} (1.57)	(SG-F)	0.370	2.5×10^{-4}	2.5×10^{-4}
		Downer step	Falling head	Vertical & horizontal	8.4×10^{-6} (1.53)	5.5×10^{-7} (1.60)	(SF)	0.004	1.8×10^{-6}	3.1×10^{-5}
	Up-stream	Infield (Inside)	Falling head	Vertical & horizontal	2.2×10^{-7} (1.57)	3.2×10^{-7} (1.69)	(SF)	0.078	8.5×10^{-6}	9.2×10^{-5}
		Infield (Outside)	Constant head	Vertical	3.4×10^{-6} (1.43)		(S-FG)	0.200	8.9×10^{-5}	4.6×10^{-5}

(wet density g/cm^3)

3 Field investigation at Kano River embankments

3.1 Field permeability test

Field permeability tests were conducted on an open-cut cross-section on the upstream side at Kano Rover 8.5k (see Fig. 8) . The bench was divided into three areas: A (outside the embankment), B (center), and C (inside the embankment). Field permeability tests were conducted in each area using the following two methods. First is a method by JGS-1316 using a Marriott siphon (hereafter referred to as the 1316 method), and the other is a method using a water meter with a test hole of the same size as the 1316 method. In the field permeability test conducted using a water meter method, the water level in a test hole is kept constant by adjusting the water flow rate, and the amount of water injected is measured using a water meter (hereafter referred to as the WMPT method).

Fig. 8 shows the positions of the test holes (labeled 1316 holes and WMPT holes). Each test hole was 30 cm in diameter and 40 cm deep, and the distance between the 1316 and WMPT holes was 50 cm. All test holes had the same dimensions, using which both test methods were performed; however, the test holes were named after the previously performed test method.

For comparison, a series of laboratory tests were also conducted. Test samples were collected using the same sampling method as that used in the investigation conducted at the Oda River mentioned in the previous chapter. Each specimen was collected using a single PVC pipe and was used to measure the permeability only in the vertical direction.

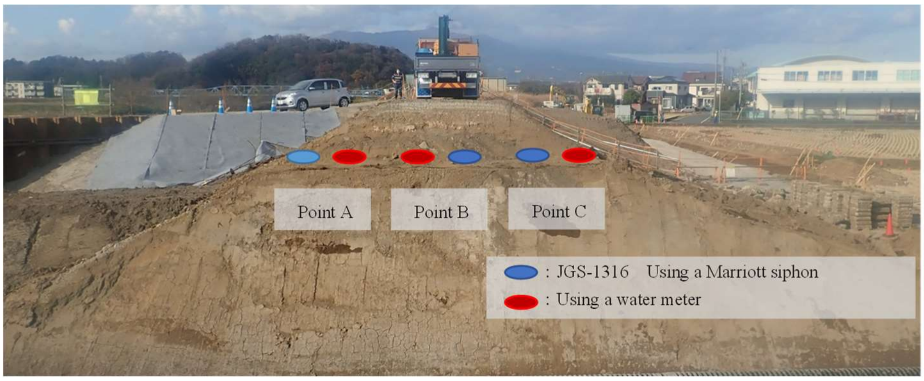

Fig. 8. Test site at the open-cut cross-section on the upstream side of the Kano River

3.2 Test results

The field and laboratory permeability test results are listed in Tables 3 and 4, respectively. Each table also reports the coefficient of permeability estimated by Creager's method using 20 % grain size, namely, D_{20}. In Table 3, the coefficients of permeability obtained by the laboratory test in areas A and B, which contain rich fine-grain particle content, are on the order of the 4th to 5th power for both the 1316 and WMPT methods. On the other hand, the coefficients of permeability obtained from the laboratory test in area C, which has a rich sand content, are on the order of the fourth power and consistent with the estimated values based on D_{20}.

Focusing on the difference between the test holes located at points A and B, a slight difference in particle size can be observed. However, there is almost no difference between the test methods performed on the same hole. Furthermore, even if the WMPT hole at point C is highly permeable, cannot maintain a steady water level with a Marriott siphon, and is difficult to measure, the WMPT method can be used depending on the supply capacity of the submersible pump. We confirmed that the WMPT method is useful for determining the coefficient of permeability in the field of embankment soil with a wide range of grain sizes, including coarse particles.

In Creager's method, the estimated coefficients of permeability differ significantly between the test holes in both areas A and B. This is caused by the large difference in the D_{20} values owing to the slight increase in the fine grain content of the 1316 holes. For embankment bodies with fine-grained sandy soil, the difference in the range of fine-grained fractions greatly affects the value of D_{20}. Therefore, care must be taken when using Creager's estimation method.

In the laboratory permeability test results reported in Table 2, areas A and B with rich fine contents had coefficients of permeability of the sixth power order, while area C with rich sand had coefficients of permeability of the fifth power order. There is almost no difference in the permeability test results at the test holes in each area. Subsequently, since there is no difference in D_{20}, there is no difference in the coefficients of permeability obtained using Creager's method.

Fig. 9 shows the relationship between the coefficients of permeability obtained by Creager's method, 1316 method, WMPT method, and laboratory permeability test, arranged in double logarithms. The results of the two field test methods, that is, the 1316 and WMPT methods, agree with each other. However, the laboratory permeability test obtains smaller permeability compared to the field permeability test, regardless of the grain size. The coefficients of permeability obtained by Creager's method are smaller than those obtained using the field permeability test over a wide range of grain sizes and do not match until coarse sandy soil with $D_{20} = 0.5$ mm.

The above results are consistent with those of investigations conducted in various places by the authors in the past, such as [1] to [4]. Underestimating the permeability immediately leads to a risky evaluation of seepage properties; therefore, note that the coefficients of permeability estimated from laboratory tests and grain size should not be overestimated.

Table 3. Field permeability test results.

	Test hole	1316 method (m/s)	WMPT method (m/s)	D_{20} (mm)	Creager (m/s)
Point A	1316 hole	7.98×10^{-5}	7.67×10^{-5}	0.0136	2.11×10^{-7}
	WMPT hole	1.32×10^{-4}	1.46×10^{-4}	0.0906	1.42×10-5
Point B	1316 hole	5.69×10^{-5}	5.64×10^{-5}	0.0248	6.16×10^{-7}
	WMPT hole	1.20×10^{-4}	1.04×10^{-4}	0.0922	1.48×10^{-5}
Point C	1316 hole	3.68×10^{-4}	5.49×10^{-4}	0.4448	5.66×10^{-4}
	WMPT hole	Impossible to measure	4.48×10^{-4}	0.2686	1.70×10^{-4}

Table 4. Laboratory permeability test results.

	Test hole	Laboratory test (m/s)	D_{20} (mm)	Creager (m/s)
Point A	1316 hole	1.89×10^{-6}	0.0047	2.73×10^{-8}
	WMPT hole	2.48×10^{-6}	0.0044	2.45×10^{-8}
Point B	1316 hole	1.10×10^{-6}	0.0092	9.30×10^{-8}
	WMPT hole	3.79×10^{-6}	0.0076	8.90×10^{-8}
Point C	1316 hole	1.82×10^{-5}	0.3791	3.96×10^{-4}
	WMPT hole	2.32×10^{-5}	0.3406	3.01×10^{-4}

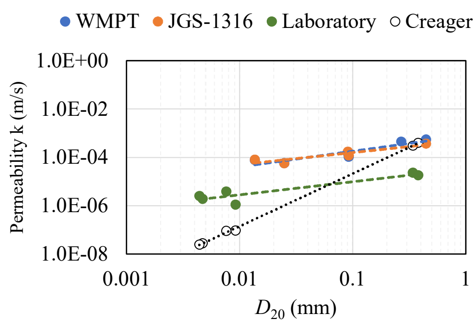

Fig. 9. Relationship between 20 % grain size and permeability coefficient.

4 Summary

The coefficients of permeability obtained from the field permeability tests were generally larger than those estimated from the grain size. This tendency was particularly pronounced in the embankment body with rich fine-grained particle content. In addition, the permeability obtained from the laboratory permeability test was generally lower than that obtained from the field permeability test. It can be interpreted that the field permeability itself includes horizontal permeability anisotropy, which is one of the reasons why the value is larger than that obtained in the laboratory permeability test. In particular, the fact that the field permeability test conducted in this study used a relatively large-diameter and deep test hole, with a diameter of 30 cm and a depth of 40 cm, is considered to be an important reason for reflecting the scale effect of the permeability of the embankment.

In addition, a novel simpler method for conducting field permeability tests using a water meter is presented in this study.

Acknowledgments

The authors would like to express their gratitude to the Chubu Regional Development Bureau, Chugoku Regional Development Bureau, and Ministry of Land, Infrastructure, Transport and Tourism for their cooperation in conducting the investigations reported in this study. In addition, the authors express their sincere gratitude for the financial support provided by the Japan Society for the Promotion of Science (Grant-in-Aid for 16H04412 and 20H02245).

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