The paper was published in the proceedings of the 11th International Conference on Scour and Erosion and was edited by Thor Ugelvig Petersen and Shinji Sassa. The conference was held in Copenhagen, Denmark from September 17th to September 21st 2023.

Statistical and Experimental Studies on the Hydraulic Conductivity of Levees in Relation to Micro-topographies

Wenyue Zhang,[1] and Akihiro Takahashi[2]

[1]Department of Civil and Environmental Engineering, Tokyo Institute of Technology, Tokyo, Japan; e-mail: zhang.w.al@m.titech.ac.jp
[2]Department of Civil and Environmental Engineering, Tokyo Institute of Technology, Tokyo, Japan; e-mail: takahashi.a.al@m.titech.ac.jp Corresponding author.

ABSTRACT

Micro-topographies in the alluvial environment, which characterize the layers under levees, have been pointed out to be related to a vulnerability against backward erosion piping. To reveal the characteristics of the micro-topographies, a statistical study was conducted on the hydraulic conductivity of the levees along the Kinu River in Japan. Discussions are made on the composition, richness, and reliability of the existing data by paying attention to types of soils in the alluvial environment and the difference between different micro-topographies. In addition to the existing data mostly estimated by the empirical equations based on grain size distributions, to obtain the in-situ hydraulic conductivity, the Guelph permeameter was applied on the levees of the Tama River and the Kinu River in Japan, from which confidence in applying the method to an alluvial environment was built, and limitations of the method were also found.

INTRODUCTION

It has been reported that the depositional features in an alluvial environment are largely related to Backward Erosion Piping (BEP, commonly referred to as piping) events (Dunbar et al. 2018). "Micro-topography" is a commonly used term referring to the geomorphic units with a spatial scale of 10^1 m and temporal scale of 10^3~10^1 years (Kaizuka 1958). In an investigation in the Kinu River in Japan after the 2015 Kanto-Tohoku Heavy Rainfall (MLIT 2016), it was found that 7 out of 9 spots where soil boiling occurred were located in the micro-topographies classified as "natural levee", which had been considered to provide seepage paths for the under seepage (JICE 2012). The combination of different micro-topographies with different hydraulic conductivity, and the heterogeneity within a micro-topography, are regarded to be critical factors related to BEP. Therefore, it is important to reveal the hydraulic characteristic of the micro-topographies.

To study the features of the micro-topographies, a statistical study was conducted on the levees along the Kinu River in Japan, from which it was revealed that the lack of reliable data from the in-situ tests largely limited quantitative discussion on the micro-topographies. To obtain complementary data, a simple in-situ permeability test was needed. As trials, in-situ tests using Guelph permeameter were performed on the levees of the Tama River and the Kinu River in Japan.

STATISTICAL STUDY ON THE HYDRAULIC CONDUCTIVITY OF LEVEES

Source of Data. Under the *Design Guideline for Levees* (MLIT 2017), systematic investigations were conducted on levees along the governmentally regulated rivers in Japan, during which boreholes were drilled, and basic soil tests were conducted on the collected samples. Based on the newly performed investigations and old documents, a database about the soil properties of levees was built, including (1) borehole logs, (2) the summary of soil testing results on the samples, and (3) the soil profiles showing the geological cross-section of the levees. The section between 0~53 km at the left and right banks along the Kinu River, where leakage events were reported, is selected as the target for the study. In the focused section, 344 borehole logs, 1140 soil samples, and 66 soil profiles are available in total.

In addition to the database, to include the information about the corresponding micro-topographies and the leakage events, the Landform Classification Map for Flood Control and the investigation report by MLIT (2016) are also referred to. By combining all the information above (Zhang and Takahashi 2022), a discussion can be made on the hydraulic characteristics of the levees.

Comparison between Different Estimating Methods. The distributions of the hydraulic conductivity estimated by different methods are shown in Figure 1. These are compiled from the hydraulic conductivities used for vulnerability assessment against piping by seepage analysis. Remarkably, hydraulic conductivity in the same location can be estimated by one or multiple methods. It is found that although the newest guideline (JICE 2012) recommends in-situ tests for the foundations and laboratory tests on the re-constituted samples for the embankment bodies, most of the hydraulic conductivities in the database are estimated by the empirical data based on grain size distribution.

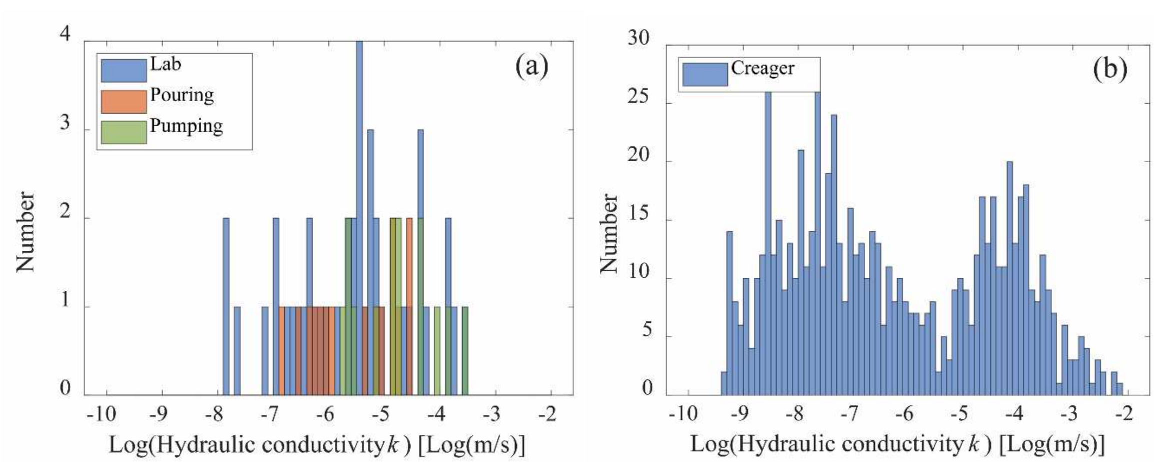

Figure 1. Hydraulic conductivities in the focused section estimated by (a) Laboratory seepage tests and in-situ permeability tests (Pouring method and Pumping method), (b) Creager's method.

Among the estimating methods in Figure 1, constant head or falling head laboratory seepage tests are usually conducted on disturbed samples (commonly with diameter D = 100 mm and length L = 120 mm) (JGS 2009). The pouring method and pumping method are the in-situ permeability tests during which the water table in boreholes is raised or drawn down (commonly with diameter D = 66~116 mm, and length of the testing region $L > 4D$) (JGS 1995). Creager's method, which is most widely applied in Japan (PWRI 2013), estimates hydraulic conductivity k (m/s) by:

$$k = \begin{cases} 0.36 D_{20}^{2.368} \times \frac{1}{100}, & if\ D_{20} > 0.03 \\ 0.0647 D_{20}^{1.885} \times \frac{1}{100}, & if\ D_{20} < 0.03 \end{cases}$$

where D_{20} is the 20% passing grain size (mm).

From Figure 1, it is found that the estimations by the pouring method tend to be smaller than the ones by the pumping method, which is regarded to be related to the smearing during the process of pouring water into the boreholes (Inazaki and Konishi 2010).

For a direct comparison between different estimating methods, the hydraulic conductivities estimated in the same depth in the same boreholes are picked out and plotted in Figure 2. Although the volume of data is limited, it is found that:

1. The estimations by Creager's method are comparable more to the laboratory seepage tests, while the in-situ seepage tests tend to give larger estimations. Although the results from in-situ tests are usually regarded to be more reliable in engineering practice, without a strictly designed experimental study with comparable conditions, conclusions cannot be made on which method represents the "true" hydraulic conductivity.
2. The laboratory and in-situ tests are mostly conducted on sandy soil. Given the required cost and labour, it is understandable that the tests were conducted only on the permeable layers believed to be related to seepage problems. However, without enough data, it is hard to ensure the applicability of the empirical equations on the finer materials.

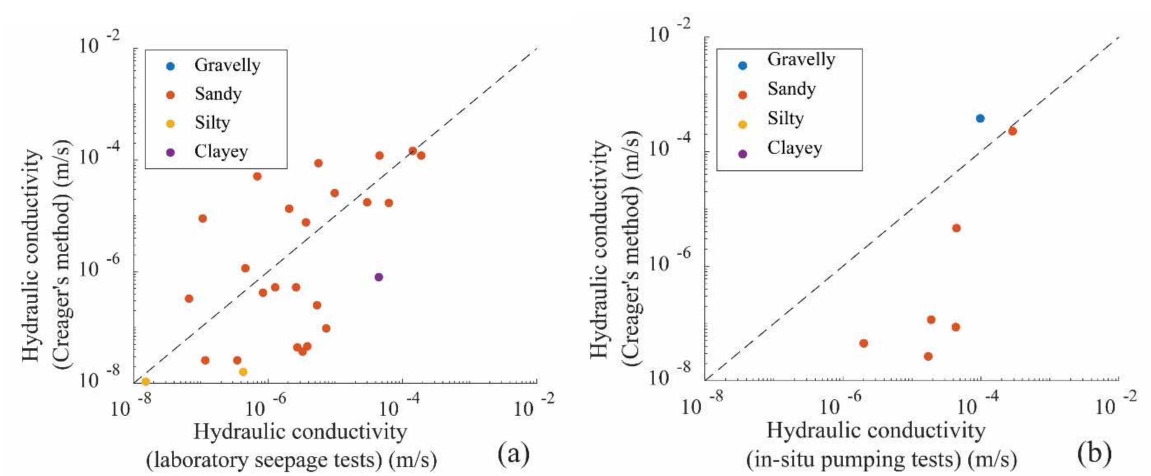

Figure 2. Comparison between different estimating methods: (a) Creager's method vs. laboratory seepage tests; (b) Creager's method vs. in-situ pumping tests.

Although the reliability of the over-simplified Creager's method cannot be ensured, considering the abundance of data, the discussions in the following are made based on the hydraulic conductivity estimated by Creager's method.

Hydraulic conductivity of Different Types of soil. Distributions of hydraulic conductivity estimated by Creager's method of different types of soil are presented in Figure 3. The foundations here indicate the natural foundation of the levees, while the embankment bodies indicate the artificial earthen structures. It is revealed that:

1. It is clearly shown in the figures that there are two "groups" of soil, (1) the clayey and silty soil, and (2) the sandy soil, corresponding to the two peaks in the distributions. This is similar to the discovery of Moriyama (1997) that in the grain size distribution of the natural levees in the Kiso River Alluvial Plain, the materials could be divided into the "sand population" coming from the crashed riverbed materials, and the "clay population" coming from the weathered materials from the mountainous areas. Although the relationship between the observations in two different flood plains cannot be clarified in this study, it is clear that certain grain size is gapped in around 0.03 mm of D_{20} in the alluvial deposits of the Kinu River, which is coincident with the gap of around 0.03 mm in the grain size distribution of the natural levee deposits in the Kiso River Alluvial Plain (Moriyama 1997).
2. The hydraulic conductivity of silty and clayey soil cannot be distinguished by Creager's method, which probably results from the oversimplified empirical equation that does not take the plasticity of soil into account.
3. Generally, there are more sandy and gravelly components in the foundations than in the embankment bodies, which have the potential to be the seepage paths leading to piping.

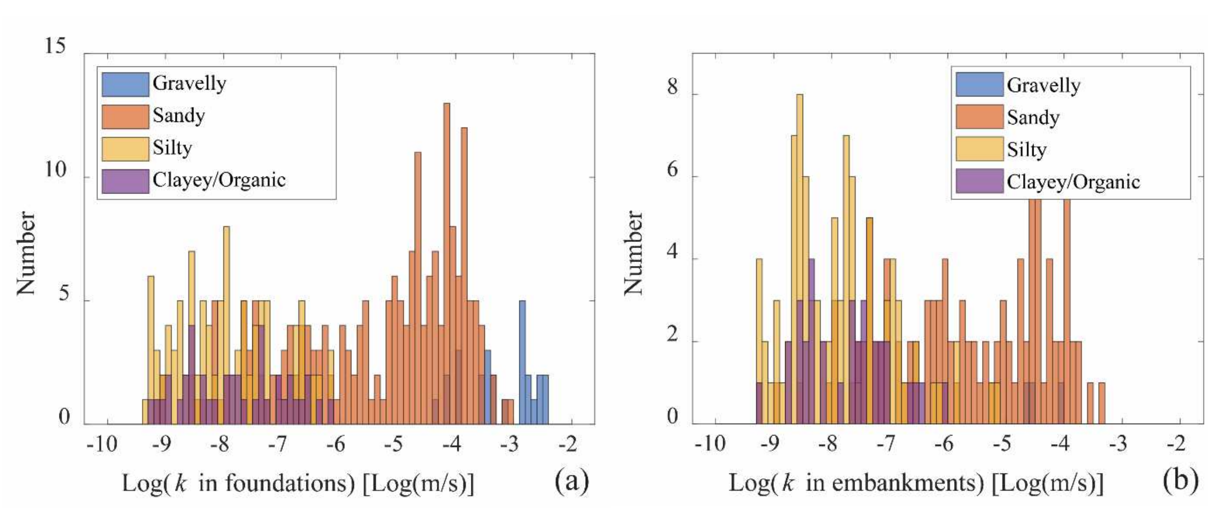

Figure 3. Distribution of hydraulic conductivity of different types of soil (a) in the foundations, and (b) in the embankment bodies.

Hydraulic Conductivity of different micro-topographies. To distinguish different micro-topographies, distributions of hydraulic conductivity (estimated by Creager's method) in natural levees (NL), flood plains (FP), and terraces (T) are presented in Figure 4. It is found that:

1. Distributions of hydraulic conductivity of different micro-topographies cannot be clearly distinguished. Since the micro-topographies only characterized certain deposit layers in the foundation while the samples are collected all along the boreholes, the distinction may only be possible if detailed investigations are conducted.
2. The "clayey population" and the "sandy population" exist in the deposits of natural levees and flood plains, while the terraces consist mostly of the "clayey population". The clayey materials in the terraces are regarded to be the volcanic-originated aeolian sediments called Kanto Loam (Research Institute of River Environment 2009).

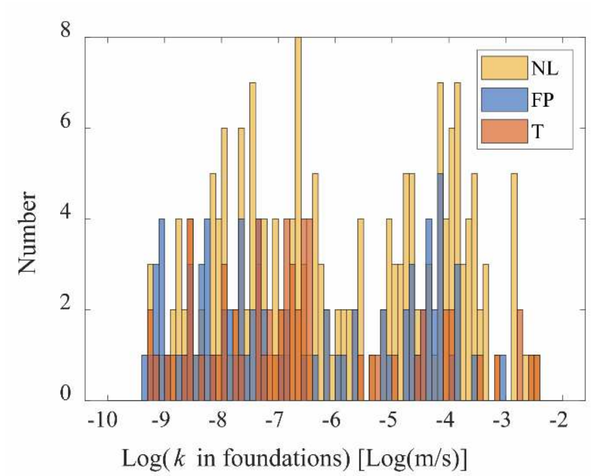

Figure 4. Distributions of hydraulic conductivity in the foundations of different micro-topographies.

IN-SITU EXPERIMENTS

As illustrated above, the abundance and accuracy of existing data cannot support further quantitative discussion on micro-topographies. To distinguish and characterize different micro-topographies, and to study heterogeneity and spatial distribution of hydraulic conductivity, in-situ data from multiple locations with sufficient spatial density are needed.

In-situ Testing Method for Hydraulic Conductivity. Given the amount of data in demand, time and labour are critical considerations when choosing the testing methods. The Guelph permeameter, which can be conducted by a single operator, requiring limited time (within tens of minutes), may be a reasonable choice for the study (MacDonald et al. 2012). As shown in Figure 5, by maintaining a constant head in the auger hole, a wetting zone develops around the auger hole. Glover's solution, which was derived by integrating the point source along the well axis, estimates the field saturated hydraulic conductivity k_s (m/s) by (Stephens 1979):

$$k_s = \frac{Q}{2\pi L^2}[\sinh^{-1}(L/r) - (1 + r^2/L^2)^{1/2} + (r/L)]$$

where Q (m^3/s) is the flow rate from the apparatus in the steady state, L (m) is the depth of water maintained in the auger hole, r (m) is the radius of the auger hole.

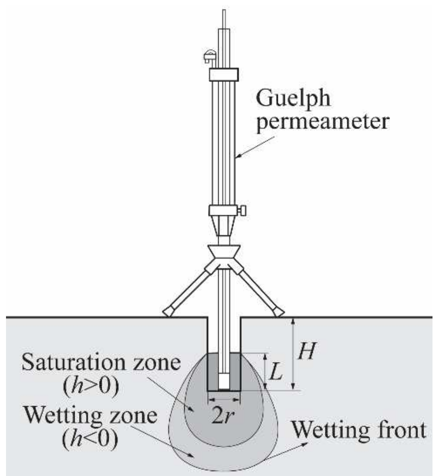

Figure 5. Illustration of the Guelph permeameter.

The Guelph permeameter is applicable in the unsaturated zone above the groundwater table, which is a common situation in the levees and the micro-topographies in the alluvial plain. By repeatedly deepening the auger holes and conducting the seepage tests, hydraulic conductivities along depth can be retrieved.

Despite all the advantages mentioned above, the applicability of the Guelph permeameter has still been argued, especially in clayey soil or in soil with high heterogeneity (Archer et al. 2014). However, most of the existing studies are conducted by researchers of agriculture, the targeting environments of which may not be directly comparable to the alluvial environments in this study. Therefore, it is important to verify the reliability of the method in the targeting environments before wide application.

Tests in the Tama River. In September 2021, trial tests were conducted at the river bank of the Tama River in Kanagawa Prefecture (Figure 6 (a)). The location noted as R 13.0k in the coordination system for rivers (right bank, 13.0 km, measured along the central line of the river from the estuary) is classified as natural levees based on the map. The Guelph permeameter was applied at the depths of 30, 50, and 70 cm in two auger holes with a radius r = 3 cm (Figure 6 (b)). In every depth, seepage tests with constant head L =5 and 10 cm were conducted in sequence. The soil in the tested location, classified as sand (S), was very soft, with a relatively homogeneous texture (Figure 6 (c)). The hydraulic conductivity was so large that all the seepage tests were finished within minutes. For comparison, undisturbed samples (H=120 mm, ϕ=100 mm) were also collected by the samplers made of polyvinyl chloride pipes (Figure 6 (d)) and were taken back to the laboratory for constant head seepage tests (JGS 2009).

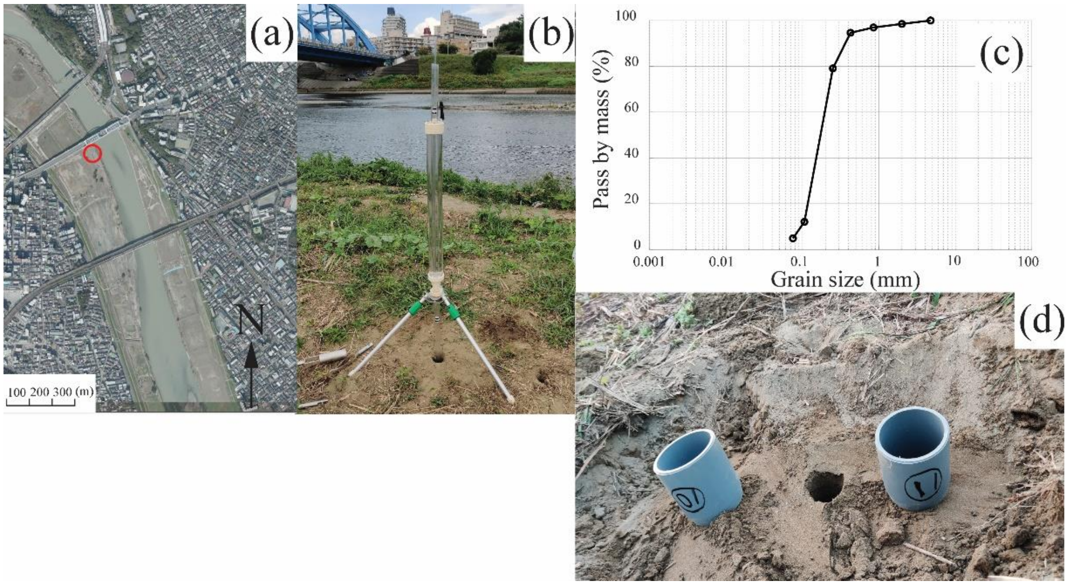

Figure 6. (a) The tested spot at R 13.0k of the Tama River, (b) application of the Guelph permeameter, (c) grain size distribution of the tested soil, (d) collection of undisturbed samples.

In Figure 7, hydraulic conductivity along depth in the two auger holes is estimated by the Guelph permeameter. A similar trend is found in the two auger holes, indicating a less permeable layer at the depth of around 50 cm. In the same location, the difference between the tests with $L =$ 5 and 10 cm is within 50%, which is much smaller than the difference between different depths or different auger holes. The results of the in-situ tests are close to the results of the laboratory tests in the shallow portion, all of which are larger than the estimations by Creager's method (around 2×10^{-5} m/s). The larger void ratio at the depth of 45 cm in the auger hole 1 leads to apparently larger hydraulic conductivity, which is possibly due to the disturbance in the sampling process. In general, the Guelph permeameter is regarded to be applicable in the sandy deposits of natural levees.

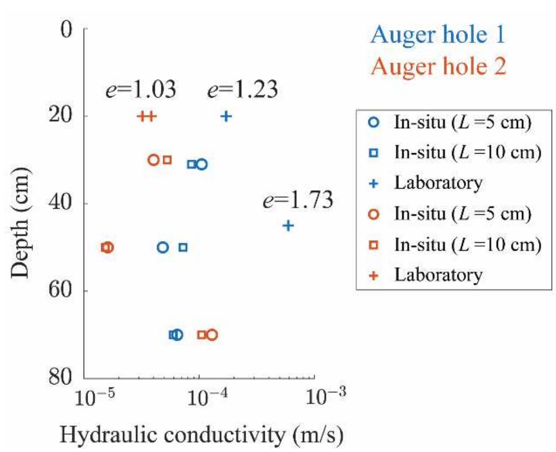

Figure 7. Hydraulic conductivities retrieved at R 13.0k of the Tama River

Tests in the Kinu River. In December 2021, the levee at L 29.0k (left bank, 29.0 km from the estuary) of the Kinu River in Ibaraki Prefecture was excavated out for the renewal of the sluiceway, during which investigation of the soil profile was conducted (Figure 8). At the exposed cross-section at the upstream side, two auger holes (r = 3 cm) were drilled, in which the Guelph permeameter was applied with constant head L = 10 and 20 cm. All the seepage tests were finished within 10 minutes. Both of the tested spots were regarded to be the embankment fills consisting of sandy silt (MLS) with low plastic Index I_p = 6~11. The soil was relatively soft, without apparent heterogeneity.

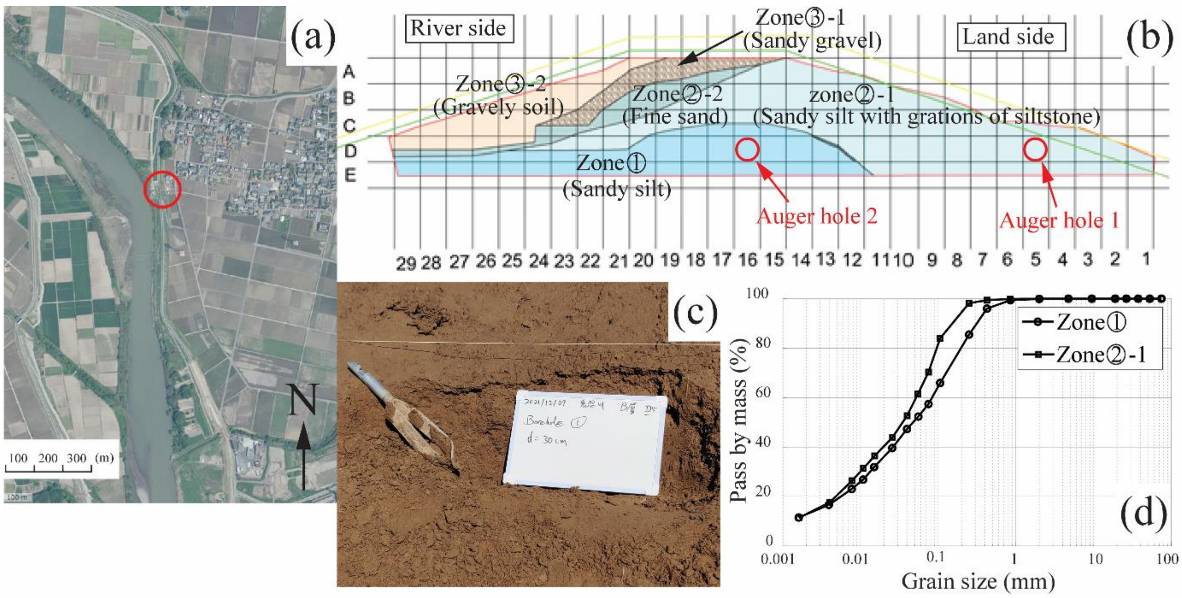

Figure 8. (a) The excavated levee at L 29.0k of the Kinu River, (b) sketching of the exposed cross-section at the upstream side, (c) the soil in Zone ○,2-1, and (d) grain size distribution of the tested soil.

The hydraulic conductivities estimated by the Guelph permeameter, as well as the results estimated by falling head laboratory tests using undisturbed samples by the Asano Taisei Kiso Engineering Cooperation at the corresponding zones, are summarised in Figure 9. Different from the cases in the Tama River where the water depth L of the in-situ tests has little effect on the result, hydraulic conductivity from the test with L = 10 cm can be 100% larger than the result from the test with L = 20 cm here. The tests with L = 20 cm were conducted in the same spots right after the tests with L = 10 cm, where the moisture of soil around the auger holes was larger than in the initial condition. Therefore, the difference is considered to be caused by the initial water content of in-situ tests, which may have larger effects in the finer soil than in the sandy soil. Hydraulic conductivities by laboratory tests are lower than the estimations by in-situ tests, but with less than an order of difference. All of the hydraulic conductivities by in-situ and laboratory tests are much larger than the estimation by Creager's method (around 10^{-8} m/s). In general, the Guelph permeameter is considered to apply to the sandy silt used in the embankment fills of levees.

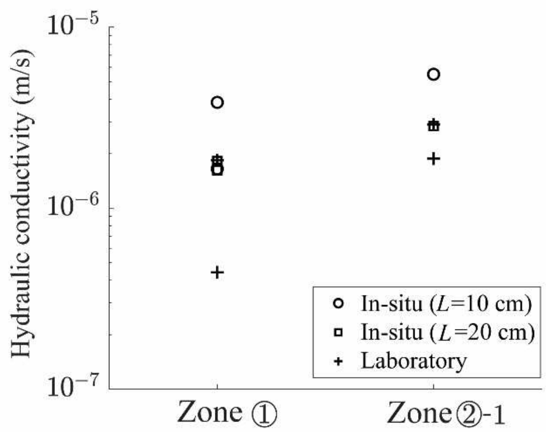

Figure 9. Hydraulic conductivities retrieved at L 29.0k of the Kinu River

CONCLUSIONS

By collecting data from the database, discussions have been made on the hydraulic characteristics of levees related to micro-topographies. Due to the limitation of existing data, trail tests were conducted to get the in-situ hydraulic conductivity using the Guelph permeameter. It is concluded that:

1. Most of the hydraulic conductivities in the existing database for vulnerability assessment against piping by seepage analysis are estimated by the empirical Creager's method, which cannot distinguish silty and clayey soil. The lack of laboratory and in-situ seepage tests, especially in the finer soil, weakens the confidence in the existing data.
2. Although distinctions cannot be made between different micro-topographies due to the lack of details of the existing data, the discovery by geologists about the "clayey population" and the "sandy population" in the alluvial deposits is confirmed. By analysing the ratio of the two populations, stories may be told about the formation of alluvial plains.
3. For the sand in the bank of the Tama River and the sandy silt in the embankment body of the Kinu River, the Guelph permeameter can give reasonable results in a short time. Although variation can be induced by various factors like the initial water content of the soil, scale effects, or heterogeneity, estimations by the Guelph permeameter for the targeted soil are considered to be applicable for engineering practice.
4. More studies on the applicability of the Guelph permeameter are undergoing, including trial tests in other types of soil and figuring out the methods to drill deeper auger holes through the gravelly layers. With more confidence in applying the Guelph permeameter in the targeting environment, a series of in-situ tests are to be done, based on which discussion on the hydraulic characteristics of micro-topographies can be made.

REFERENCES

Archer, N. A. L., Bonell, M., MacDonald, A. M., & Coles, N. (2014). "A constant head well permeameter formula comparison: its significance in the estimation of field-saturated hydraulic conductivity in heterogeneous shallow soils.", *Hydrology Research*, *45*(6), 788-805.

Dunbar JB, Ensign AL, Torres N, and Corcoran MK. (2018). "Analysis and Comparison of Documented Seepage and Sand Boil Events on the Lower Mississippi River from 1937 to 2011." Volume 1, Main text. USACE. <http://hdl.handle.net/11681/28597> (Jan. 10, 2022).

Fukuda, M., & Uno, T. (1997). "Roles of mean pore size index and grain size distribution in permeability phenomenon." (In Japanese), *Proceedings of JSCE*, (561), 193-204. <https://doi.org/10.2208/jscej.1997.561_193> (Jan. 10, 2022).

Inazaki, T. and Konishi, C. (2010). "Relationship between permeability and grain size characteristics of substrata of levee systems." (in Japanese), *Advances in River Engineering*, *16*, 377-382. <http://library.jsce.or.jp/jsce/open/00906/2010/16-0377.pdf> (Jan. 10, 2022).

JGS (Japanese Geotechnical Society). (1995). *Japanese Geotechnical Society Standards: Geotechnical and geoenvironmental investigation methods*, Maruzen Publishing.

JGS. (2009). *Japanese Geotechnical Society Standards: Laboratory testing standards of geomaterials* (In Japanese), Maruzen Publishing.

JICE (Japan Institute of Country-ology and Engineering). (2012). *Guideline for the structural evaluation of levees* (in Japanese), <http://www.jice.or.jp/cms/kokudo/pdf/tech/material/teibou_kouzou02.pdf> (Jan. 10, 2022).

Kaizuka, S. (1958). "Landform Evolution of the Kanto Plan." (In Japanese), Geographical Review of Japan, 31(2), 59-85. < https://doi.org/10.4157/grj.31.59> (April. 3, 2023).

MacDonald, A. M., Maurice, L., Dobbs, M. R., Reeves, H. J., & Auton, C. A. (2012). Relating in situ hydraulic conductivity, particle size and relative density of superficial deposits in a heterogeneous catchment. *Journal of Hydrology*, *434*, 130-141.

Moriyama, A. (1977). "Grain size distributions of surface sediments of the Kiso River alluvial plain." (In Japanese), *Geographical Review of Japan*, *50*(2), 71-87, <https://doi.org/10.4157/grj.50.71> (Jan. 10, 2022).

MLIT (Ministry of Land, Infrastructure, Transport and Tourism). (2016). "Materials for the 4th Technical Committee on the Kinu River Dike: Report for the detail investigation of the leakage spots in the levees" (in Japanese), <https://www.ktr.mlit.go.jp/ktr_content/content/000642509.pdf> (Jan. 10, 2022).

MLIT. (2017). *Design Guideline for Levees* (in Japanese), <https://www.mlit.go.jp/river/shishin_guideline/bousai/gijyutukaihatu/pdf/teibou_sekkei.pdf> (Jan. 10, 2022).

PWRI (Public Works Research Institute). (2013). *Points for the examination and design of levees against seepage* (In Japanese), <https://www.pwri.go.jp/team/smd/pdf/syousasekkei_point1306.pdf> (Jan. 10, 2022).

Research Institute of River Environment. (2009). "Study on the channel properties and channel regulation of the Kinu River: The river with exposed diluvium", The River Foundation, < https://www.kasen.or.jp/Portals/0/pdf_kasen03/study02b_25.pdf> (Nov. 10, 2022).

Stephens, D. B. (1979). Analysis of constant head borehole infiltration tests in the vadose zone.

Zhang, W. and Takahashi, A. (2022). "Statistical and parametric studies on natural levees as weak points against leakages in river levees", *Geotechnical and Geological Engineering* 40 (11), 5643-5666.