Sensors and Materials, Vol. 34, No. 11 (2022) 4223–4235
MYU Tokyo

S & M 3107

Development and Verification Experiment of Ultrasmall-pore Water Pressure Gauge by Laboratory and Full-scale-model Levee Experiments

Shunzo Kawajiri,[1*] Naoya Momohara,[2] Masato Sakurai,[2] Akinobu Ogasawara,[3]
Keigo Koizumi,[4] Dai Nakamura,[5] and Takayuki Kawaguchi[5]

[1]Graduate School of Engineering, Kyushu Institute of Technology,
1-1 Sensui-cho, Tobata-ku, Kitakyushu, Fukuoka 804-8507, Japan
[2]OYO Corporation, 43 Miyukigaoka, Tsukuba, Ibaraki 305-0841, Japan
[3]National Institute of Technology, Toyota college, 2-1 Eiseicho, Toyota, Aichi 471-0067, Japan
[4]Graduate School of Engineering, Osaka University, 2-1 Yamadagaoka, Suita, Osaka 565-871, Japan
[5]Faculty of Engineering, Kitami Institute of Technology, 165 Koen-cho, Kitami, Hokkaido 090-8507, Japan

(Received September 22, 2022; accepted November 7, 2022)

Keywords: levee, pore water pressure, sand boil, LPWA

In recent years, levees have been collapsing and residents have been being robbed of their lives and properties almost every year in Japan. For soil levees, the fluctuation of the pore water pressure in the ground is a dominant parameter of their weakening. The multipoint monitoring of the pore water pressure in a levee allows us to grasp the risk of levee collapse directly. In this study, we developed a new ultrasmall-pore water pressure gauge (UPWP gauge) whose production cost and power consumption are lower and whose installation is easier than those of commercially available pore pressure gauges. We performed basic laboratory experiments for this UPWP gauge and pooling experiments for a full-scale-model levee and assessed their performance. Our results revealed that the errors of the values measured using the UPWP gauge in the laboratory test were within ±15 mm for the set water levels. Furthermore, in the verification of the full-scale test levee, the elevation process, and the maximum pore water pressures of the UPWP and the existing pore pressure gauges were in good agreement.

1. Introduction

Several lives were lost by levee collapses caused by floods during heavy rain disasters in Tohoku and Kanto in 2014,(1) Hokkaido in 2016,(2) West Japan in 2018,(3) and North Kyushu in 2020.(4) Scenes of residents in muddy streams being rescued by helicopters and boats with great risks to life are seen every year in Japan. Under such a background, the Ministry of Land, Infrastructure and Transport, in 2018, started to promote the installation of low-cost river water gauges, mainly on small- and medium-sized rivers from which sufficient water-level information has not been obtained. A system to quickly identify community residents with a smartphone through a web portal site using the information obtained from the river water gauge has been

---

[*] Corresponding author: e-mail: kawajiri.shunzo644@mail.kyutech.jp

https://doi.org/10.18494/SAM4130

ISSN 0914-4935

established. However, during the heavy rain caused by Typhoon 19, which hit the Kanto, Koushinetsu, and Tohoku districts in 2019,(5) flood damage due to simultaneous levee collapses at 140 locations along 71 rivers in seven prefectures again caused suffering to many people. This fact suggests that river levels alone are insufficient as evacuation information in the event of a levee collapse.

The fluctuation of the pore water pressure in the ground is a major parameter of the weakening of a levee made of soil.(6,7) Although the importance of such pore water pressure observation was recognized, only a few examples of the pore water pressures of actual levees and their utilization as evacuation information have been found.(8) This is because of the cost of installing plural pore water pressure observation systems in a levee, which is a long structure. However, the multipoint monitoring of the pore water pressure in a levee allows us to grasp the risk of levee collapse directly. It is expected that the combination of pore water pressure data, which directly reflects the weakness of a levee, and the conventional river water level information will allow a more rational provision of the timing of evacuation. Taking such a background into consideration, in this study, we aim to observe the pore water pressure of a levee at multiple points using an all-weather pore pressure gauge that is smaller and whose production cost and power consumption are lower than those of conventional devices, to build an observation network that transmits data to a river manager automatically from a distant place and to establish a system for visualizing of the risk of levee collapse using this observation network.

As a basic study, we have developed a new ultrasmall pore water pressure gauge (UPWP gauge) whose production cost and power consumption are lower and installation is easier than those of commercially available pore pressure gauges. In this paper, we report the results of a laboratory verification test to confirm the basic performance of our UPWP gauge and the results of the verification of the full-scale-model levee conducted with actual installation of the gauge in real levees in mind.

2. Prototype of UPWP Gauge and Verification Basic Experiment

Figure 1 shows the two prototype UPWP gauges that we produced for verification by laboratory experiments. Figure 2 shows the schematic circuit diagram of Type 1, including the

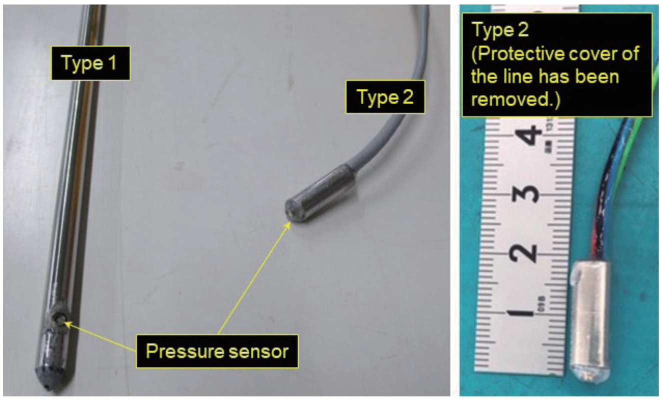


Fig. 1. (Color online) Prototype UPWP gauges used in laboratory validation.

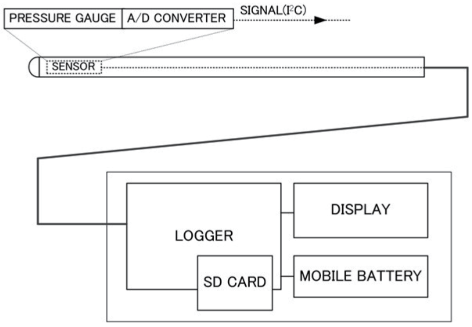


Fig. 2. Schematic of electric circuit of Type 1.

data recorder and display for the basic verification test. In Type 1, the sensing part of the pressure gauge of around 3.3 mm diameter is attached to the side around the tip of a stainless-steel rod of about 8 mm diameter. Type 1 was produced under the assumption that the whole stainless-steel rod is inserted into the ground structure already built. The basic configuration of Type 2, such as the electric circuit, is the same as that of Type 1. However, the sensing part is attached further downward, on the lower part of a stainless-steel capsule of 20 mm length, and the surrounding of the pressure gauge is coated with silicon gum. Type 2 is a prototype produced under the assumption that the UPWP gauges are installed during the construction of the ground structure. Figure 3 shows the pressure sensors attached to Types 1 and 2. Table 1 shows the main specifications of the pressure sensor. In this study, an ultracompact pressure sensor of around 2 mm diameter was adopted. Water entry into the stainless-steel rod and capsule was prevented by attaching an O-ring to this pressure sensor. Moreover, since energy-saving pressure sensors were used for this study, the power consumption of the UPWP gauge produced experimentally was 0.09 mW. Since the power consumption of the existing pore pressure gauge verified in the full-scale test levee (to be discussed later) is 144 mW, the power consumption of the UPWP gauge is one-1600th, which is superlow, that of commercially available gauges. Figure 4 shows an outline of the verification experiment conducted in the laboratory. In this experiment, the Type 1 and Type 2 UPWP gauges were installed and fixed in a tank in which the amount of degassed water can be varied. Then, an arbitrary water level in the tank was set and water pressure was measured with the UPWP gauges. The power source of the UPWP gauges was a mobile battery, and measurement was performed with a small logger that records voltage values. In this verification experiment, we compared pressure values measured using the UPWP gauges at various water levels between 50 and 900 mm in the tank with the set water levels. Figure 5 shows the set water levels in the tank and the water levels calculated from the water pressure measured with the UPWP gauges. For the water levels measured in the tank and those calculated from the water pressure measured with the UPWP gauges, the error is around ±2% regardless of the increase or decrease in the water level of the tank. Figure 6 shows the difference between the set water levels and the water levels measured in the tank. This result shows that the measured values are smaller than the set water levels when ushing Type 1, on which the sensing face of the pressure gauge was attached to the side. However, the difference between the measured values

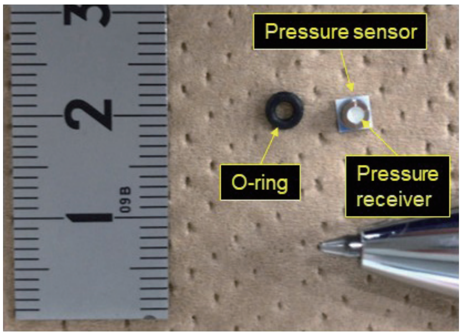


Fig. 3. (Color online) Pressure sensor and O-ring.

Table 1
Specifications of digital pressure sensor module.

Product type and features	Board level pressure sensor type: digital pressure and altimeter sensor modules Board level pressure sensor style: absolute
Electrical characteristics	Board level pressure sensor supply voltage: 1.5–3.6 V
Dimensions	$3.3 \times 3.3 \times 2.75$ mm^3
Usage conditions	Pressure: 200 kPa Operating temperature range: −20–85 ℃
Operation/application	Output interface: I2C, I²C or SPI Proof pressure range: 10 kPa Output/span: 24 bit ADC Board level pressure sensor accuracy: ±0.05
Packaging features	Board level pressure sensor package: surface mountable

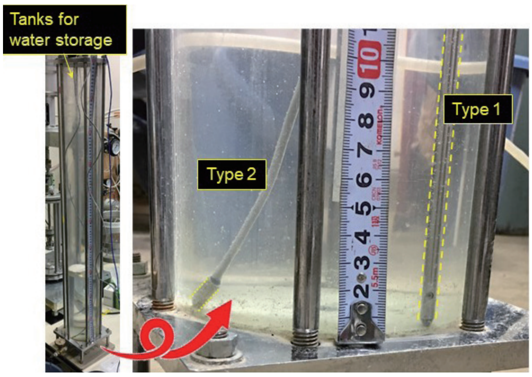


Fig. 4. (Color online) Setup of laboratory equipment.

and the set water levels is within ±0.015 m for both Types 1 and 2. Here, the heights of levees that collapsed in recent floods in Japan were approximately 4000,(1) 7000,(3) and 5000 mm.(5) In these examples, the difference between the measured values for the levee heights examined in this study was around 0.38% at maximum (=15/4000 × 100%); therefore, the error of the measured values for the levee heights is small. Although the pressure sensor can resist pressures

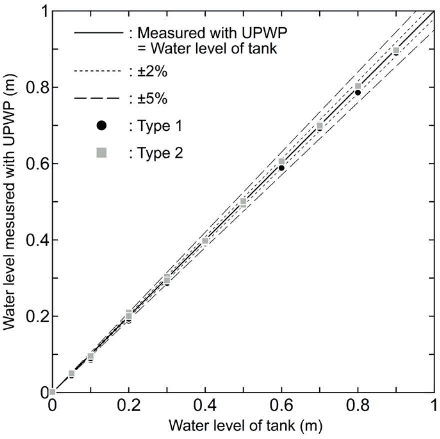


Fig. 5. Set water levels in tank and water levels calculated from water pressure measured with UPWP.

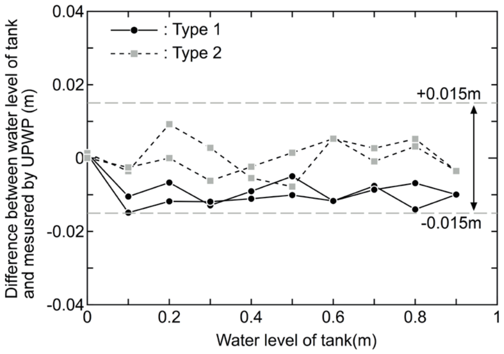


Fig. 6. Difference between set water levels and measured water levels of the tank.

of 200 kPa (approximately 20 m depth), it is necessary to evaluate the performance of the UPWP gauge at greater depths in the future.

The presence of air around the water pressure sensor part is one of the origins of the error when measuring pore water pressure in the ground.(8) When the air volume around the pressure-sensing part is large, water pressure changes in the ground are offset by air compression, which causes errors in the measured values. The local air drift caused by air around the pressure-sensing part may be of concern depending on the shape of the water pressure gauge. Therefore, in this study, the authors attempted to observe the vicinity of the pressure-sensing part of the UPWP gauges through the observation of the inner structure of the ground by X-ray CT scanning. Figure 7 shows a schematic illustration of the test apparatus and a photograph of the testing system. The Type 2 UPWP gauge was set in the measuring cylinder with gravel soil (maximum grain size $D_{\max}$ = 4.75 mm) and silica sand No. 4 ($D_{\max}$ = 2 mm) [Fig. 7(a)]. Then, the inside was observed by X-ray CT scanning with water supplied into the measuring cylinder via a water pipe [Fig. 7(b)]. The X-ray CT scanner used in this experiment was inspeXio SMX-225CT.(10,11) Figure 8(a) shows an X-ray CT scanning image obtained from the vicinity of the center part of the UPWP gauge. The black parts in this CT scanning image indicate regions with high material density and the white parts indicate those with low material density. This CT scanning image shows that the ground material is uniformly distributed around the UPWP gauge. Furthermore, the UPWP gauge developed for this study is simple and consists of few parts; therefore, we believe that the risk of failure is low. Next, Fig. 8(b) shows the void part with the lowest density in the image obtained by the three-dimensional reconstruction of the image shown in Fig. 8(a) followed by image processing. Since CT scan images are digital, the cavity part can be detected by image processing. The black region in Fig. 8(b) is the cavity part.(10,11) A cavity is detected around the pressure-sensing part in Fig. 8(b), although its volume is small. From this, we infer that water pressure in soil is measured with the pressure-sensing part. On the

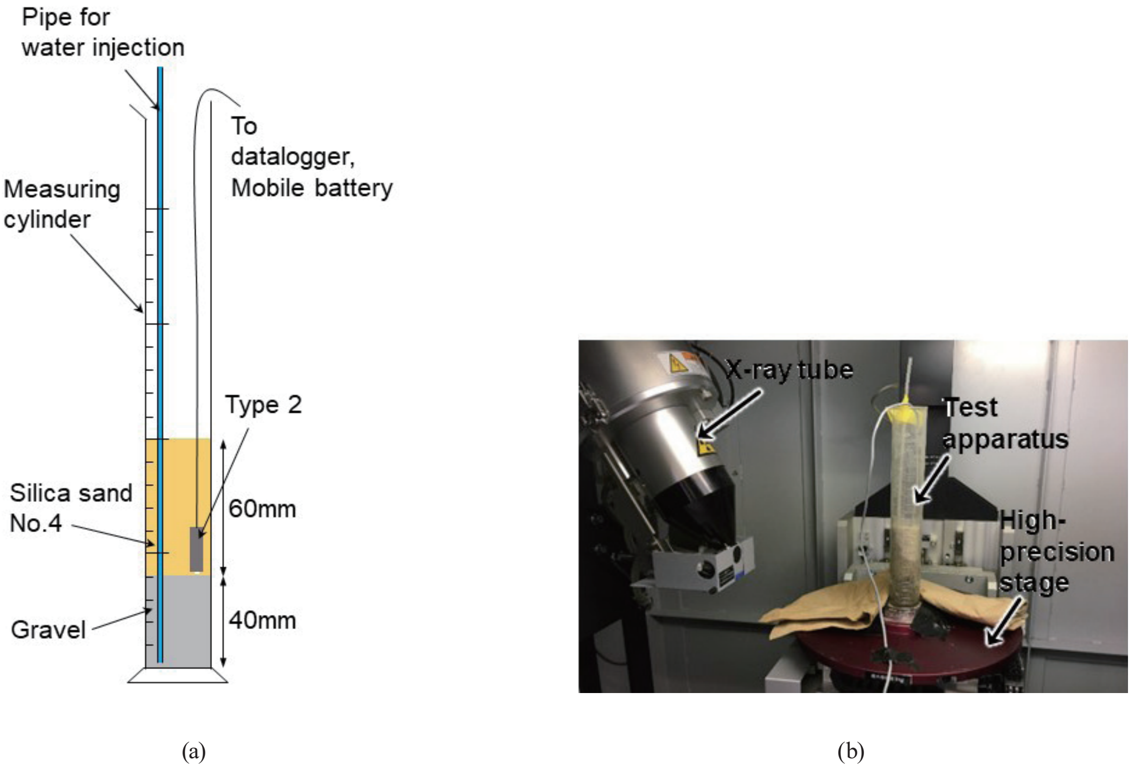


Fig. 7. (Color online) (a) Schematic illustration of test apparatus. (b) Photograph of testing system.

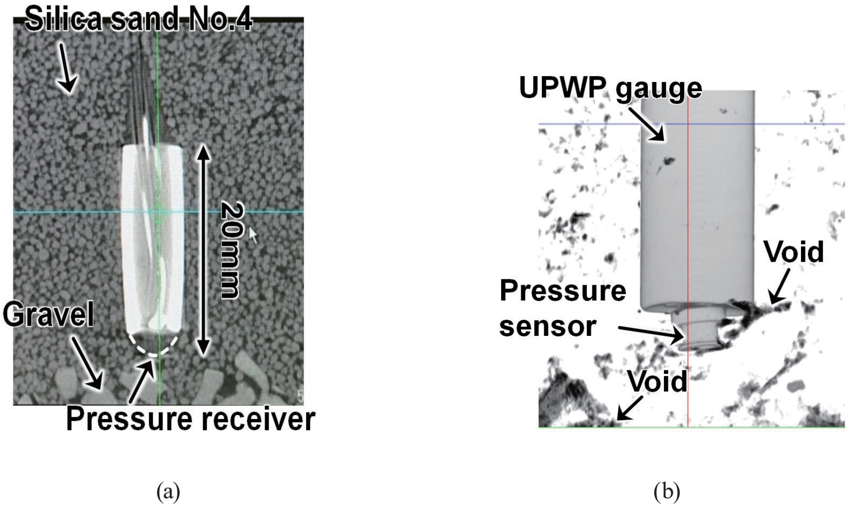


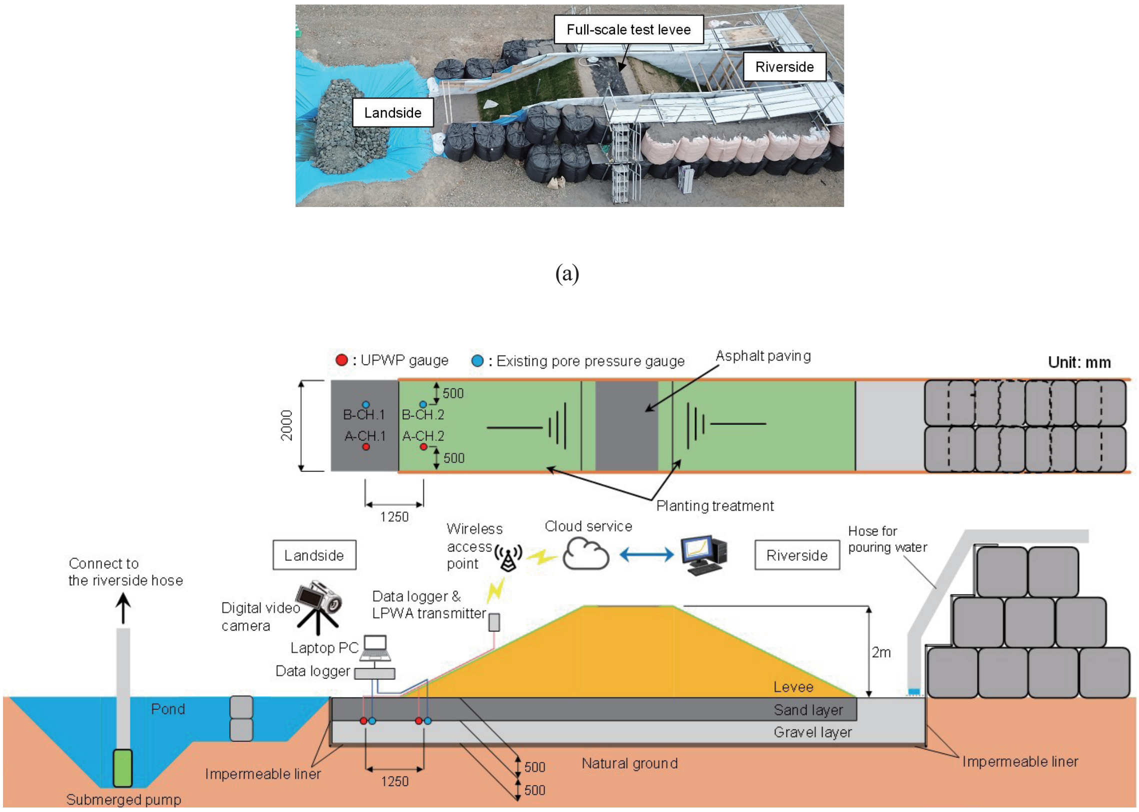
Fig. 8. (Color online) Results of X-ray CT scanning. (a) Vertical cross section of CT image. (b) Reconstructed 3D image around UPWP gauge.

basis of the above result, it is judged that the prototype UPWP gauge has sufficient accuracy for practical application, which was verified under conditions close to those of an actual levee using the full-scale test levee.

3. Verification Experiment of UPWP Gauge Using Full-scale Test Levee

3.1 Outline of full-scale test levee

The performance of the UPWP gauge for only water and an extremely small ground model was confirmed by basic verification experiment. The result revealed that the UPWP gauge is capable of measuring pore water pressure in soil with acceptable accuracy for practical use. Next, we built a full-scale test levee and observed pore water pressure behaviors in the levee using the UPWP gauge in a pooling experiment, assuming the installation of the UPWP gauge in a real levee. Figure 9 shows the test levee used in this study: (a) overview of the test levee and (b) positions of the measurement devices. Furthermore, Fig. 10 shows the grain size distribution of the geomaterials used to construct of the test levee. "Percentage finer" on the Y-axis in Fig. 10 is the ratio of the amount of particles above a certain size to the total amount of particles. The test levee in this study is 2 m in height, 13 m in width, and 2 m in depth with a slope gradient of 1:2. The dimensions of the levee body and the ground material used this test levee are based on the construction manual for levees in Japan.$^{(12)}$



(a)

(b)

Fig. 9. (Color online) Photograph and schematic illustration of full-scale test levee. (a) Overview of test levee. (b) Cross section of test levee and PWP gauge locations.

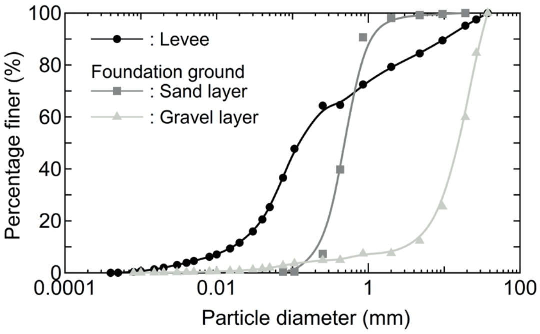


Fig. 10. Grain size distribution of test levee and foundation ground.

Here, backward erosion piping (BEP) is one of the failure forms of a levee at the time of a flood. Figure 11 shows a conceptual diagram of the occurrence mechanism of BEP.(13) Water pressure acts on the foundation ground of the levee when the river level rises during a flood, resulting in the internal erosion of the foundation ground. When the river water level is maintained high, the extent of internal erosion expands and the levee, losing foundation ground, finally collapses. In levee collapse due to BEP, the risk of collapse may reach a critical level before the visually identifiable overflow of the levee. Therefore, the evacuation of residents living near the levee may be critically delayed in some cases. In recent years, this phenomenon has been seen often in Japan where floods frequently occur. On the other hand, sand boiling often occurs on the land side as a precursory phenomenon of BEP. Figure 12 shows sand boiling during an actual flood.(2) In the event of sand boiling, it is expected that great pore water pressure, which is a driving force behind spouting of the soil in the foundation ground out to the ground, will act upward. Therefore, in this experiment, we observed the pore water pressure on the land side at the time of sand boiling using the UPWP gauge. It has been reported that BEP and sand boiling easily occur when the foundation ground of the levee consists of sand and gravel. Therefore, in this study, we set the soil configuration of the foundation ground shown in Fig. 9 on the basis of data of levee soil from a disaster area in a previous flood. Increases and decreases in river water levels in the experiment were reproduced by drawing water from a pond created near the land side and pouring it into the river side with a pump. The hourly variation of the river water levels was set by referring to the water-level fluctuations during floods that caused BEP and sand boiling in the past. Figure 9 shows installation locations of the UPWP gauges. The UPWP gauges were set in the central part of the land side and the foundation ground on the lower side of the levee toe. Moreover, existing commercially available pore pressure gauges were set at different locations to enable the comparison of observed data. The soil of the test levee is less uniform than the soil layer used in the laboratory experiment and large stones may exist locally. Therefore, we improved the Type 1 gauge to prevent breakage and called it Type 3 [Fig. 13(a)]. Type 3 has internal wiring of higher total rigidity and strength as a measurement instrumentation; hence, its diameter is 10 mm. For the installation of a UPWP gauge to the full-scale test levee, a hole of approximately 10 mm diameter was prepared beforehand and a UPWP gauge was inserted into it [Fig. 13(b)]. The capacity of the existing pore

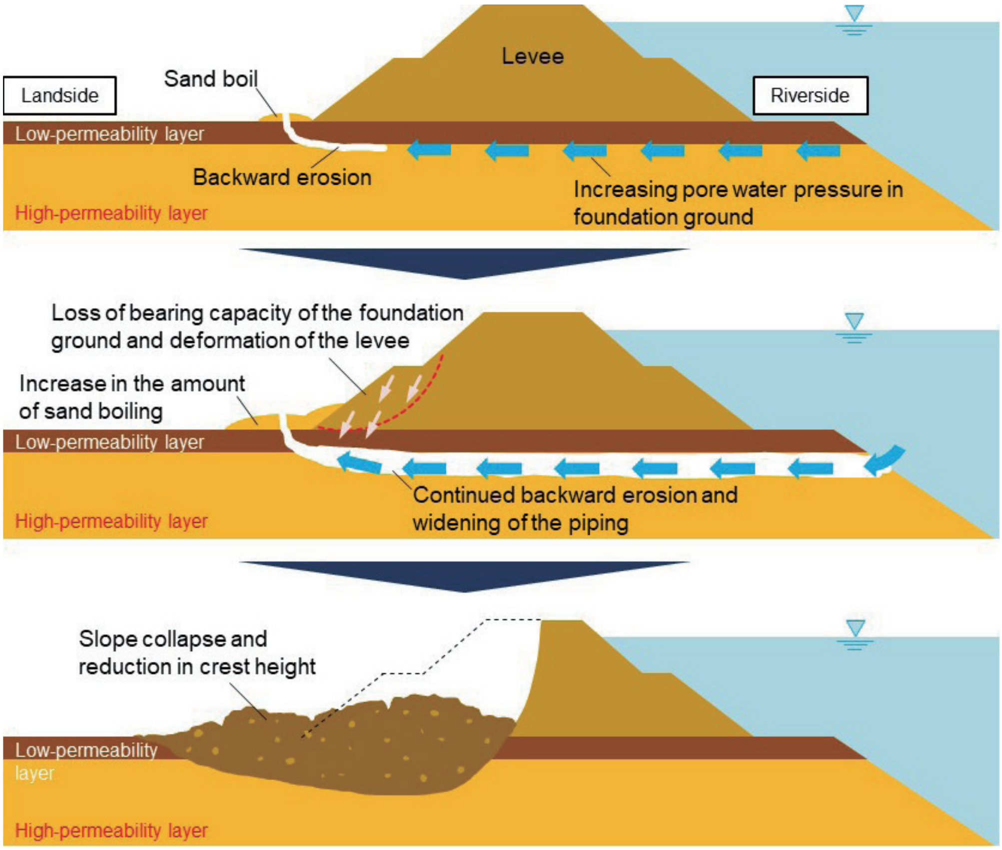
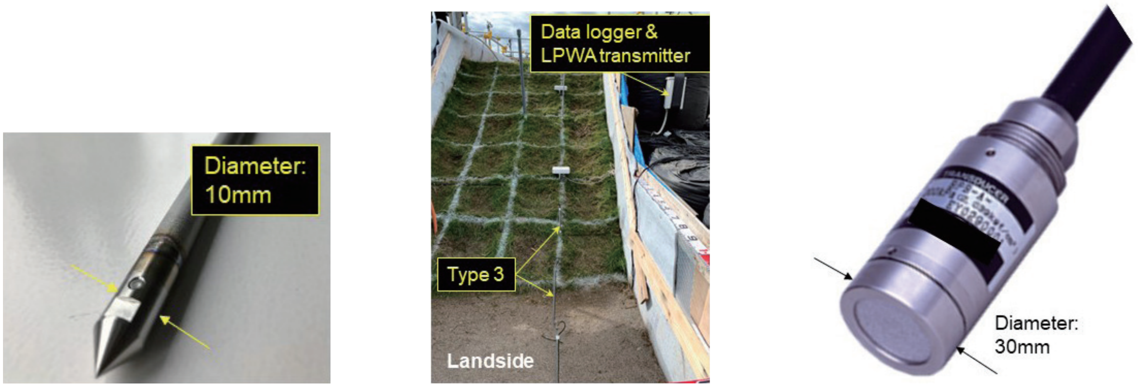


Fig. 11. (Color online) Illustration of the process of backward erosion piping.

Fig. 12. (Color online) Sand boiling at Tokoro river, Hokkaido, Japan.

pressure gauge (B-Ch.1, B-Ch.2) is 200 kP, and its diameter is 30 mm [Fig. 13(c)]. Filters consisting of porous metal are attached to the water pressure-sensing part. For this pore pressure gauge, a laptop PC was connected to a data logger that was connected to a 100 V power supply, and data were acquired at the measurement interval of 1 s. Cordless handsets of low-power-



(a) (b) (c)

Fig. 13. (Color online) PWP gauge used in full-scale model levee experiment. (a) UPWP gauge Type 3. (b) Installation of Type 3. (c) Existing PWP gauge.

wide-area (LPWA) communication(14) were attached to A-CH.1 and A-CH.2 of the UPWP gauges to ensure low power consumption, and observation was performed with lithium batteries as the electric source.(15) In other words, the commercial power supply of 100 V is not needed for the UPWP gauge. Furthermore, since there was a limit of the daily channel capacity in the LPWA communication used in this experiment, the measurement interval was set to 15 min in the experiment. The measurement results of the UPWP gauges are seen in real time from a distant location through a web portal site.

3.2 Results and discussion

Figure 14 shows the change in pore water pressure u_w at the center of the land side ground and the toe of the slope on the land side. u_w of the toe of the slope on the levee side increased with the river water level, followed by an increase in u_w at the levee ground, regardless of the pore pressure gauge classification. This tendency was seen in both the first and second river water level elevations. The timing at which u_w of the UPWP gauge began to increase is earlier than that in this case of the existing pore pressure gauge at the first river water level elevation. On the other hand, at the second river water level elevation, the difference in the timing of the increase in u_w is smaller. Since a filter made of porous metal is attached to the pressure-sensing part of the existing pore pressure gauge, the filter needs to be filled with water to allow the pressure to be measured as water pressure: this causes a time delay. On the other hand, since the pressure-sensing part of the UPWP gauge is exposed, its response to water pressure is faster than that of the existing pore pressure gauge. The comparison of the maximum values of u_w at the time of the first elevation of the river water level revealed that the UPWP gauge detected u_w larger than that detected with the existing pore pressure gauge by around 1 kN/m^2 in the levee ground. We infer that this was because the filter of the existing pore pressure gauge was not filled with water in the initial stage of the experiment and included air, which reduced u_w

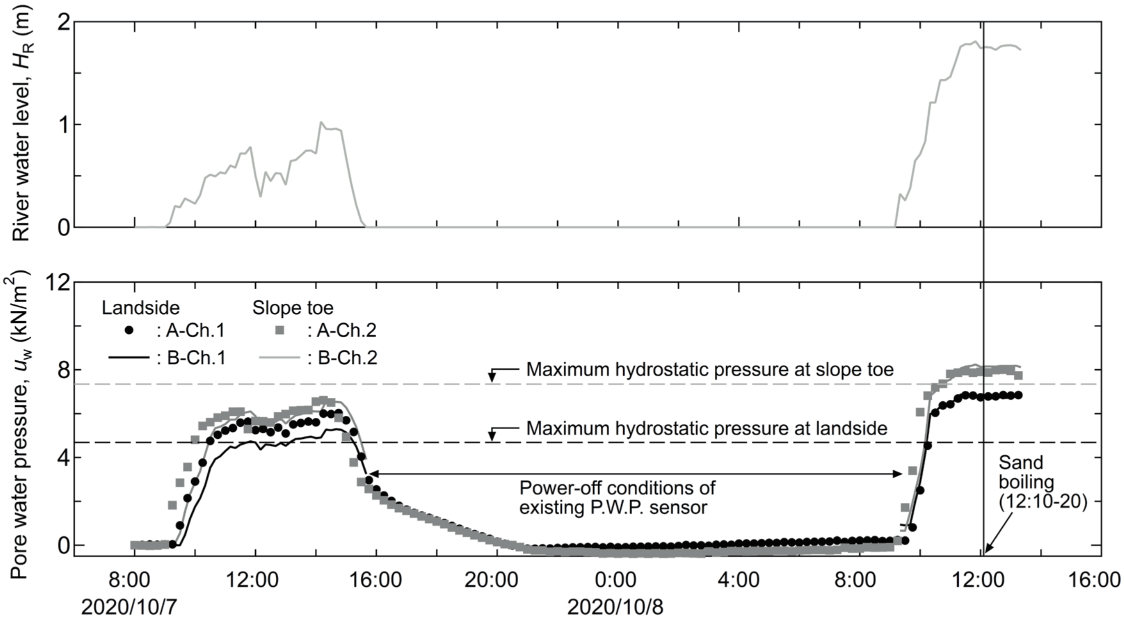


Fig. 14. Measured pore water pressure and river water level.

measured with the existing pore pressure gauge. Furthermore, the difference in the measurement result of around 1 kN/m^2 corresponds to around 0.1 m, which we presume to not affect the estimation of water levels in high levees.

At the time of the second elevation of river water levels, the elevation processes and maximum values of u_w of the UPWP and existing pore pressure gauges are in good agreement regardless of the observation points. This is because the adhesion of soil to both types of pore pressure gauges was improved by the first elevation of u_w and the filter of the existing pore water pressure gauge was filled with water. From the results of this experiment, we judged that the UPWP gauge has performance equal to that of the existing pore pressure gauge. In addition, it was revealed that for the UPWP gauges, which do not have filters of porous metal, it is not necessary to consider the effects of water in the filter, and hence, the interpretation of its measured data is easier than that in the case of the existing pore pressure gauge.

Figure 15 shows an enlarged view of the levee ground at the time when sand boiling was observed in the experiment. A large amount of air gushed out at around 12:10. A small sand hill was formed at the location of gushing air. There was a hollow in the central part of the sand hill, and sand gushing out of the hollow part was eventually clearly observed (at around 12:20). After that, at 13:45 on Oct. 8 when the maximal H_R was continuously observed, a sand hill formed by the sand boiling first identified at around 12:20 was combined with a new sand hill formed in its vicinity, resulting in even greater sand boiling and a larger sand hill. u_w at the time of occurrence of such sand boiling greatly exceeded the hydrostatic pressure shown in Fig. 14, reflecting the state that the soil of the foundation ground gushed out to the surface. In this study, we demonstrated that a system in which a UPWP gauge and LPWA are combined is effective for observing the increase in pore water pressure in the ground to a value higher than the hydrostatic

Fig. 15. (Color online) Process of sand boil occurrence in test levee.

pressure. On the basis of the results above, the authors aim to build up multipoint observation networks for pore water pressure by installing plural UPWP gauges in river levees that are currently in service.

In recent years, the installation of river water gauges has rapidly progressed in river levees in Japan in response to the increase in flood damage. Since the levees consist of soil, their material properties vary greatly. Therefore, it is necessary to install more pore pressure gauges than the number of existing water gauges in order to monitor water levels and measure river water levels that act as external force. We believe that the construction of such a system and the combination of early detection of local hazardous points on river levees that are long and straight with conventional river water level monitoring will enable us to more rationally inform residents of the risk of levee collapse. Currently, data of the durability of actual levees under various weather conditions are insufficient. Therefore, we have installed UPWP gauges in actual river levees in Hokkaido, Japan, to advance observation for the verification of pore water pressure data, focusing on cold environments with snow.

4. Conclusions

In this study, we developed a new UPWP gauge that is low in cost and power consumption. It will enable us to measure the pore water pressure in a levee. We performed indoor verification tests to determine the basic performance of the new UPWP gauge and experiments with a full-scale test levee in consideration of its installation on real levees and obtained the following findings.

1) We developed the UPWP gauge of 8 mm diameter with low power consumption. In the indoor verification experiment, the error between the preset and observed values of water levels in the water container was ±0.015 m.

2) We observed a cavity in the ground around the UPWP gauge by X-ray CT scanning, but did not identify any local dead air space caused by the shape of the water pressure gauge.
3) In the full-scale test levee experiment, we successfully measured pore water pressure in the ground when sand boiling occurred on the land side, using the UPWP gauge.
4) The pore water pressure measured with the UPWP gauge at the time of the first elevation of the river water level in the full-scale test levee experiment was greater than that obtained with the existing pore pressure gauge by around 1 kN/m^2 (corresponding to a water level of around 0.1 m). However, at the time of the second elevation of the river water level, the increase processes and maximum values of u_w of the UPWP and existing pore pressure gauge were in good agreement.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Numbers 20H02405 and 20H00266. The authors were also assisted by Ms. Honoka Minami and Mr. Kento Okamura, students at Kitami Institute of Technology, in conducting the research. Their aid is sincerely appreciated.

References

1 S. Yasuda, Y. Shimizu, and K. Deguchi: Soils Found. **56** (2006) 581. https://doi.org/10.1016/j.sandf.2016.07.001
2 S. Kawajiri, T. Kawaguchi, Y. Watanabe, H. Hayakawa, Y. Miyamori, D. Nakamura, and S. Yamashita: Soils Found. **59** (2019) 764. https://doi.org/10.1016/j.sandf.2019.01.006
3 S. Nishimura, Y. Takeshita, S. Nishiyama, S. Suzuk, S. Shibata, S. Shuku, M. Komatsu, and M, B. Kim: Soils Found. **60** (2020) 300. https://doi.org/10.1016/j.sandf.2020.01.009
4 T. Mukunoki, D. Suetsugu, K. Sako, S. Murakami, Y. Fukubayashi, R. Ishikura, T. Hino, S. Sugimoto, K. Wakinaka, S. Ito, and A. Koyama: Soils Found. **61** (2021) 600. https://doi.org/10.1016/j.sandf.2021.01.008
5 S. Ohtsuka, Y. Sato, T. Yoshikawa, T. Sugii, T. Kodaka, and K. Maeda: Soils Found. **61** (2021) 1172. https://doi.org/10.1016/j.sandf.2021.05.009
6 K. Terzaghi, R. B. Peck, and G. Mesri: Soil Mechanics in Engineering Practice (John Wiley and Sons, Inc., New York, 1996) 3rd ed.
7 X. Wang and M. Castay: Can. Geotech. J. **49** (2012) 812. https://doi.org/10.1139/t2012-043
8 S. Nishiie, S. Nishimura, and N. Yamazoe: Jpn. Geotech. Soc. Spec. Publ. **7** (2019) 648. https://doi.org/10.3208/jgssp.v07.099
9 N. Sugawara: Oyo Technical Report **26** (2006) 45 (in Japanese).
10 Y. Minabe, S. Kawajiri, T. Kawaguchi, D. Nakamura, and S. Yamashita: Procedia Eng. **143** (2016) 292. https://doi.org/10.1016/j.proeng.2016.06.037
11 B. Song, D. Nakamura, T. Kawaguchi, and S. Kawajiri: Int. J. GEOMATE **21** (2021) 112. https://doi.org/10.21660/2021.84.j2162
12 Japan Institute of Construction Engineering (JICE): A Guide to the Structural Study of River Levees (Revised Edition) (2012) (in Japanese).
13 V. M. Van Beek: Ph.D. Thesis, Delft University of Technology (2015). https://doi.org/10.4233/uuid:4b3ff166-b487-4f55-a710-2a2e00307311
14 G. Park, W. Lee, and I. Joe: Eurasip J. Wirel. Commun. Netw. (2020) Article number: 176. https://doi.org/10.1186/s13638-020-01783-5
15 K. Koizumi, H. Tsutsumi, H. Hoshino, and Y. Fujiwara: Proc. Kansai Geo-Symposium (2021) 76–81.