MEASUREMENT OF PORE WATER PRESSURES IN ROCKFILL DAMS BY WIRELESS TRANSDUCERS

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ABSTRACT

The purposes of this paper are to introduce a wireless pore water pressure transducer (WPT) and to verify the performance of the transducers installed within embankments of dams. A WPT was developed in order to improve the efficiency during installation of transducers and stability of measurements. It was specified that WPT has more than 10 years lifetime to confirm measurement of data from construction and first reserving phase to steady state phase of dam's behavior. However, based on the results of long term measurement data from the real dams, the transducers had a tendency that the lifetime was shorter than the estimated values. Then, after five and a half years, these were out of order and not able to perform data communication. The reason they were out of order was examined from the capacity test of their batteries and voltage data of batteries measured in site. From the results, we clarified that capacity of battery was sufficient but the inner resistance of battery was increasing according to the elapsed time. If the inner resistance of battery increases, the voltage descent will happen when the high electric current is required, for example, in a data communication procedure. Then we set the batteries in parallel to moderate the effect of voltage descent. Improved transducers can reduce the increase of inner resistance values according to the elapsed time comparing with test models. Then we verify the long term performance of the transducers depended on not only capacity but also inner resistance of batteries.

INTRODUCTION

Buried transducers, for example pore water pressure and earth pressure transducers, are installed to ensure the stability and safety of embankment structures as fill type dams under construction and in use. Most are electrical transducers changing physical values into electrical signals and require wire cables to supply electrical power and convey measured data signals.

These cables cause some problems such as (1) decreases in working efficiency while digging trenches for the cables, setting the cables and burying the trenches and (2) decreases in measuring stability with breaks in the cables, decline in insulation and damage from thunderbolts. Therefore, we developed a wireless transducer by applying underground communication technology with low frequency electromagnetic waves to

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improve the efficiency during installation of transducers and stability of measuring performance. This wireless sensor is a “wireless pore water pressure transducer (WPT)”.

Test models of WPT were installed adjoining conventional sensors with cables in two rock fill dams, and their values compared to check the validity of WPT. The WPT was expected to perform properly for ten years or more under conditions of daily measuring and weekly communicating through a receiver on the ground once a week. However, test models installed in dams failed to communicate with the receiver five and a half years after installation.

In this paper, we examine the validity of WPT by comparing with data of conventional sensors connected with cables. In addition, we investigated why the WPT test model only functioned for five and a half years, a considerably shorter period than the ten years expected based on battery capacity tests in the laboratory and measured data of battery voltage in a dam.

WIRELESS PORE WATER PRESSURE TRANSDUCER

Low frequency electromagnetic waves show characteristic larger attenuation by distance, but the effect of conductivity and permittivity of transmit is lower than high frequency electromagnetic waves. Therefore, it is possible to communicate short distances in the soil or water by low frequency electromagnetic wave.

By applying this feature of low frequency electromagnetic waves (8.5 kHz) and digital data communication technology that can improve the precision for reading faint signals, it is possible to send and receive data under conditions when the signal to noise (S/N) ratio is greater than two, and interactively communicate under the ground within a distance of 100 m.

Figure 1 presents a schematic of WPT showing the outward appearance and inner components of the test model of WPT installed in real dams. WPT is composed of circuit boards, a communication antenna, batteries, a pore water pressure sensor and case. Diameter and height of the WPTs are 125 mm and 205 mm. The pore water pressure sensor is the same as used for conventional sensors with cables. In the test model of WPT, three batteries are set in series.

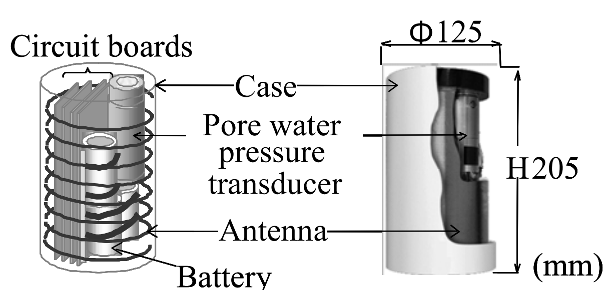


Figure 1. Schematic for Test model of Wireless Pore Water Pressure Transducer (WPT)

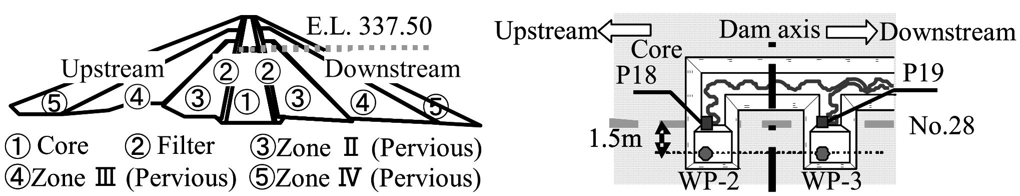
LONG TERM FIELD TEST IN REAL DAMS

Field test in Dam A

Dam A, shown in Figure 2, is a center core type rock fill dam with a height of 69.9 m, longitudinal length of 312.5 m and volume of 157,500 m^3. Test models of WPT (WP-2 and WP-3) were installed adjoining conventional pore water pressure transducers with cables (P18 and P19) at EL.337.50 m of section No. 28 in January 2004 and their data were compared. The arrangement of these transducers is shown in Figure 2 (b). Test models of WPT were installed by the core boring method (Kohgo et al. 2006) at the tip of the cable trench 1.5 m from the section No. 28 in which conventional sensors with cables were installed.

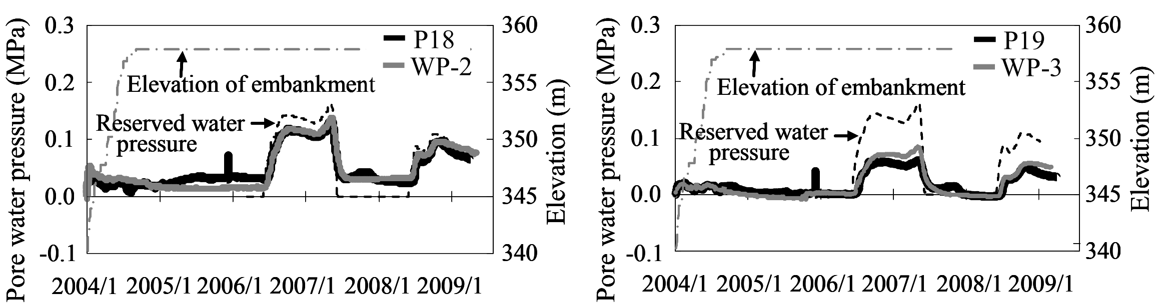
Data measured by the transducers installed at EL.337.50 m near section No. 28 in Dam A are shown in Figure 3. Figure 3 (a) shows the data of P18 and WP-2 and Figure 3 (b) of P19 and WP-3. In these figures, changes in the elevation of embankments under construction and reserved water pressure at the elevation of the transducers are shown together. Here, reserved water pressure is the value that differs between the reserved water level and the elevation of transducers multiplied by the density of water. If the water level is below the elevation of the transducers, its value is assumed to be 0 kPa.

From Figure 3, the difference between the values of WPT and conventional sensors with cables is small, and remains almost the same during the entire period of the tests. On 5th March 2009, every WPT could communicate with the receiver on the ground surface. However, after 9th July 2009, WP-3 could not communicate with the receiver. Therefore, this test model of WPT cannot perform properly more than five and a half years later after installation.



(a) Cross section (b) Installed position of sensors

Figure 2. Outline of Dam A and Position of Installed Sensors



(a) P18 and WP-2 (b) P19 and WP-3

Figure 3. Data Measured for Conventional Sensors with Cables and WPTs in Dam A

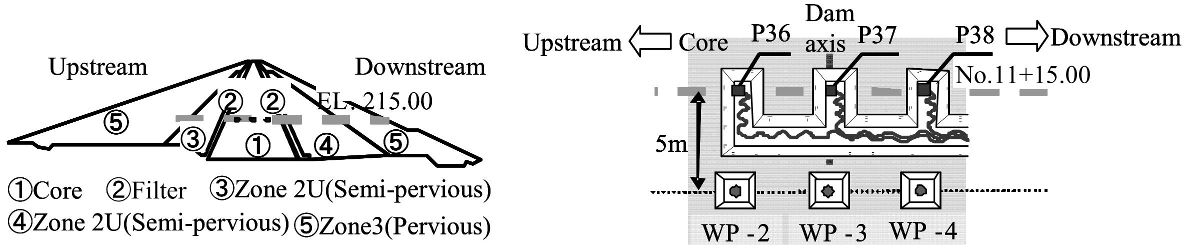
Field test in Dam B

Dam B, shown in Figure 4, is a center core type rock fill dam of 50.0 m height, 256.0 m longitudinal length and volume of 801,000 m^3. Test models of WPT (WP-2, WP-3 and WP-4) were installed adjoining conventional sensors with cables (P36, P37 and P38) at EL.215.00 of section No. 11+15.00 in May 2004. The arrangement of the test models is shown in Figure 4 (b). Test models of WPT were installed by the core boring method at the tip of the cable trench 5 m from the section No. 11+15.00 in which conventional sensors with cables were installed.

Data measured for the transducers installed at EL.215.00 m around section No. 11 in Dam B are shown in Figure 5. Figure 5 (a) shows the data of P36 and WP-2 and Figure 5 (b) shows the data of P37 and WP-3. Figure 5 (c) shows of the data for P38 and WP-4. In these figures, changes in the elevation of the embankment under construction and reserved water pressure at the elevation of the transducers are shown together. Reserved water pressure was calculated in the same manner as Dam A. If the water level was below the elevation of the transducers, its value was assumed to be 0 kPa.

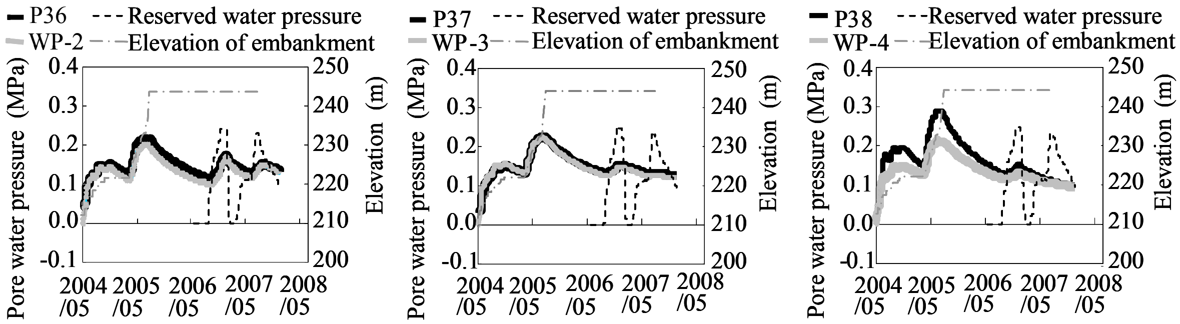
On 27th December 2007, all WPTs could communicate with the receiver on the ground surface but after that we didn't perform data collection. In September 2009, the test models of the WPTs could not communicate with the receiver on the ground surface because the WPTs installed in Dam B were the same test models as for Dam A, so the tests were stopped.

Figures 5 (a) and (b) show the values of P36 and P37 are almost the same as WP-2 and WP-3 throughout the entire period of the tests. In Figure 5 (c), the values of WP-4 show comparable lower values than P38 during the period from embanking to the time the reserved water level reached the transducer elevation during the first filling. However, the tendencies of the data measured for WP-4 and P38 were similar throughout the entire test period, and after the reserved water level reached the transducer elevation, both became almost the same. The values of WP-4 and P38 were likely different at first because of differences in the installed position and installation method, and these influences were moderated by the reserved water. From these results, we conclude that WPTs can measure data as well as conventional sensors with cables in Dam B.



(a) Cross section (b) Installed position of sensors

Figure 4. Outline of Dam B and Position of Installed Sensors



(a) P36 and WP-2 (b) P37 and WP-3 (c) P38 and WP-4

Figure 5 Data Measured for Conventional Sensors with Cables and WPTs in Dam B

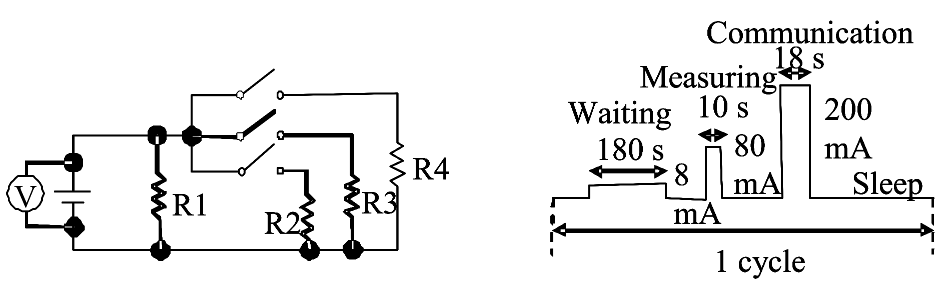
LOADING TEST OF BATTERY

Test Condition

WPT is expected to work properly for ten years, but a period of development was comparably shorter than the expected period. Then accelerated battery loading tests were done in the laboratory to estimate the performance of batteries used in WPTs. Figure 6 (a) shows the schematic of a testing device that imitates the electric consumptions of WPTs and the loading patterns for the loading test.

Test device is composed of a voltmeter to measure the voltage of the battery and four resistors imitating the electric consumptions under each mode; R1 is the sleeping mode, R2 is the waiting for order mode, R3 is the measuring mode and R4 is the communication mode. Here, the sleeping mode is the state when only the clock in the WPT works, waiting for order mode is the state when the WPT can receive a signal from the ground surface, measuring mode is the state when the WPT can measure the pore water pressure and the communication mode is the state when the WPT can communicate with the receiver on the ground surface.

Table 1 shows the test specifications. In test 1, the loading pattern shown in Figure 6 (b) was loaded 20 times a day and the amount of electricity consumed in ten years was hastily consumed in a half year. Similarly, in tests 2, 3 and 4, the loading patterns were loaded ten, four and one times a day, and periods of the test were shortened to 1/10, 1/4 and once in ten years.



(a) Testing device (b) Loading pattern

Figure 6. Schematics of Testing Device and Loading Pattern

Table 1. Test Specifications

Test case	Period of test	Time / cycle	Frequency of loading
Test 1	0.5 year	72 min	20 times/day
Test 2	1 year	144 min	10 times/day
Test 3	2.5 year	6 hour	4 times/day
Test 4	10 year	24 hour	1 time/day

The lithium ion battery used in the WPT has 13.0 Ah nominal capacity and discharges 3 % of the nominal capacity in a year, so we must allow for self discharge of the battery and the battery is not guaranteed to perform properly after reaching a cut off voltage of 2.0 V.

Test Results

Figure 7 shows the changes in the voltage values of the battery during the sleeping and communication modes in each test. In each test, the four test devices shown in Figure 6 (a) were used simultaneously and each value shown in Figure 7 is the average of four devices. From Figure 7, the tendency of voltage values during the communication and sleeping mode in tests 1, 2 and 3 is considerably different from that in test 4. In tests 1, 2 and 3, the voltage values during both modes were kept above 3.0 V throughout the entire period and rapidly decreased to 0 V through with the cut off voltage 2.0 V at the end. Such behaviors in the voltage values may be caused by complete consumption of battery capacity during the test period. On the other hand, in test 4, voltage values under the communication mode decreased moderately with the passage of time and reached the cut off voltage, and voltage during the sleeping mode kept a nominal voltage value of 3.6 V throughout the entire period of the test. From these results, we conclude that in case 4, the voltage of a battery during the communication mode reaches the cut off voltage before the battery capacity is fully consumed.

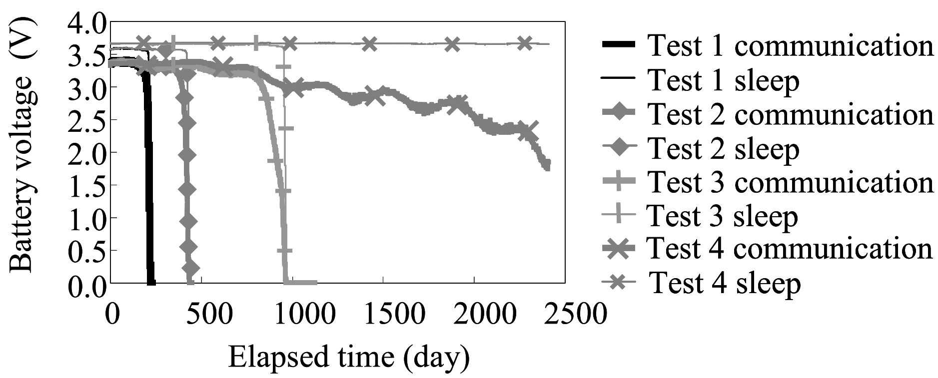


Figure 7. Changes in Battery Voltage under Sleep and Communication Modes

To confirm this hypothesis, we estimated the capacities consumed under each mode. First, the electric current was calculated from the resistance of each resistor and the battery voltage measured under each mode, and then it was multiplied by each loading time to obtain the capacities consumed under each mode. These values were then added through the actual working period until the voltage during the communication mode reached the cut off voltage of 2.0 V. This is defined as the "consumed capacity for loading". Next, we calculated the self discharged capacity through the actual working period. This value is the self discharged capacity for one year 0.39 Ah, which is 3% per year of the nominal capacity of 13.0 Ah, multiplied by the actual work period. These values can be calculated by summing the consumed loading and self discharge capacities. This result is defined as the "actual consumed capacity". Finally, the ratio of the actual consumed capacity and nominal capacity is defined as the "consumed capacity ratio". Table 2 shows the actual working period, consumed capacity for loading, actual consumed capacity and consumed capacity ratio for each test. Figure 8 shows the consumed capacity in each test, including the consumed capacities during the sleep mode, waiting mode, measuring mode and communication mode, and self discharged capacity. Based on Table 2 and Figure 8, we show the capacities of the battery are consumed fully in tests 1, 2 and 3, but 26% of the nominal capacity remain in test 4.

Table 2. Consumed Capacity Ratio in each Test

Test case	Supposed period	Actual working period	Consumed capacity for loading	Actual consumed capacity	Consumed capacity ratio
Test 1	0.5 year	0.57 year	13.0Ah	13.3Ah	102.3%
Test 2	1 year	1.14 year	13.0Ah	13.4Ah	103.1%
Test 3	2.5 year	2.49 year	11.4Ah	12.3Ah	94.6%
Test 4	10 year	6.45 year	7.0Ah	9.6Ah	73.8%

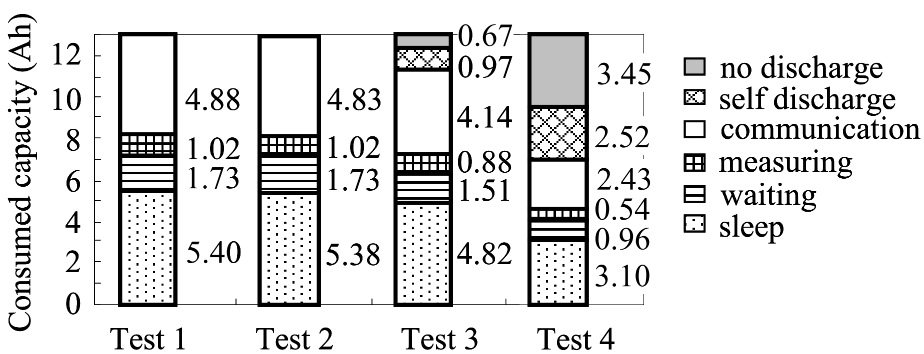


Figure 8. Consumed Capacity in each Test

Generally terminal voltage at the connecting resistor is lower than electromotive force (terminal voltage without connecting resistor). This phenomenon is caused by the virtual resistors in the battery that are connected in a series and the virtual resistor has an internal resistance. Internal resistance causes a voltage drop proportional to the magnitude of the electric current. If the electric current is small, influence of the internal resistance on the voltage drop is not remarkable. On the other hand, if the electric current is large, problems caused by the voltage drop are not negligible. Generally, internal resistance increases with deterioration of a battery according to the discharge. One of the reasons for internal resistance is that the effective areas on the pole plates deteriorate in the battery.

We estimated the values of internal resistance in tests 3 and 4 to clarify the influence of the internal resistance on the test results. Internal resistance was calculated from the values of battery voltage and electric current under the communication mode and electromotive force. Equation is shown below and assumes the electromotive force is equal to the battery voltage during the sleeping mode.

$$R_{in} = (V_{sleep} - V_{send}) / I_{send} \quad (1)$$

$$I_{send} = V_{send} / R_{send} \quad (2)$$

Here, R_{in} is the internal resistance (Ω), V_{sleep} is the battery voltage during the sleeping mode (V), V_{send} is the battery voltage during the communication mode (V), I_{send} is the electric current during the communication mode (A) and R_{send} is the resistance of resistor R4 referred in Figure 6 (a) (Ω).

Figure 9 shows the changes in the estimated internal resistance. The internal resistance shows a similar tendency up to 750 days in both tests. Subsequently, internal resistance in test 3 increased rapidly to 10 Ω approximately 900 days later and the battery voltage during the communication mode become lower than the cut off voltage of 2.0 V. On the other hand, internal resistance successively increased in test 4. The relationship between internal resistance and elapsed time is approximated by an exponential curve as Eq. (3).

$$R_{in} = 1.0094 \exp(0.0009t) \quad (3)$$

Here, R_{in} is the internal resistance (Ω) and t is elapsed time (day).

In test 4, the capacity of the battery remains enough but the internal resistance successfully increased with time. Then, the battery voltage dropped below the cut off voltage during the communication mode, which requires a large electric current.

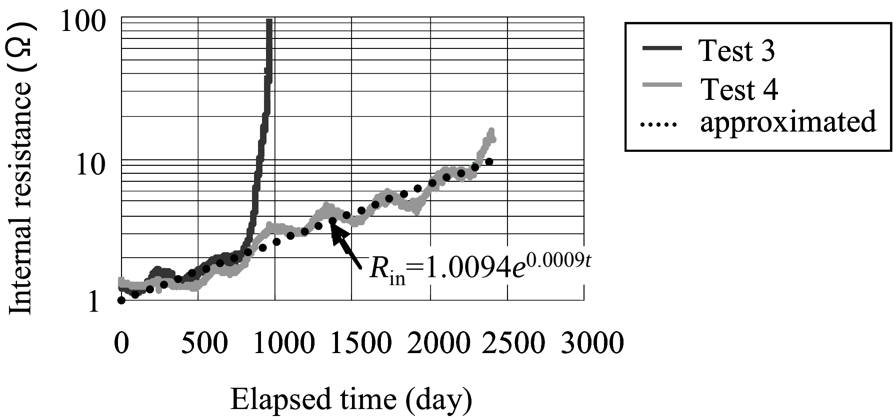


Figure 9. Changes of the Internal Resistances in Tests 3 and 4

Comparison with Test Results in Real Dams

We measured the battery voltage values during the communication mode in test models of WPT installed in Dam A. And the test model of WPT was improved during the development phase and the improved WPT installed in some dams. The improved WPT contained an increased number of batteries in parallel and decreased consumption of electricity during the communication mode. If batteries are set in parallel with systems, the electrical current of each battery is reduced $1/n$ times so the voltage drop induced by internal resistance becomes $1/n$ times.

Figure 10 shows the changes in battery voltage during the communication mode of test model in Dam A and improved WPT and results of the battery loading test 4. Here, the results of the battery loading tests were revised to compare easily because the numbers of batteries used in the test model of WPT and battery loading tests differ. From Figure 10, the data measured in Dam A and results of battery loading tests show similar tendencies in decreasing ratios of battery voltage become large after approximately 500 days and then the values remain almost the same. We then estimated the capacity consumed during ten years to be 11.6 Ah by revising the data of the battery loading tests by daily measuring and weekly communication. The value of consumed capacity during ten years was below the nominal capacity of a 13.0 Ah. From these results, the capacity of the battery appears enough to perform properly for ten years under the expected conditions. Therefore, we conclude the reason the test models of WPT in Dam A can only communicate approximately five and a half years is not due to the lack of battery capacity but a drop in voltage during the communication mode induced by an increase in internal resistance.

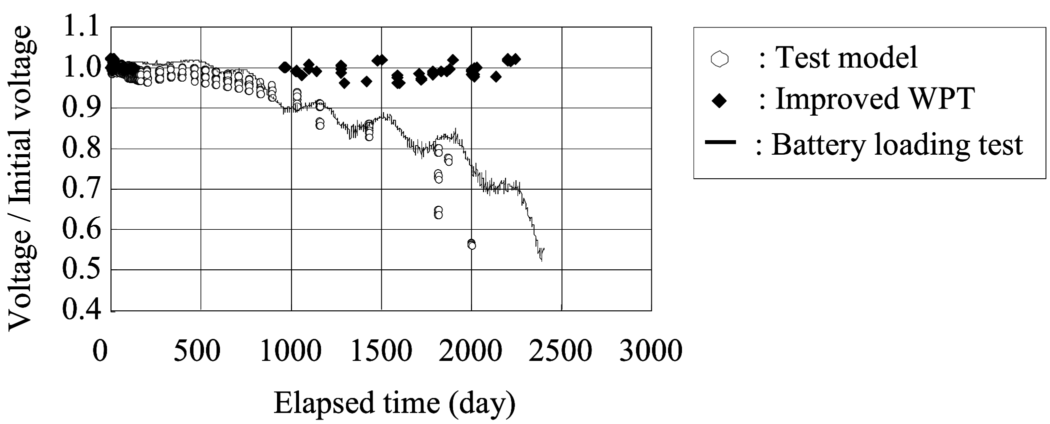


Figure 10. Comparison of the Voltage / Initial Voltage between the Test model and Improved WPT

Figure 11 shows the changes in internal resistance of the test model and improved WPT. Their tendencies are quite different. In the improved WPT, no increase in the internal resistance is recognized even after 2000 days. We assumed the changes in internal resistance can be approximated by the exponential function as also shown in Figure 9, and both the test model and improved WPT can be approximated by the exponential curves shown in Figure 11. In the test model, changes in the internal resistance were approximated well by the exponential curve. In the improved WPT, the internal resistance appears to remain below 10 Ω after ten years based on the approximated function.

These results show the effect of a voltage drop induced by internal resistance can be modified with improvement and long term performance of WPT can be advanced. The improved WPT is expected to perform properly during a ten year working period.

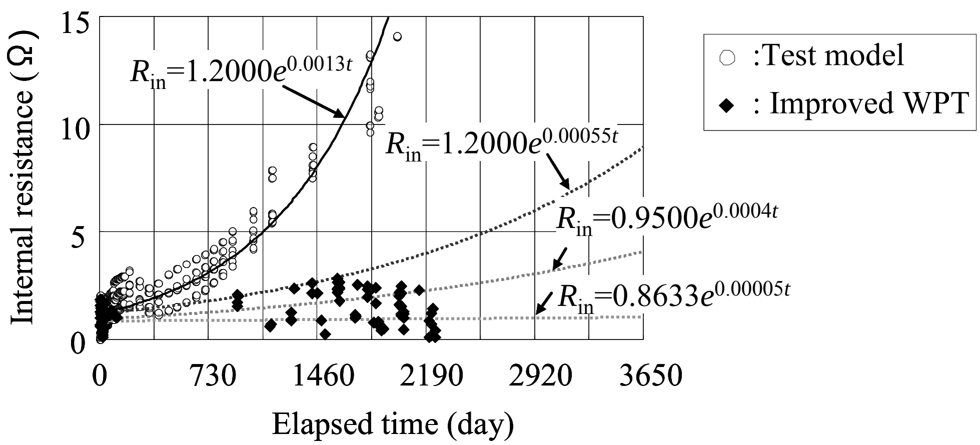


Figure 11. Comparison of Internal Resistance between the Test Model and Improved WPT

CONCLUSION

From the test results measured in real dams, we confirmed that WPT can measure data as well as conventional sensors with cables. The validity of WPT is obvious from the ease of installation and measurement performance. However, the test model of WPT installed in real dams cannot work properly after five and a half years. We clarified by the battery loading tests in the laboratory and field the reason for this phenomenon is not due to a lack of battery capacity but to a drop in voltage during the communication mode inducing internal resistance in the battery.

Test model of WPT was improved and the improved WPT installed in dams. The results of the improved WPT show the effect of a drop in voltage induced by internal resistance can be modified and long term performance of WPT advanced.

Hereafter, the behavior of the improved WPT must be clarified and the long term performance of WPT confirmed.

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