INTERNATIONAL COMMISSION ON LARGE DAMS
76th ANNUAL MEETING
SOFIA, BULGARIA, JUNE 2-6, 2008
Symposium: "Operation, Rehabilitation and Up-grading of Dams"

IMPROVEMENT OF EARTH PRESSURE MEASURING METHOD IN ROCK-FILL DAMS

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ABSTRACT

Central core-type rock-fill dams are occasionally prone to hydraulic fracturing due to arch-actions, which are caused by differences in stiffness between zones. Earth Pressure Cells and pore water-pressure meters are installed inside most dams to monitor their stress states. However, in conventional earth pressure measurements, measurement errors have been reported, which were possibly attributable to the shapes and embedding methods of the earth pressure cells. Of the errors, those that are attributable to the shape of cells have been investigated, and the results have been reported. On the other hand, there has been almost no quantitative study on measurement errors attributable to embedding method of the cells. Therefore, the authors quantitatively evaluated measurement errors caused by embedding methods aiming to improve the measuring method for earth pressure cells to be installed in the central core-type rock-fill dams. The results were used to improve the embedding method of the earth pressure cell in Minamiaiki Dam of the Kannagawa Pumped Storage Power Plant. This paper describes improved embedding methods of earth pressure cells and measurements conducted using the cells.

1. INTRODUCTION

1.1 Overview of Minamiaiki Dam

The Kannagawa Power Station is a pumped-storage hydroelectric power station constructed by the Tokyo Electric Power Company (TEPCO) and has an effective head of 653 m, a turbine discharge of 510 m3/s, and a maximum output of 2,820 MW (470MW x 6 units).

Minamiaiki Dam, which is the upper dam of the power station, is a 136-m high central core-type rock-fill dam and has a crest length of 444 m. Embankment works of the dam started in October 1999 and were completed in September 2003. The first water filling started in September 2004, and the water level reached the high water level in September 2005.

Earth pressure cells were installed inside the core zone of the dam at EL 1415 m, 1430 m, and 1445 m, where effective stress was predicted to drop by excess pore water pressures (Figure 1), and at the bases of upstream and downstream filter zones and the core zone. Earth pressure cells were also installed inside the upstream and downstream rock zones and filter zones at EL 1445 m to monitor stress distribution.

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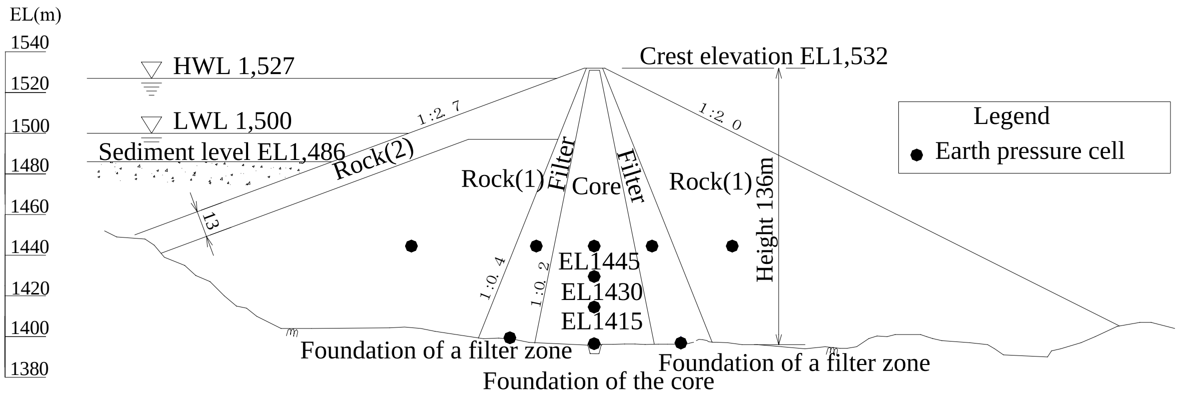
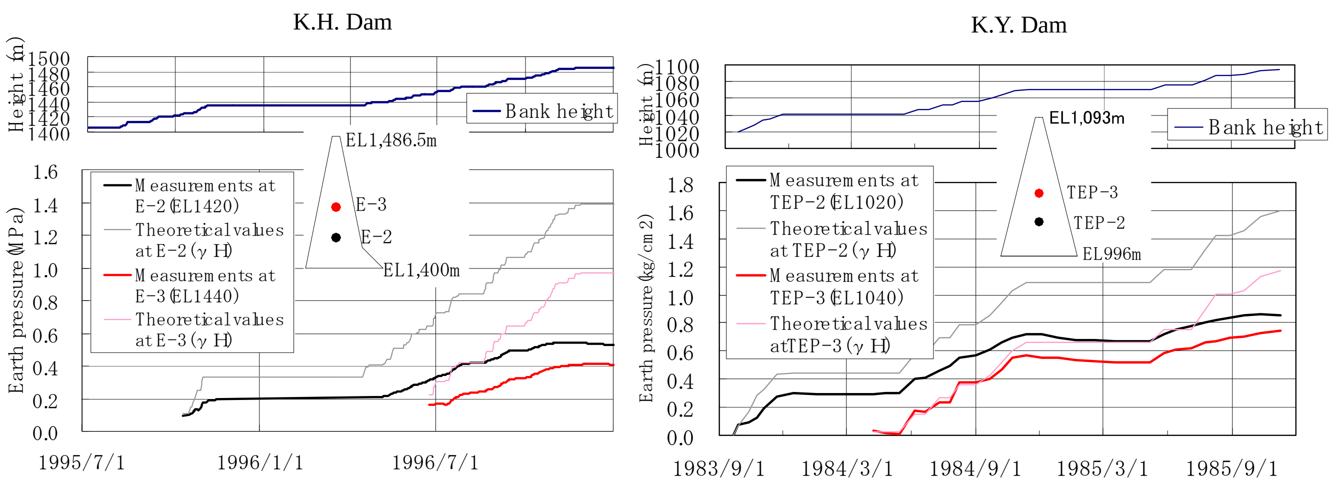


Figure-1 Typical Profile of Minamiaiki Dam

1.2 Difficulties of Monitoring Earth Pressures inside a Dam

Central core-type rock-fill dams are prone to hydraulic fracturing due to arch-actions, which are caused by differences in stiffness between zones. Therefore the stress status of central core-type rock-fill dams are usually monitored by earth pressure cells and pore water-pressure meters installed inside the dams. However, earth pressures inside cores are difficult to monitor accurately but are prone to measurement errors as shown in our measurements in the past (Figure 2). The errors have been possibly attributable to the shapes and embedding methods of the cells. [i] Then, studies have been reported on the effects by the shapes of the cells, such as the theory by Tsitovich et al. on stress concentration [ii] and studies on methods for correcting earth pressure measurements [iii] . On the other hand, measurement errors attributable to embedding methods have been suggested [iv] but have not been quantitatively investigated. Thus, much is left unveiled on the effects of embedding method.



※the theoretical values (soil density ×height of the embankment)

Figure 2 Earth Pressure Measurements in the Past (Inside Dam Cores)

2. IMPROVED EMBEDDING METHODS FOR BETTER MEASUREMENT ACCURACIES

2.1 Problems of Conventional Embedding Methods

Core zones of most rock fill dams are embanked using heavy construction machines such as large-sized vibration rollers. Moreover, large stones of maximum grain size of 150 to

200 mm are used to construct cores. (Dam sections constructed using these ordinary methods are hereinafter referred to as the “*ordinary bank sections*”). The installed earth pressure cells are prone to damages by excess loads imposed by heavy machines and contacts to large stones. Therefore earth pressure cells are installed embedded in soil of small grain sizes, which is compacted using light-weight machines. (Such areas for protecting cells are hereinafter referred to as the “embedded sections”). The measurement errors in the conventional embedding method is attributable to the differences in stiffness between the ordinary and embedded sections. Since most of the embedded sections are less stiff than the surrounding ordinary bank sections, loads applied on the top of the embedded sections spread to the more stiff ordinary bank sections. As the result, the reading of earth pressure cells will show less figure than actual one.

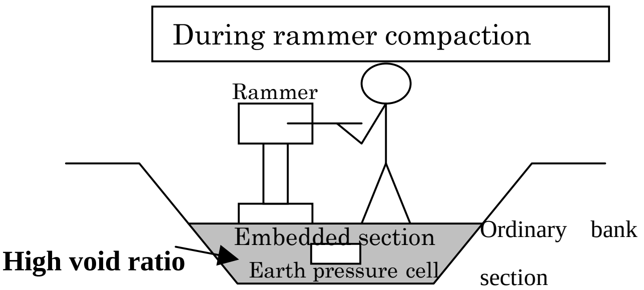
The following sections describe quantitative evaluation of 1) the measurement errors caused by differences in stiffness between the embedded and ordinary bank sections, and 2) those caused by the size and shape of the embedding area.

2.1.1 Effects of Stiffness Differences between the “Embedded Sections” in which Earth Pressure Cells are installed and the “Ordinary Bank Sections”

Principal factors that determine differences in stiffness between the embedded and ordinary bank sections are likely to be the specifications of roller compaction and materials.

Of these, the specifications of compaction denote use of light-weight machines(e.g. rammer) for the embedded sections while large-sized heavy machines are used for the ordinary bank sections. Light-weight machines are used mainly because of two reasons. The first reason is to protect cells. The other is because large-sized heavy machines are impossible to be used in a small space, which is created by excavating the ordinary bank section. As shown in the table of Figure 3.1, the void ratio in the embedded section that is rammer compacted is higher than in the ordinary bank sections, and consequently the volume compression is higher. Therefore, the stiffness of the embedded section is likely to be lower than in the ordinary bank sections.

The specifications of materials denote that small grain size materials are used around cells in order to protect the cells, which causes differences in stiffness between the embedded and ordinary bank sections (Figure 3.2).



Initial void ratio (immediately after roller compaction)

	Ordinary bank section	Soil in which a gauge is embedded
Specifications of roller compaction	Compaction by 10-t roller	Compaction by rammer
Dry density(t/m3)	1.975	1.894
Initial void ratio	0.390	0.450

(tested using an actual machine)

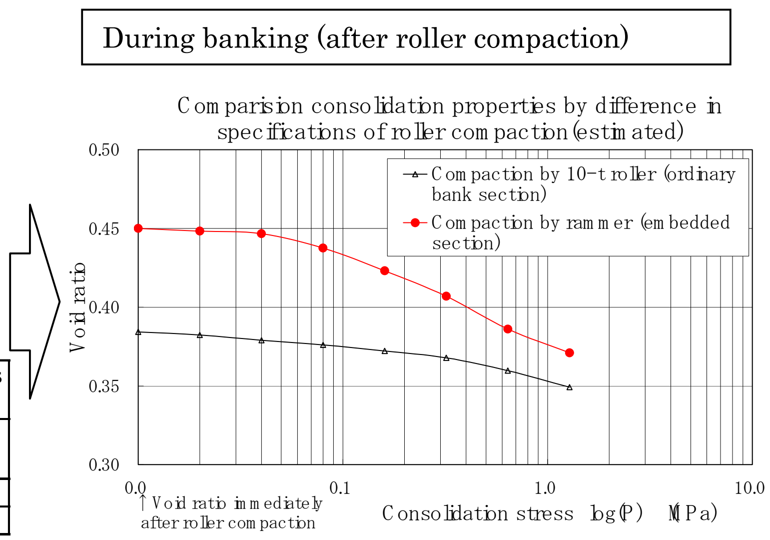
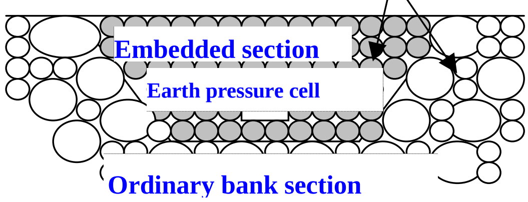


Figure 3.1 Cause of stiffness differences between the ordinary and embedded sections in the conventional installation method (specifications of compaction)

Differences in grain size cause differences in stiffness.



Maximum grain sizes of the ordinary and embedded sections in the conventional method

	Maximum grain size (mm)	Note
Ordinary bank section	150	Measurement in a dam of TEPCO
Embedded section	20、50	Measurement in a dam of TEPCO

Figure 3.2 Cause of stiffness differences between the ordinary and embedded sections in the conventional installation method (specifications of materials)

2.1.2 Effects of the Size of Embedded Section

Measurement errors caused by the sizes of embedded sections are likely to depend on the thickness and width of the section (Figure 4).

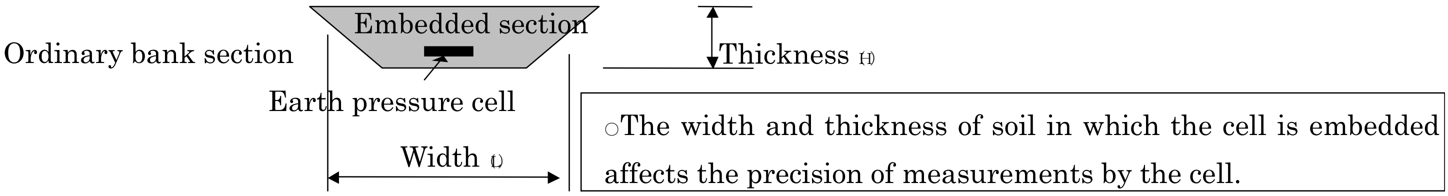


Figure 4 Range of Soil surrounding Earth Pressure Cell

2.2 Investigating Improved Methods

The investigations described above suggest that measurement errors can be reduced by 1) not using light-weight compactors, 2) not using small grain size soil, and 3) determining appropriate thickness and width of soil surrounding cells. This section describes investigations on these topics. Since 3) determining appropriate thickness and width of soil surrounding the cells is closely related to topics 1) and 2), its investigations are included in the investigations of 1) and 2).

2.2.1 Improvement by Not Using Light-weight Compactors on the Embedded Sections

To understand the differences in stiffness of embedded sections by differences in compaction method, we conducted a test using different compactors. The test showed that the stiffness of the embedded sections varied depending on compactor (Table 1). We also conducted a linear elasticity Finite Element Method analysis using the test results (Figure 5, Case A-1; compaction using a rammer. Case A-2: roller compaction using a large-sized vibration roller), which showed that use of the light-weight machines caused measurement errors of about 7% at the embedded sections (Table 2). This compaction test using the rammer was conducted in an open space. However, the since the actual space is very small, disabling sufficient compaction, larger measurement errors are possible to occur.

Table 1 Difference in Stiffness by Compactor Used

(Calculated stiffness during banking)

	Compaction by 10-t roller	Compaction by rammer	Notes
Initial void ratio(after compaction)	0.390	0.450	Immediately after roller compaction
Void ratio (after banking)	0.349	0.375	Load application of 1.25 MN/m2
Coefficient of volume compressibility	43.6	24.3	
Modulus of deformation(MN/m2) (during banking)	26.5	14.7	

(Estimated from results of tests using actual machines and indoor tests)

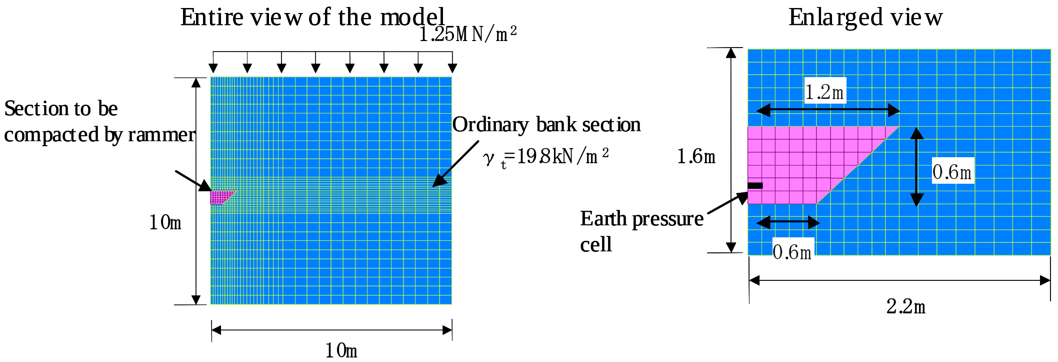


Figure 5 Analytical Model (Linear Elasticity Analysis)

Table 2 Analytical Results (Measurement Errors by Conventional Roller Compaction Methods)

Condition	CaseA-1(≒conventional method)		CaseA-2	
	Embedded	Ordinary bank section	Embedded	Ordinary bank section
Modulus of deformation(MN/m2)	14.7MN/m2	26.5MN/m2	26.5MN/m2	26.5MN/m2
Vertical earth pressure at the position of the cell (measurement:σ v (m))	1.194Mpa		1.284Mpa (=σ v (t))	
Percentage of measurement to the true earth pressure value (σ v (m) / σ v (t))	93.0%		100%	

Therefore, embedded sections were decided to be roller compacted using large-sized vibration rollers in principle. Since large-sized vibration rollers cannot be used in the conventional method that involves excavating the ordinary bank section, we decided to spread the soil for covering cells on the ordinary bank section so that large-sized vibration rollers can be used (Figure 6). To enable the rollers to climb on the spread soil, the side of the embedded section was decided to have an inclination of 1:3 as in the ordinary bank sections.

To prevent damages to cells, the soil near the cells must be compacted using light-weight machines. We investigated the size and shape of the range to be compacted using a light-weight machine that would result in the minimum measurement errors by conducting a linear elasticity analysis while changing the thickness and width of the range. The analysis showed that the thinner and wider the range to be compacted using a light-weight machine, the smaller the measurement errors (Figure 7.1). Since a thickness of 10 cm was found to result in measurement errors not exceeding 1%, the thickness of the soil to be compacted using a light-weight machine was decided to be 10 cm. The width was decided to be 3.5 m, which is the minimum width on which a whole large-sized vibration rollers could mount .

The embedded section was decided to be constructed as summarized in Figure 8. The method was estimated to reduce measurement errors of earth pressure from 7% in the conventional method to 1%.

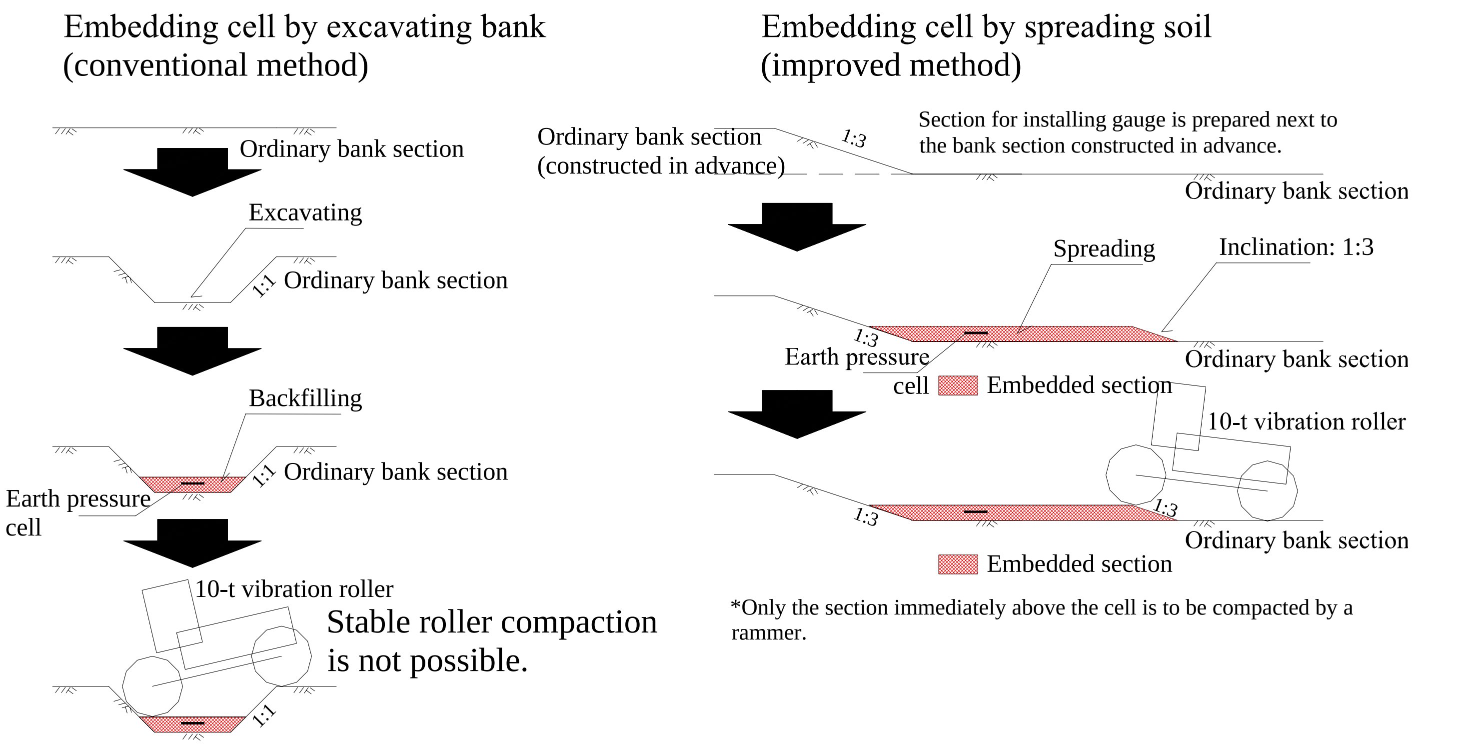


Figure 6 Method Enabling Roller Compaction using Heavy Machines

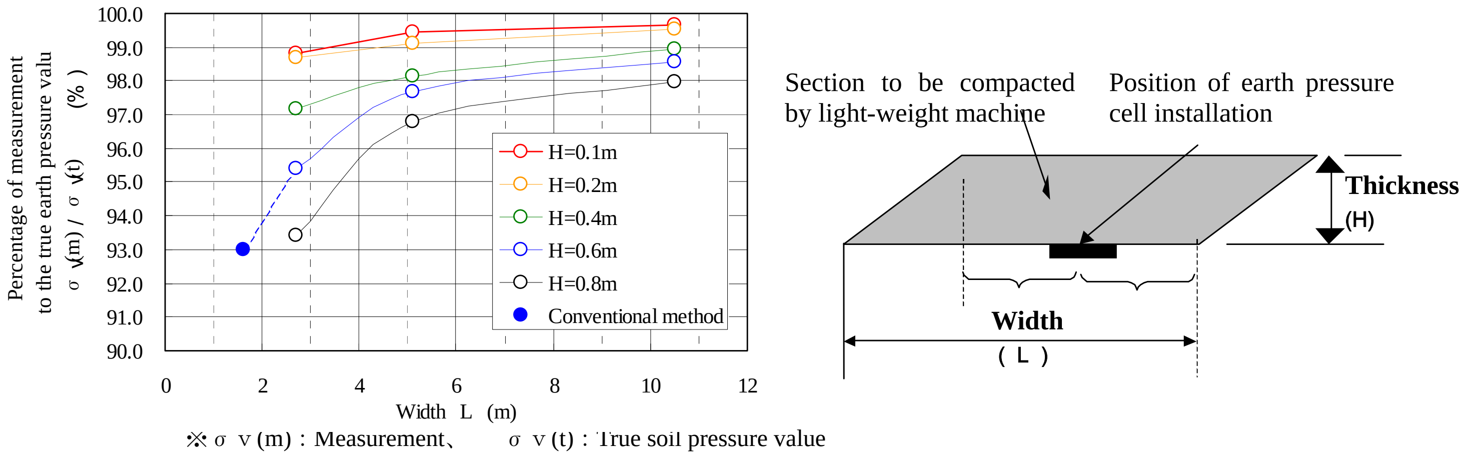


Figure 7.1 Analytical Results (Measurement Errors caused by Differences in the Shape and Size of the Section to be Compacted by Light-weight Machine)

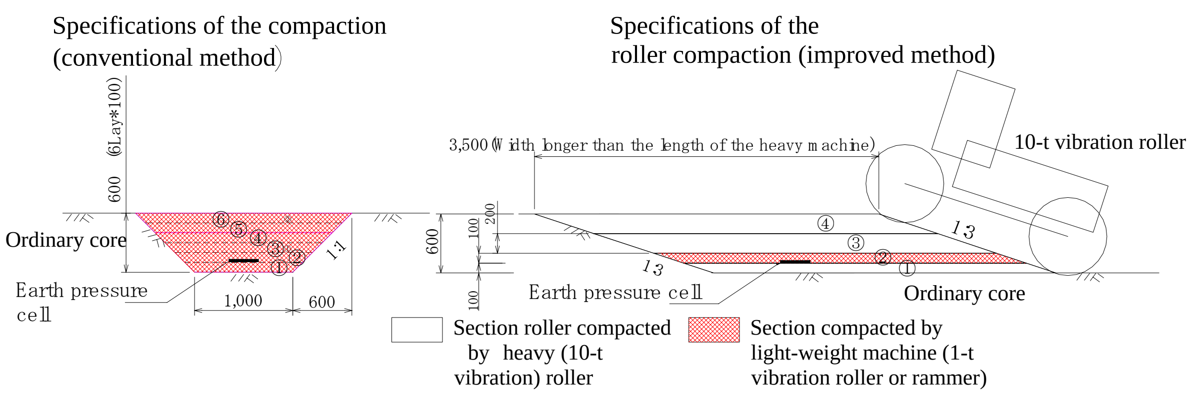


Figure 8 Mitigating Restrictions to Roller Compactor

2.2.2 Improvement by Not Using Small Grain Size Soil in the Embedded Sections

By not using small grain size soil in the embedded sections, the differences in stiffness between the ordinary and embedded sections will be reduced but it will also 1) increases measurement errors attributable to the arrangement of soil particles on the surface of a earth pressure meter, and 2) increase the risk of damaging the cell.

Measurement errors attributable to the arrangement of soil particles on the surface of a earth pressure cell involve the mechanism shown in Figure 9. Thus measurement errors increase if the arranging soil particles are large. Miura [v] reported that arranging soil particles smaller than 1/8 of the diameter of a earth pressure cell reduced measurement errors to less than + 5%. At this site, the maximum grain size was decided to be 1/15 of the cell diameter, which reduced measurement errors to almost zero [vi]. As we used earth pressure cell of about 300 mm in diameter, the maximum grain size of the soil on the surface of the cell was decided to be 20 mm. The thickness of the range, which had the maximum grain size of 20 mm, was decided to be 10 cm above and under the cell (total of 20 cm) (Figure 10).

The method for preventing damages to the cell was devised based on our experiences on installing earth pressure meters at the bottom of the dam. It involved using materials of a maximum grain size of 50 mm for 20 cm above the embedded section, which consisted of the soil of the maximum grain size of 20 mm (Figure 10).

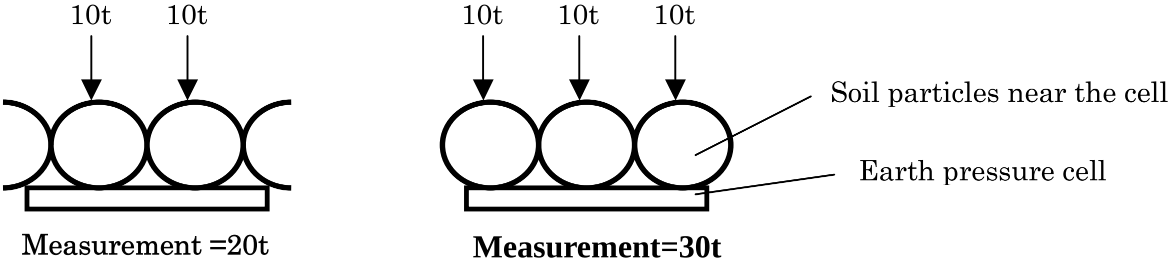


Figure 9 Error caused by Arrangement of Soil Particles on a Sensor (Schematic Illustration)

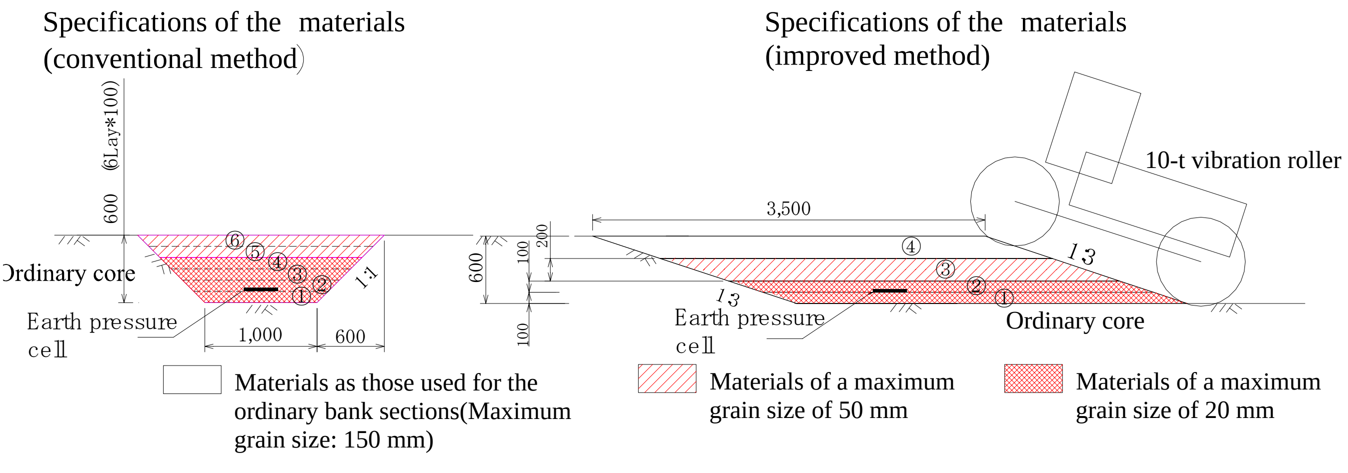


Figure 10 Mitigating Restrictions by Maximum Grain Size of Soil around Earth Pressure Cell

2.3 Improved Embedding Method

Based on the investigations above, the authors developed an improved embedding method of the cell as summarized in Figure 11.

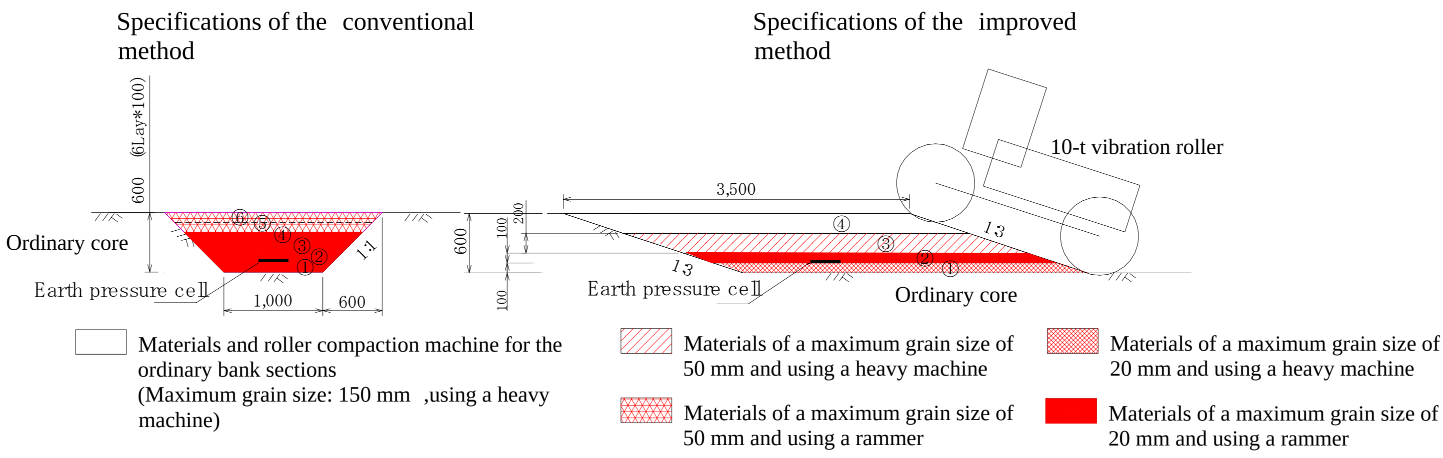


Figure 11 Improved Method for Embedding Earth Pressure Cells

3. EXAMINING THE REASONABLENESS OF MEASUREMENTS DURING BANKING

The reasonableness of earth pressure measurements from the cells that were installed using the improved embedding method were examined.

3.1 Examining the Reasonableness of Measurements by Comparing with Theoretical Earth Pressure Values

The earth pressure measurements during banking were very similar to the theoretical earth pressure values (soil density x height of the embankment), showing the effects of the improved method (Figures 12.1 to 12.3). But as the elevation of the embankment becomes higher, the rises in earth pressure measurement gradually slowed down. It is considered that since the high sections of the core were narrow and thus the stress was transmitted from the core zone to filter zones.

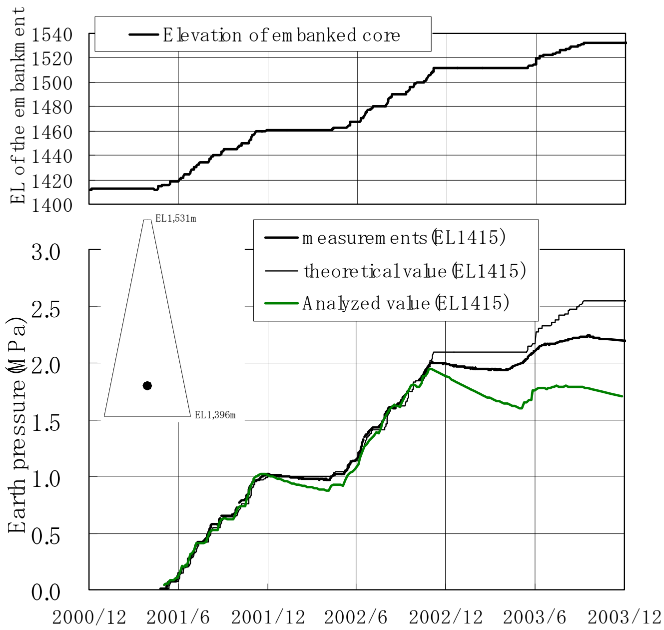


Figure 12.1 (EL1415)

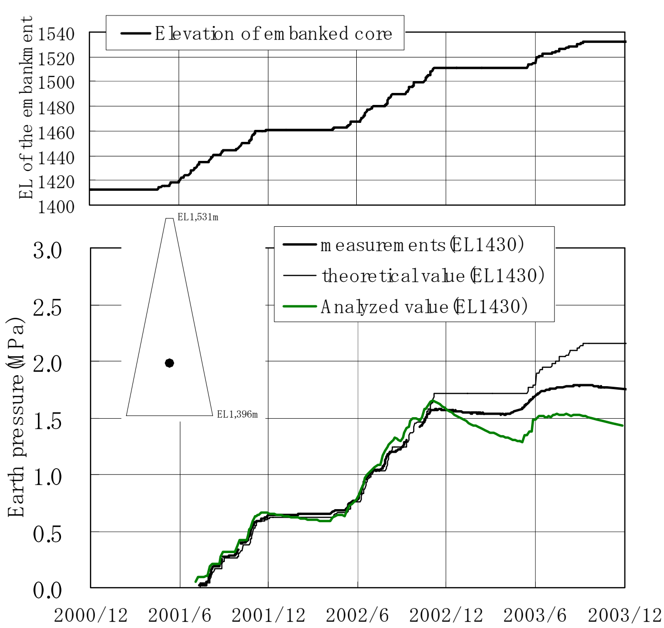


Figure 12.2 (EL1430)

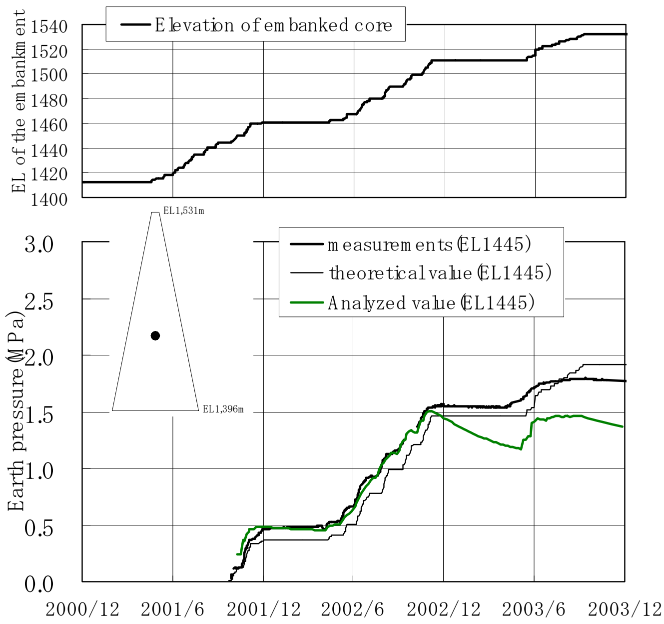


Figure 12.3 (EL1445)

Figure 12 Comparison between Measurement, Theoretical Value and Analytical Value

3.2 Examining the Reasonableness of Measurements by Comparing with Values determined by Numerical Analysis

Since the effects of stress distribution among zones were not considered in the comparison of the measured and theoretical earth pressure values, we also compared the earth pressure measurements with values calculated by numerical analysis.

3.2.1 Overview of Numerical Analysis

Numerical analysis was conducted using the model of Sekiguchi and Ota [vii]), for which comparative examination with dam measurements has been reported (elasto-plasticity effective stress analysis). The property values of the dam are shown in Table 4. The property values of the core and filter values were the data of quality control tests conducted for each banking elevation of 10 m, and those of the rock zones were the data of the quality control tests conducted every year. Of the models used for the analysis, the model at the completion of banking is shown in Figure 13.

Table 4 Property Values used in the Analysis

	core	Fine-grained filter	Coarse-grained filter	Rock (1)	Rock (2)	Foundation rock	Basis of parameter setting
Unit weight γ (kN/m3)	21.1～21.8	21.4～22.9	20.6～22.8	21.1～22.6	21.0～22.2	20.0	Quality control test of the materials
Initial void ratio e0	0.369～0.441	0.178～0.263	0.160～0.306	0.167～0.257	0.181～0.252	-	Ibid
Compression index λ	0.022～0.023	0.017	0.022	0.036	0.036	-	Consolidation test for the core and filters. Inversely determined from the differential settlement gauge measurements for the
Swelling index κ	0.007～0.008	0.004	0.004	0.011	0.011	-	Ibid
Consolidation yield stress Pc(kPa)	300～356	696	519	441	441	-	Ibid
Internal friction angle ϕ (°)	38.8	33.6	36.1	38.0	38.8	-	Triaxial cosolidation test
Young's modulus E(MPa)	-	-	-	-	-	1.47×10^2 ～3.92×10^3	In-situ rock test
Poisson's ratio ν	0.333	0.300	0.300	0.300	0.300	0.200	
Initial permeability coefficient k0(m/sec)	6.82×10^-9 ～2.71×10^-8	2.46×10^-6 ～6.60×10^-5	1.57×10^-4 ～6.46×10^-4	1.66×10^-3 ～1.30×10^-2	3.88×10^-3 ～6.01×10^-3	2.66×10^-7 ～2.66×10^-6	Banking control data

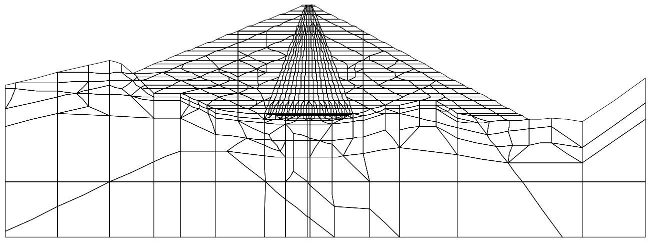


Figure 13 Configuration of Mesh used for the Analysis (at Embankment Completion)

3.2.2 Comparing Results of Numerical Analysis and Measurements

Since earth pressure is closely related to pore water pressure, behaviors of pore water pressure are also described in this section. Values estimated by numerical analysis reproduced measurements well (Figures 14.1 and 14.2), but differences were observed in the points described below.

• Pore Water Pressure

Rises in excess pore water pressure during banking were larger in the analysis than in actual measurements. Drops in excess pore water pressure while banking was suspended were also larger in the analysis. These differences were attributable to the fact that the analytical values were always based on saturated conditions while the actual states of the dam were:

1) Unsaturated in the core zone during banking, resulting in small increases in excess pore water pressure by increases in overburden load, and
2) Unsaturated at the boundary between the core and filter zones while banking was suspended, resulting in small drops in excess pore water pressure in the unsaturated region where hydraulic conductivity was low.

• Earth Pressure

The measured and analytical earth pressure values were similar during banking.
However, the values estimated by the numerical analysis were smaller than actual measurements for the periods during which banking was suspended. This was possible attributable to:

1) Analytical drops in excess pore water pressure were faster than the actual drops,
2) Drops in excess pore water pressure caused consolidation and settlement of the core zone,
3) Settlement of the core zone is faster than the filter zones, resulting in larger arching action estimations than the actual actions, and
4) The estimated earth pressures were larger than actual values in the filter zones and were smaller in core zone.

The numerical analysis could not reproduce the actual behaviors of earth pressure during the periods of banking suspension, but the analytical values during these periods agreed with the measurements if the values were kept unchanged during these periods. Thus, the measurements by the earth pressure cells were likely to be reliable.

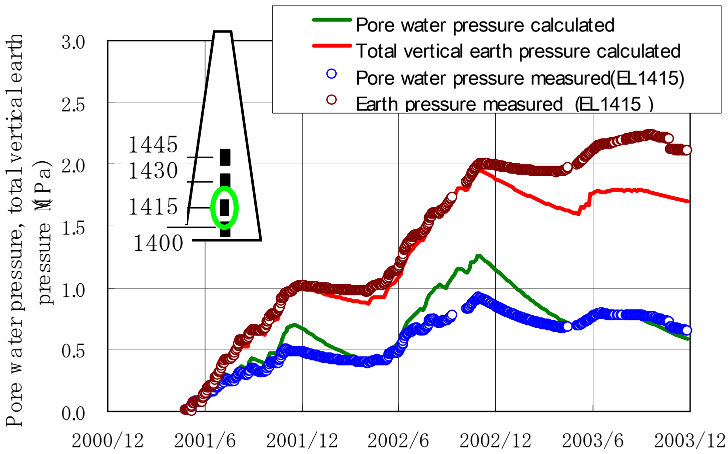


Figure 14.1 (EL1415)

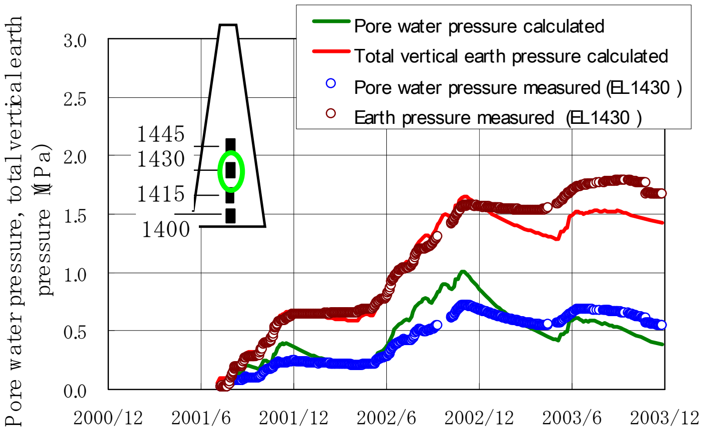


Figure 14.2 (EL1430)

Figure 14 Comparison between Measured and Analytical Values (Pore Water Pressure and Earth Pressure)

4. CONCLUSIONS

Measurement errors of earth pressure cells installed within rock fill dams are possibly attributable to the shapes and embedding methods of the cells. The latter is caused by differences in stiffness between the sections at which the cells are installed and the ordinary bank sections.

Factors that determine the differences in stiffness between the embedded and ordinary bank sections are likely to be the specifications of roller compaction and materials. Our experimental investigations on the specifications of roller compaction showed that the conventional compaction method, which involved use of light-weight machines, resulted in lower stiffness at the embedded sections than in the ordinary bank sections. Thus, sections where earth pressure cells are installed should be roller compacted using heavy machines in principle.

However, the embedded sections cannot be roller compacted using heavy machines in order to prevent damages to the cells. So, we determined the thickness and the width of the range to be roller compacted using light-weight machines that would result in minimum measurement error by conducting a simple analysis. Then, we found that the thinner and wider the range to be roller compacted using a light-weight machine, the smaller the measurement errors.

Based on the findings, we developed an improved method for embedding earth pressure cells, which was shown by numerical analyses to reduce measurement errors to about 1%.

Since heavy machines cannot be used in the conventional method, which involves excavating the ordinary bank section, we also developed a method for enabling the use of heavy machines, which involves spreading soil into which cells are to be embedded onto ordinary bank sections.

The specifications of the soil materials into which cells are to be embedded were also improved. Differences in stiffness between the embedded and ordinary bank sections were minimized by using soil of not very small maximum grain sizes.

The values estimated by an elasto-plasticity analysis (Sekiguchi-Ota model) agreed well with the measurements. Thus, the improved method for embedding earth pressure cells are likely to be appropriate.

5. ACKNOWLEDGEMENTS

The authors thank Mr. Yasuaki Yano of the Minamiaiki Construction Office of the Kannagawa Hydro Power Plant Construction Office of Tokyo Electric Power Company (at that time) and Mr. Tomokazu Suzuki of Tokyo Electric Power Service Co., Ltd. for their assistance in investigating the improved method.

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