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Six-year performance of synthetic-rubber-sheet facing for the upper pond of seawater pumped storage hydropower plant

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ABSTRACT: The demonstration experiments of the seawater pumped-storage power plant have been conducted by operating a life-seized plant with a maximum output of 30 MW to deal with engineering concerns relating to the use of seawater. During the operation in about 6 years, neither defect of the upper pond nor any leakage has been detected, even though much marine organisms have adhered to the EPDM waterproofing sheets. It is also found that the swollen phenomena of waterproofing sheets during the storm condition did not incur the instability of itself and its securing structures. The applied sealing system is confirmed to be in a sound condition during any period in an operation of the plant, taking the monitoring data with the instruments and the inspections with thoroughly drainage of the upper pond into consideration. The degree of the swollen sheets under a strong wind can be estimated by an analytical method, verified by the results of the in-situ monitoring, laboratory test and numerical analysis, which upgrades the design of the sheet lining from the economical viewpoint.

1 INTRODUCTION

For a seawater pumped storage hydropower plant, an upper pond is generally arranged in a flat area atop a steep cliff above the shoreline. To prevent seawater in the upper pond from infiltrating into the ground, the upper pond is a membrane type fill dam. In this case, the use of geo-membranes made of such sealing materials as asphalt, concrete and waterproofing sheets is considered appropriate.

At the demonstration plant, we examined the sealing structure including the foundation for the sealing materials and the method of fixing the waterproofing sheets, taking various types of geo-membranes, asphalt concrete and concrete slabs into consideration. We also examined the leakage detection system for use in the event of leakage, as well as an appropriate return system of leaked seawater into the upper pond. As a result, we decided on a membrane-type fill dam that uses exposure-type waterproofing sheets (synthetic rubber – EPDM, or ethylene-propylene-diene terpolymers) in the upper pond of the demonstration plant (Takimoto et al. 1995, 2002). Figure 1 shows the present state of the upper pond.

This report is to verify the appropriateness of the sealing system for a membrane-type fill dam of the demonstration plant based on the six-year operation. We measure the swelling of waterproofing sheets under a strong wind, and estimate a theoretical, experimental and analytical degree of sheet swelling.

Figure 1. General view of the seawater pumped storage power plant.

2 GENERAL BEHAVIOR OF SEALING SYSTEM OF THE UPPER POND

Impoundment with seawater was started at the upper pond in August 1998. With the maximum rising elevation limited to 1 m/day, the upper pond was filled to a depth of about 20 m. The bottom of the upper pond is at an elevation of about 130 m and the maximum elevation of seawater is 152 m.

Judging from the measurement results of the leaked water drained into the bottom gallery, we confirmed there was no leakage of seawater but a little fresh groundwater. Regarding the sheet-fixing system, we observed no remarkable movement linked to changes in the water level of the upper pond.

We conducted similar monitoring while the demonstration plant was in six-year operation. Measurements of the behaviour of the sheet-fixing system and the dam crest confirmed that these settlements were likely to converge to about 10 mm and 15 mm, respectively in about three years. There was no deformation that would cause problems with the structure. We made twice comprehensive inspection on the upper pond by entirely draining it, along with visually inspecting the sealing system. In the course of each inspection, we observed no local deformation in the waterproofing sheets due to uneven settlement of the foundation, a possible problem feared in the design stage. As for the concern about seawater leakage, there was no evidence of such leakage.

From the above figures, we confirmed that the sealing system consisting of mainly EPDM waterproofing sheets was working properly at the initial stage of impoundment and during the subsequent operation of the demonstration plant.

3 BEHAVIOUR OF WATERPROFING SHEETS UNDER STRONG WIND CONDITION

3.1 *Observed behaviour of waterproofing sheets*

Generally speaking, when there is a strong wind, an area with a lower pressure than in the surrounding area is formed around the dam due to the separation and disturbance of the air stream behind the structure. A similar phenomenon sometimes occurs over the dam upstream slope of the upper pond. At that time, if surface sealing is done with impermeable geomembranes such as waterproofing sheets, the sheets are subjected to a lifting force due to the decrease in air pressure on the slope. Because of this, especially when there is a strong wind, the sheets will swell. This could cause a separation of the sheets, damage to the fixing system, movement of the cushion fabrics, or wrinkling of the sheets, all of which are likely to have a harmful effect on the sealing system.

Figure 2 shows a example of the swollen waterproofing sheets when hit by a strong wind observed at the upper pond of the demonstration plant. The maximum wind velocity at that time was 28 m/sec (average for 10 minutes). The swelling of the sheets through remote monitoring (ITV) images was estimated at about one meter. Similar phenomena typically occur in strong typhoons. Figure 3 illustrates the correlation between wind velocity and the observed height of the sheet's swelling. From the figure, it can be seen that the swelling of the sheet at the upper pond occurs when there is a wind velocity greater than about 10 m/sec and that there is a clear correlation between the wind velocity and the height of the sheet's swelling.

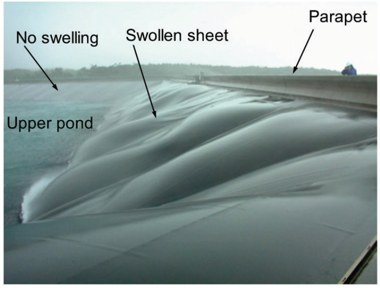


Figure 2. Swollen behavior of the lining sheet of the upper pond under strong wind.

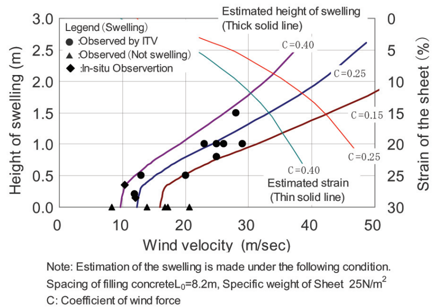


Figure 3. Relation between the swollen height and the wind velocity.

On the other hand, as shown in Fig. 3, observation data reveal cases where sheet swelling occurred or didn't occur even under similar wind conditions. We could hypothesize that sheet swelling is linked to the supply of air through the fill dam to the back of the sheet although, as a mechanism of the sheet's swelling, a decline in air pressure over the sheet caused by wind is a major factor.

However, from the standpoint of sealing system design, it is enough if we can estimate the height of the sheet's swelling or the elongation of the sheet. Thus, in our examination of the swelling phenomenon of the sheet, we conclude that sheet swelling is caused only by a change in wind velocity over the sheet and the formation of a lower pressure area (hereinafter referred to as "negative pressure").

Negative pressure is generally estimated by:

$$q_0 = \frac{\gamma}{2g} \times cV^2 \qquad (1)$$

where q_0 = negative pressure acting on the sheet; γ = specific weight of air; g = gravity acceleration; c = coefficient of wind velocity; V = wind velocity. The coefficient of wind velocity (c) is a parameter determined by the shape of the structure concerned and the characteristic of wind. Here, if the coefficient of c is approximately between 0.25 and 0.50, the wind velocity that produces a negative pressure of about 25 N/m^2, equal to the sheet's weight, is approximately between 8 m and 12 m/sec. These figures more or less agree with the results of our in-situ observations.

The deformation of the sheet under negative pressure depends on the fixing conditions around it. With rectangular perimeter securing, however, if the aspect ratio is more than 2 (in the case of the demonstration plant, length of the slope = 16.4 m, space between securing components = 8.2 m, aspect ratio = 2.0), the deformation of the sheet is two-dimensional except for portions of the edge of the longitudinal axis (Takimoto et al. 1995).

The relationship among tensile force, strain of the sheet (ε) and deformation (height of swelling) of sheets, and the shapes of the sheet's swelling are proposed by Giroud et al. (1995). In addition, as an EPDM sheet shows the property of being nonlinearly elongated when strained, this must be considered in relation to tensile stress. With an EPDM sheet used in the demonstration plant, the relationship has been obtained through a laboratory test as expressed by:

$$T_0 = A \times E\varepsilon = A \times (137 \times 1.17^{-\sigma})\varepsilon \qquad (2)$$

where A = cross-sectional area of the sheet; and E = modulus of the sheet. Using these relationships, the deformation of swollen sheets due to the negative pressure (q_0) can be analytically identified (Kashiwayanagi et al. 2006). The estimated swollen heights of the sheets calculated based on dimensions and weight of the sheets used at the demonstration plant (space between fixing systems = 8.2 m, weight per unit area of the sheet = 25 N/m^2) are compared in Fig. 3 with the actually measured heights. Good agreement is recognized between the estimated and measured values when the coefficient of wind velocity is in the 0.15 to 0.40 range.

3.2 *Experimental study*

The negative pressure acting on the slope under the strong wind is examined by the laboratory experiment. The model of 0.1 m high with the scale of 1 to 50 represents the upper part of the dam of 5 m deep from the crest, which is likely subject to the swelling of sheets, and is arranged in the wind channel of 20 m long, 3 m wide and 1.5 m high. The experimental equipment is shown in Fig. 4.

The measurements are made for the pressure decline on the slope surface and the velocity distribution above the slope respects to the uniform wind velocity at upstream channel (V_0). The pressure decline(P-P_1), which is negative pressure, on the slope is identified by the static pressure difference between of the upstream channel (P_1) and of the slope surface (P) with five (5) tasimeters arranged on the slope (Fig. 5). The wind velocity above the model is measured

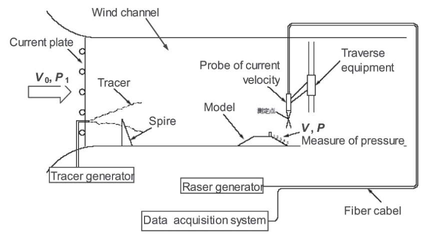


Figure 4. Evaluation of wind velocity around upper pond by the model test.

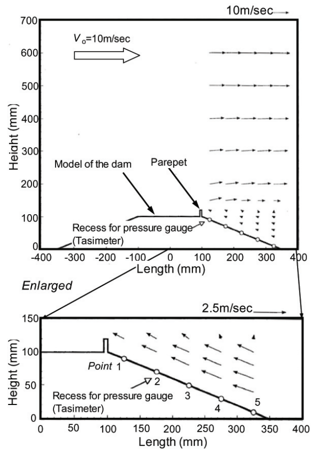


Figure 5. Wind velocity of the experiment (V_0 = 10 m/sec).

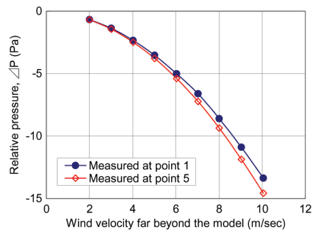


Figure 6. Pressure decline on the slope of the experiment.

by the Razer Doppler current meter as the ensemble mean of 5000 data. The measurement results are shown in Fig. 5 and Fig. 6 for the velocity distribution and the relation between the negative pressure and the upstream wind velocity.

It is found that significant reverse current occur at the downstream slope behind the dam parapet. The negative pressure on the slope shows the monotone increasing corresponding to the increase of the wind velocity. Taking these figures of the negative pressure, the coefficients of wind velocity defined by equation (1) converge to 0.22 to 0.24, shown in Fig. 9, under higher wind velocity.

3.3 *Analytical study*

An applicability of a numerical analysis for the current situation around the dam is verified by the simulation of the laboratory experiment discussed above. The FLOW-3D (Flow Science Inc., USA) is applied for the analysis. The analysis model shown in Fig. 7 has the slip condition at the upper boundary. The distribution of pressure around the experimental model and the detailed velocity distribution behind the dam crest are shown in Fig. 8 (a) and (b), respectively on wind velocity (V_0) of 10 m/sec.

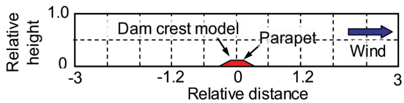
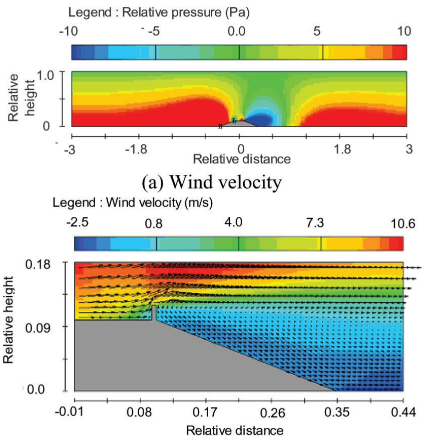


Figure 7. Model representation for the analytical evaluation.



(b) Wind velocity behind the dam

Figure 8. Example of the analysis.

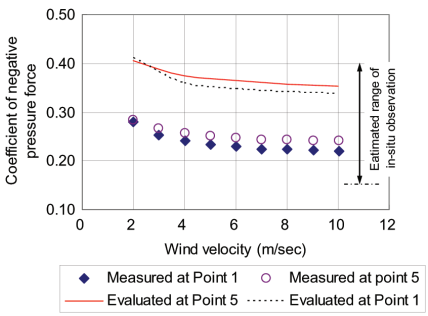


Figure 9. Comparison of the wind coefficient (Location of measure points is shown in Fig. 5).

The significant lower pressure and the reverse current are identified around the downstream slope. These figures show good agreements as a whole with the experimental results. The coefficients of wind velocity (c) range from 0.4 to 0.35 corresponding to the wind velocity, which are larger than the figures estimated by the experiment, but in the range of the observed figures. Although parameters such as the friction property on the model surface, numerical model of a turbulent flow could be identified as causes of such discrepancy, the further study will be necessary from the standpoint of the quantitative evaluation of the flow condition by the numerical analysis.

4 CONCLUSIONS

This paper aims to verify the design of the sealing system with EPDM waterproofing sheets used for the upper pond of a sweater pumped storage hydropower plant. The swelling behaviour of waterproofing sheets under strong wind is examined through the results of the in-situ observation, theoretical method, laboratory experiment and numerical analysis. Our conclusions are as follows:

(1) It is confirmed that there was no leakage of seawater, and that the sealing systems of the upper pond remains in sound condition in operation.
(2) Comprehensively, the observed swelling behaviour of the waterproofing sheets shows good agreements with the results of each study made here.
(3) The coefficient of the wind velocity is confined in a range of 0.15 to 0.40. This provides useful figures on the design of waterproofing sheets.

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