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A prediction method for long-term behavior of prestressed concrete containment vessels

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ABSTRACT:This Paper presents results of studies on the long-term behavior of PCCVs at Turuga Unit No.2 and Ohi Unit No.3/4 power stations. The objective of this study is to evaluate the measured strain in the concrete and reduction force in the tendons, and to establish the prediction methods for long-term behavior of PCCVs. Comparing the measured strains with those calculated due to creep and shrinkage of the concrete, those in contrast were investigated. Furthermore, the reduced tendon forces are calculated considering losses in elasticity, relaxation, creep and shrinkage. The measured reduction in the tendon forces is compared with the calculated. Considering changes in temperature and humidity, the measured strains and tendon forces were in good agreement with those calculated. From the above results, it was confirmed that the residual prestresses in the PCCVs maintain the predicted values at the design stage, and that the prediction method of long-term behaviors has sufficient reliability.

1. INTRODUCTION

In Japan, four power plant using PCCVs are in operation and one PCCV is now under construction. A structural integrity test (SIT)1) of the first PCCV at Tsuruga Power Station Unit No.2 was carried out in February of 1986, and that of Ohi Unit No.3,2) Unit No.4 and Genkai Unit No.33) were carried out in February of 1991, 1992 and 1993 respectively. For these PCCVs, concrete strains and temperatures have been measured periodically since concluding the SITs. In addition, lift-off tests (3 for Tsuruga4), 1 for each unit of Ohi5)) to investigate reduction in tensile force of representative tendons, as the inservice inspection(ISI) have been made.

2. OBJECTIVE

The objective of this investigation is to establish a reliable prediction method for long-term behavior of PCCVs based on a comparison between measured and culcutated results of concrete strains and tensile forces of tendons.

3. OUTLINE OF ACTUAL PCCVs

PCCV cross-sectional views are shown in Fig.1. Tsuruga Unit No.2 and Ohi Unit No.3/4 PCCVs have same dimensions with inner diameter of 43.0m, inner heights of 64.5m. All PCCVs are made up a of cylindrical wall with 43.0m inner diameter, 43.0m height, 1.3m thickness, and a hemispherical dome with 21.5m inner radius, 1.1m thickness. The PCCV of Tsuruga Unit No.2 has a B/M of 8.5m thickness and a 3 buttress BBRV prestressing system, Ohi Unit No.3 and 4, on the other, has B/M of 11.1m thickness and a 2 buttress VSL system. Locations of measured strain and temperature are shown in Fig.1.

4. MEASUREMENT METHOD FOR CONCRETE STRAIN AND TENDON FORCE

Strains and temperatures in the concrete were measured periodically 2～4 times in a year since concluding the SIT. A thermal strain due to temperature changes in the wall is included in measured value of strain. Therefore, a thermal strain was removed from the measured value based on temperature by approximate calculation assuming that the cylindrical and spherical walls of PCCV maintain their shapes as keeping the aspects after thermal deformation. Tensile forces of tendons to be inspected were measured individually at the anchoring portion by the filler gauge method5) generally adopted in ISI of the PCCV. Consequently, tendon tensile force in both ends were not always the same.

5. RESULTS OF MEASURED CONCRETE STRAIN

The Typical long-term behavior of strains are shown in Fig2-Fig7, where t is the effective age since concrete casting and ε is the strain fluctuation since beginning SIT. As shown in these figures, the strains show a tendency to decrease in summer and increase in winter at the dome and mid height of the cylinder. This periodical fluctuation may be caused by changes of seasonal humidity. From the past investingations,6)～8) it has been shown that a fluctuation in humidity has an effect on concrete strain by shrinkage and creep. Specifically, the results from a long term behavior test9) showed that a change in humidity from 40 to 60% in winter and summer respectively had a direct effect on strain and deformation of concrete. Therefore, the expected relative humidity change in atmosphere outside of the PCCV were taken into account in the calculations. Specifically, the equation 2 to be substituted for the design equation for creep and shrinkage(eq.1) was developed as follows.

$$\Phi(t,t_o) = \Phi_{do} \cdot \beta_d(t-t_o) + \Phi_{fo}(\beta_f(t) - \beta_f(t_o))$$
$$\varepsilon_s(t,t_o) = \varepsilon_{so}(\beta_s(t) - \beta_s(t_o)) \quad \cdots\cdot \text{eq.(1)}$$

Where Φ_{fo} and ε_{so} are substituted as,

$$\Phi_{fo} = 1.8 + 0.18\sin\left[2\pi(t-t_o^*)/(365 \cdot C)\right]$$
$$\varepsilon_{so} = 225 + 18\sin\left[2\pi(t-t_o^*)/(365 \cdot C)\right] \quad \cdots\cdot \text{eq.(2)}$$

t : effective age at calculation
t_o : effective age at prestressing
t_o^* : effective age since concrete casting to the first Oct.
C : a coefficient of effective age

The measured and calculated strains of Tsuruga Unit No.2 and Ohi Unit No.3, No.4 showed relatively good agreement, therefore it was confirmed that it is possible to predicte sufficiently strain and shrinkage of concrete. On the other hand, shown in Fig.7, at the bottom portion of the cylinder, the strain changes indicate an opposite tendency, that is, the strain decrease in winter and increase in summer. It is assumed that this behavior is due to thermal strain by temperature change in the concrete wall. Radial displacement of the wall increases proportionaly to the mean temperature, but becomes constrained by the base mat, thus creating thermal stress. Although this thermal stress is not considered in Sec. 4 above, it is considered based on the measured temperature(Fig.7). Comparing with the sum of calculated strain due to shrinkage, creep and thermal, the measured strain shows good agreement. Though the result of Ohi Unit No.3 is shown in this paper, for Tsuruga Unit No.2 and Ohi Unit No.4, similar results were obtained.

6. RESULTS OF MEASURED TENSILE FORCE

The lock-off and lift-off force of tendon are shown in table1～table3, which were investigated in ISI of Tsuruga Unit No.2 and Ohi Unit No.3, No.4. The lock-off force is measured at the end of tendons right after the prestressing, and the lift-off force is measured at ISI, and is equal to residual tensile force. The reduction force come from loses in elasticity(ΔF_1), relaxation(ΔF_2), creep(ΔF_3) and shrinkage(ΔF_4). ΔF_1 is calculated based on FEM analysis, ΔF_2 is obtained by Larson-Miller method10) and ΔF_3 and ΔF_4 are obtained as discribed in Sec.5 ; Tendon arrangements are shown in Fig.8. As shown in these tables, the relationship between lift-off tensile force and calculated force of each tendon is very good. That is, the difference in measured and calculated tensile force is almost less than errors in measurement (statistical estimation based on all obtained measured data by the filler-gauge method including ISI data, shows that errors in measurement 2% of tendon tensile force; 700t). Lift-off force is at the tendon anchoring portion, and does not imply average force in the tendon full length, but since the measured and calculated force indicate good agreement, it is assumed that lift-off force implies nearly average tendon force. From the above mentioned, it was confirmed that the prediction method for long-term behavior of tendon tensile force has sufficient accuracy. However, in a few tendon, tensile force has some difference at each end in a single tendon. To explain these phenomena, an additional study is now being carried out.

7. CONCLUSION

As measured and calculated values on long-term behavior of concrete strain and tendon tensile force indicate good agreement, the prediction method for the behavior has sufficient accuracy. Evaluation method and design method are almost the same except for the influence of seasonal humidity changes, consequently, it is conjectured that PCCVs maintain the required prestress force during plant life.

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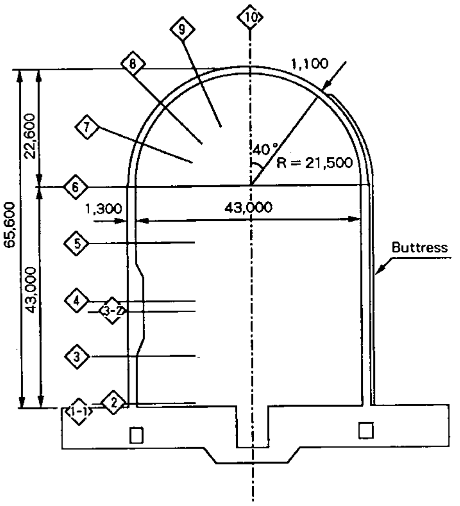
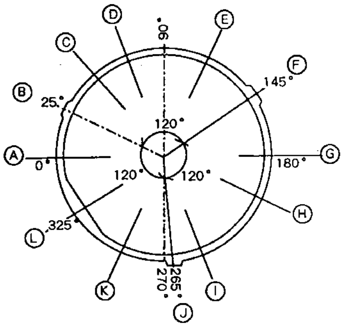
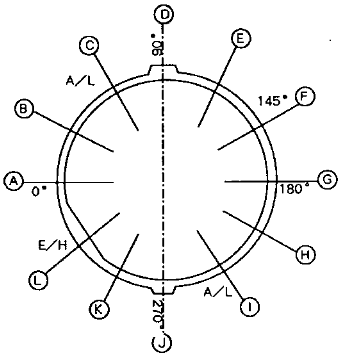


(1) Vertical Section
(Tsuruga Unit No.2,Ohi Uint No.3/4)

Fig.1 PCCV Cross-Sectional Views



(2) Horizontal Section
(Tsuruga Uint No.2)



(3) Horizontal Section
(Ohi Unit No.3)

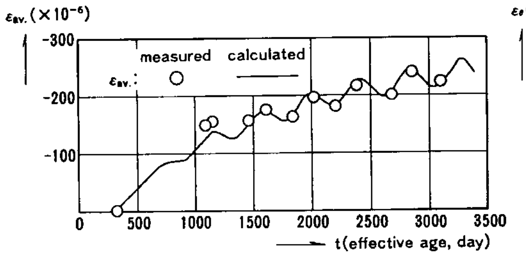


Fig.2 Long-Term Behavior of Concrete Strain
(Sec.9&10 in Dome;Tsuruga No.2)

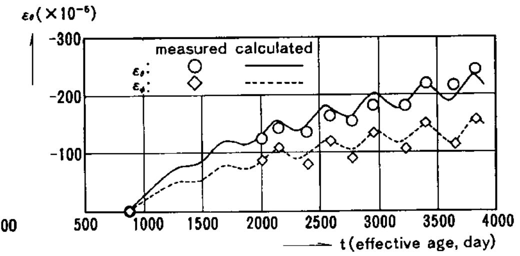


Fig.3 Long-Term Behavior of Concrete Strain
(Sec.3 in Cylindrical Wall;Tsuruga No.2)

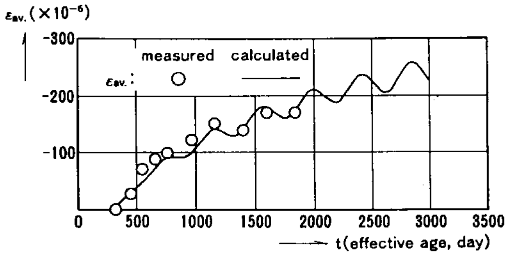


Fig.4 Long-Term Behavior of Concrete Strain
(Sec.8 in Dome;Ohi No.3)

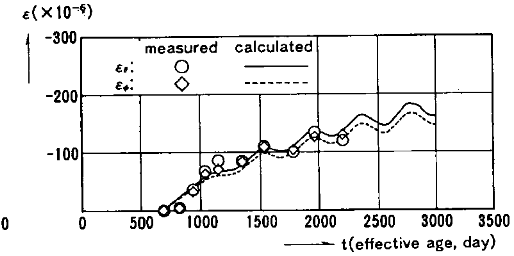


Fig.5 Long-Term Behavior of Concrete Strain
(Sec.6 at Spring-Line;Ohi No.3)

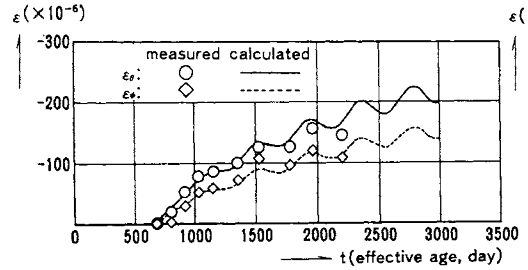


Fig.6 Long-Term Behavior of Concrete Strain
(Sec.5 -3 in Cylindrical Wall;Ohi No.3)

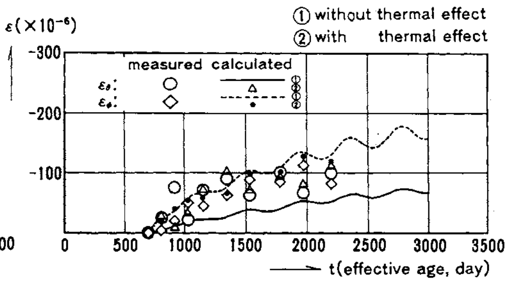
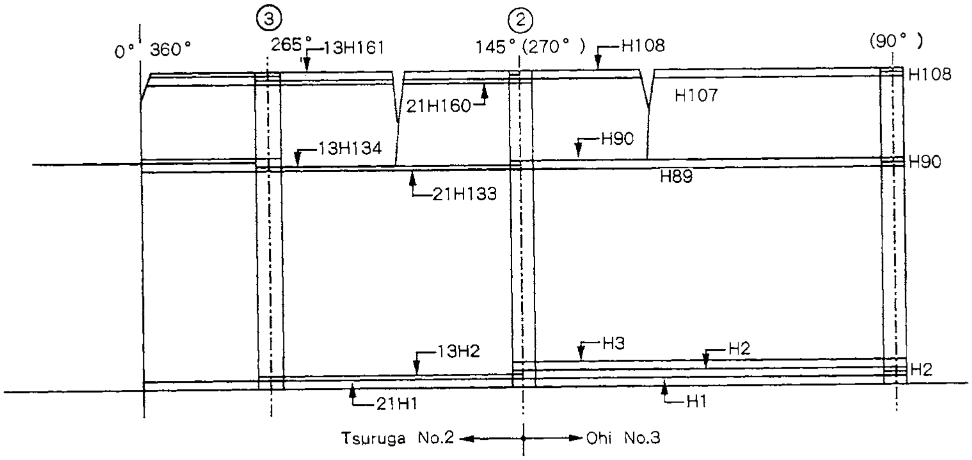
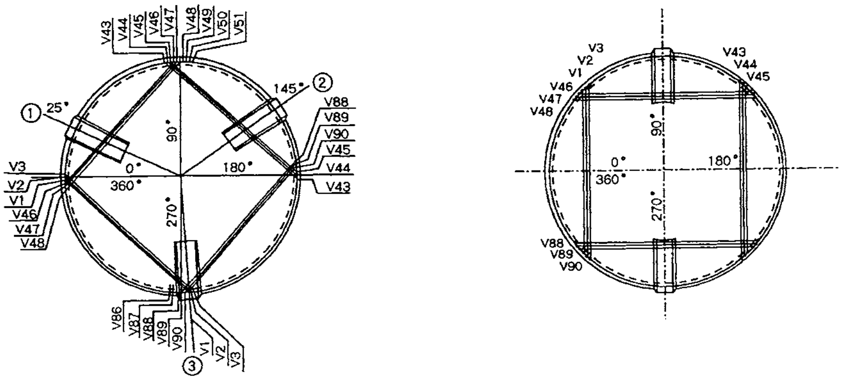


Fig.7 Long-Term Behavior of Concrete Strain
(Sec.2 in Cylindrical Wall;Ohi No.3)



(1) Hoop Tendons (Tsuruga Unit No.2,Ohi Uint No.3)



(2) Inverted U Tendons(Tsuruga Uint No.2)

(3) Inverted U Tendons(Ohi Unit No.3)

Fig.8 Tendon Arrangements

Table 1. Lift-off Test Results of Tendon in Tsuruga No.2

				No.1 ISI			No.2 ISI			No.3 ISI							No.1 ISI			No.2 ISI			No.3 ISI		
Tendon No.			T_0	T_1			T_2			T_3			Tendon No.			T_0	T_1			T_2			T_3		
			meas.	① meas.	② cal.	①/②	③ meas.	④ cal.	③/④	⑤ meas.	⑥ cal.	⑤/⑥				meas.	① meas.	② cal.	①/②	③ meas.	④ cal.	③/④	⑤ meas.	⑥ cal.	⑤/⑥
Hoop Tendon	H 5	Av.	691	653	657	0.99	—	—	—	—	—	—	Hoop Tendon	H150	Av.	679	—	—	—	631	632	1.00	—	—	—
		Δ	−11	−60	—	—	—	—	—	—	—	—			Δ	8	—	—	—	−33	—	—	—	—	—
	H10	Av.	690	—	—	—	—	—	—	650	641	1.01		H157	Av.	687	—	—	—	—	—	—	651	634	1.03
		Δ	3	—	—	—	—	—	—	3	—	—			Δ	0	—	—	—	—	—	—	1	—	—
	H25	Av.	699	654	650	1.01	—	—	—	—	—	—		H161	Av.	691	631	647	0.98	—	—	—	—	—	—
		Δ	1	−22	—	—	—	—	—	—	—	—			Δ	21	−19	—	—	—	—	—	—	—	—
	H37	Av.	689	627	625	1.00	632	617	1.02	622	612	1.02	Inverted U Tendon	V16	Av.	687	655	645	1.02	—	—	—	—	—	—
		Δ	−18	−20	—	—	−34	—	—	−27	—	—			Δ	10	22	—	—	—	—	—	—	—	—
	H44	Av.	689	—	—	—	631	622	1.01	—	—	—		V23	Av.	691	661	659	1.00	663	653	1.02	653	650	1.00
		Δ	− 3	—	—	—	−50	—	—	—	—	—			Δ	−12	−15	—	—	11	—	—	−11	—	—
	H54	Av.	690	—	—	—	—	—	—	633	639	0.99		V31	Av.	688	—	—	—	655	649	1.01	645	645	1.00
		Δ	13	—	—	—	—	—	—	9	—	—			Δ	− 4	—	—	—	13	—	—	4	—	—
	H58	Av.	682	644	639	1.01	—	—	—	—	—	—		V50	Av.	693	—	—	—	—	—	—	652	643	1.01
		Δ	−10	−25	—	—	—	—	—	—	—	—			Δ	− 3	—	—	—	—	—	—	6	—	—
	H86	Av.	693	—	—	—	—	—	—	616	618	1.00		V56	Av.	688	655	649	1.01	—	—	—	—	—	—
		Δ	− 4	—	—	—	—	—	—	−41	—	—			Δ	−20	−63	—	—	—	—	—	—	—	—
	H102	Av.	689	634	650	0.98	636	642	0.99	627	640	0.98		V63	Av.	686	—	—	—	681	652	1.04	666	649	1.03
		Δ	25	34	—	—	24	—	—	41	—	—			Δ	22	—	—	—	16	—	—	29	—	—
	H115	Av.	686	—	—	—	641	631	1.02	—	—	—		V82	Av.	690	—	—	—	677	645	1.05	—	—	—
		Δ	3	—	—	—	−29	—	—	—	—	—			Δ	−21	—	—	—	−29	—	—	—	—	—
	H119	Av.	692	636	655	0.97	—	—	—	—	—	—		V85	Av.	693	663	662	1.00	—	—	—	—	—	—
		Δ	12	−51	—	—	—	—	—	—	—	—			Δ	−10	−30	—	—	—	—	—	—	—	—
	H141	Av.	697	649	668	0.97	650	660	0.98	639	656	0.97		—	—	—	—	—	—	—	—	—	—	—	—
		Δ	3	6	—	—	−15	—	—	7	—	—			—	—	—	—	—	—	—	—	—	—	—

Table 2. Lift-off Test Results of Tendon in Ohi No.3

				No.1 ISI							No.1 ISI		
Tendon No.			T_0	T_1			Tendon No.			T_0	T_1		
			meas.	① meas.	② cal.	①/②				meas.	① meas.	② cal.	①/②
Hoop Tendon	H10	Av.	673	634	638	0.99	Inverted U Tendon	V18	Av.	692	679	666	1.02
		Δ	12	8	—	—			Δ	− 4	− 6	—	—
	H24	Av.	672	634	625	1.01		V29	Av.	692	658	658	1.00
		Δ	− 3	5	—	—			Δ	− 2	25	—	—
	H45	Av.	672	650	636	1.02		V56	Av.	686	662	651	1.02
		Δ	−13	6	—	—			Δ	5	− 3	—	—
	H71	Av.	675	646	630	1.03		V80	Av.	667	655	631	1.04
		Δ	− 2	5	—	—			Δ	−21	2	—	—
	H101	Av.	672	640	640	1.00		—	—	—	—	—	—
		Δ	− 8	29	—	—			—	—	—	—	—

Table 3. Lift-off Test Results of Tendon in Ohi No.4

				No.1 ISI							No.1 ISI		
Tendon No.			T_0	T_1			Tendon No.			T_0	T_1		
			meas.	① meas.	② cal.	①/②				meas.	① meas.	② cal.	①/②
Hoop Tendon	H10	Av.	678	658	645	1.02	Inverted U Tendon	V18	Av.	698	661	673	0.98
		Δ	− 5	− 8	—	—			Δ	0	− 2	—	—
	H24	Av.	678	639	631	1.01		V29	Av.	698	640	665	0.96
		Δ	5	3	—	—			Δ	3	6	—	—
	H45	Av.	676	641	641	1.00		V56	Av.	684	639	649	0.98
		Δ	6	6	—	—			Δ	− 6	1	—	—
	H71	Av.	675	639	630	1.01		V80	Av.	679	638	644	0.99
		Δ	8	3	—	—			Δ	5	5	—	—
	H101	Av.	673	663	642	1.03		—	—	—	—	—	—
		Δ	−16	2	—	—			—	—	—	—	—

To=Lock-off Test Results ^{tonf}

Ti=Lift-off Test Results ^{tonf}

Av= $(T_A+T_B)/2$ ^{tonf}

Δ = (T_A-T_B) ^{tonf}