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Study on the evaluation of the prestressing force prediction of PCCV tendons using Monte Carlo simulation

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ABSTRACT : In this paper, we discussed the influence of the distribution of various factors on the predicted lift-off loads of the PCCV tendons in Ohi power station unit No.3 of The Kansai Electric Power Co.,Inc.. We applied Monte Carlo simulation to calculate the range in which the predicted values can be distributed. Comparison was made both between the calculated results and the measured loads by 1st year ISI, and the calculated results at 40th year and the required values for design.

1 INTRODUCTION

Prestressed concrete containment vessels (PCCV) in reactor buildings of PWR 4 Loop type nuclear power plants are designed so as to keep enough structural integrity in their plant life. Especially, the resisting pressure ability is obtained by prestressing the tendons of concrete containment vessels. The forces change with the passage of time by various factors, therefore, required structural integrity against the design pressure shall be confirmed throughout plant life in actual PCCVs. Measuring the lift-off load is one method for evaluating the loss of tendon forces.

In this paper, we discussed the influence of the distribution of various factors for calculating lift-off load, such as sectional area of strand, Young's modulus of tendon and concrete and coefficient of creep on the variation of predicted tendon forces in order to establish evaluation method of tendon forces which has higher reliability and rationality. We applied Monte Carlo simulation to calculate the range in which the predicted values can be distributed. Comparison was made both between the calculated results and the measured loads by 1st year ISI, and the calculated results at 40th year and the required values for design.

Fig.1. shows the outline of PCCV in Ohi power station unit No.3.

2 INSERVICE INSPECTION

Inservice Inspection (ISI) is performed in order to examine whether the quality and structural integrity are normally retained and confirm the safety as a nuclear power plant. Procedures of ISI are determined for each plant. Frequency and items of ISI in Ohi power station are determined as follows.

(a) ISI shall be performed 1,3 and 5 year after the beginning of plant operation, and performance of ISI in the subsequent years shall be determined according to the past results of ISI.

(b) Main items of ISI are visual examination of concrete surface, anchorage area of tendons and surrounding area, measuring of lift-off loads and examination of corrosion protection medium.

Tendons to be examined shall be selected from among each type, hoop or inverted U.

In this paper, we selected H45 and V29, the tendon end forces of which are to be measured throughout plant life, among all the ISI tendons of Ohi power station unit No.3 for our study.

3 CALCULATION METHOD OF LOSS OF TENDON FORCES

Elastic deformation loss (ΔF_1), relaxation loss of tendon (ΔF_2), creep loss (ΔF_3) and drying shrinkage loss (ΔF_4) are considered in the analysis to evaluate the loss of tendon forces.

$$\Delta F_{1234} = \Delta F_1 + \Delta F_2 + \Delta F_3 + \Delta F_4 \qquad (1)$$

where

ΔF_1 : elastic deformation loss
ΔF_2 : relaxation loss of tendon
ΔF_3 : creep loss of concrete
ΔF_4 : drying shrinkage loss of concrete

Elastic deformation loss (ΔF_1) was computed by F.E.M. analysis of PCCV model.

Relaxation loss (ΔF_2) was calculated according to the following equation.

$$\Delta F_2 = A_P \cdot \gamma \cdot f_0 (1.0-2.0(\Delta f_3+\Delta f_4)/f_0) \qquad (2)$$

where

A_P : sectional area of tendon
γ : relaxation coefficient (by Larson-Miller Method)
f_0 : initial tensile stress of tendon

Creep loss of concrete (ΔF_3) and drying shrinkage loss (ΔF_4) were calculated according to the following equations.

$$\Delta F_3 = A_P \cdot \Delta f_3 \qquad (3)$$

$$\Delta F_4 = A_P \cdot \Delta f_4 \qquad (4)$$

$$\Delta f_3 = n \cdot \phi(t,t_0) \cdot \sigma_c/(1.0+n \cdot \sigma_c(1.0+0.5\phi(t,t_0))/f_0) \qquad (5)$$

$$\Delta f_4 = E_P \cdot \varepsilon_s(t,t_0) \Big/ (1.0+n \cdot \sigma_c(1.0+0.5\phi(t,t_0))/f_0) \qquad (6)$$

where

E_P : Young's modulus of tendon
E_C : Young's modulus of concrete
n : ratio of Young's modulus ($=E_P/E_C$)
σ_c : initial average stress of concrete
$\phi(t,t_0)$: creep coefficient of concrete at time t for constant stress acting since time of loading t_0
$\varepsilon_s(t,t_0)$: drying shrinkage strain at time t since time of loading t_0

4 VARIABILITY OF FACTORS

Loss of tendon forces are calculated based on the various factors, such as mechanical properties of strand and concrete, and initial stresses etc.. We used actual material data measured during construction period of Ohi power station unit No.3 and the measured data of strains of the plant in this study.

Table 1. shows the factors and the numerical data considered in the Monte Carlo simulation, the distributions of which are shown as histograms in Fig.2..

Sectional area of strand and Young's modulus are the data actually used in Ohi power station unit No.3. Young's modulus of concrete is the measured data at Structural Integrity Test (SIT) in Ohi power station unit No.3.

Variabilities of creep and drying shrinkage were evaluated as those of the measured values divided by the calculated values. However, measured strains are hard to be divided into creep strain and drying shrinkage strain, and it can be thought that the drying shrinkage strain has less influence on the loss of tendon forces than the creep strain. Therefore, we regarded the variability of strain as due to the creep strain only. Namely, creep strain in the measured strain is regarded as ${}_{m}\varepsilon - {}_{c}\varepsilon_{s}$, and the creep coefficient calculated by using measured strain is expressed as follows.

$$ {}_{m}\phi_{cr} = ({}_{m}\varepsilon - {}_{c}\varepsilon_{s}) / {}_{c}\varepsilon_{0} \qquad (7) $$

where

${}_{m}\phi_{cr}$: creep coefficient by using measured strain
${}_{m}\varepsilon$: measured strain
${}_{c}\varepsilon_{s}$: drying shrinkage strain (calculated)
${}_{c}\varepsilon_{0}$: elastic strain by analysis

We evaluated the relaxation coefficient of tendons as averaged fixed values because of their small number of experimental data. Initial average stress of concrete and elastic deformation loss of concrete are also evaluated as fixed values based on the result of F.E.M. analysis. As for initial average force of tendons, coefficient of variation was calculated based on the assumption that 2% error of measurement is equal to 2.17 times the standard deviation which corresponds to 97% confidence limit.

5 ANALYSIS CONDITION AND ANALYTICAL RESULTS

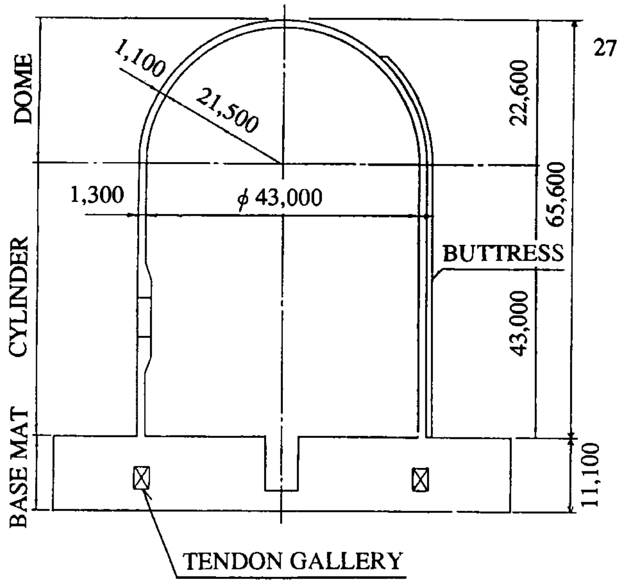
We selected PCCV tendons of H45 and V29 as sample tendons of Ohi power station unit No.3, and applied Monte Carlo simulation based on the factors shown in Table 1. to calculate the range in which the predicted values can be distributed. The adopted trial number of Monte Carlo simulation is 10,000 which is thought to be enough to obtain approximately the same results, and the distribution shape of random numbers is assumed to be normal.

Table 2. and 3. show the time dependent variation of average and coefficient of variation of each loss as a result of analysis. The results show that the creep loss (ΔF_3) of H45 and V29 is the largest as to the value of average, and creep loss (ΔF_3) and drying shrinkage loss (ΔF_4) of H45 and V29 are the largest as to the increasing ratio of average. As for variability, coefficient of variation of creep loss is the largest both in H45 and V29.

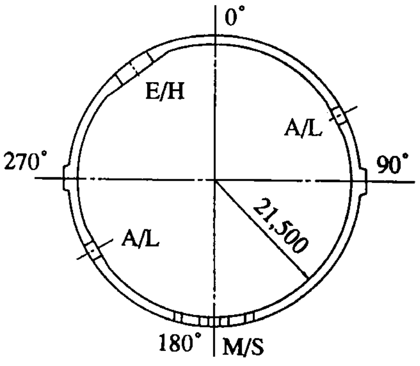
Fig. 3. shows the predicted values of tendon forces as a result of analysis. According to this, measured loads at 1st year ISI are within the range of $\pm 3\sigma$ of the predicted values which corresponds to 99.7% confidence limit, and the predicted values at 40th year are greater than the required values for design.

6 CONCLUSION

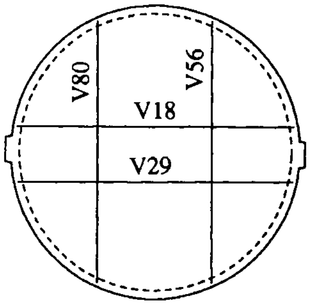
Investigations were made by the method of Monte Carlo simulation as to the influence of the distribution of various factors on the predicted lift-off loads of the PCCV tendons in Ohi power station unit No.3 of The Kansai Electric Power Co.,Inc.. As a result, the measured loads at 1st year ISI are within the range of $\pm 3\sigma$ of the predicted values which correspond to 99.7% confidence limit, and the predicted values at 40th year are greater than the required values for design.



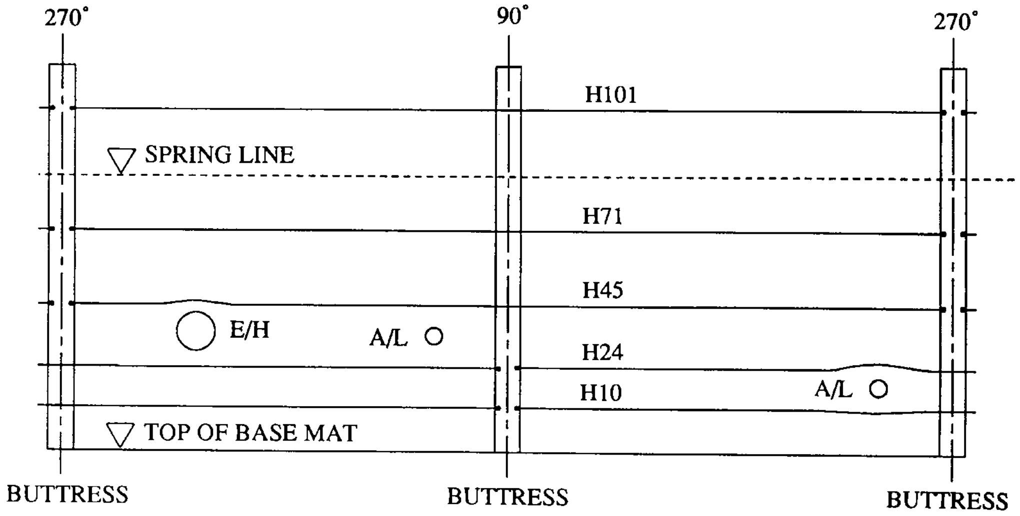
(a) Vertical section



(b) Horizontal section



(c) Arrangement of inverted U tendons (plan)



(d) Arrangement of hoop tendons (envelope)

Fig.1. Outline of PCCV at Ohi power station unit No.3

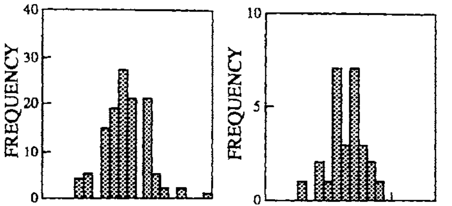
Table1. Factors considered in the analysis

Factors		Data used for calculation
Sectional area of tendon A_p(mm^2)	Average	(1) 5417.3 (2) 5416.3
	Standard deviation	(1) 1.9 (2) 1.4
Relaxation coefficient γ	Fixed value	(3) calculated value
Young's modulus of tendon E_p(kgf/cm^2)	Average	(1) 1.978×10^6 (2) 1.946×10^6
	Standard deviation	(1) 0.016×10^6 (2) 0
Young's modulus of concrete E_c(kgf/cm^2)	Average	4.18×10^5
	Standard deviation	0.29×10^5
Initial average stress of concrete σ_c(kgf/cm^2)	Fixed value	H45 V29 92.55 64.57
Creep coefficient (measured/calculated) $\phi(t,t_0)$	Average	1.05
	Standard deviation	0.39
Drying shrinkage strain of concrete $\varepsilon_s(t,t_0)$	Average	(3) calculated value
	Standard deviation	Considered as variability of coefficient of creep
Initial average tendon force F_0(tonf)	Average	H45 V29 583 661
	Standard deviation	H45 V29 5.4 6.1
Loss of tendon force by elastic deformation of concrete ΔF_1(tonf)	Fixed value	H45 V29 5.1 8.8

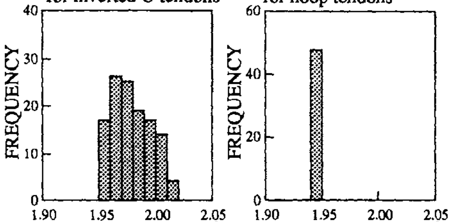
Notes : (1) is the value of inverted U tendons

(2) is the value of hoop tendons

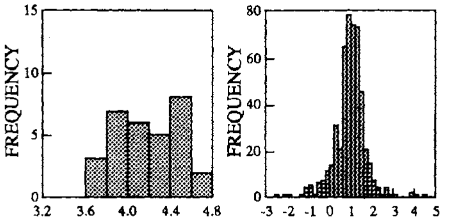
(3) is the time dependent value throughout plant life



(a)Sectional area of strand for inverted U tendons (b)Sectional area of strand for hoop tendons



(c)Young's modulus of inverted U tendons (d)Young's modulus of hoop tendons



(e)Young's modulus of concrete (f)Creep coefficient

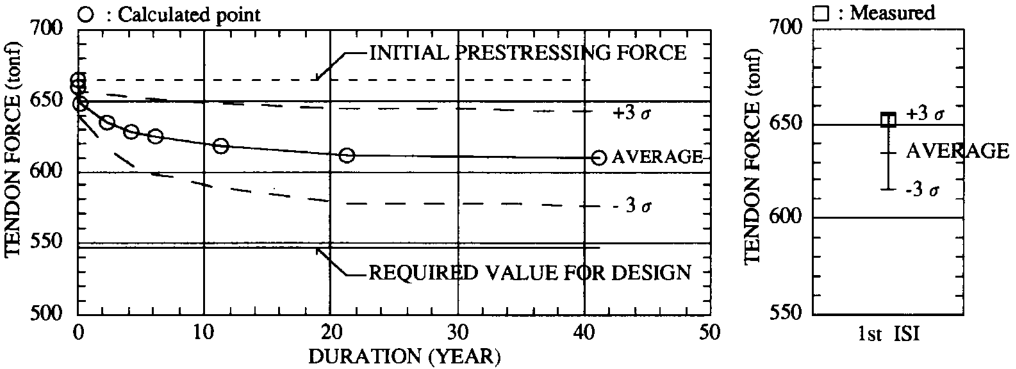
Fig.2. Histogram of material properties of factors

Table2. Time dependent variation of each loss of tendon forces as a result of analysis (H45)

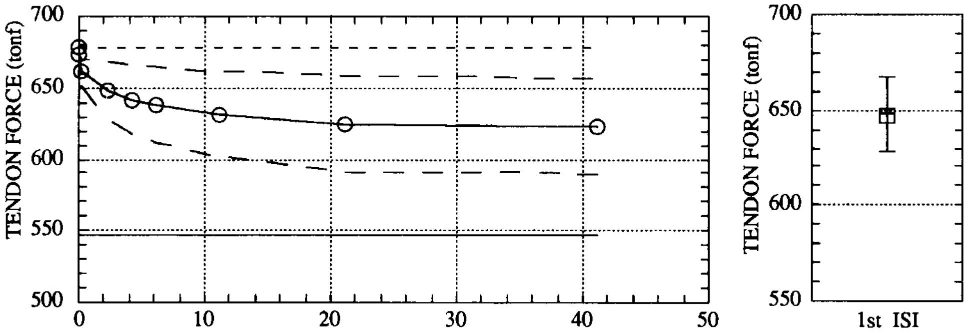
		1st year ISI	3rd year ISI	5th year ISI	10th year ISI	20th year ISI	40th year ISI
Elastic loss ΔF_1	Fixed value	5.1 t	5.1 t	5.1 t	5.1 t	5.1 t	5.1 t
Relaxation loss ΔF_2	Average	4.8 t	5.0 t	5.1 t	5.2 t	5.5 t	5.8 t
	Coefficient of variation	2.63 %	3.28 %	3.64 %	4.19 %	4.76 %	4.87 %
Creep loss ΔF_3	Average	17.0 t	21.3 t	23.5 t	27.1 t	30.3 t	30.7 t
	Coefficient of variation	39.01 %	39.09 %	39.10 %	38.46 %	38.50 %	38.64 %
Drying shrinkage loss ΔF_4	Average	3.5 t	5.2 t	7.2 t	10.4 t	13.3 t	14.3 t
	Coefficient of variation	0.68 %	0.82 %	0.89 %	1.00 %	1.11 %	1.13 %
Total loss ΔF_{1234}	Average	30.4 t	36.7 t	40.9 t	47.9 t	54.2 t	55.9 t
	Coefficient of variation	21.40 %	22.23 %	21.87 %	21.16 %	20.81 %	20.48 %

Table3. Time dependent variation of each loss of tendon forces as a result of analysis (V29)

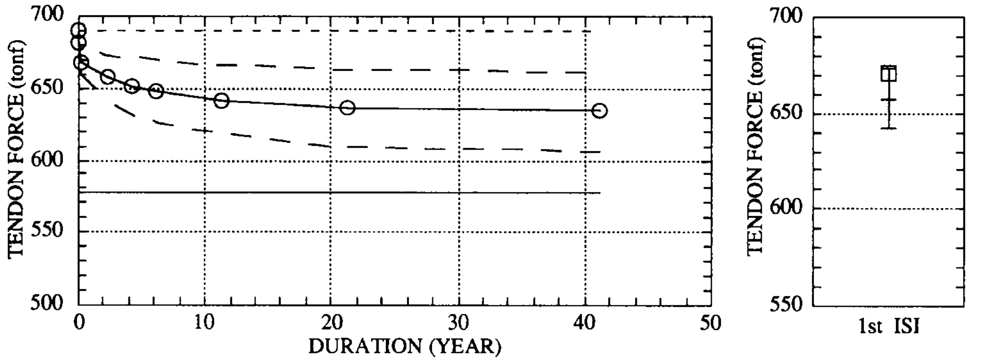
		1st year ISI	3rd year ISI	5th year ISI	10th year ISI	20th year ISI	40th year ISI
Elastic loss ΔF_1	Fixed value	8.8 t	8.8 t	8.8 t	8.8 t	8.8 t	8.8 t
Relaxation loss ΔF_2	Average	6.7 t	6.9 t	7.2 t	7.4 t	7.8 t	8.2 t
	Coefficient of variation	1.99 %	2.43 %	2.64 %	2.97 %	3.32 %	3.43 %
Creep loss ΔF_3	Average	14.1 t	17.4 t	19.1 t	21.8 t	23.9 t	24.5 t
	Coefficient of variation	38.87 %	39.57 %	39.25 %	38.71 %	39.03 %	39.29 %
Drying shrinkage loss ΔF_4	Average	3.6 t	5.7 t	7.7 t	11.1 t	14.4 t	15.4 t
	Coefficient of variation	0.92 %	0.97 %	1.00 %	1.04 %	1.09 %	1.10 %
Total loss ΔF_{1234}	Average	33.2 t	38.8 t	42.8 t	49.0 t	54.9 t	56.9 t
	Coefficient of variation	16.08 %	17.25 %	17.01 %	16.60 %	16.39 %	16.27 %



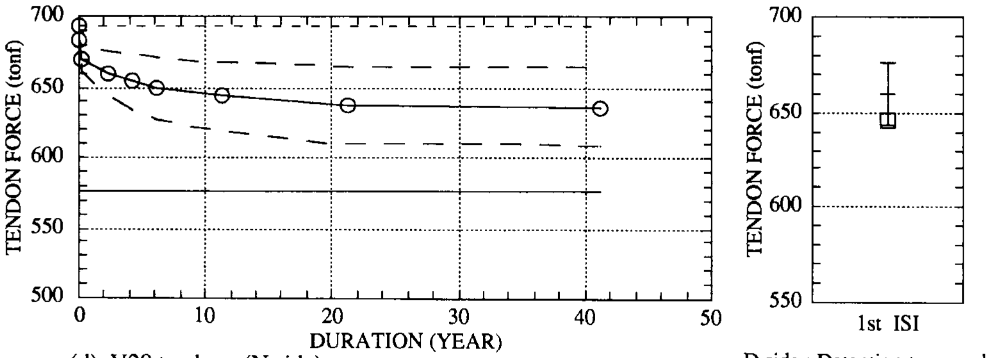
(a) H45 tendon (D side)



(b) H45 tendon (N side)



(c) V29 tendon (D side)



(d) V29 tendon (N side)

D side : Detention type anchor
N side : Normal type anchor

Fig.3. Evaluation of prestressing force prediction of tendons as a result of analysis