COMMISSION INTERNATIONALE DES GRANDS BARRAGES ------- LA 78EME CONGRES DES GRANDS BARRAGES *Hanoi-Vietnam, may 2010*	

DESIGN AND CONSTRUCTION OF PENSTOCKS USING HT100 AND HIGH PERFORMANCE CONCRETE AT KANNAGAWA HYDROPOWER PLANT

Hiroshi WATABE
Deputy Manager: Hydropower Construction Group, Construction Department, Tokyo Electric Power Co., Inc.

Noritaka TOYOTA
Civil Engineer: Civil Engineering Group of Hydro Power Facilities,

Construction Department, Tokyo Electric Power Co., Inc.

Katsutoshi KUBOTA
Manager: Civil Engineering Group of Hydro Power Facilities,

Construction Department, Tokyo Electric Power Co., Inc.

JAPAN

1. INTRODUCTION

Tokyo Electric Power Co., Inc. (TEPCO) has been engaged in the development of pumped storage power generation in order to ensure high quality and stable power supply. TEPCO's Kannagawa Hydropower Plant is located near the Tokyo metropolitan area where electricity consumption is high.

The general layout of the Kannagawa Project is shown in Figure 1. The Kannagawa Hydropower Plant is a pure pumped storage power plant with an effective head of 653 m at a maximum discharge of 510m^3/s and generates a maximum output of 2,820 MW with six motor-generators. Table 1 describes the features of the upper dam and the lower dam.

In the Kannagawa Project, since the maximum internal pressure acting on the penstock was about 11 MPa, the HT100, which has a tensile strength of 950 N/mm², was authorized and applied to the material of penstocks for the first time in Japan. The HT100 was developed on the basis of certain designated requirements, which are mainly toughness and weldability.

Further, in the case of penstocks embedded in rocks, concrete is required to backfill the spaces between the penstocks and the surrounding bedrock so that the internal pressure is shared by both. For the Kannagawa Project, the application of high performance concrete fulfills the requirements to be placed without segregation in the inclined shafts, which are about 1 km with 48 degrees and has about 700 m difference in elevation.

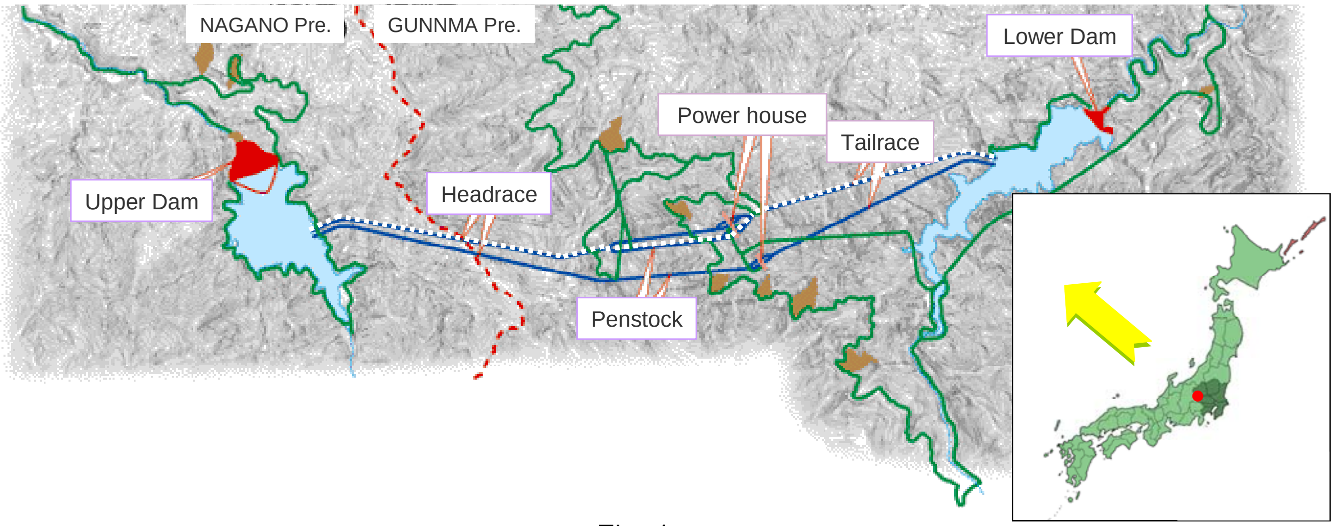


Fig. 1
Location and general layout of the Kannagawa Project

Table 1
Features of the upper dam and the lower dam

Item	Upper dam	Lower dam
Dam type	Rockfill (Center core)	Concrete gravity
Height	136 m	120 m
Crest length	444 m	350 m
Volume	7,200,000 m^3	720,000 m^3
Effective storage capacity	12.67 million m^3	

2. OVERVIEW OF FACILITIES

As shown in Figure 2, the penstocks of the Kannagawa Hydropower Plant are embedded in the rocks, extending over a length of about 1.4 km with a 745 m difference of elevation and having a maximum design head of about 11 MPa, and these inside diameters ranging are from 8.2 m to 2.3 m. The inclined shafts have about 1 km with 48 degrees and an inside diameter of 4.6 m.

TEPCO decided to adopt a high tensile strength steel of 950 N/mm^2 (HT100) to the penstocks of the Kannagawa Hydropower Plant in order to reduce the construction costs based on the reduction of their thickness. Table 2 describes the materials used for unit 1 and 2 penstocks and their weights. The total weight of units 1 and 2 penstocks was 5,154 tons, and the quantity of the HT100 steel was 2,331 tons, which accounted for close to a half of the whole.

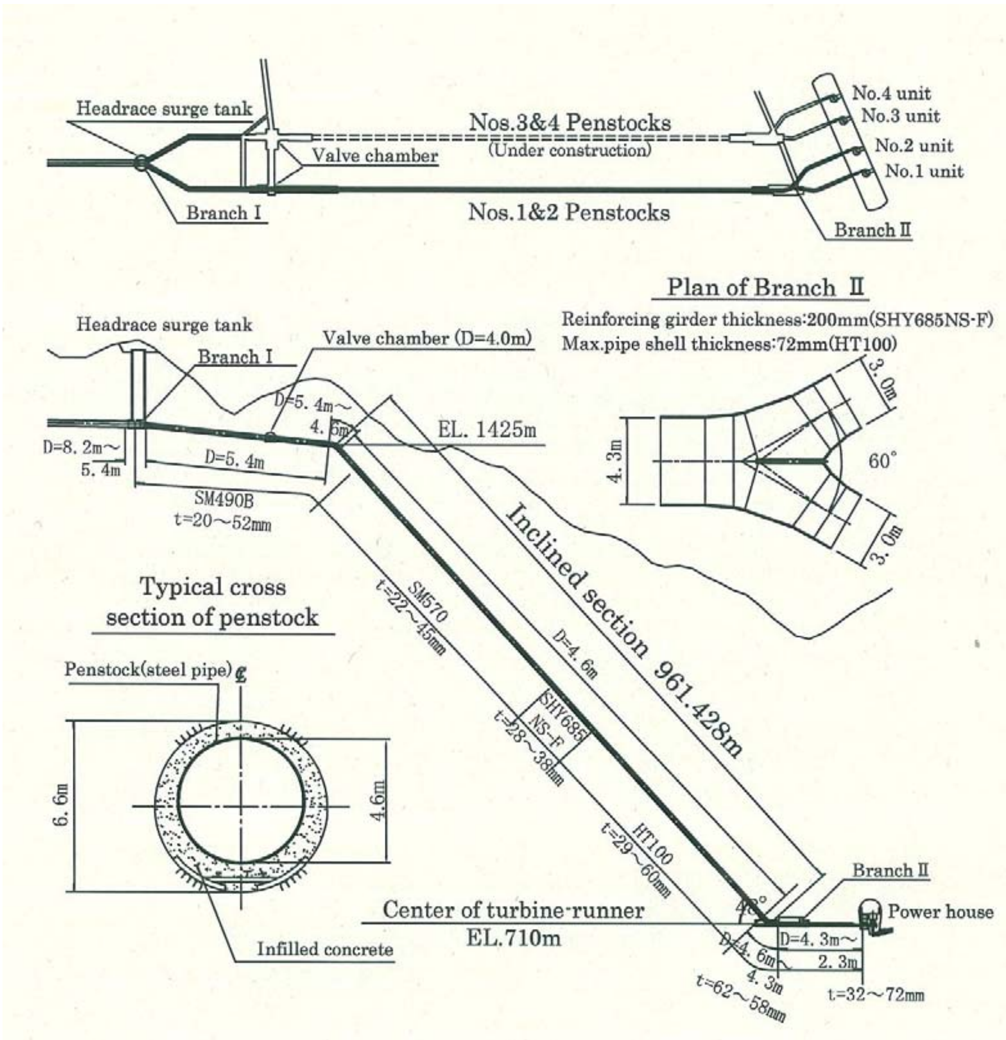


Fig. 2
Overview of the penstocks of the Kannagawa Hydropower Plant

Table 2
Materials and weights of steel for unit 1 and 2 penstocks

Steel	Thickness (mm)	Weight (ton)	Notes
HT100	29-72	2,331	72-mm thick steel is for the branch Ⅱ.
HT-80 (SHY685NS-F)	28-38, 62	312	62-mm thick steel is for jointing inlet valves.
	200	8	200-mm thick steel is for stiffening the branch Ⅱ.
SM570	22-45	1,335	

SM490B	20-52, 70	1,168	70-mm thick steel is for reinforcing the branch Ⅰ.
Total		5,154	

3. DEVELOPMENT OF HT100 TO PENSTOCKS

3.1 DEVELOPMENT OF HT100 TO PENSTOCKS

In Japan, the application of high tensile strength steel superior to HT-80, which has a tensile strength of 780 N/mm^2, to penstocks has been anticipated in order to reduce construction costs. Therefore, the research on higher tensile steel HT100, which has a tensile strength of more than 950 N/mm^2, has been carried out in TEPCO, the mills and the fabricators.

HT100 was developed on the basis of the below requirements.

(1) The mechanical properties of steel material are as safe as HT-80.
(2) The same joint performance as HT-80 is under the weld control conditions.
(3) Manufacturing costs per allowable stress do not exceed that of HT-80.

Further, as the HT-80 was, the toughness of the HT100 steel plates and welding joints was established on the basis of the below performances.

(a) The spread of the brittle crack must be stopped in the base plates of the HT100 (at 0℃).
(b) The brittle fracture must not occur in the welding joints of HT100 (at 0℃).

3.1.1 Evaluation of HT100 Steel Plates

The results of the preliminary performance tests for HT100 steel plates are shown in Table 3 and Figure 3. It was verified that all chemical compositions of the HT100 steel plates satisfied the required quality standards. Further, it was confirmed that the yield strength, tensile strength and sharpy absorbed energy (toughness) of the HT100 steel plates satisfied the requirements.

In Japan, tensile stress tests are usually conducted along the C-direction of the plates. In the tensile stress tests of the HT100 steel plate (thickness: 50 mm), the 0.2% offset yield strength and tensile strength of the L-direction bearing water internal pressure tended to be smaller than that when it was the C-direction. Therefore, the tensile strength tests of the HT100 steel plates were carried out in both L- and C-directions in the actually executed works.

Since the sharpy impact tests of the HT100 steel plates confirmed that the sharpy absorbed energy near the 1/2-thickness of the plate thickness tended to be inferior to that at the 1/4-thickness position, the toughness performance of the HT100 steel plates was checked at positions of 1/4-thickness and 1/2-thickness during actual construction.

Table 3
Chemical compositions of HT100 steel plates

Thickness		Chemical compositions (%)				
		C	P	S	C_{eq}(*)	P_{CM}(**)
50 mm	Ladle check	0.10	0.006	0.002	0.546	0.261
	Requirement	≦ 0.14	≦ 0.010	≦ 0.005	≦ 0.59	≦ 0.29
75 mm	Ladle check	0.11	0.004	0.000	0.599	0.299
	Requirement	≦ 0.14	≦ 0.010	≦ 0.005	≦ 0.62	≦ 0.33

(*) C_{eq}=C+ Si/24+Mn/6+Ni/40+Cr/5+Mo/4+V/14

(**) P_{CM}=C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/15+V/10+5B

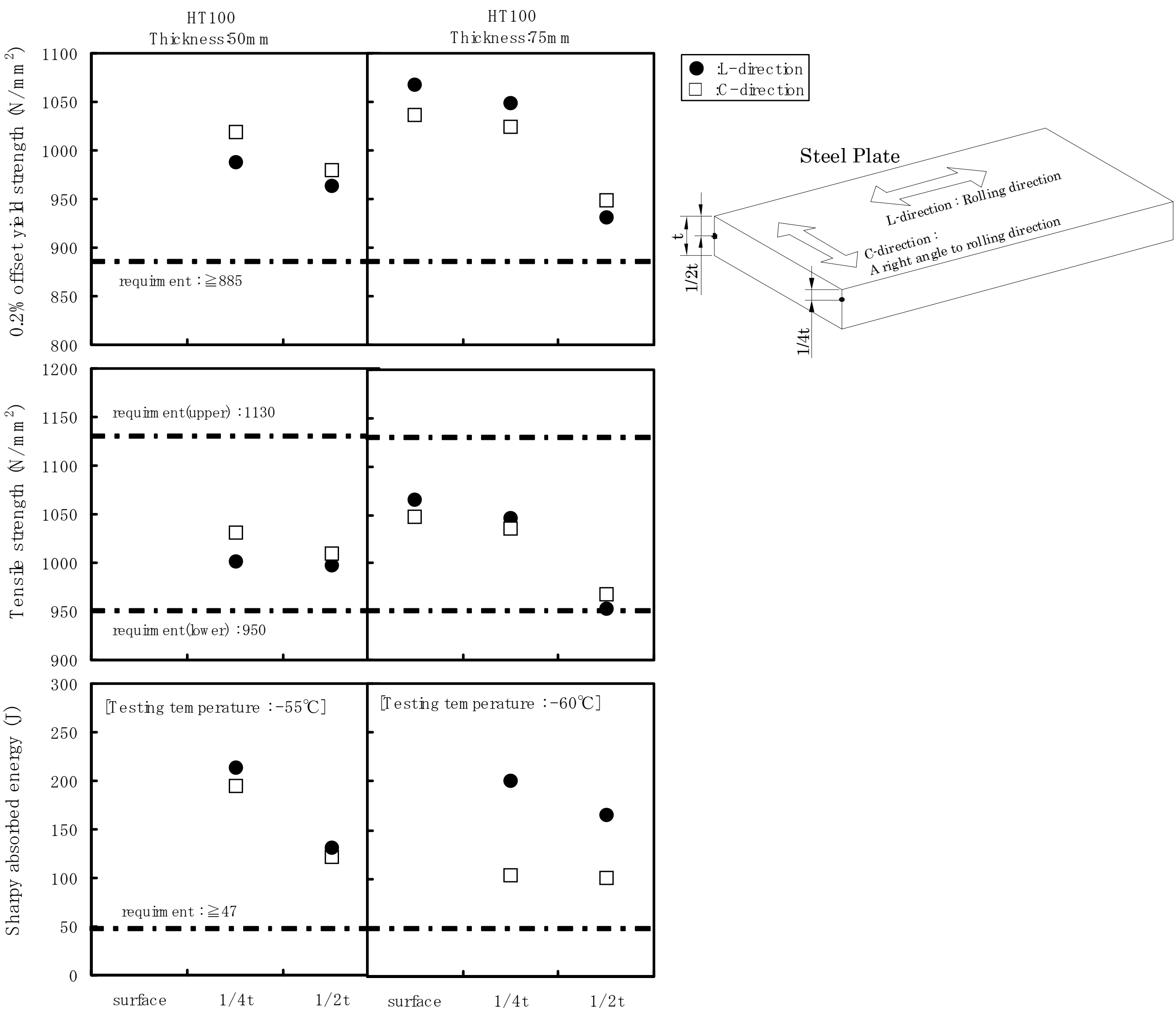


Fig. 3
Results of tensile stress and sharpy impact tests of HT100 steel plates

3.1.2 Evaluation of Toughness of HT100 Steel Plate's Welding Joints

One of the preliminary performance tests for welding joints, which is the K-groove, the test pieces were picked out of each position of "Depo", "Bond", "HAZ" as shown in Figure 4.

The results of the sharpy impact test for the toughness of welding joints are shown in Figure 5. It was confirmed that the toughness of the HT100 plate's welding joints satisfied the required quality.

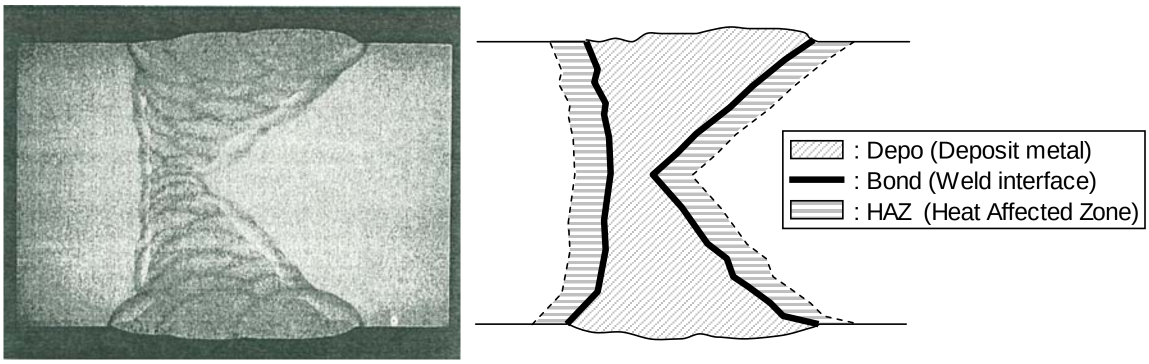


Fig. 4
Preliminary performance test pieces of HT100 steel plate's welding joints

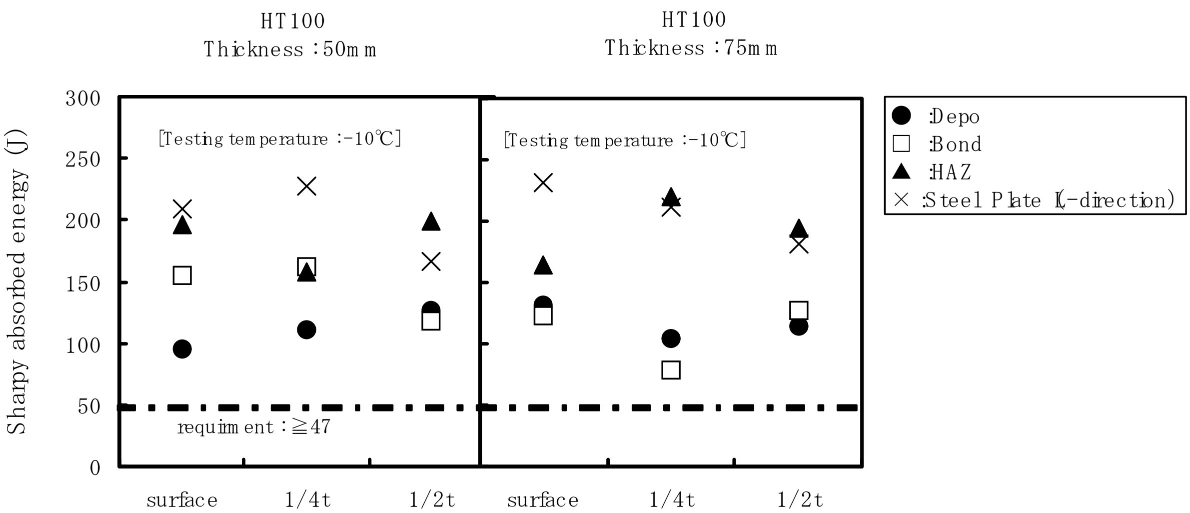


Fig. 5
Results of sharpy impact tests for toughness of HT100 steel plate's welding joints

3.2 SPECIFICATIONS OF THE HT100 PLATES AND THE WELDING JOINTS

Based the on the above results, the application of HT100 steel to the penstocks of the Kannagawa Hydropower Project was decided on. The specifications of the HT100 steel plates and welding joints are shown in Table 4.

Table 4

Specifications of HT100 steel plates and welding joints

Thickness (mm)			t≦50	50<t≦75
Steel plates	Allowable strength		400 N/mm^2	
	Chemical compositions	C	≦ 0.14	≦ 0.14
		P	≦ 0.010	≦ 0.010
		S	≦ 0.005	≦ 0.005
		C_{eq}	≦ 0.59	≦ 0.62
		P_{CM}	≦ 0.29	≦ 0.33
	0.2% offset yield strength		≧ 885 N/mm^2	
	Tensile strength		950 ～ 1,130 N/mm^2	
	Charpy absorbed energy (Testing temperature)		≧ 47 J (-55℃)	≧ 47 J (-60℃)
Welding joints	Tensile strength		≧ 950 N/mm^2	
	Charpy absorbed energy (Testing temperature)		≧ 47 J (-10℃)	≧ 47 J (-10℃)
Welding conditions	Preheated temperature	SMAW(*)	≧ 100℃	≧ 125℃
		MAG(*)	≧ 80℃	
		SAW(*)	≧ 100℃	≧ 125℃
	Interpass temperature	SMAW	100 ～ 230℃	100 ～ 230℃
		MAG	80 ～ 230℃	
		SAW	100 ～ 230℃	100 ～ 230℃
	Postheating conditions		Over 150℃ for 2 hours	
	Limit heat input		The mean not exceeding 45 kJ/cm, and the maximum not 50 kJ/cm	

(*) SMAW: Shielded Metal Arc Welding, MAG: Metal Active Gas welding SAW: Submerged Arc Welding

4. DESIGN OF PENSTOCKS

4.1 DESIGN AGAINST INTERNAL PRESSURE

In the design of embedded penstocks in the rocks, internal pressure is partially shared by the surrounding bedrock in order to reduce construction costs through a reduction in their thickness.

The thickness of the penstocks is determined so that the stress acting on the penstocks calculated using the theoretical formula may not exceed the allowable stress of the penstocks. In addition, the design is established on the safe side so that the stress acting on the penstocks may not exceed the yield point of the steel material even if the bedrock is assumed to bear no internal pressure.

The joint efficiency depends on the welding places and the sampling ratio during the nondestructive inspection. For the Kannagawa Project, a reduction of the plate thickness was adopted by assuming a 100% joint efficiency under the inspection of all of the longitudinal joints.

4.2 DESIGN AGAINST EXTERNAL PRESSURE

To ensure safety against external pressure, penstocks embedded in the rocks are designed to have a safety factor of 1.5 or more against the critical buckling pressure calculated using the theoretical formula.

The groundwater level in the natural ground surrounding the penstocks may be just below the surface level according to investigations. Therefore, the drain facilities are designed to reduce the groundwater pressure to 40%, which is the critical buckling pressure of penstocks in the inclined shafts.

As shown in Figure 6, the drain facilities consist of both a direct drain for draining water from the void between the penstock and the infilling concrete and an indirect drain for draining seepage water, which comes from the bedrocks, from the void between the concrete and the rocks. This double-drainage system is effective because even if when one of the drains is rendered inoperable due to clogging from caustic lime, the other system will serve to reduce the external water pressure up to the aforementioned 40%.

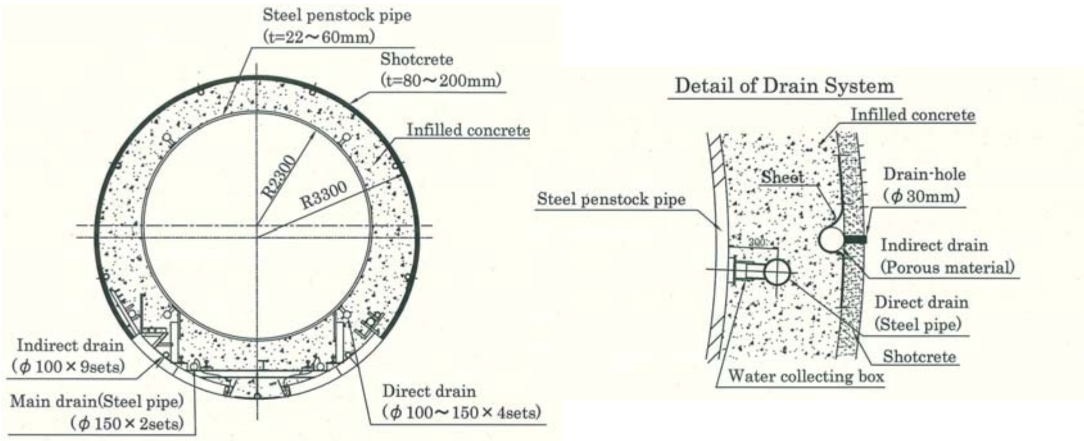


Fig. 6
Designs of the drain facilities

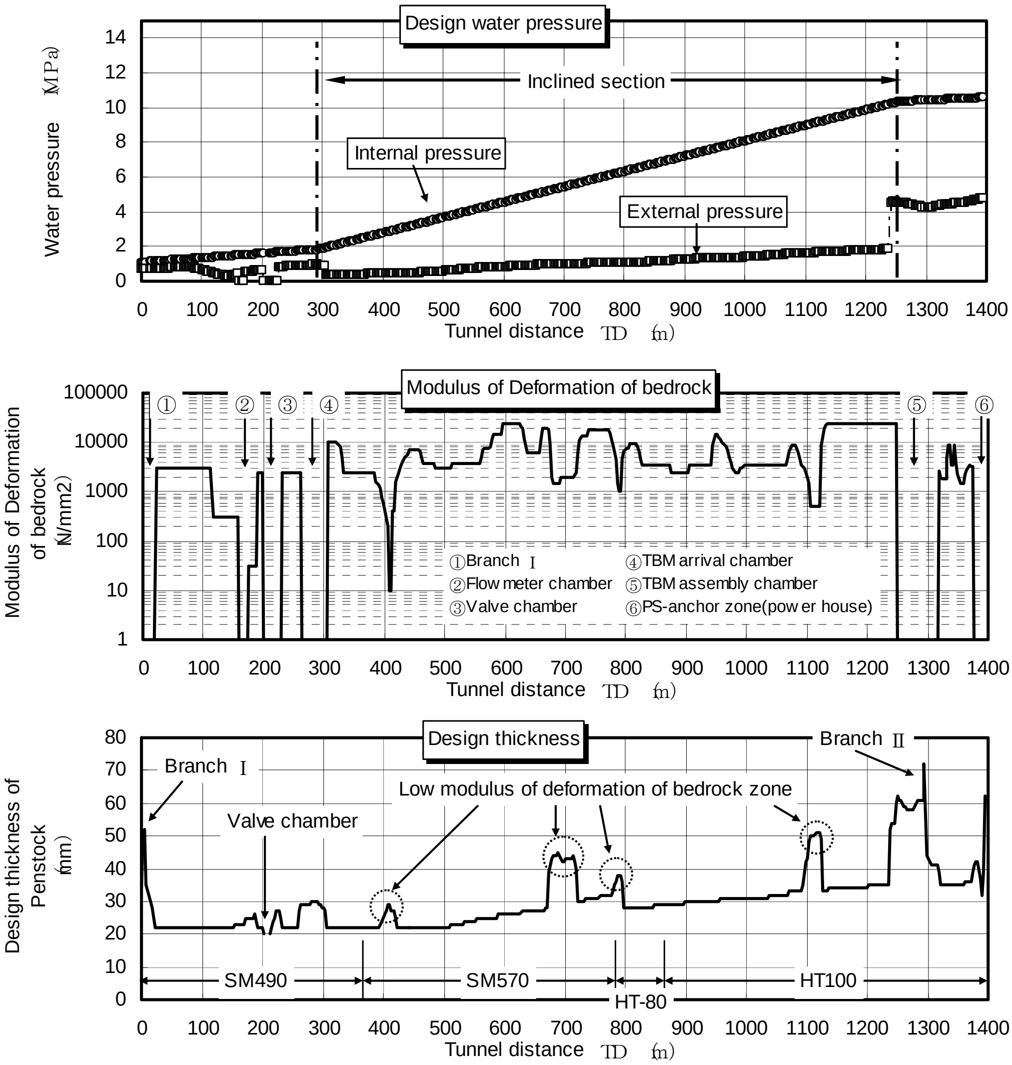
4.3 RESULTS OF THE DESIGN FOR PENSTOCKS

In designing the steel material and the thickness of the penstocks, the thickness was determined as follows;

First, the largest plate thickness, for each unit section with a 3 m-long pipe, was calculated with each candidate material among the following;

(1) Plate thickness dictated by the internal pressure, (2) plate thickness dictated by the external pressure, and (3) the smallest plate thickness dictated by the restrictions under construction conditions.

Then, the most cost-effective material was decided on with the costs for



materials, manufacturing and installation taken into account.

The resultant designs of unit 1 and 2 penstocks of the Kannagawa Hydropower Plant are shown in Figure 7.

Fig. 7
Resultant designs of unit 1 and 2 penstocks

5. INSTALLATION OF PENSTOCKS

An overview of the penstock installation of the Kannagawa Hydropower Plant is shown in Figure 8. The penstocks were constructed by cutting the steel plates, preparing edges and bending the plates at the manufacturer’s plant. And then, due to transportation limits, these were constructed by transporting the half-pipe parts to the site, welding the parts into 3 m-long pipes and then into 15 m-long unit pipes in the site's temporary workshop, and installing in the inclined shafts and welding the 15 m-long unit pipes.

The installation of penstocks in the inclined shafts was a critical path of the construction schedule. Since the adoption of HT100 steel reduced the penstock weight in the inclined shafts, the length of the installation unit pipe increased from 12 m (four 3 m-long pipes), the longest in the past, to 15 m (five 3 m-long pipes). As for the results, the construction period was shortened by 20%.

In the inclined shafts, a construction method that was based on the installation of two 15 m-long unit pipes taken as one work cycle was adopted. The installation speed of HT100 steel sections including concrete filling was 11 days/30m. The mean installation speed of the entire inclined shafts was 10 days/30m. The method of automatic MAG (metal active gas) welding from one side of the inner surface was adopted for the inclined shafts.

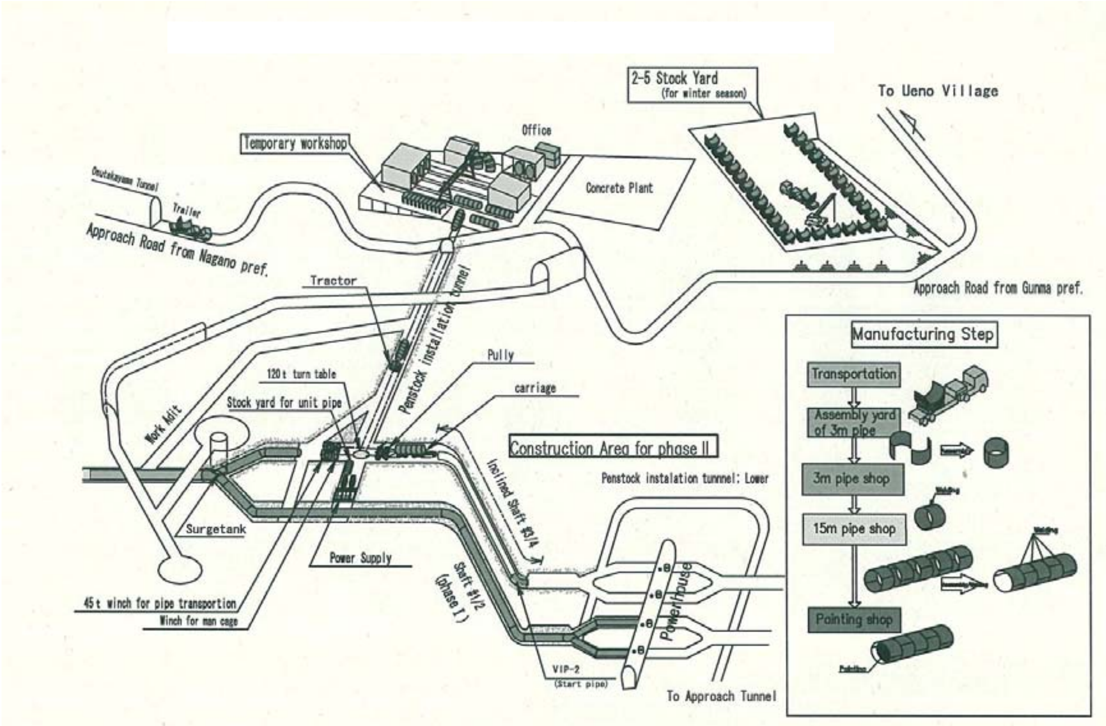


Fig. 8

Overview of the penstocks installation in the Kannagawa Hydropower Plant

Photo.1

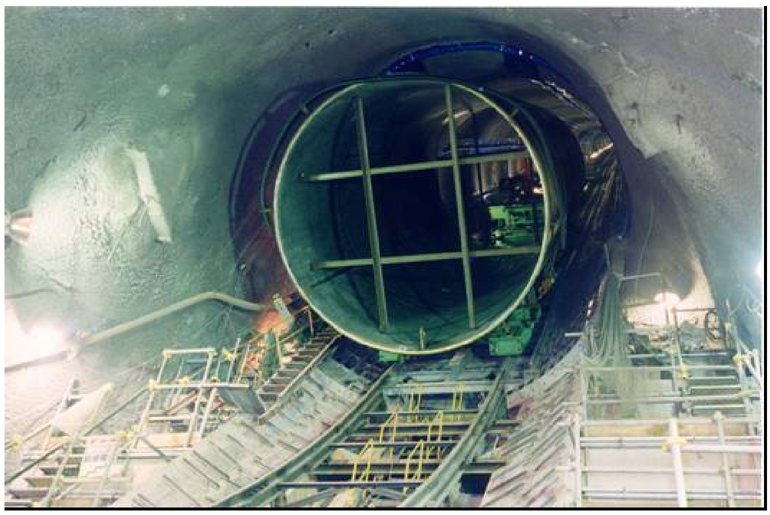


Photo.2

6. APPLICATION OF HIGH PERFORMANCE CONCRETE

6.1 DESIGN OF CONCRETE MIXTURE IN THE INCLINED SHAFT

In the case of embedded penstocks in the rocks, the placing of concrete is required to backfill spaces between the penstocks and the surrounding bedrock so that internal pressure is shared by both. For the Kannagawa Project, it is necessary for concrete to be placed without segregation and with self-compactability into the inclined shafts.

The placing of concrete was designed on the basis of the requirements below.

(1) Fresh concrete are flowable and self-compactable without segregation.
(2) Autogenous shrinkage is kept to the minimum as much as possible.
(3) Young's modulus is over 20,600MPa. (The compression strength at the age of 28 days is over 21 N/mm^2.)

Since there was no precedent on pumping concrete into inclined shafts which are about 1 km with 48 degrees and have about 700m difference in elevation, a preliminary placing test was conducted to determine the specified mixture of high performance concrete after the laboratory tests. The specified concrete mixture is shown in Table 5.

Table 5
Specified mixture of high performance concrete

G_{max} (mm)	W/P (%)	F/P (%)	Content of coarse aggregate (m^3/m^3)		Air (%)	
20	47	30	0.31		4.5	
Unit weight (kg/m^3)						
W	C	F	S	G	SP	VA
180	266	114	865	828	1.5%*P	0.16%*W

G_{max}: Maximum size of coarse aggregate, P: Cement + Fly ash,
W: Water, C: Cement, F: Fly ash, S: Sand aggregate, G: Coarse aggregate,
SP: High-range AE water reducing agent (polycarbonate),
VA: Separation-preventing admixture (water-soluble cellulose ether)

6.2 ESTABLISHMENT OF QUALITY CONTROL CRITERIA

Since the quality control tests of fresh concrete were difficult to perform in the narrow inclined shafts, they were conducted at the placing position of the upper horizontal tunnel. To ensure that the concrete maintained its required performance after flowing down the inclined shafts, quality control criteria was set as shown in Table 6.

As the results of the quality control tests, all of the concrete satisfied the required values.

Table 6
Quality control criteria of high performance concrete

Items	Criteria after flowing down	Criteria before flowing down
Slump flow	Over 40 cm	60 ～ 80 cm
50cm traveling time	Over 3 sec.	4 ～ 16 sec.
Autogenous shrinkage	Less than $180*10^{-6}$	—
Compression strength (Strength at age of 28 days)	Over 21 N/mm^2	Over 21 N/mm^2
Air	Less than 6%	0.5 ～ 3.5%
Concrete temperature (℃)	5 ～ 35℃	5 ～ 30℃

7. ACTUAL BEHAVIORAL OBSERVATION OF PENSTOCKS

The application of HT100 steel plates and high performance concrete to penstocks called for meticulous behavior monitoring. An example of the relationship between the penstock's tensile stress and the water pressure of the HT100's position is shown in Figure 9. The tensile stress is the mean taken from the diametrical square area measured at selected point of the penstocks.

The measured behavioral characteristics of the penstocks are in alignment with the theoretical formula that was utilized in the design. Further, the evaluations have also concluded that the safety of the penstocks is intact and there is a sizeable margin of allowable stress.

In conclusion, it can be affirmed that utilization of both the HT100 and high performance concrete for the first time in Japan satisfied the certain designated requirements.

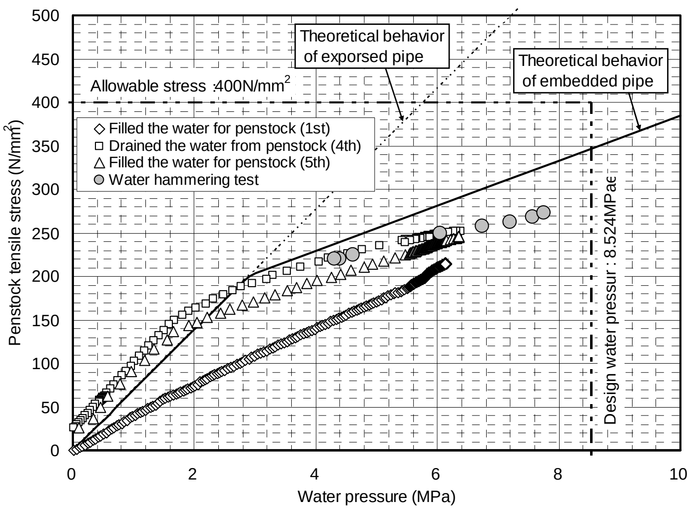


Fig. 9
Relationship between the tensile stress and the water pressure of penstock

8. CLOSING REMARKS

Application of the HT100 made it possible to reduce the cost at base on the reduction of the thickness, welded volume, and the construction period by the lengthening of the unit pipe length due to reduced pipe weight. Further, the application of high performance concrete made it possible to shorten the construction period due to reduced clearance and omission of concrete compaction.

As a result of these efforts, the construction of penstocks of the units 1 and 2 were completed successfully and neither irregular stress nor strain was observed by the measuring system since Unit 1 operations began in December 2005.

REFERENCES

1) Yoshifumi NISHIWAKI, Toshio MAEJIMA and Katsutoshi KUBOTA : Study for the application of High Tensile steel (HT-100) to penstock, Japan Society of Civil Engineers, No.672/VI-50, 37-56, March 2001 (in Japanese)
2) Katsutoshi KUBOTA, Masayuki MINAMI and Nozomu WATANABE : Construction of steel penstocks using HT100 at Kannagawa Hydropower Plant, High Strength Steels for Hydropower Plants, 5th and 6th of July 2005
3) Katsutoshi KUBOTA, Fumiharu KAWASHIMA and Noritaka TOYOTA : Actual behavioral observation of penstocks in the Kannagawa Hydropower Plant, Hydraulic gate & penstock, No.226, March 2006 (in Japanese)
4) Tomoyuki TSUKADA, Hiroshi WATABE, Noritaka TOYOTA and Yoshihiro SHINDO, Advanced Technologies for Kannagawa Pumped Storage Power Plant, The 6th East Asian Area Dam Conference, 381-390, October 2009

SUMMARY

The Kannagawa Hydropower Plant is to be a pure pumped storage power plant generating a maximum output of 2,820 MW with six motor-generators. The first unit began commercial operations in December 2005.

In the Kannagawa Project, the HT100, which has a high tensile strength of 950 N/mm^2, was incorporated into penstocks as Japan's initial efforts to reduce construction costs. Further, for the Kannagawa Project, the application of high performance concrete fulfilled the requirements of the concrete to be placed without segregation in the narrow inclined shafts, which are about 1km-long with 48 degrees and have about 700m difference in elevation.