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RELIABILITY OF SEAWATER PUMPED-STORAGE POWER GENERATION BASED ON A NEW PILOT PLANT PROJECT

by

Kenji Takashima
Member, Dr. Eng., Assistant Director-General for Planning and Coordination Division,
Incorporated Administrative Agency, Japan Nuclear Energy Safety Organization (JNES), Japan
Tokyu REIT, Tranomon Bldg.3-17-1, Tranomon Minato-ku,Tokyo,105-0001 Japan
E-mail: takashima-kenji@jnes.go.jp

Hiroyuki Maki
Member, Managing Officer, Shimizu Corporation, Japan
2-3, Shibaura 1-chome, Minato-ku, Tokyo, 105-8007 Japan
E-mail: hiroyuki-maki@shimz.co.jp

and
Kuniaki Sato
Member, Dr. Eng., Professor Emeritus of Saitama University, Japan, Advisor of CTI Engineering Co., Ltd.
F Tower Building, 3-21-1 Nihombashi Hama-cho, Chuo-ku, Tokyo, 103-8430 Japan
E-mail: satou-kuniaki@tokyo.ctie.co.jp

SYNOPSIS

A seawater pumped-storage power generation system has many advantages in comparison with usual power generation systems. In view of the construction budget, it is beneficial to build a new lower reservoir which is located in the vicinity of a populated area to meet the high demand for electric power. However, building such power generation system poses several engineering and environmental problems such as the adhesion of marine organisms on walls of penstocks, the corrosion of steel materials in penstocks, unexpected seawater leakage and wind-driven spray from the upper reservoir to the surrounding environment.

To develop seawater pumped-storage generation engineering, the authors examined the corresponding data obtained from field tests performed in a new seawater pumped-storage power generation project, which was conducted by the Government of Japan (the Ministry of Economy, Trade and Industry, Japan) at a site on the northern shore of the main island of Okinawa. The results of the study showed that adopted measures for solving problems along a new design policy were practical and reliable methods of constructing a seawater pumped-storage power plant and for achieving profitability.

INTRODUCTION

Many river water pumped-storage power plants have been constructed in Japan since 1934. Today, there are serious constraints which make it difficult to put these plants to use because it is necessary to preserve the environment, and because of topographical and geological requirement. The number of adaptable sites for new plant construction is decreasing. To take advantage of topographical potential head difference between sea water level and the upper reservoir, a new idea for seawater pumped-storage power plant has been conceived.

The advantages of such seawater pumped-storage power plants can be summarized as follows:

(1) Construction costs are reduced because it is not necessary to construct a new lower reservoir.

(2) There are few restrictions on topography in contrast with river water dams which make necessary both upper and

lower reservoirs; the system provides a new water source in nature.

(3) The system can be placed near high power demand areas facing the coast, making it unnecessary set long electric wires.

As for the above-mentioned merits, a seawater pumped-storage power plant can meet the supply and demand of an electric power control system. The generation of electricity by water pumped-storage power plant involves two processes; one is unloading discharge of potential water energy, and the other is its recharge to an upper reservoir from lower seawater basin (Haws, E.T., 1997[2], Hirose, M., 1991[3], Kiho, S., 1992[4], 2000[5], 2002[6]).

The three objectives of the study are to gain an understanding of engineering problems in seawater pumped-storage power plants, the second is to focus on the establishment of proper design concept, and the third is to challenge technical and environmental methods in practice and to increase profitability.

The new pilot plant project was set up in 1987 with the purpose of developing a new pumped-storage power generation to meet the increase of electricity and also to meet the supply and demand of electricity in Okinawa.

OUTLINE OF THE PILOT PLANT

The idea for a pilot plant was innovated to supply electric power for the Okinawa main island. (Its population is 1.3 million which includes the total land area of 1,200km^2. The island is in a subtropical region and has a total rainfall height of 2,037mm/year and an average temperature of 22.4 degrees Celsius.)

Photo. 1 and **Fig. 1** show an aerial view of the plant and its location, respectively. The power station and the conduits (penstock, discharge tunnel) are located below the ground to preserve the natural environment and landscape. **Fig. 2** shows a vertical profile of the plant system and **Table 1** shows specifications of the designed items. The pilot plant is located on the north coast of main island of Okinawa facing the Pacific Ocean. The bedrock geology consists of a kind of sedimentary rock with sandstone and phyllite of the Cretaceous Period in the Mesozoic Era. This plant can make use of a 136m effective head difference between the upper reservoir and the sea level to obtain a maximum discharge of 26m^3/s and a maximum yielding capacity of 30MW. The upper reservoir was constructed on a plateau at an elevation of approximately 150m, an inland distance of about 600m from the coast, and designed features are octagonal dam in plane shape, 25m in height with a surrounding embankment with a crest length of 848m. The effective water storage capacity of the upper reservoir is 560,000m^3. The underground power station is situated on 200m from the coastline at about 30m below sea level.

The upper reservoir is conducted to a penstock with a length of 314m, inside diameter of 2.4m, and the discharged seawater is introduced to an outlet facing the Pacific Ocean through a reinforced concrete tailrace (discharge tunnel) 205m long with an inside diameter of 2.7m.

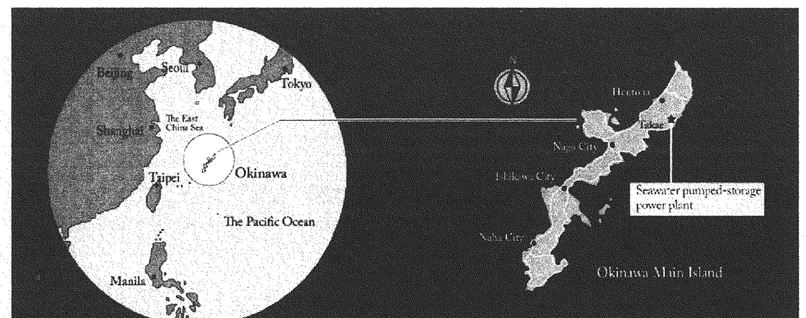


Fig.1 Okinawa location of pilot plant

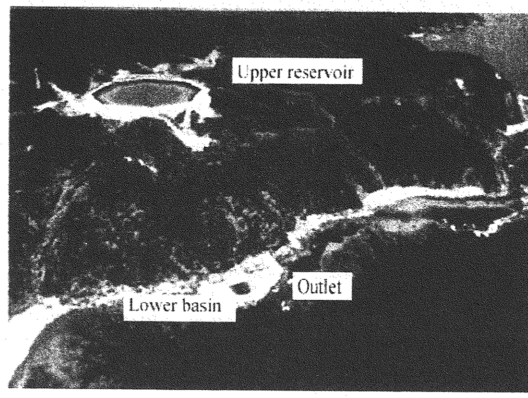
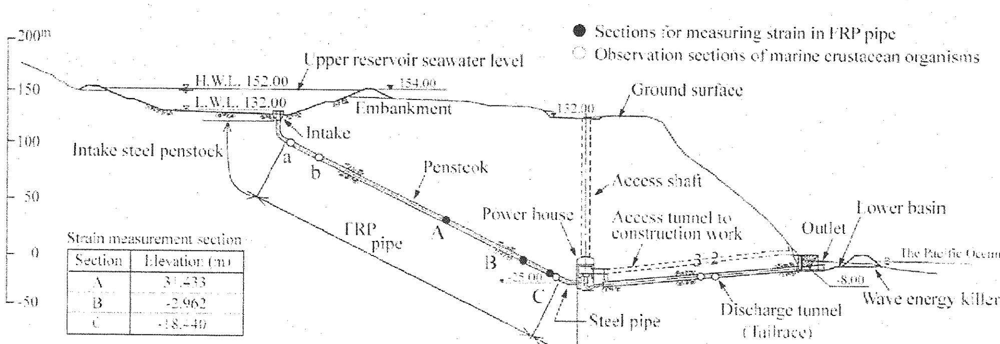


Photo. 1 Aerial view of pilot plant

Table 1 Specifications of the pilot plant

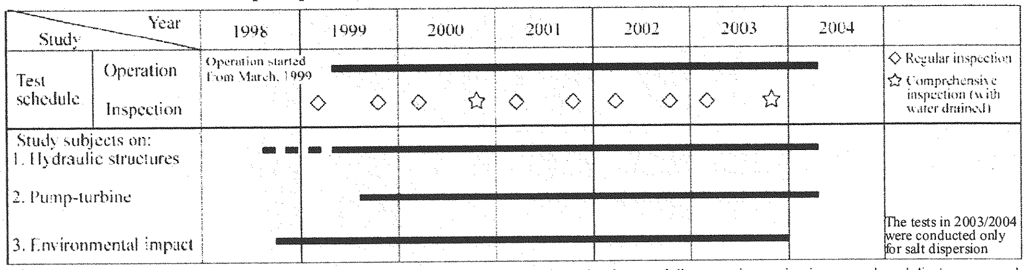
Items		Unit	Specified data
Power generation plan	Effective head	m	136
	Maximum power discharge	m^3/sec	26
	Output	MW	30
Upper reservoir	High water level	m	EL+152
	Low water level	m	EL+132
	Water surface area	km^2	0.05
	Gross storage capacity	m^3	0.59×10^6
	Effective storage capacity	m^3	0.56×10^6
	Type of dam	—	Fill dam
	Height	m	25
	Crest length	m	848
	Embankment volume	m^3	420×10^3
Penstock	Configuration	—	Circular
	Inside diameter	m	2.4
	Length (FRP pipe)	m	300
	Length (total)	m	314
Discharge tunnel	Configuration	—	Circular
	Inside diameter	m	2.7
	Length	m	205
Power station	Type	—	Underground power station
	Width	m	16.4
	Height	m	32.8
	Length	m	40.4
Pump-turbine	Type	—	Francis on a longitudinal axis



EL.: Determined with reference to the mean sea level of Tokyo bay (elevation 0m)

Fig.2 Vertical profile of pilot plant

Table 2 Test schedule of the pilot plant



◇ Regular inspection had been carried out for pump-turbine after dewatering and through submerged direct eye inspection in penstock and discharge tunnel

☆ Detail/Full inspection was done by pump-turbine overhaul and by counting number of adheared marine organisms on penstock wall after dewatering.

Table 3 Tested items for the pilot plant

Plant elements \ Tested Items	Seawater tightness in upper reservoir & penstock	Metal corrosion due to seawater	Head losses owing to marine organisms	Stability in operation & lower basin
Upper reservoir	Rubber sheet tighness & drainage system			Stability of embankment
Penstock	Tightness of mechanical joints	Corrosion of FRP/steel pipe	Adhesion of marine crustacean organisms to pipe wall	
Tailrace & lower basin			Effect of coating material	Calmness of lower basin
Pump-turbine		Corrosion of pump-turbine runner	Hydraulic efficiency of runner	Stability of pump-turbine running
Environmental Impacts	Wind driven dispersed salt water			Undesirable impacts on coral-reef

The schedule for the study subjects and tested items are shown in **Table 2** and **Table 3**, respectively. The test period lasted from March 1999 to March 2004. The main matters of interest are concerned with hydraulic structures (such as intake, penstock, and discharge tunnel, upper and lower reservoirs), pump-turbine on electric equipments, and environmental impact assessment around reservoirs, and their corresponding items had been tested from 1999 to 2004. **Table 3** shows the tested items for different pilot plant elements.

TECHNICAL PROBLEMS TO BE SETTLED AND TEST SCHEDULE

The problems to be settled in the light of knowledge and experience of traditional hydroelectric power generation are as follows:

(1) The strict prohibition of seawater leakage from the upper reservoir to base rock and groundwater salinization caused by leaking seawater.

(2) The prevention of undesirable influence from wind-driven seawater on ecological elements such as vegetation and agriculture field in the vicinity of the upper reservoir.

(3) Fewer electric energy losses while generating power and pumping operation due to the adhesion of marine organisms to pipe walls and turbine runners in electric machines.

(4) Protection of metallic and plastic materials from seawater corrosion, and escape from dynamic damages under high water pressure and changeable velocity.
(5) Stable seawater intake and discharge regardless of tidal and wave oscillations.
(6) Minimization of biologic damage on natural coral reef near and around lower basin.

In order to solve those technical problems, various in-situ tests and examinations were carried out as shown in **Table 3**. In the table, the items tested corresponding to involving problems are divided into three categories: hydraulic structures, pump-turbine, and environmental impacts.

PRACTICED STRUCTURES AND DISCUSSION OF STUDIED RESULTS

The national project on seawater pumped-storage power plant was set up under specified scheme and study plan. Practiced structures and discussion of the results in our study will be introduced in regard to every main facilities and equipments. In present case, the dead storage in upper reservoir was reduced as much as possible. The total storage volume was 590,000m^3 in designed full seawater including the dead water volume. Most important design policy for seawater pumped-storage power generation is emphasized on environmental annoyance and its evasion.

a. Upper Reservoir

Storing seawater volume of the upper reservoir involves generating electric capacity, discharge rate and head difference between upper reservoir and lower basin. Required volume of the upper reservoir was designed as the total sum of effective storage volume equal to the product of generating discharge and duration of operation, and dead storage volume. To maintain the efficiency of power generation, the form of the intake's mouth was improved so that dead storage was reduced as much as possible. As shown **Fig. 2**, the intake mouth was a morning glory type, which could induce a required discharge in a good hydraulic efficiency.

To prevent seawater leakage from the upper reservoir into surrounding soil and atmosphere environment, a set of sealing system shown in **Fig. 3** was employed. In this system, both the upper reservoir embankment and excavated foundation ground were overlaid on crushed stone layers below drainage layer, non-woven fabric was placed on it, and then covered it with 2mm thick Ethylene Propylene Diene Monomer sheet (EPDM or lining sheet). The lining sheet exhibiting excellent water-tightness, flexibility and durability were fixed by means of numerous precasted sheet anchors.

Where seawater leakage poses problems from the lining sheet, the seawater may possibly penetrate into the drainage porous bed and flow into the drainage pipe connected to the inspection gallery. The seawater penetration into the drainage pipe was drained into a pit and then returned to the upper reservoir using the pump installed in the pit. For detecting seawater leakage, the drainage pipe is equipped with an electric conductivity detector (Takimoto, J. et al.,1995[8)]). The synthetic rubber lining sheet is sensitive to solar radiation heat, ozone and ultraviolet rays, and may sustain physical change and degradation with time. A set of exposure tests was conducted beforehand for different rubber samples at the pilot plant site to examine durability of the sheet. In the exposure test of rubber sheets, elongation ε_{rup} at fracture and tensile strength σ_l were measured for different exposure time t. The tensile strength σ_l and the elongation at rupture ε_{rup} with time t for two types of rubber sheets A and B are shown in **Fig. 4**. According to their tested results, the elongation at fracture tends to decrease for more or less five years, compared with that at the initial stage but to remain constant thereafter. It is probable that tensile strength reduces slightly with exposure time. In **Fig.5**, the elongation retention rate $Er = \varepsilon_{rup} / \varepsilon_{rup\ i}$ normalized by an initial elongation value ε_{rup} was plotted together with those of other test sites.

This figure shows that the fracture point of lining sheet reduces with elapsed time.

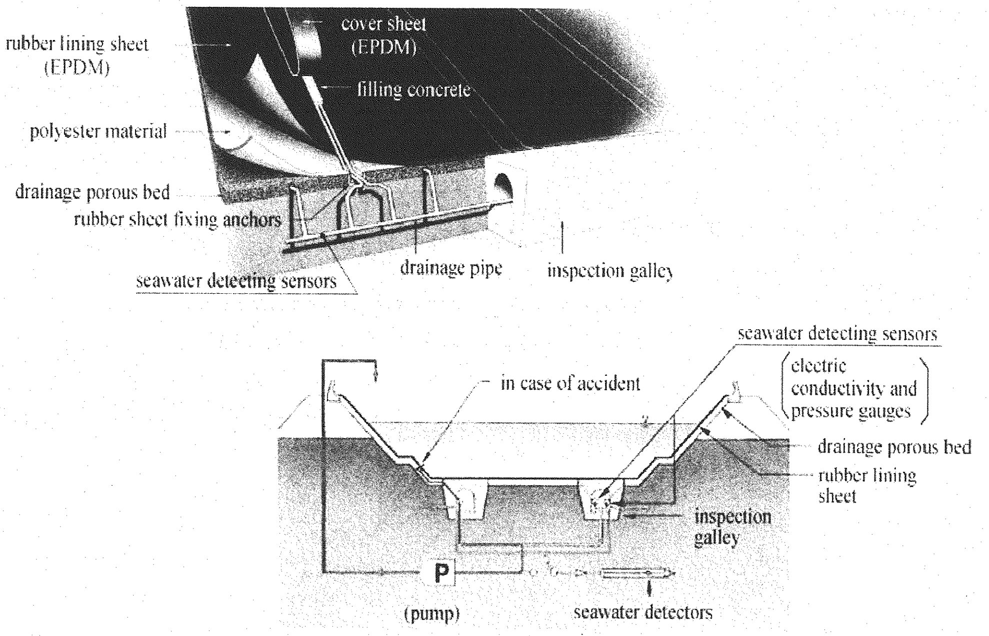


Fig. 3 Lining with rubber sheet and upper reservoir design

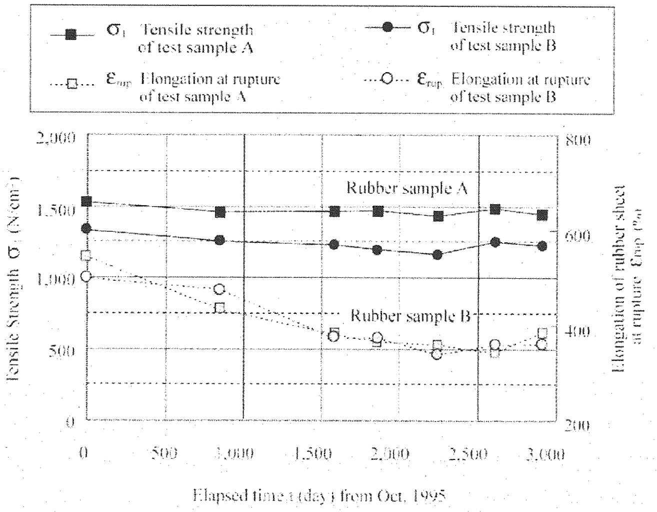


Fig. 4 Tested results of ruptured tensile strength (σ_t) and elongation (ε_{rup}) with elapsed time (t) for different rubber samples A and B

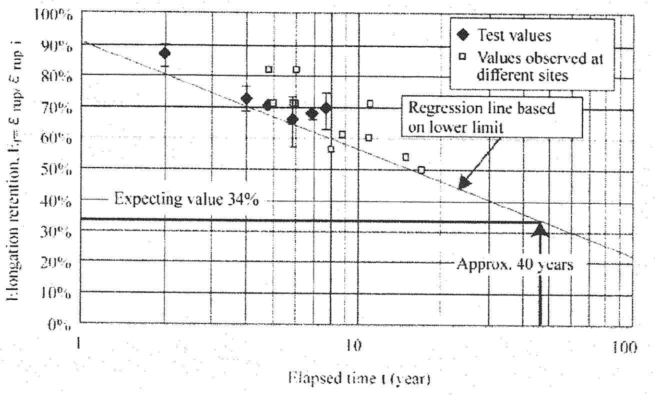


Fig. 5 Correlation between elongation retention (E_r) and elapsed time (t) for lining rubber sheet on semi-logarithmic scale

Thus, by focusing attention on the time dependency on the rubber elongation, we were able to define a life time of the lining sheet as "a period of keeping elongation capacity satisfying a required design value," and calculated it taking into account the safety factor. The elongation retention rate can be obtained by a ratio 34%. If the longevity of the lining sheet is assumed to be over 40 years, the adopted lining sheet will provide a sufficient durability to be implemented.

Thus, the water proof system of upper reservoir was constructed on the basis of the above mentioned design concept. All the results of the five-year experiment showed no abnormal problems in the lining sheet, precast sheet anchors and inspection gallery and no seawater leakage.

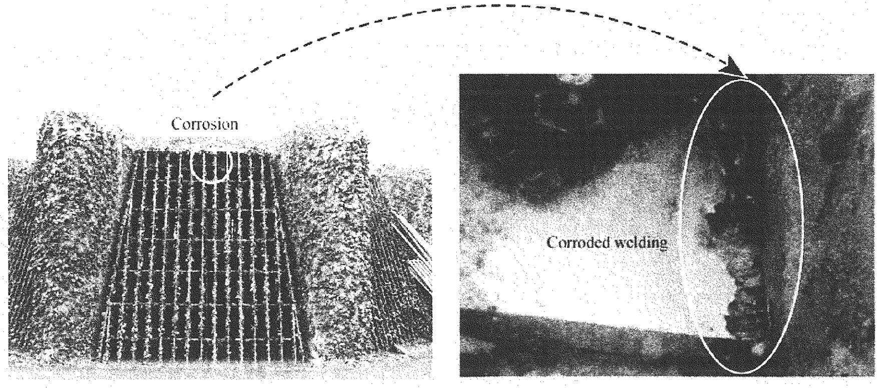
We also confirmed by periodical inspections that the salinity detection system for watching the failure of the lining sheet had worked well without any malfunctions. Accordingly, we proved that the water proof system was valid.

b. Intake and outlet

As is demonstrated in **Fig. 2**, the seawater on the process of power generation travels from the upper reservoir through the intake to penstock, pump-turbine, discharge tunnel and outlet, and finally flows into the ocean. The use of seawater possibly poses undesirable problems such as material corrosion and adhesion of marine organisms. In this section, the tested results conducted from the facilities, penstock, discharge tunnel, stable operation and environmental impacts are discussed.

Both intake and outlet are equipped with screens to remove floating dust. These screens are essential to prevent abrasion of the pipeline wall and hydraulic machines from suspended particles and flowing dust. Corrosion resistant duplex phase stainless steel; SUS329J4L (Japan Industrial Standard) was applied to the intake screen while the fiber reinforced plastic (FRP) was employed as the screen frame for the outlet screen and SUS329J4L was used for its joining material.

As is shown in **Photo. 2**, the adhesion of marine organisms can be observed over almost all the intake lattice: barnacles on a screen with high velocity and *pinctada maculata* (a species of pearl shells) on welded joints in the area of low velocity while they were accumulated in single layer. In the early stages of test plant designing, many screen bars were framed with a wider pitch in anticipation of the adhesion of marine organisms. As was predicted earlier, SUS329J4L showed a positive corrosion resistant. However, as can be seen in **Photos. 2 (a)** and **(b)**, crevice corrosion near bolt connections was detected. Furthermore, this crevice corrosion causes more corrosion due to bio-film which consists of marine microorganisms even if the welded scale is completely removed.



(a) Colony of crustacean organisms (b) Corrosion of welded steel

Photo. 2 Colony of crustacean organisms on lattice of intake screen and corrosion of welded steel

Thus, head loss or impedance to the influx due to adhesion of marine organisms on the FRP intake screen may be limited locally as compared with that of the FRP penstock, as was discussed previously. This finding will be helpful in designing and constructing a commercial plant.

c. Penstock

A penstock is connected to an intake and a pump-turbine. In the pilot plant, two materials of intake steel and FRP were used for composing of the penstock pipe as shown in **Fig. 2**. Because the penstock is under a high water pressure with quite large velocity, it must have enough strength to sustain the high pressure and water-tightness as well as large velocity. Moreover, the penstock should maintain a smooth wall surface to lessen head loss. Although steel pipes have usually been used for most penstocks in hydroelectric power plants, the main pipe in the pilot plant was made from FRP material which can exhibit excellent resistance against corrosion from seawater, and also has a smoother wall surface than one of steel pipe, in addition to having a greater resistance to the adherence of marine organisms (Komatsu, T. et al., 1994[7)]). Prior to construction of the pilot plant project, roughness height and Manning's roughness coefficients of pipe wall caused by sticking of marine organisms were examined experimentally by conducting seawater immersion tests for different several materials. The results of these tests are summarized in **Table 4**. They reveal that FRP pipe in it is indeed capable of maintaining initial low roughness in comparison with steel pipe and mortar pipe.

Averaged wall roughness of the FRP pipe after immersion tests in seawater slightly increased with lower increment rate than those of steel pipes and mortars one because of the presence of many joints among FRP unit pipes.

Direct eye inspection tests were carried out to check habitation of marine organisms on the penstock wall with and without watering as scheduled in **Table 2.** During the inspection tests in 2000 and 2003, the penstock was completely drained to conduct a full examination on the inside wall.

Table 4 Manning's roughness coefficient of pipe wall in seawater immersion test

Materials of pipe	Sticking thickness (mm)		Manning's roughness coefficient, n ($s/m^{1/3}$)		
	Average	Maximum	Before immersion test (1)	After immersion test (2)	(3) = (2)/(1)
FRP	0.4	8.5	0.013	0.014	1.08
Steel	4.6	19	0.011	0.017	1.55
Mortar	2.3	10	0.012	0.017	1.42

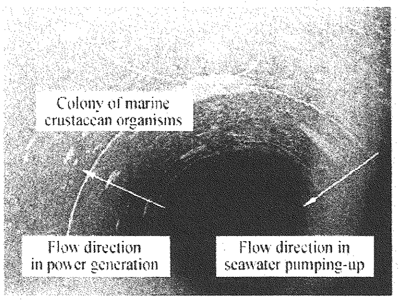
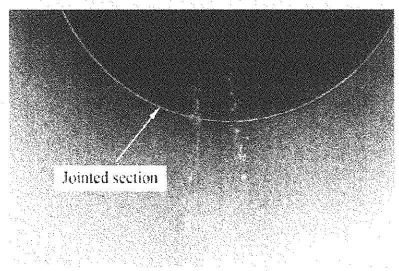


Photo. 3(a) Colony of marine crustacean organisms at an upper section (crown) of the FRP penstock pipe



Less adhesion of marine crustacean organisms
Photo. 3(b) Colony of marine crustacean organisms at a lower section of the FRP penstock pipe

Photos. 3 (a) and **(b)** show marine organisms observed at the crown and bottom of a FRP penstock section.

The organisms which adhered to the upper part of the pipe include some numbers of barnacles. Their roughness amounted to less than 30mm in height. This decrease in organism growth should be noted for the following reasons: shellfishes tend to avoid inhabiting environment a) where suspended substance such as silt and clay settles and clings on the pipe wall at and during a low velocity or stagnation, b) where bubbling separation of dissolved oxygen in seawater appears on the crown of penstock pipe. Eye inspection showed many species of organisms and colonies around the rubber joints among FRP units owning to local pressure and velocity change.

Fig. 6 shows changes in the population density of adhered marine organisms at the sections depicted by pointing circles in **Fig. 2** (a and b sections are in the distance of 30m and 70m downstream from the intake, respectively). An averaged velocity in calculating Manning's roughness n was 5.74m/s. The population density gradually increases but levels off at around 60 organisms/m^2. Evidence of colonies occupied by many shellfishes in the marked circle on the FRP penstock wall surface (**Photo. 3 (a)**) shows the size of their individuals. According to the above findings, it can be inferred that most shellfishes on the FRP penstock are tore off from the surface by high-seawater flow as they grow to a certain size. The roughness coefficient n is around 0.010 less than 0.012.

When we attempted to manually remove stuck marine organisms with hammer strikes, it was found that oysters could be pulled off easily and that barnacles could also be removed by light knocks without damaging the FRP pipe.

In this section, the roughness coefficient used in designing the FRP penstock is compared with those of observed values in the pilot plant project to discuss its validity. Referring to several studies Manning's roughness can be estimated using Fukuhara, K., 1984[1].

$$n = 0.0372 \times k^{0.160}, \qquad v = (1/n) R^{3/2} i^{1/2} \tag{1}$$

where, n: Manning's roughness coefficient (s·m$^{-1/3}$), v: average velocity, R: hydraulic radius, i: hydraulic gradient and k: wall roughness height (m)

A preliminary investigation suggested that a dominant factor in adhering marine species at the site of the experiment was barnacles and that its critical growing thickness was nearly 20mm. Assuming that the average roughness height k is about half of the adhesion thickness (10mm), the roughness coefficient is estimated n = 0.018 in terms of Eq. (1). This value was used as a design roughness coefficient. Findings indicated that the designed value n = 0.018 had been overestimated after tracing its reality n = 0.011 during the test period of three years from 2001.

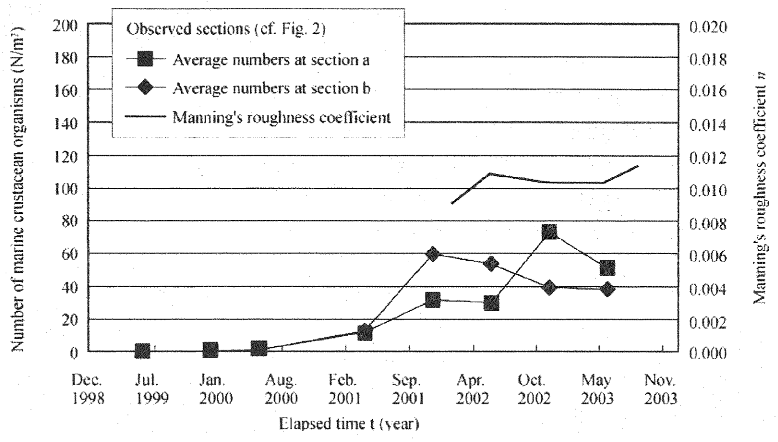


Fig.6 Number (N) of marine crustacean organisms and coefficient (n) of Manning's roughness in penstock

As for a commercial plant, it is possible to apply a smaller roughness coefficient for a new project in the future if the design velocity would be 10m/s or around its value for a commercial plant. It should be noted that the marine organisms on the penstock wall yield a smaller roughness coefficient value contrary to engineers' prediction.

The efficiency depending on wall roughness change in electric power (W) and electric energy (Wh) (product of electric power W and time h (hour)) during both power generation and pumping operation are given in **Fig. 7**. The wall roughness dependency curves for different discharges: 20.2 ~ 26.0m^3/s are computed from Bernoulli's equations by taking into account the friction factor f (= $124.5n^2/D^{4/3}$, D: diameter of pipe). It reveals was found that the energy losses between n = 0.010 and 0.018 are estimated to be nearly 3 % for power generation process and 1.5 % for the pumping operation

The findings shown in **Fig.7** suggest that the roughness coefficient of the penstock channel influences the energy efficiency significantly and that the FRP pipe with a low wall roughness may ensure the best efficiency of the power plant. In this regard, there is room for examination in an optimal design in effective head difference, penstock diameter, and wall roughness.

In the light of the stability design of embedded penstock in rock mass, the penstock needs to be designed to resist both internally applied water pressure and reacting rock stress. Because a jointed behavior of an embedded FRP penstock pipe has not yet been thoroughly elucidated, the FRP pipe in the pilot plant was designed with assumption that it would sustain all the internal seawater pressure without surrounding rock mass support. In fact, however, resulting stress in an embedded pipe is likely to be lightened since the bedrock plays a role in resistivity against pipe deformation. Mechanical properties of FRP pipe and tested correlations of averaged circumferential strain (ε) on four points vs. internal pressure (p) at measured points in penstock section C (cf. **Fig. 2**) are shown in **Table 5** and **Fig. 8**, respectively. **Fig. 8** shows the relationships between water pressure (p) and circumferential strain (ε), illustrating the hysteresis curves of elasto-plastic behavior in three cases of water refilling after the initial water filling and dewatering at cross-section C, and an elastic ε - p relation without bedrock support. Their relationships reveal the total of the internal pressure (more than 50% of water pressure) even though a creep may have taken place in bedrock. The resultant load shared by the bedrock will increase as the thickness of the pipe shell decreases.

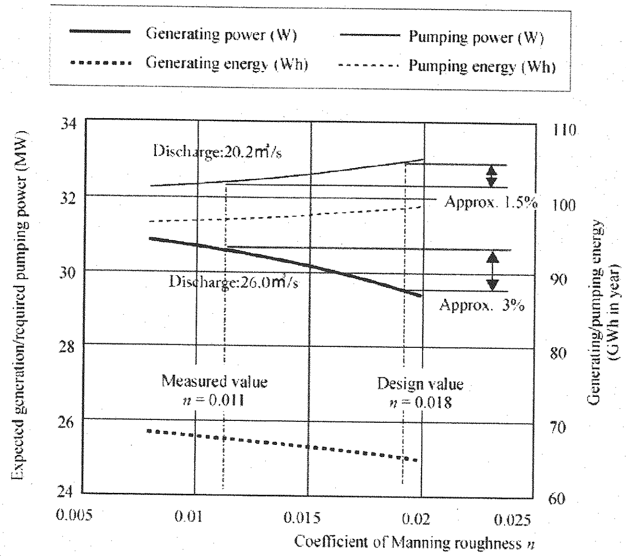


Fig. 7 Computed diagram on expected generation power/required pumping energy due to roughness dependency

Table 5 Measurement sections

Measured sections	Thickness of pipe	Center elevation	P	Kc	Ec	F*1)
	(mm)	EL (m)	(MPa)	(kgf/mm)	(N/mm²)	
A	48.2	31.43	1.36	81844	216.9	FC
B	45.7	-2.96	1.75	92904	216.9	FC
C	45.7	-18.44	2.20	92904	216.9	NC

Note: The internal diameter of 2.4 m for the sections from A to C.
P: Design head pressure with the reservoir high water level and water hammer pressure taken into account.
Kc: Circumferential tension and compression rigidity.
Ec: Circumferential elastic modulus.
*1) Filling concrete:
FC (Softened fly ash and concrete), NC (Normal concrete)

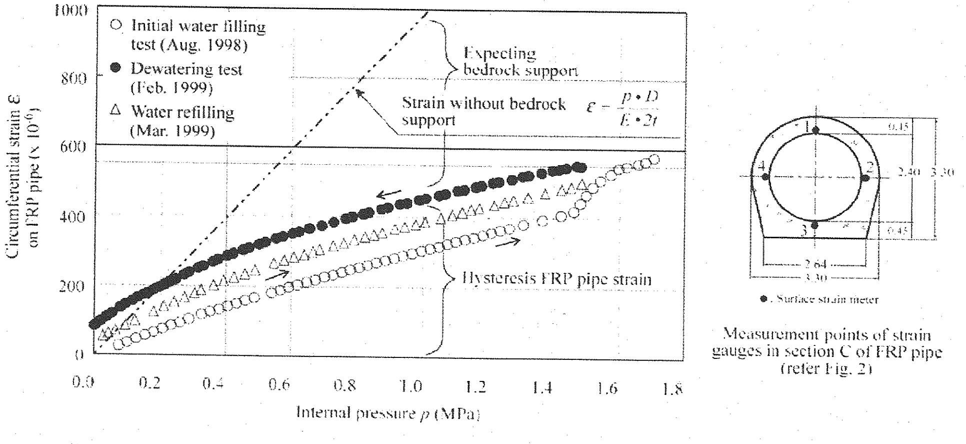


Fig.8 Relationships between internal pressure (p) and circumferential strain (ε) on FRP penstock at section C

It is technically possible that the pipe wall thickness can be reduced in comparison to the traditional design method. The pilot plant project has verified that FRP is capable of reducing the adhesion of marine organisms as well as of maintaining a smaller roughness coefficient over a long period. For the duration of the test plant, striking abrasion of the FRP pipe wall is unlikely to take place, and the water-tightness was found to be adequate around mechanical joints of the pipe.

Although FRP is regarded as an excellent material for a penstock exposed to seawater, it is still unpopular and expensive to produce. For these reasons, a steel pipe covered with heavy-duty anti-corrosive coating was employed for curved sections of penstock (cf. **Fig. 2**). Thick vinyl ester resin (750μm) containing glass flakes was introduced as coating material, and also a set of electrodes of cathodes protection device was placed on the steel pipe wall to prevent electric corrosion.

d. Tailrace (Discharge tunnel)

The tailrace is a reinforced concrete (RC) tunnel connecting penstock with lower reservoir. Special measures to prevent deterioration of reinforced concrete by seawater flow were taken by improving the water/cement mixing ratio, corrosion protective covering of reinforcing bars, and by increasing the thickness of protective covering layer. There still is some concern that the adherence of marine organisms to the wall of tailrace might bring about an increase in head loss. In the tailrace design, Manning's roughness coefficient of 0.018 was adopted. As was expected, the colony of marine organisms clustered together on the upper part of the tunnel where coating had not been applied. The change in their population density and Manning's roughness coefficient n are shown for coated and uncoated conditions in **Fig. 9** (1, 2 and 3 sections situate on 0m, 100m and 180m upstream from the outlet, respectively (**Fig. 2**)), in which a saturated density seems to arrive at about 100 organisms/m^2 on uncoated wall. The half section of downstream portion within 100m from outlet was covered with antifouling coating and kept smooth to prevent the adhesion of seawater inhabitants. The major species of organisms are barnacles with a height/thickness of 1 ~ 2cm and the biggest is 4cm thick, such shellfishes as oysters and small mussels over the upper side of the tunnel in a single layer. Therefore, periodic removal works were necessary every three months.

The roughness coefficients on the tailrace wall increased and leveled off in those values. It is probable that the roughness coefficient reaches around 0.015 which was smaller than design value 0.018. Accordingly, in designing the RC tunnel through which seawater runs, the application of an antifouling coating layer on the tailrace wall is useful for preventing increases in roughness as well as for enhancing concrete durability.

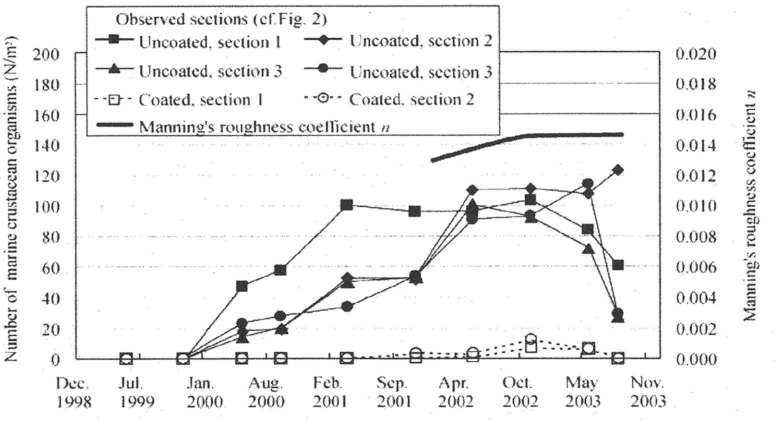
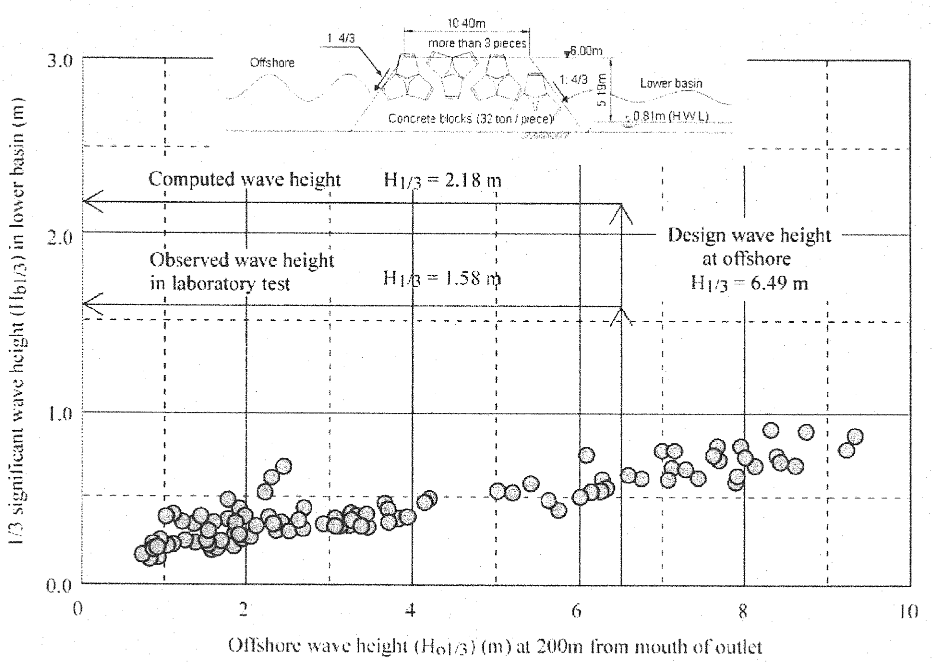


Fig.9 Number (N) of marine crustacean organisms and Manning's roughness coefficient (n) in discharge tunnel

LOWER BASIN AND ITS STILLNESS

The lower basin played an important role in stable operation of pilot plant through water table stillness regardless of tidal oscillation, wind waves and typhoon tides. The basin was protected by 900 numbers of concrete blocks (wave energy killers) arranged at a radius of 50m around the outlet mouth to maintain water table stillness. In the designing the lower basin field data on ocean weather wind, information about wave heights and tidal waves over of a period of 35years (from1943 to1977) were used. **Fig. 10** shows the relationship of significant wave heights ($H_{1/3}$) observed in and out of the lower basin.

A set of observed data shows a linear relation ($H_{b\ 1/3} = 0.1H_{o\ 1/3}$), and the significant wave height in the basin is almost reduced to one tenth of offshore value. Meanwhile, we do not have to worry about air inhaling and coming into the discharge tunnel in pumping operation, because the outlet center level is kept at 2.9m below the low seawater level and also normal operation of the plant is kept sound even in periods of high waves experienced from some passed typhoons. Since 1994, the power plant has been hit by typhoons more than 20times, but neither sliding nor deformation of blocks in the lower reservoir basin were not reported.



Note: Significant wave height ($H_{1/3}$) is approximately equal to the averaged value of the highest one-third of meaured waves.

Fig.10 Relationship between measured wave height in offshore and lower basin

IMPACTS ON THE SURROUNDING ENVIRONMENT

The pilot plant is located in a wood rich district with a wide variety of biologically indigenous species and subspecies. In order to avoid bad influence and damage on this natural environment, practical measures for solving these problems were focused on the design and practice of the plant. Environmental preservation issues arising from this pilot plant project can be summarized as follows: the mitigation of the "water pollution of subsurface caused by seawater infiltration/dispersion from the upper reservoir". In addition, the "impact of seawater pumping and disinfection on the marine environment." in the lower basin. In addition to those directly relevant to environmental impacts which are listed in **Table 3**, some other important matters were noted; namely minimizing negative influences by construction and below-seawater level excavation, preventing erosion of vegetation planted on slopes and slope slide, and creating a new sound ecosystem after project development.

To assess the effectiveness of those environmental protection measures, required data were collected in three processes as shown in **Table 6**: a preliminary survey prior to plant construction, monitoring during the plant construction, and monitoring during the pilot plant operation, including both before and after operation periods.

In the result the authors reached the following conclusions in regard to environmental subjects: The numbers of wild animals including some of protected species were investigated, and water qualities of streams and groundwater in and around development site have been almost unchanged during the project investigation. The environmental impact by seawater around the upper reservoir was detected in both little soil salinity and plants salinization under abnormal weather and typhoon seasons. In regard to the marine environment around the lower basin, no changes for the worse in seawater quality were found from the periodical monitoring in the pilot plant project. Changes from the original nature were neither observed in the biological system of marine organisms nor in coral ecology.

Tests and monitoring along categories and their items in **table 6** are summarized as follows:
①Subtle effects on original vegetation and plantation due to seawater vaporization and its wind driven quality after constructing the upper reservoir were not detected except for a few effects just near reservoir seawater table. The effect of saline concentration did cause any damage to the biological environment nevertheless the temporal salinity driven by strong winds on typhoon days was observed only on the leaves of trees and soil surface. ②The living numbers of precious faunas around the project site did not change before and after pilot plant construction. ③The quality of seawater, original sedimentary deposits and maritime current under the influence of the lower basin were kept stable. ④The living aspect and inhabitants numbers remained unchanged after the pilot plant construction and operation.

Table 6 Summarized list of surveyed and monitored assessment items on environment

Survey·Monitoring / Items	Preliminary survey prior to plant construction	Monitoring during plant construction	Monitoring during plant operation
Flora	Natural vegetation in area 2 km × 1 km near the pilot plant (twice in 1985)	Investigation on specified trees at six points (three times in 1995-1997)	Investigation of natural vegetation & forest (before and after typhoon seasons in 1998-2002)
Fauna	Living animals in area 2 km × 1 km near the pilot plant (seven times in 1986-1988)	Census of birds, amphibians, reptiles, soil animals and aquatic organisms in several locations (once or twice a year 1990-1997)	Census of animals, birds, amphibians, reptiles, insects, soil animals, and aquatic organisms (twice a year 1998-2003)
Ocean environment	Current water quality & sediment at several points in front of the outlet (eight times in 1985-1988)	Measurement of suspended solids at three observation points (twice a year 1990-1996)	Current velocity & intake discharge (twice a year 1998-2000) Water quality of specified items (twice a year 1997-2001)
Marine organisms	Coral, mediolittoral & benthic organisms, marine algae & plants, planktons on several observation points and lines near the outlet (one to four times a year 1985-1988)	One to seven observation points in front of the outlet and wave absorbing mound in coral reef (twice a year 1990-1997)	The same items in preliminary survey (twice a year 1997-2002)

CONCLUSIONS

A full-scale pilot plant with the maximum electric capacity of 30MW was constructed to establish a new design concept in engineering, and to deal with anticipated technical and environmental problems. Operation of this plant was carried out in cooperation with the Okinawa Electric Power Co., Japan under a full interest, planned tests and monitoring of the environment. Many people in Okinawa depend on this pilot plant operation to obtain stable electric power when becoming increasingly in demand.

This paper has discussed the reliability of seawater pumped-storage electric power generation system dealing with a full range of technical and environmental problems, and focusing on such structures and facilities as the upper reservoir, penstock, discharge tunnel, safe pump-turbine operation, the lower basin and environmental monitoring.

The main findings of this study are summarized as follows:

(1) The upper reservoir with EPDM (Ethylene Propylene Diene Monomer) sheet preventing seawater leakage and its detection system performed sufficiently.

(2) FRP pipe exhibited corrosion protection against seawater and a low friction loss. Manning's roughness coefficient n after invading by marine organisms on pipe wall was 0.011.

(3) In the designing the hydraulic pipe, a taken-over task of hydraulic pressures to the surrounding bedrock will realize a material cost reduction through decreasing the thickness of FRP penstock.

(4) For preventive measures against steel pipe corrosion due to seawater, a heavy-duty protective coating with a cathodic corrosion protection system proved to be effective.

(5) An increase in roughness coefficient n resulting from adhesion of marine organisms may result in a 3% hydraulic energy loss compared with an estimated generation power and 1.5% on required pumping electric power in the range of $n = 0.011 \sim 0.018$.

(6) An anti-fouling coating in the reinforced concrete tailrace (discharge tunnel) was found to be useful for preventing the adhesion of marine organisms.

(7) A set of surveyed and monitored results before and after the pilot plant construction has not led leading any detrimental changes in the environment.

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