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Original Paper

Hydrographic Model Test on Prevention against Vortex Occurrence for Vertical Bulb Turbine

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Abstract

A vertical bulb turbine unit with elbow type draft tube has been developed due to avoidance of complicated assembling and long standstill period at overhaul in comparison with conventional horizontal bulb turbine unit. Before designing the prototype vertical bulb unit, a hydrographic model test was carried out to establish the ideal design concept for this innovative generating unit.

Froude similarity is not available for vortex occurrence. Consequently, an intake structure without air entraining vortices under all the flow conditions is developed, and it is confirmed that the surge wave at load rejection is not affected harmful influence for other constructions.

Keywords: Water turbine, Air entraining vortex, Free surface flow, Surge wave, Hydrographic model test

1. Introduction

Hydroelectric power generation in Japan has a long history spanning over 100 years. Hydropower was the main source of electricity, and many medium to high head hydro plants were actively developed for their economic advantages until the mid 1960s, when hydropower was replaced by thermal power. In the late 1970s, however, by applying horizontal shaft bulb turbine generators in low head sites with a large flow rate, hydropower became an economically viable source of energy. Therefore, hydropower systems of this type are being built in many sites over Japan. In 1990s, these large bulb generating units were overhauled. The complicated works due to bulb units and spill overtopping power due to long standstill period became problems. Thus vertical bulb turbine unit was developed as these solutions. Figure 1 shows sectional drawing of vertical bulb unit and table 1 indicates technical data for turbine (1). The construction of vertical bulb turbine and generator is not drastically different from conventional horizontal one but it will be possible to assemble or disassemble in one piece if a compact size to be hanged by gantry crane because of vertical installation. This attains to simplify the assembling and to shorten the overhauling period.

Now a prototype of this vertical bulb turbine unit (2) is operating in Japan and the water passage shape of the power station is similar to morning glory shaft spillway (3). As the turbine is vertical axial shaft machine, the intake flow is vertical and draft exit flow is horizontal due to elbow type. If the water depth of intake is shallow, it will be possible to cause air entraining vortex and harmful vibration because of deep intake (4). Thus, the model apparatus was made geometrically similar to prototype from intake to turbine, and the observation of air entraining vortex and several countermeasures against vortex occurrence were examined by hydrographic tests. Two model apparatuses, the scale ratios of which were 1/20 and 1/40 respectively, were provided and the phenomena of vortex occurrence were compared with the different scale effect. As the result, the countermeasure to avoid the air entraining vortex was developed under any conditions. The load rejection tests were done under any operating conditions by the same model, and it was confirmed by measuring the flow velocity and pressure at every point that the surge wave, caused by load rejection, did not influence a harmful damage to other constructions. In the present paper these test results are described.

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2. Hydrographic Model Test on Prevention against Vortex Occurrence

2.1 Configuration

Figures 2 and 3 show the model stand outline drawings scaled down 1/40 and 1/20 respectively. Since the prototype of vertical bulb unit was planned to locate at the right bank of upstream of an existing hydroelectric power station, the downstream of intake for new plant is near the intake of the existing power station. Thus, model test should be done with not only the observation of vortex but also the distinction of vortex occurrence caused by operation or standstill of existing power station.

Froude similarity between model and prototype is, in general, applied to hydrographic model tests of the open channel. However there are many papers [(5),(6),(7),(8)] which describe that Froude similarity no longer holds good because the vortex phenomena occur by the inertia force overcoming the viscous one. Therefore two model apparatuses of different scale are provided and compared. The scope of homologous similarity for 1/40 scale model is including the upper reservoir and the operation or standstill of existing power station was simulated by the valve opening or closing. On the other hand, the scope of similarity for 1/20 scale model is limited only to downstream of intake conduit for vertical bulb unit because of laboratory space. The operation or standstill of existing power station was carried out by distinguishing between eccentric or equivalent flow in the conduit for 1/20 scale model. Eccentric flow was determined by the test result of 1/40 scale model that velocity ratio between right and left bank sides was 1:1.24[(4)]. The pipeline of both models is a closed loop and flow is circulated by pump. Froude similarity is denoted as follows to determine the flow rate for model.

$$\frac{V_m}{V_p} = \left(\frac{D_m}{D_p}\right)^{0.5} \quad \text{Or} \quad \frac{Q_m}{Q_p} = \left(\frac{D_m}{D_p}\right)^{2.5} \quad \cdots \ (1)$$

Table 2 shows scale ratio for each model calculated by Froude similarity.

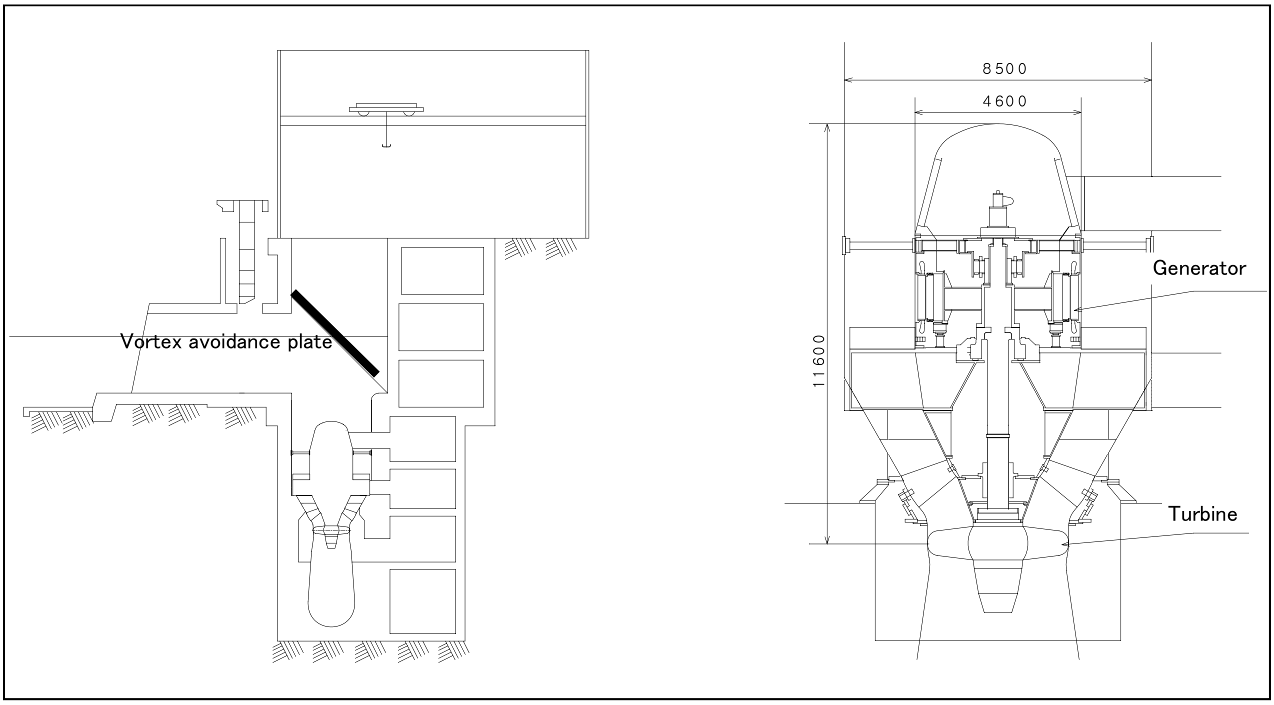

Fig. 1 Section of vertical bulb generating unit

Table 1 Specification of hydraulic turbine

Type	Vertical Bulb
Net head	15.54 m
Flow rate	100 m^3/s
Output	14000 kW
Rated speed	167 min^{-1}
Specific speed	640 m-kW
Number of unit	1

Table 2 Scale ratio between model and prototype

Scale ratio	$D_p/D_m=20$	$D_p/D_m=40$
Length	$K_L= D_p/D_m=20$	$K_L= D_p/D_m=40$
Velocity	$K_V=V_p/V_m=K_L^{1/2}$ =4.47	$K_V=V_p/V_m=K_L^{1/2}$ =6.32
Flow rate	$K_Q=Q_p/Q_m=K_L^{5/2}$ =1788.9	$K_Q=Q_p/Q_m=K_L^{5/2}$ =10119.29
Time	$K_t=t_p/t_m=K_L^{1/2}$ =4.47	$K_t=t_p/t_m=K_L^{1/2}$ =6.32
Head	$K_H=H_p/H_m=K_L$ =20	$K_H=H_p/H_m=K_L$ =40

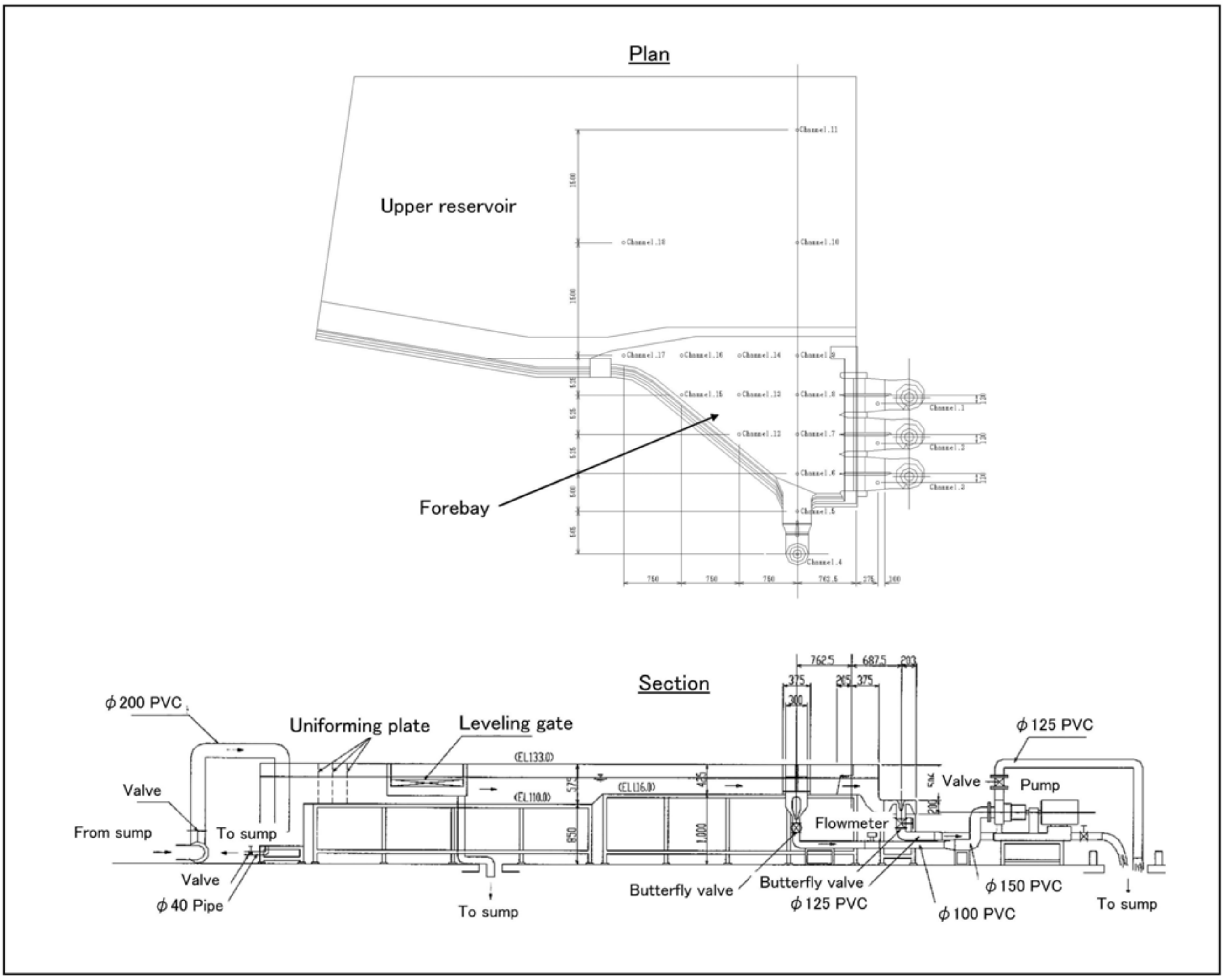

Fig. 2 Hydrographic model scaled 1/40

2.2 Model test of 1/40 scale

2.2.1 Test stand

The model stand consists of two parts, one of which is main river part as upper reservoir and the other is a fore-bay part as intake of existing and new power stations. The part of river is made of painting steel plate and provided balancing tank, and reservoir and flow rectifier are installed in the upper side. The water leveling gate is provided in the left bank to keep the water level constant. The velocity in the fore-bay is measured by PIV and water level is adjusted by leveling gate which is controlled by point gauge. Flow rate is measured by electromagnetic flow meter of 100mm and adjusted by a sluice valve.

2.2.2 Test condition

As it is possible to cause air entraining vortex when the water depth is shallow and flow rate is large, the model test was done under the lowest headwater level (EL.123.5m) and the maximum flow rate(100m^3/s) which are the most severe condition. As the standard to evaluate the occurrence of air entraining vortex, there is Standard Method for Model Testing the Performance of a Pump Sump: TSJ S002(2005) published by Turbomachinery Society of Japan. According to TSJ S002 the critical flow rate for air entraining is determined as follows.

$$\frac{V_m}{V_p} = \left(\frac{D_m}{D_p}\right)^{0.2} \quad \text{Or} \quad \frac{Q_m}{Q_p} = \left(\frac{D_m}{D_p}\right)^{2.2} \quad \cdots \ (2)$$

In case of 1/40 scale model, this critical flow rate, evaluated by Eq.(2), is calculated three times that from Froude similarity. Therefore model test was examined under the flow rate conditions of this critical value and Froude similarity.

2.2.3 Test result

First of all, the model was tested under the Froude similarity. As the flow rate of prototype is 100m^3/s, model one is calculated as 0.01m^3/s by Eq.(1). In this case, the phenomenon is unsteady whether the vortex appears or not. When the flow rate increases a little, a vortex occurs evidently. And the vortex occurs constantly under the flow rate of 0.03m^3/s calculated by Eq.(2). Figure 4 shows the sketch of this condition. Besides the relation between vortex occurrence and operation of existing power station cannot be clarified from this test.

From the viewpoint of spatial position and flow rotation to cause the vortex, clockwise vortex occurred at the right side viewed from upstream and counterclockwise one is at the left side as illustrated in Fig.4. Since the superficial velocity of flow, in open channel at the upstream of intake, becomes faster near the center of channel and slower near the side-walls, the vortex appears due to the unbalance of superficial flow. If once the vortex occurs, it develops from the inside of faster velocity to the wall of slower velocity with its rotation. Furthermore, this vortex does not occur every time and if appears it has not the regularity to rotate clockwise or counterclockwise under the flow rate calculated by Froude similarity.

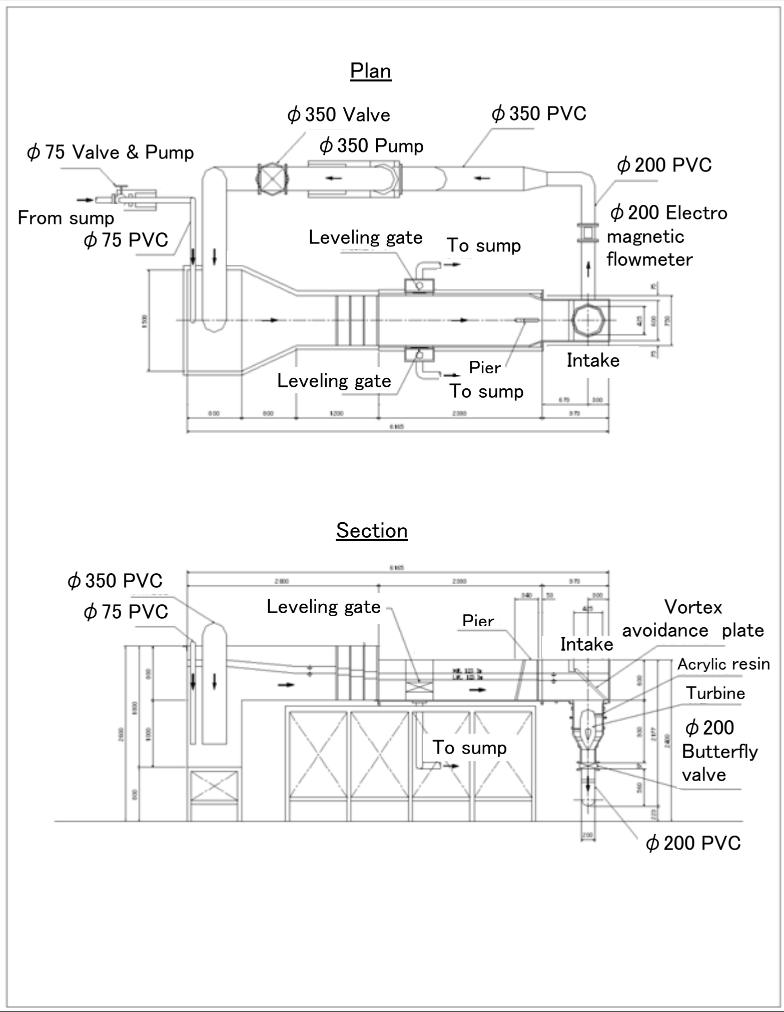

Fig. 3 Hydrographic model scaled 1/20

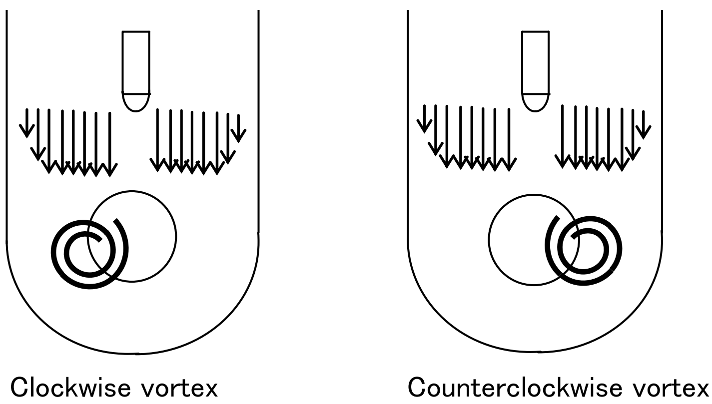

Fig. 4 Vortex occurrence of 1/40 scale model

2.3 Model test of 1/20 scale

2.3.1 Test stand and condition

The scope of similarity between model and prototype was from the inlet of intake conduit to the vertical axis of power station as shown in Fig.3. The automatically driven butterfly valve of 200mm is provided at the downstream of turbine to close similar to guide vane for load rejection test. The electromagnetic flow meter of 200mm is provided at the downstream of this valve and the flow is reached to the circulating pump as closed loop.

The equivalent or eccentric flow can be adjusted by the rectifier at the inlet of conduit. To confirm the occurrence of vortex was done by visual observation and video tape recorder. The test condition is the same as 1/40 scale model.

2.3.2 Test result

As the model stand is scaled down 1/20, the flow rate for model is calculated $0.056 m^3/s$ by Froude similarity. The photograph of equivalent flow is shown in Fig.5. The air entraining vortex was confirmed constantly by the observation of model test independently whether the existing power station was operating or not. Figure 6 shows a photograph under the flow rate $0.137 m^3/s$ according to TSJ S002. In this case, much air entraining vortex occurred continuously independently whether the existing power station was operating or not. The phenomenon to cause the vortex was apparently different from 1/40 scale model, namely the air entraining vortex was observed by 1/20 scale model under any condition of flow rate larger than that of Froude similarity in spite of that there is a different scale of vortex. Therefore it is concluded that Froude similarity cannot apply concerning the occurrence of air entraining vortex because of the different observations under the flow rate by Froude similarity among two models.

Fig. 5 Intake flow under the discharge of Froude similarity

Fig. 6 Intake flow under the discharge of TSJ S002

2.4 Countermeasure to avoid air vortex

From the test result of 1/20 scale model, it is confirmed that the air entraining vortex always appears if the countermeasure to avoid is not existed at the intake. Thus, it is necessary to provide a facility to avoid air vortex. There are some facilities of countermeasure for prevention of vortex. In the present case an inclined plate of being flow uniformed is applied at the inlet of intake (above the generating unit) because of economic consideration [(4), (9)]. As a vortex occurs due to an unbalance of superficial flow in this model test, an inclined plate has some parts through the water as shown in Fig.7 (shaded portion in this figure) to rectify the flow. This rectifying plate was placed by 45° angle of inclination and designed hinged construction at the lowest part to set vertically during the period of dismantling the generating unit. Namely it is assumed that the water flow through the slit in the vortex avoidance plate breaks the mechanism of superficial vortex occurrence and a strong shear flow becomes into a uniform flow. Figure 8 shows no vortex appearance owing to this inclined plate of rectifying flow. A vortex did not occur under the critical flow rate of TSJ S002 in this model test.

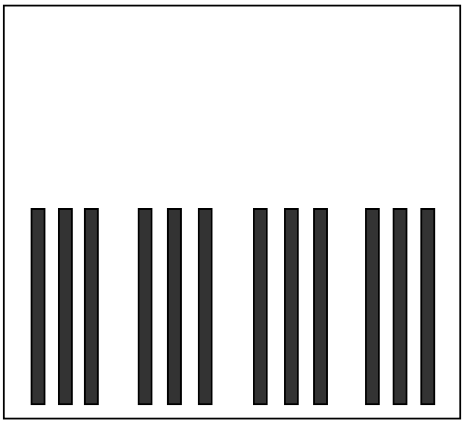

Fig. 7 Vortex avoidance plate

Fig. 8 Intake with vortex avoidance plate

3. Load Rejection of Hydrographic Model Test

3.1 Test stand and procedure

Load rejection was tested with the same model stand of vortex occurrence and its prevention. Test procedure was executed by rapid closure of butterfly valve at downstream of turbine similar to guide vane of prototype. For the test of 1/40 scale model the valve was closed by hand and that of 1/20 was done by electric driven valve automatically.

Since the surge wave, to be influenced the behavior in upper reservoir, is the phenomenon of free surface flow at the open channel, the water level can be converted from model to prototype by Froude similarity. Therefore the closing time was according to Froude similarity indicated in Table 2. For dam type of hydroelectric project with high head, a rising water level at load rejection is negligible because the dam water volume is much larger than the flow rate of power station. On the other hand, a rising water level at load rejection is high at the intake for dam type of hydro project of large flow rate with low head. Furthermore this rising head is propagated toward upper side, so called surge wave [10]. This phenomenon will be harmful on the opposite shore or bank.

3.2 Test result of surge wave

The phenomenon of surge wave at load rejection for prototype can be simulated by 1/40 scale model because the scope of similarity from upper reservoir to the turbine is satisfied in this model. The test result of load rejection for 1/40 scale model is examined under the condition of that all existing units are at standstill and new one is operating in order to compare with that of 1/20 scale model. Although the equivalent closing time is planned as about 4s for prototype, it is difficult to close precisely by 0.63s, which is converted into model. Thus, the closing times of 4 cases are determined for model shown in Table 3 which is converted into prototype.

Figure 9 shows the variation of water level rising at Channel 4 (above the turbine) where the maximum value appears. The relation of positions between each Channel number and its position in upper reservoir is shown in Fig. 3 (plan). The measured maximum water level rising is between 1.1m and 1.15m, and the trend of the water level rising becoming shorter as the closing time is shorter is found in Fig.9, which is reasonable. But this trend is not so remarkable. Figure 10 shows the maximum height due to surge wave from intake of new unit to opposite shore. It is demonstrated from Fig.10 that there is small difference of results among 4 closing times and the maximum height is 1.2m, that is not harmful influence.

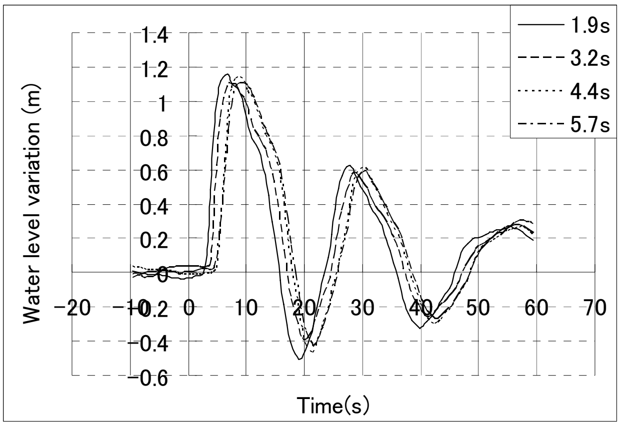

Fig. 9 Water level variation at Channel 4

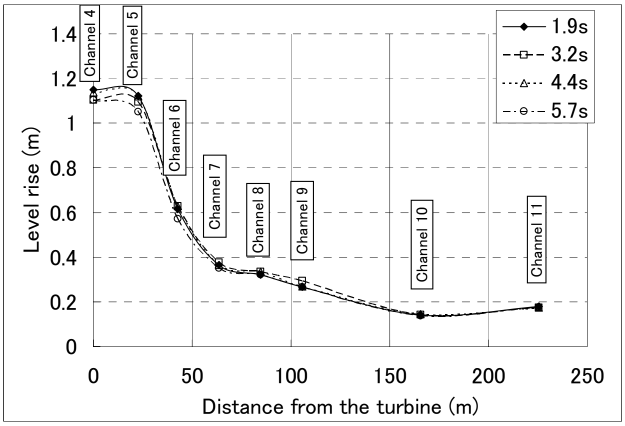

Fig. 10 Maximum water level at load rejection

The water level of 4 cases was not so varied from the starting shutdown 0s to near valve closing time and raised rapidly after fully closed position of valve as shown in Fig.9. It is considered due to the relation between the discharge characteristic and closing time of butterfly valve. Namely the valve closing between fully open and half causes little discharge variation while the closing from half to fully closed causes large discharge variation with suddenly decreasing. Besides the closing time in the model is less than 1s. On the other hand, since the discharge characteristic for guide vane of prototype has linear variation from fully open to fully closed, the water level will be raised at earlier time in prototype.

Concerning the propagation velocity of surge wave, it can be calculated the difference of peak time between Channels 4 and 5. As the surge wave reached Channel 4 after 6.6s and after 8.9s for Channel 5 in the case of closing time of 1.9s, the time different was 2.3s. As the distance between Channels 4 and 5 is 565mm in 1/40 scale model as shown in Fig.3 corresponding to 22.6m for that of prototype, the propagation velocity of surge wave is obtained as 9.8m/s (22.6/2.3=9.8). The scheme of ideal surge wave is shown in Fig.11. The formula [11] of propagation velocity in this figure is as follows.

$$c = \omega - V_1 = \sqrt{gH_1}\left[\frac{1}{2}\frac{H_2}{H_1}\left(\frac{H_2}{H_1}+1\right)\right]^{\frac{1}{2}} \quad \cdots(3)$$

Table 3 Condition at load rejection

Headwater EL.	EL.123.5m
Flow rate	100m^3/s
Closing time	1.9, 2.4, 4.4, 5.7 s

As the surge wave does not appear at t=0 for Eq.(3), H_2=H_1 and V_2=V_1. Substituting it into Eq.(3), the propagation velocity of surge wave is taken as follows.

$$\omega = \sqrt{gH_2} + V_2 \qquad \cdots(4)$$

As the velocity at the flow rate 100m^3/s is V_2=0.89m/s for prototype because of the water depth H_2=7.5m and width of water passage 15m, ω=9.46m/s from Eq.(4). Since this propagation velocity is near the values indicated in Table 4, it is confirmed that Froude similarity can be applied in this case.

The test result of 1/20 scale model cannot be compared with that of 1/40 scale model except around intake conduit of new power station because 1/20 scale model was not constructed up to the opposite shore. Figure 12 shows the comparison between two models without the inclined plate of rectifying flow. The water level of 1/20 scale model denotes 4.25m (prototype) upstream compared with 1/40 model because the measuring point is at the centerline of vertical axis for 1/40 and upstream inlet of axis for 1/20 respectively. The water level is rising after first wave at load rejection from the test result of 1/20 scale model shown in Fig. 12. This is because of the model stand. Namely as the circulating pump of model stand is operating after load rejection, the water level is rising up to the crest of overflow facility which is provided in the intake conduit. On the other hand, as the model of 1/40 scale model is similar to prototype including the upper reservoir, the rising height is not remarkable compared with 1/20 model. Therefore the actual phenomenon will be similar to the result of 1/40 model.

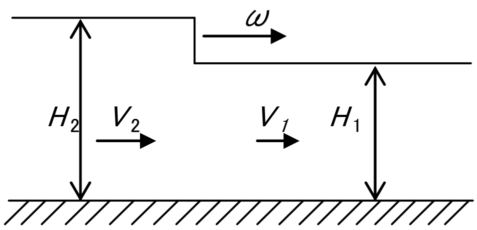

Fig. 11 Ideal surge wave

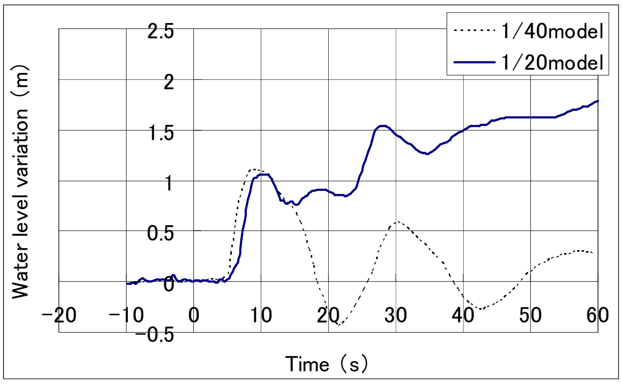

Fig. 12 Comparison with different scale model

Table 4 Surge wave measurement

t_c (s)	Channel 4 (s)	Channel 5 (s)	⊿t (s)	V (m/s)
1.9	6.6	8.9	2.3	9.8
3.2	7.7	10	2.3	9.8
4.4	8.7	11.3	2.6	8.7
5.7	9.6	11.4	1.8	12.5

4. Conclusion

By this hydrographic model test of two different scales, an air entraining vortex at intake and flow pattern at load rejection were observed. The results are summarized as follows.

(1) Froude similarity is not available for air entraining vortexes in this test. To confirm the avoidance of vortex, it is necessary to enable to flow at larger flow rate than the recommended value in TSJ S002 as shown in Eq.(2).

(2) The inclined plate with slitting is effective to avoid air entraining vortex in case of vertical axis deep intake.

(3) Froude similarity is available for surge wave occurred by load rejection at open channel of turbine upstream.

(4) As the inclined vortex avoidance plate was provided in the prototype according to the hydrographic model test, an air entraining vortex did not appear.

Vertical bulb generating unit is expected as an alternative turbine of conventional horizontal one (12). It is necessary, however, to review the prevention of vortex at turbine intake in the first stage of planning. The air entraining vortex of this prototype was not caused due to the hydrographic model test. Recently there are several papers (13),(14) which describe that CFD can be analyzed precisely for the phenomenon of air entraining vortex at free surface of pump sump. It is not possible to compare between pump sump and hydro power intake simply because the shape of intake is much different. But it is expected to solve this problem by CFD because hydrographic model test requires abundant manpower and materials.

Nomenclature

c	Relative propagation velocity of surge wave	ω	Propagation velocity of surge wave
D	Nominal diameter		
g	Acceleration of gravity	*Suffix*	
H	Water depth (same as suffix)	*1*	Downstream side
K	Scale ratio	*2*	Upstream side
Q	Flow rate (same as suffix)	*L*	Length
t	Time (same as suffix)	*C*	Closing
V	Velocity (same as suffix)	*m*	Model
		p	Prototype

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