Investigating to Cavitation Behavior of Orifice Tunnel

S.S.Pan (China Ship Scientific Research Center, P.O.Box116,Wuxi,Jiangsu,214082,CHINA)
T.Xiang & B.Wu (Reconnaissance Planning & Design Institute of Yellow River Conservancy Commission, Zhengzhou,Henan,450003,CHINA)

Abstract

Strong velocity scale effect on cavitation for orifice tunnels was revealed through comparing the results of model tests in vacuum tanks and that of prototype measurements at construction site. A new formula predicting incipient cavitation number of orifice rings is presented in this paper. The predicted data for the prototype scale are coincident well with the prototype measured one.

1. Introduction

Diversion tunnels, which are used to by-pass a river during the construction of hydraulic dam, are usually discarded after the dam is completed. However, 3 diversion tunnels with a diameter of 14.5m will be put into use as the permanent flood tunnels at the Xiaolangdi multi-purpose dam of Yellow River in China. For dissipating large amount of flow energy, 3-stepes of orifice rings are furnished in each of those 3 flood tunnels---they are so-called “Orifice Tunnel ”(Hsu., Namikas, Xiang, ect.,1988[1]). The sketch of the orifice tunnel is shown in Fig.1. The geometrical parameters of the orifice tunnels are chosen as follows: the diameter of orifice tunnel D=14.5m; the space between each of the two orifice rings L=3D=43.5m respectively; the blockage factors of each orifice ring $\beta_1=d_1/D=0.69$, $\beta_2=d_2/D=0.724$, $\beta_3=d_3/D=0.724$; the rounding edges of each ring $r_1=0.02$m, $r_2=0.20$m, $r_3=0.30$m. The constructed orifice tunnel has a “S” tunnel at upper-stream and a controlling gate followed by an open-channel at down-stream.

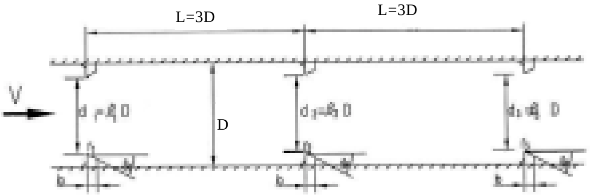

Fig. 1 Sketch of orifice tunnel D=14.5m L=43.5m $\beta_1=0.69$ $\beta_2=\beta_3=0.742$ b=2.0m $r_1=0.02$m $r_2=0.20$m $r_3=0.30$m

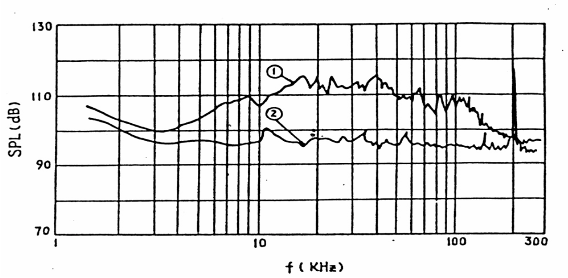

Fig.3 Acoustic signal of model tests in vacuum tank (1/50 scale)[2]

There is high a efficiency of energy dissipation for the flow running through orifice rings as shown in Fig.2. It can be seen that more than 50 meters of water head loss is exhausted at the velocity of 10m/s, i.e., at the flow flux of $1650m^3/s$ (Wu, Chai & Xiang,1995,[2]). On the other hand, unfortunately, the orifice tunnel may incur a problem of cavitation. A limited cavitation may be permitted during the tunnel operation, as it appears in the shear flow layer taken off from the edge of orifice ring and it is far away from the wall of the tunnel. However, a developed cavitation, especially a highly developed cavitation, should be surely avoid because it may cause the problem of vibration and erosion and lead to unsafe running of the tunnel. In order to investigate the cavitation behavior of the orifice tunnels, several model tests in vacuum tanks and one model test in a water tunnel were carried out. Prototype measurements for one of the orifice tunnels, which might be most sensitive to cavitation among the 3 orifice tunnels, were conducted for examining all sorts of the hydraulic & constructive parameters including cavitation behavior after the construction of the tunnel was finished. The Reynolds number of the model tests is about10^5 and that of prototype measurements reaches to 10^8. The scale effect on cavitation of orifice rings and the cavitation behavior of this orifice tunnel are discussed in this paper.

2. Model Tests in Vacuum Tanks

Vacuum tanks are often used to perform cavitation tests of hydraulic models under depressurized conditions in China. Several cavitation model tests of Xiaolangdi Orifice Tunnels had been performed during its design stage to optimize the cavitation behavior of the tunnel with the high efficiency of energy dissipation. Among them two orifice model tests were conducted in the facilities of hydraulic institutes in Nanjing and Beijing with the size scale ratio of 1/50 and 1/40 respectively.

According to the Froude Number Simularity Law the water level of both upstream and downstream of the tunnel in vacuum tank were simulated during tests. By lowering the air pressure above water surface, cavitation number of the flow in the tunnel will be changed and cavitation would be onset at a certain water level difference. Acoustic spectrum signals of the flow were utilized to identify whether cavitation occurs or not. Fig.3 is a typical acoustic spectrum diagram of the orifice tunnel model tested in vacuum tank (Wu, Chai & Xiang, 1995,[2]). The SPL level of curve No.1 (which represents the test case with cavitation) is higher than that of curve No.2 (which represents the test case without cavitation) for about 5db to 10db in the frequency range 6kHz to 160kHz.

It was also found that the radius of the rounding edge of orifice rings has a very significant influence on the cavitation behavior of the tunnel. An additional ring, which was fitted on the corner just upstream of the orifice ring, is helpful for delaying cavitation onset of the orifice tunnel. With a view of both high efficiency of energy dissipation and cavitation behavior of the tunnel some local geometrical sizes of the 3 orifice rings have been modilied.

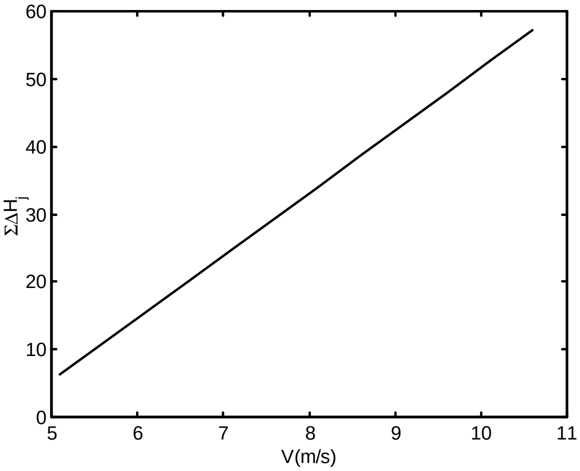

Fig.2 Dissipating energy of orifice tunnel vs. low velocity

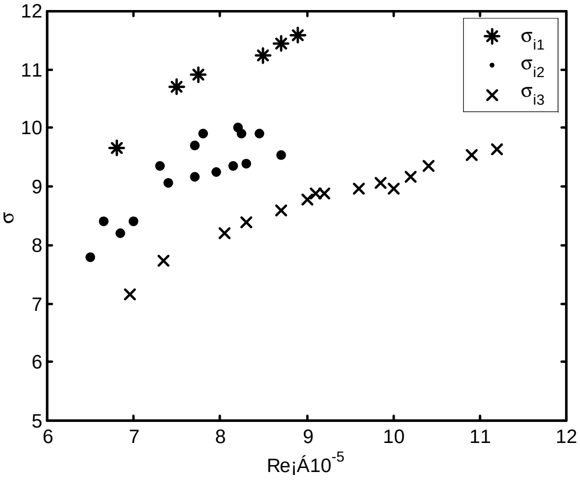

Fig.4 Incipient cavitation number measurement from model test (1/40 scale) in vacuum tank

Fig.4 is the diagram of incipient cavitation number vs Reynolds number of the orifice rings No.1, No.2 & No.3

measured from 1/40 model test respectively (Li, etc. 1992, [3]). The definition of cavitation number here is different from that in Ref. [3] and has referred to the flow velocity of tunnel instead of referring to the mean velocity of the hole of orifice ring. The tested Reynolds Number for orifice No.1 & No.2 is ranged between about 6.5×10^5 and 9×10^5, while the tested Reynolds number for No.3 is between about 7×10^5 and 11.5×10^5.

As the tested flow velocity of tunnel in Ref.[3] is merely 1.2m/s to 1.8m/s (the highest is 2.3m/s for No.3 orifice ring), it is far not enough to show the cavitation behavior of vortex, especially for those occurring in the shear flow layer. Strong scale effect on cavitation will be expected in predicting the prototype behavior of orifice tunnel by transferring the model results tested in vacuum tanks.

3. Model Test in Water Tunnel

In order to investigate into the value of the scale effect on cavitation caused by velocity, the Froude simulation number criterion had to be given up, and another model test in water tunnel with velocity as high as possible was designed. Cooperating with Dr. Keller, this test was carried out in a cavitation tunnel at Obernach, Germany when one of the authors was engaged in his visiting research project at the Institute.

In view of the limitation of the size and the rectangular section of the water tunnel, the orifice models were manufactured as 2- dimensional ones with the same geometrical parameters as shown in Fig.1 but the size scale ratio is taken as 1/30. The arrangement of the models as well as the measuring devices is shown in Fig. 5(Keller & Pan, 1999, [4]). The water quality was carefully controlled to made $p_{ts} \approx 0$ once the cavitation inception was observed. In Fig.6 the velocity scale effect on cavitation of orifice plates tested in water tunnel are shown. Some useful results can be obtained from this figure:

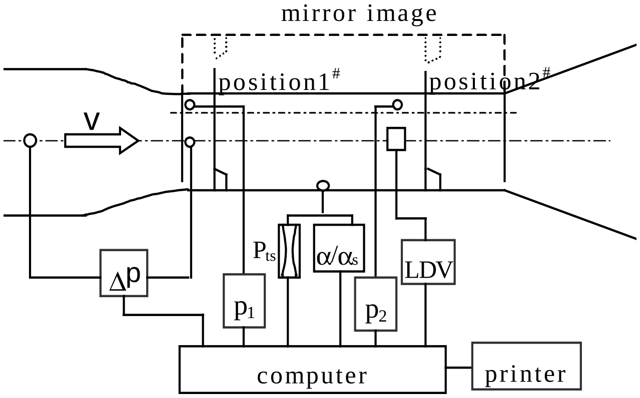

Fig.5 Sketch of the model test in water tunnel
tunnel with 2-dimantion orifice model [4]

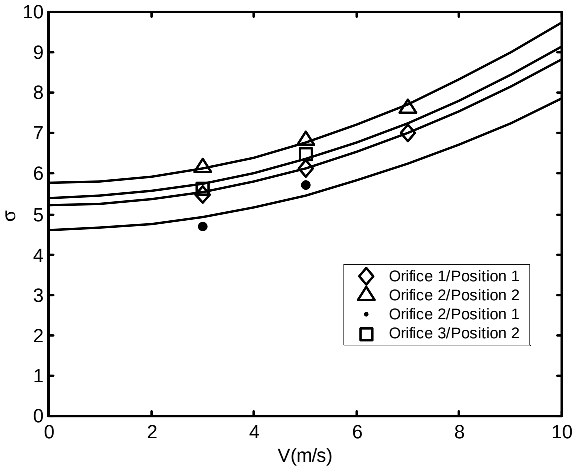

Fig.6 Velocity scale effect on cavitation tested in water

- There is strong velocity effect on cavitation for the orifice plates (2- dimensional orifice rings). For example, the incipient cavitation number at velocity of 7m/s is 1.3 times that of at velocity of 2m/s.
- Four curves in Fig.6 seem to in conforming with Keller's scale effect formula (Keller,1994, [5])

$$\sigma_i = \sigma_0 \left[1 + (V/V_0)^m\right] \qquad (1)$$

in which V_0 is a reference velocity taken as 12.7m/s, m is an exponent taken as 2.0 in Keller's laboratory, and σ_0 is a constant depended on the contour of the testing body.

∗ The tensile strength of the testing water, and hence the cavitation behavior of the orifice plate at position 2#, strongly depends on whether or not an orifice plate is placed at position 1# in front of the testing body and whether or not there is any cavitation on the front orifice plate. The details of the phenomenon are shown in Table 1.

Table 1

V(m/s)	Cavitation state of orifice 1/position 1#	$P_{ts}$of testing water after position 1#	Cavitation state of orifice 2/ position 2#
5	non-cavitation	0.25, 0.33	cavitation inception
	cavitation inception	0.08, 0.12	cavitation developed
7	non-cavitation	0.35, 0.32	cavitation inception
	cavitation inception	0.08, 0.07	cavitation developed

4. Prototype Measurement

The prototype measurements were conducted at the end of Spring of 2000 for examining all sorts of hydraulic and constructive performances, including the cavitation behavior for No.1 Orifice Tunnel (Zhang, etc. 2000, [6]). Six pressure sensors were mounted at the positions of 0.5D upper-stream and 0.5D down-stream of each ring to measure the mean pressure and the pulse pressure of the flow. Four hydrophones were mounted at positions of 1D down-stream of each ring and position of 0.5D down-stream of the 3rd ring for monitoring the acoustic signals and the cavitation events of each orifice ring in this Orifice Tunnel. The flow discharge of the tunnel could be adjusted by controlling the opening rate of a gate which is positioned at the down-stream of 3rd orifice ring and nearby the exit of the tunnel, and the data of flow discharge were measured from the down-stream hydrographic station. The flow Reynolds number reaches to 1.1×10^8.

Two procedures of monitoring the acoustic signals were used to identify whether or not cavitation had appeared:

a) Monitoring step by step at different opening-rates of the gate (steady flow);

b) Monitoring continuously during the process of opening of the gate (unsteady flow).

Fig.7 presents the acoustic spectrum of flow through orifice ring No.3 measured with procedure a). It can be observed that the sound pressure level corresponding to the situation of opening-rate 0.9 is higher than that of opening-rate 0.8 for about 10db within almost the whole measured frequency range, while only very little difference of SPL between opening-rates 0.7 and 0.8 exists. Therefore, it can be estimated that cavitation on orifice ring No.3 was appearing at the flow condition of near 0.9 opening-rate of the gate.

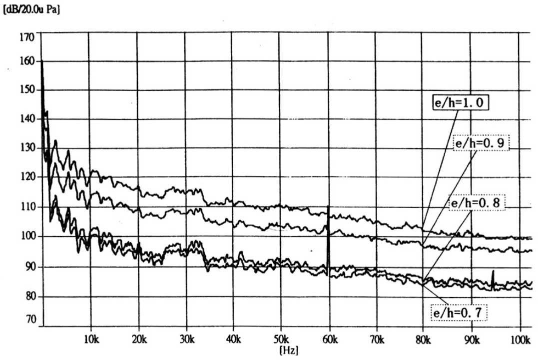

Fig.7 Noise spectrum of prototype orifice plate at different opening rates of the gate[6]

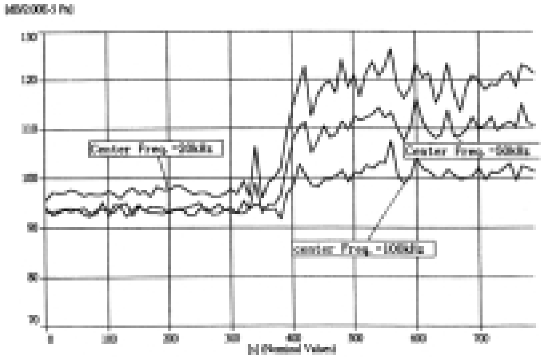

Fig.8 Acoustic signal of prototype orifice plate during the opening process of the gate[6]

The acoustic signals of the flow through orifice ring No.2 measured by using the procedure b) are shown in Fig.8, in which the monitored frequencies are 20kHz, 50kHz and 100kHz respectively. There is a jump of about 8db ~ 20db of the acoustic level occurring at the time of 380s ~ 420s, which corresponds to opening-rate of the gate of about 8.4 ~ 8.6. The results of the cavitation observations from these prototype measurements are summarized in Table2.

Table 2

Orifice ring	Velocity in orifice tunnel	incipient cavitation number
No.1	7.8	10.3 (critical)
No.2	6.74 6.67 (6.84)	12.9 12.6 (11.8)
No.3	6.74 6.67 (6.84)	11.8 11.5 (10.6)

In the table the data are measured with procedure b) while (those in brackets with procedure a). From comparing with the model tests data in Fig. 4, a significant scale effect on cavitation of the orifice tunnel can be observed.

5. Scale Effect on Cavitation Inception of Orifice

The minimum pressure of the flow in orifice tunnel usually occurs in the shear flow layer taken off from the tip edge of the orifice ring, therefore the cavitation should firstly occur in the separating shear flow. The value of incipient cavitation number is mainly determined by the value of minimum pressure in the separating shear flow. Obviously the higher the flow speed is, the lower the minimum pressure in the eddies of the separating shear flow will be, hence the more likely cavitation occurrence in the orifice tunnel will be. This kind of situation is rather similar to that of disk and foil. However, the flow in orifice is the inner-flow and the flow in other two cases are the out-flow as shown in Fig.9.

Lots of research results on disk and foil have been published during past years. There are empirical formulas to predict the incipient cavitation number σ_i for disk (Arndt, 1995, [7]) and for foil (McCormick, 1962, [8]):

$$\sigma_i = a + b\,Re^m \qquad \text{for disk} \qquad (2)$$

$$\sigma_i = k\,C_L^2\,Re^n \qquad \text{for foil} \qquad (3)$$

where a, b and k are constants, C_L is lift coefficient of foil, m is usually equal to 0.5 but may roughly equals to 0.4 for the disk with somewhat round edge, and n equals to 0.4.

According to the Froude number simulation rule which was followed in the model tests of orifice tunnel, there is a relationship between the size scale ratio λ_L and the velocity scale ratio λ_V:

$$\lambda_V = \lambda_L^{0.5} \qquad (4)$$

Substitute (4) into (2) and (3), the following relation can be derived:

$$\sigma_i \text{ or } (\sigma_i - \sigma_0) \;\sim\; (L/L_{ref})^{0.4}\,(V/V_{ref})^{0.4} \;\sim\; (V/V_{ref})^{1.2} \qquad (5)$$

Therefore the authors suggest that the Keller's scale effect formula (1) may be modified as follows:

$$\sigma_i = \sigma_o [\, 1 + (V/V_{ref})^{1.2} \,] \tag{6}$$

where V_{ref} may be taken as the flow velocity in the prototype one.

In fact, considering that the thickness of boundary layer on the orifice edge is not a constant but depends on Reynolds number and on the flow condition of the incoming flow, the pressure drop due to vorticity in the flow, ΔP_{vort}, which may be unprooerly described in Ref. [5]as

$$\Delta P_{vort} \sim V^4 \tag{7}$$

should be expressed as

$$\Delta P_{vort} \sim V^m = \begin{cases} V^{3.0} & \text{for laminar flow} \\ V^{2.4} & \text{for turbulent flow with } Re < 3\times10^6 \\ V^{2.3} & \text{for turbulent flow with } 4\times10^6 < Re < 3\times10^9 \end{cases} \tag{8}$$

The formula (6) just corresponds to the situation of turbulent flow.

Taking V_{ref}= 10.5m/s, it can be derived that σ_{02}= 8.29, σ_{03} =7.48 respectively for the No.2 orifice and No.3 orifice from the tested results of 1/40 model tests in vacuum tank (the data in Fig.4). Therefore the incipient cavitation numbers of orifice rings No.2 & No.3 vs the flow velocity in orifice tunnel can be expressed as

$$\begin{aligned} \sigma_{i2} &= 8.29[1 + (V/10.5)^{1.2}] && \text{for orifice ring No.2} \\ \sigma_{i3} &= 7.48[1 + (V/10.5)^{1.2}] && \text{for orifice ring No.3} \end{aligned} \tag{9}$$

The curves calculated by formula (9) are presented in Fig. 10. It can be seen clearly from the curves that the incipient

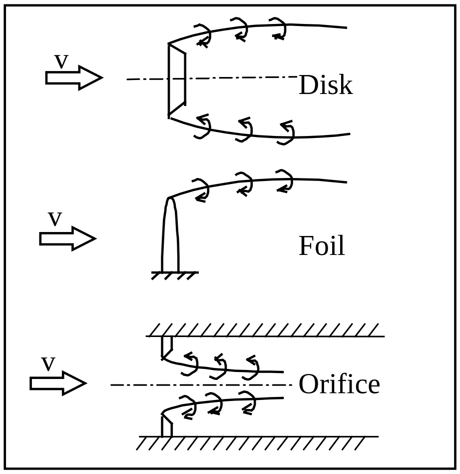

Fig.9 Separating shear flow of Disk, Foil and Orifice

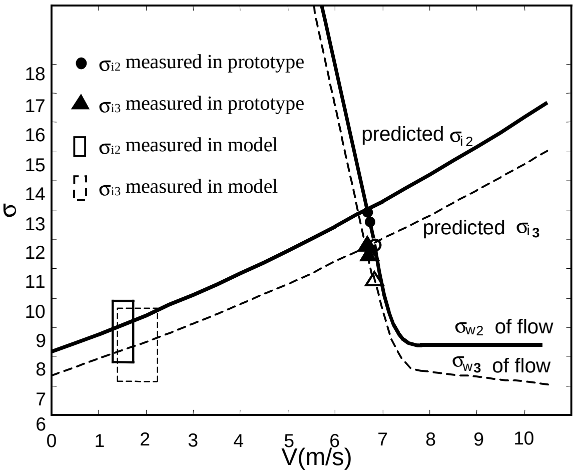

Fig.10 Cavitation behavior of prototype orifice tunnel predicted with the formula of scale effect on cavition

cavitation number of orifice rings increases with flow velocity — that is so-called the velocity scale effect on cavitation of the orifice.

The relations of the flow cavitation numbers σ_{w2} and σ_{w3} vs velocity are also shown in Fig.10, which are taken from the model test results and the prototype measurement results. The σ_{w2} or σ_{w3} decreases sharply with increasing of flow velocity at first, and then keeps nearly constant when the velocity reaches a certain value between 7m/s to 8m/s. The crossing points of the predicted σ_{ij} curves with the σ_{wj} curves are the predicted cavitation inception points of the j^{th} orifice ring. That means, the abscissas and the ordinates of these points are the flow velocities and the incipient cavitation numbers of the orifice rings respectively. The right-side part of these crossing points between the curve of σ_{ij} vs. velocity and the curve of σ_{wj} vs. velocity corresponds to the operation state with cavitation of the orifice tunnel, while the left-side part corresponds to the operation state without cavitation. Those full dots " ● " & " ▲ " denote the cavitation inception data measured in the prototype orifice tunnel, while those blank dots "O " & " Δ " denote the similar data measured at the flow condition of 0.9 opening rate of the gate, on which cavitation has been developed a litter bit. It can be seen from Fig.10 that the predicted data of the incipient cavitation number and its corresponding flow velocity for the prototype scale are coincident well with the measured ones from the prototype site.

6. Discussion

a. The high energy dissipation efficiency of the orifice tunnel is acquired by two ways. The first one is the sharp pressure drop and the strong pressure fluctuation when the flow passes through the orifice rings. The second one is the numerous eddies in the shear flow taken off from the edge of the orifice rings and the vortex near the downstream of the rings. The former correlates to the geometric shape and size of the orifice rings as well as the velocity of the flow in the tunnel, and the latter depends mainly on the velocity of the flow and the local geometric shape----- the edge of the orifice rings. Therefore, the efficiency of the energy dissipation and the behavior of the cavitation are a pair of contradiction for the orifice tunnel: the higher the energy dissipation efficiency is, the easier the cavitation would occur. In other words, if the cavitation is to be avoided according to the specifications of the orifice tunnel, the efficiency of the energy dissipation might be suppressed. It is one of the key points in designing the orifice tunnel that should be dealt properly.

b. The velocity of the routine model tests in the vacuum tank is rather low when the Froude number similarity law is followed in hydraulic model tests. In view of the fact that the velocity is a main factor dominating the cavitation behavior of the orifice tunnel, there may be a strong cavitation scale effect for the orifice tunnel between the results measured from the vacuum tank tests and measured from the prototype ones. It seems necessary to carry out further cavitation model tests for those important parts of the orifice tunnel with considering to Reynolds number similarity besides the model tests of whole orifice tunnel in the vacuum tank.

c. Due to the release of dissolved gases in the water under low pressure nearby the free shear flow, the quantity and the size of the gas nuclei in the incoming flow of the downstream orifice ring must be increased. That means, the tensile strength of the water in the incoming flow of the downstream orifice may obviously decrease, especially in the case where cavitation has occurred at the upstream orifice ring. In general, the incoming flow of the 1st orifice ring comes from the deep layer of the reservoir, therefore it may be expected that the water has rather high tensile strength. The tensile strength of the water in the incoming flow of the 2nd orifice ring would rapidly decrease or even reach to zero, especially when cavitation has occurred at the 1st orifice ring. The tensile strength at the 3rd orifice ring may be very low (nearly zero, or even a negative value). Therefore, the idea for designing the orifice tunnel with multi-step rings might not be an excellent one from the viewpoint of its cavitation behavior.

d. The cavitation of the orifice rings may not get in touch with the wall of the tunnel as the cavitation occurs in the region inside the flow. Even if it would get in touch with the wall, cavitation erosion might not occurre, as there is rather high air content in cavitation bubbles, especially for the 2nd and 3rd orifice rings. Therefore, there is a rather wide margin between cavitation inception and cavitation erosion. This point may be very valuable for the designer of the orifice tunnel.

e. The cavitation in the orifice tunnel is a kind of vortex cavitation. With reducing cavitation number such kind of cavitation develops rather slowly at the initial stage of cavitation developemant. Unfortunately, once the cavitation number is significantly reduced, vibration and erosion may occur due to the formation of the gross cavitation bubbles in the flow and the collapsing of the numerous small cavitation bubbles near the wall.

f. The speed of the flow in the prototype orifice tunnel increases or decreases with change of the water level of the reservoir although the size of tunnel remains unchanged. Therefore, the cavitation of each orifice ring would develop with rising of the water level in the reservoir. It is absolutely necessary to emphasize the importance of monitoring regularly during the operation of orifice tunnel at high water level situation.

Acknowledgements

The authors wish to express their sincere gratitude to Yellow River Water & Hydroelectric Power Development Corporation, China Institute of Water Conservancy and Hydroelectric Power Research, and Nanjing Hydraulic Research Institute for the successful organization of the prototype measurement and the fruitful results of the model tests. The first author would like specially to express his appreciation to Dr. Keller for the kind help in conducting the model test in Obernach water tunnel.

Reference

[1] Hsu, S. T., Namikas, D., Xiang, T. etc. “Headloss Characteristics of Closely Spaced Orifice for Energy Dissipation ”, Intern. Symp. On Hydraulics for High Dams, Beijing, China, 1988.

[2] Wu, J. H., Chai, G. Z. & Xiang, T., “Hydraulic Character and Its Optimizimg of Xiaolangdi Orifice Tunnel ”,J. of Hydraulic Engineering, 1995(in Chinese)

[3] Li, Z. Y., etc., “Experimental Research on Depressure Model Tests of Xiaolangdi Multi-orifice Tunnel”, Tech. Report of IWHR, 1992(in Chinese)

[4] Keller, A. P. & Pan, S. S. “The Problem of Scaling the Cavitation Model Test of Orifice Tunnel”, Tech. Report of Vrsuchsanstalt fur Wasserbau in Obernach, 1999

[5] Keller, A. P. “New Scaling Laws for Hydrodynamic Cavitation Inception ”, 2nd Intern. Sump. On Cavitation, Tokyo, Japan, 1994

[6] Zhang, D., etc. “Prototype Measurement for Xiaolangdi Orifice Tunnel No.1”, Tech. Report of IWHR, 2000(in Chinese)

[7] Arndt, R. E. A., “Vortex Cavitation”, Chapter 16 in Fluid Vortices, S.Green, ed., Kluwer, 1995

[8] McCormick, B. W., “On Cavitation Produced by a Vortex Trailing from a Lifting Surface”, J. Basic. Eng. Trans. ASME, 1962