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# Distance between plugs in multi-stage plug discharge tunnel

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For multi-stage plug discharge tunnel, the distance between the upper and the lower plug affects plug's energy dissipation capacity, and it is also an important index in multi-stage plug design. In the present paper, the reasonable distance between the upper and the lower plug in multi-stage plug discharge tunnel are researched by physical model experiment. The research result shows that when the contraction ratio is in the scope of 0.4~ 0.8, the reasonable distance between the upper and the lower plug in multi-stage plug discharge tunnel is equal to or more than 5.5*D*.

**[Keywords:** Plug; Multi-stage; Energy dissipation]

## Introduction

The plug, as a kind of energy dissipater with reduction and enlargement forms, has been used in large-scale hydropower projects successfully[1]. For Mica dam in Canada, the flow velocity of the flood discharge tunnel was decreased from 52 m to 35 m at the head of 175 m, using plug energy dissipaters, which are the two plugs with the lengths of 49 m and 37 m[1]. In 1998, orifice plate, which has the same energy dissipation mechanism as the plug, was applied in the Xiaolangdi hydropower project in China. Three-stage sharp-edged orifice plates in the Xiaolangdi hydropower project get the energy dissipation ratio of about 44%[2,3]. The practical application has proved that it is entirely feasible to utilize plug to dissipate flow's tremendous energy in hydropower project discharge tunnel.

A typical plug flow is shown in Figure 1. There exist vortex regions of ring form in the vicinity of plug due to flow sudden reduction and sudden enlargement; these vortices are the original regions of energy dissipation. There are strong flow shear and turbulence layers around which energy losses occur, in the course of flow sudden reduction and sudden enlargement. There are many studies on the energy dissipaters with sudden reduction and sudden enlargement forms[4,6] with focus on the effects of geometric parameters on hydraulic characteristics, such as energy dissipation ratio, cavitation performace and so on. The contraction ratio (*d/D*), defined as the ratio of the plug diameter (*d*) of the energy dissipater and the diameter (*D*) of flood discharge tunnel, is an important index affecting plug all hydraulic characteristics. Jianhua[7] and Wanzheng[8] deemed that the energy dissipation ratio of sudden reduction and sudden enlargement energy dissipater increased with the decrease of the contraction ratio. The contraction ratio influences directly the cavitation performance and the incipient cavitation number decreases with the increase of contraction ratio[9,10]. When Reynolds number is more than $10^5$, it has little impact on plug's energy loss and incipient cavitation number[10].

In actual engineering, to satisfy energy dissipation requirement and the requirement of no cavitation, multi-stage plug energy dissipater is a kind of ideal choice[10]. With respect to the distance between plugs in multi-stage plug discharge tunnel, it is an important considered factor in multi-stage plug design. The distance between plugs in multi-stage plug discharge tunnel must be larger than flow recovering length after plug; otherwise the every stage plug in multi-stage plug discharge tunnel cannot fulfill its energy dissipation function. So the distance between adjacent plugs in multi-stage plug discharge tunnel is closely related with flow recovering length after plug. Shanjun[11] researched the flow recovering distance after single plug and deemed that flow recovering distance after single plug was 3*D* (*D* is discharge tunnel's diameter); many other researchers also had the same opinion as Shanjun[12,13]. But, in fact, there are interactions between adjacent plugs in multi-stage plug discharge tunnel; so the flow recovering distance after plug in multi-stage plug discharge tunnel perhaps may not be 3*D* and it also may not be reasonable to design the distance between adjacent plugs in multi-stage plug discharge tunnel according to the standard of 3*D*. Unfortunately, the researches conducted in the past have not touched this issue, an inevitable issue for multi-stage plugs design. The purpose of the present work, therefore, was to research the reasonable distance between adjacent plugs in multi-stage plug discharge tunnel based on investigating flow recovering characteristics after plug, by means of physical model experiments.

## Research Methodology

To determine the reasonable distance between adjacent plugs in multi-stage plug discharge tunnel, it is necessary to research plug's energy loss coefficient, which can be defined as[7] :

$$\xi = \frac{p_1 - p_2}{0.5\rho u^2} \qquad \ldots (1)$$

where $p_1$ is the average pressure of section 1-1 and $p_2$ is the average pressure of section 2-2 (Figure 1). (The section 1-1 is located before plug, where flow is undisturbed and the section 2-2 is located after plug, where flow has already recovered); $\rho$ is flow's density and $u$ is flow's average velocity in discharge tunnel. According to Eq. (1), only the flow in section 2-2 recovers normally; the plug's energy loss calculated by using Eq. (1) is plug's actual energy loss coefficient. If the distance between plug and section 2-2 is too near and the flow in section 2-2 does not recover normally, the plug's energy loss calculated by using Eq. (1) is smaller than the plug's actual energy loss coefficient. For multi-stage plug, the distance between adjacent plugs is larger than upper stage plug's flow recovering distance, the function of the adjacent stage plug's energy dissipation can be fully fulfilled. On the basis of the above analysis, the determining method of the reasonable distance between adjacent plugs in multi-stage plug discharge tunnel would involve: firstly, determining single plug's actual energy loss coefficient by physical model experiment and secondly, arranging two-stage plugs discharge tunnel, gradually changing the distance between the two plugs from small to large; and thirdly measuring the energy loss coefficients of adjacent two plugs at every condition by physical model experiment, whereby the distance when the measured energy loss coefficients of adjacent two plugs are justly equal to their actual energy would give the reasonable distance between adjacent plugs in multi-stage plug discharge tunnel. The following physical model experiment arrangement was conducted according to the above analysis.

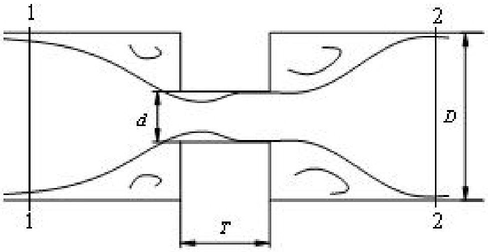

Fig. 1 — Flows through plug

### *Physical model experiment*

The physical model experiments were conducted at the high-speed flow laboratory of Hohai University (Nanjing, China); its set-up consisted of an intake system, a tank, a flood discharge tunnel with a plug energy dissipater, and a return system with a rectangular weir (physical model tunnel shown in Fig. 2). The diameter (*D*) of the tunnel model was 0.21 m

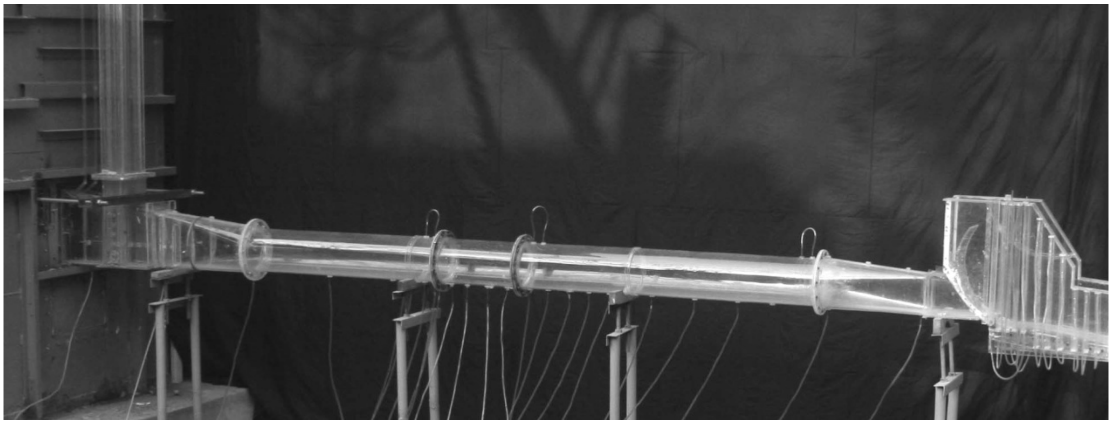

Fig. 2 — Experimental model

and the length of the tunnel model was 4.75 m, i.e., 22.6*D* from the intake to the pressure tunnel outlet at the gate. The water head about 10.0*D* could be presented by the intake system and the tank. The opening of the gate could be changed conveniently. Related researches have shown that plug's thickness *T* (Fig. 1) had little impact on its hydraulic characteristics and the selected thickness of plug was 1.0*D* in this physical model experiment. The wall pressure before and after the plug can be determined by measuring the water level height in plastic tube and the plug's energy loss coefficient can be determined by using these wall pressure and Eq. (1). The quantity of flow can be measured by flow quantity weir. The average flow velocity in discharge tunnel can be decided by flow quantity and the cross-section area of discharge tunnel.

The whole physical model includes two parts; Single plug model test experiment and two-stage plug model test experiment respectively. As shown in Figure 1, only when section 2-2 is placed in the position where the flow fully recovers, that the calculated single plug's energy loss coefficient is equal to its actual energy loss coefficient. Considering flow recovering characteristic after plug, section 2-2 was arranged enough far from plug in single plug model test experiment. In the single plug model test experiment, the plug was placed at the position of 10.0*D* from the tunnel intake and then the energy loss coefficient when the distance between section 2-2 and plug was 6*D* and the energy loss coefficient when the distance between section 2-2 and plug was 8*D* were measured. The purpose of the above arrangement was to compare experiment results and obtain single plug's actual energy loss coefficient. In the two-stage plug model test experiment, two stage plugs were installed in discharge tunnel; the first stage plug energy dissipater was placed at the position of 10.0*D* from the tunnel intake and the second stage plug was placed after the first stage plug. At every stage plug's energy loss coefficient was measured when the distance between the two plugs was 5*D*, 5.5*D,* and 6*D*. The reasonable distance between adjacent two plugs in two-stage plug discharge tunnel can be obtained by comparing the energy loss coefficient of every stage plug with that of its corresponding single plug.

## Discussion

To achieve the purpose of the present research paper, single plug's energy loss coefficient was required to be determined. The pressure in different sections was different when flow after plug did not recover, so if section 2-2 was arranged in the section of flow not recovering, the measured plug's energy loss coefficient may vary with the position of section 2-2. Single plug model experiment showed that the plug's energy loss coefficient when was the same section 2-2 was located at position of 6*D* after plug as that when section 2-2 was located at position of 8*D* after plug. This can illuminate that flow in section 2-2 of 8*D* after plug had already fully recovered and plug's energy loss coefficient of this section 2-2 was actual single plug's energy loss coefficient. The measured single plug actual energy loss coefficients are shown in Table 1.

The experimented results of two-stage plug are shown in Table 2, where: $\xi$ is single plug's actual energy loss coefficient; $\xi_1$ is the energy loss coefficient of every stage plug in two-stage plug; *L* is the distance between two plugs in two-stage plug.

If the distance between two plugs in two-stage plug is larger than the first stage plug's flow recovering length, every stage plug can fully fulfill its energy dissipation function and every plug's coefficient $\xi_1/\xi$ is ought to be 100%. On the other hand, if someone plug's coefficient $\xi_1/\xi$ is less than 100%, it can be inferred that this plug can not fully fulfill its energy dissipation function and the distance between two plugs in two-stage plug is not reasonable. From Table 2, it is known that in the scope of *d/D*=0.4~0.8, the first stage plug in two-stage plug can fully fulfill its energy dissipation

Table 1 — Single plug's energy loss coefficient

| *d/D* | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 |
|---|---|---|---|---|---|
| $\xi$ | 53.5 | 17.9 | 6.6 | 2.7 | 1.3 |

Table 2 — Experiment results of two-stage plug

| *L* | *d/D* | 1st stage plug | 2nd stage plug |
|---|---|---|---|
| 5*D* | 0.40 | $\xi_1/\xi$=100% | $\xi_1/\xi$=60% |
| | 0.50 | $\xi_1/\xi$=100% | $\xi_1/\xi$=65% |
| | 0.60 | $\xi_1/\xi$=100% | $\xi_1/\xi$=74% |
| | 0.70 | $\xi_1/\xi$=100% | $\xi_1/\xi$=88% |
| | 0.80 | $\xi_1/\xi$=100% | $\xi_1/\xi$=90% |
| 5.5*D* | 0.40 | $\xi_1/\xi$=100% | $\xi_1/\xi$=99% |
| | 0.50 | $\xi_1/\xi$=100% | $\xi_1/\xi$=100% |
| | 0.60 | $\xi_1/\xi$=100% | $\xi_1/\xi$=100% |
| | 0.70 | $\xi_1/\xi$=100% | $\xi_1/\xi$=100% |
| | 0.80 | $\xi_1/\xi$=100% | $\xi_1/\xi$=100% |
| 6*D* | 0.40 | $\xi_1/\xi$=100% | $\xi_1/\xi$=100% |
| | 0.50 | $\xi_1/\xi$=100% | $\xi_1/\xi$=100% |
| | 0.60 | $\xi_1/\xi$=100% | $\xi_1/\xi$=100% |
| | 0.70 | $\xi_1/\xi$=100% | $\xi_1/\xi$=100% |
| | 0.80 | $\xi_1/\xi$=100% | $\xi_1/\xi$=100% |

function when $L$ is $5D$, $5.5D$ and $6D$; when $L$ is $5.5D$ or $6D$, the second stage plug in two-stage plug also almost can fully fulfill its energy dissipation function. But, when $L$ is $5D$, the second stage plug in two-stage plug can not fully fulfill its energy dissipation function. The cause producing above phenomenon is that when $L$ is $5D$, there are mutual interferences between the upper and the lower stage plug, the flow after upper stage plug can not fully recover, the capacity of second stage plug's energy dissipation decreases; but when $L$ is equal to or larger than $5.5D$, the flow after upper stage plug can fully recover and every stage plug can fully fulfill its energy dissipation function. From the above analysis, it can be concluded that in the scope of $d/D$=0.4~0.8, the reasonable distance between the upper and the lower plug in multi-stage plug discharge tunnel is equal to or more than $5.5D$.

## Conclusion

For multi-stage plug discharge tunnel, the distance between the upper and the lower plug is closely related with flow recovering length after plug. The standard of reasonable distance between the upper and the lower plug multi-stage plug discharge tunnel is to ensure that every stage plug can fully fulfill its energy dissipation function. Because there are mutual interferences between the upper and the lower plug, the reasonable distance between the upper and the lower plug is normally larger than flow recovering length after single plug. In the scope of $d/D$=0.4~0.8, the reasonable distance between the upper and the lower plug in multi-stage plug discharge tunnel is equal to or more than $5.5D$.

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