EROSION PROTECTION AT DIVERSION TUNNEL OUTLETS WITH CONCRETE PRISMS

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In order to establish appropriate design criteria for a new protection measure downstream of diversion tunnels or large culverts ending in mobile riverbed, systematic physical tests have been performed using a hydraulic model. This protection measure consists of concrete prisms obtained by dividing cubes diagonally. They are placed in such a way that in case of undermining, the whole system is able to deform and to reduce erosion by still covering most of the bed in the protected area. Two series of experiments have been carried out. The first series have been devoted to the prediction of localized scour at diversion tunnel outlets in mobile riverbeds without protection measures. In the second series of experiments, the performance of concrete prisms placed downstream of the outlets for riverbed protection has been studied. Based on the systematic tests, general applicable design charts and formulas for estimating the local scour depth, the required size of the prisms and the total area to be protected have been developed.

1 Introduction

Scouring is an important engineering problem for many types of hydraulic structures including spillways, bottom outlets, culverts and diversion tunnels.

Water released from a diversion tunnel into a river should not result in scouring of the riverbed, which may cause the instability or failure of any hydraulic structures near to the scour zone. Outlet structures are therefore required to reduce the velocity of the water and to ensure dissipation of the energy.

Common structures used as erosion protection at diversion tunnel outlets are stilling basins, cut-off walls and concrete slabs. These structures have to be founded normally on rock and the construction costs are therefore usually high, also due to the need of formwork and reinforcement.

The existence of deep alluvium at the diversion tunnel outlets of Seymareh dam (one of the dams under construction in Iran) revealed execution problems and high costs in the case of traditional outlet structure construction. This was the major reason for considering the placement of large unreinforced concrete prisms for the downstream protection of the outlet. This method was successfully used as bank and bed erosion protection measure in steep mountain rivers (Schleiss et al., 1998).

The existence of similar conditions in a large number of projects around the world justifies more investigations for optimization of this erosion protection measure. In order to establish appropriate design criteria for this new protection method with concrete prisms, systematic physical tests have been performed using a hydraulic model.

2 Short overview on former studies

Several researchers have investigated the scour caused by a horizontal jet over an erodible bed which occur downstream of culverts. Several scour formulas have been developed mainly for low velocities (1 to 2 m/s) (Abida & Townsend, 1991; Abt et al., 1982, 1984, 1987; Chiew & Lim, 1996; Day et al., 2001; Mendoza, 1980; Mendoza et al., 1983; Rajaratnum & Diebel, 1981; Rajaratnum, 1998). Only a few of these formulas can be applied for flow conditions at diversion tunnel outlets.

A survey of relevant literature indicates that for protection measure with blocks, the most experimental investigations have concentrated on riprap design procedure (Maynord, 1978, 1988; Reese, 1984; Stevens & Simons, 1971). This protection measure can be used when the maximum flow velocity is about 5 m/s. In case of diversion tunnels the velocity at outlets could be reach until 10 to 15 m/s. Large concrete blocks are therefore required to protect the area downstream of diversion outlets (Fig. 1).

Figure 1: Scour in alluvial bed downstream of a diversion tunnel outlet (left), riprap protection on a river bank (middle), concrete prisms as erosion protection (right)

3 Experimental facility

The systematic experiments were performed using a test configuration as shown in Figure 2. As parameters, discharge, tailwater level and prism size were varied. Concrete prisms of 5 cm and 8 cm (obtained by dividing cubes diagonally) were investigated for erosion protection downstream of the pipe. Compared to prototype applications the model scale is about 1:30 to 1:50.

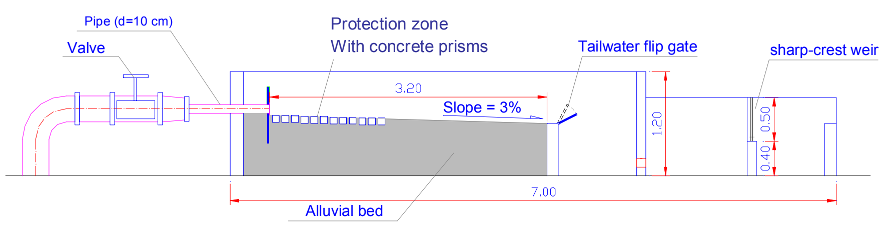

Figure 2: Longitudinal section through the experimental facility

4 Analysis of the results

The experimental results with and without using protection prisms were analyzed in order to compare the downstream local scour development under these two different conditions.

4.1 Local scour on mobile riverbed without protection

It was observed that tailwater significantly influences scour hole geometry. Figure 3 illustrates different formation of the scour hole due to low and high tailwater levels.

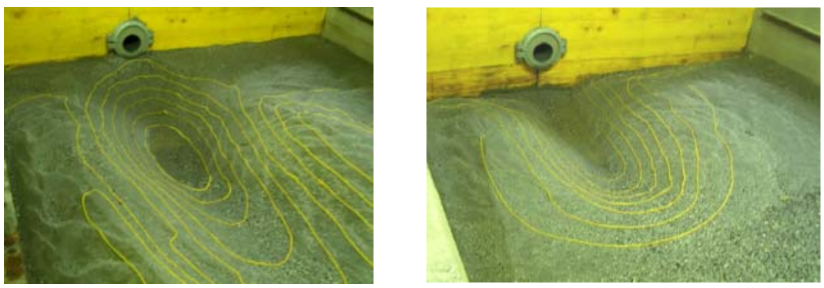

Figure 3: Scour hole for D = 10 cm and Q =12.5 l/s; high tailwater h_{TW}/D = 1.1 (left), low tailwater h_{TW}/D = 0.2 (right)

4.2 Scour formation in the case of protection with concrete prisms

4.2.1 Graphical representation of the experimental data

A linear regression was compiled correlating the experimental data of the scour hole characteristics with the prism number F_b defined as $u_0 / \sqrt{(\rho_b/\rho - 1) \cdot g \cdot V^{1/3}}$. The best dimensionless relationships for the maximum scour depth d_{sc}/D, scour depth at pipe outlet d_{toe}/D and maximum scour width W/D are presented in Figure 4. The location of the upstream and downstream boundary of the scour hole (X_1/L_P, X_3/L_P) as well as its deepest point (X_2/L_P) are given in Figure 5.

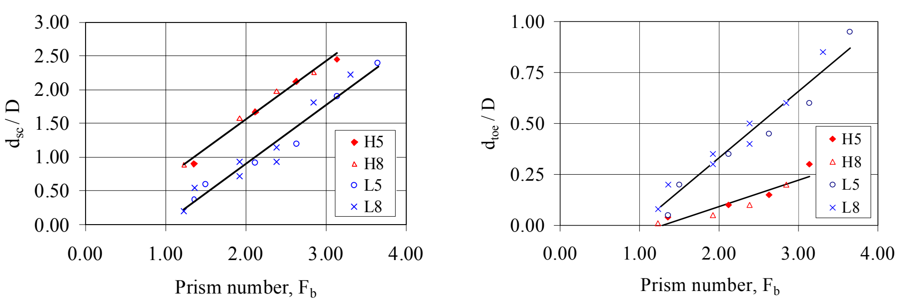

Figure 4: Relationship between scour hole depths and prism number; maximum scour depth (left), scour depth at pipe outlet (right) – "H" and "L" describe high and low tailwater depths and the numbers "5" and "8" represent the dimension of prisms.

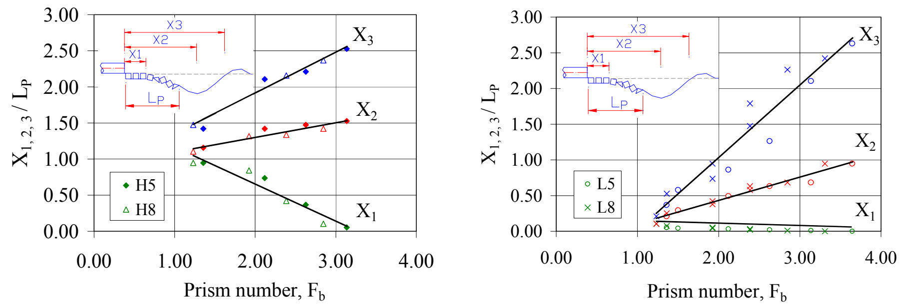

Figure 5: Relationship between scour hole location and prism number; high tailwater $h_{TW}/D = 1.1$ (left), low tailwater $h_{TW}/D = 0.2$ (right)

4.2.2 Failure criteria of the area protected by prisms

The factors affecting prisms failure were identified as the velocity at pipe outlet u_0, the mass density of the prisms and water, the prism size $V^{1/3}$, the tailwater depth h_{TW} and the length of protected area L_P.

Based on the observations made during the tests, failure of the protected area was defined when one or some of the following criteria were fulfilled (Fig. 6, right):

- Scour depth at the tunnel outlet is higher than 50% of the tunnel diameter
- Maximum scour depth is higher than 2 times of the tunnel diameter
- Maximum scour width is larger than the width of the protected area

In order to define a failure diagram for the protection prisms, the relationship between prism number and the parameter h_{TW}/L_P was plotted for all the tests in Figure 6 (left). Two lines were fitted through the tests points in the failure diagram, which divides it into three parts of “No movement”, “Acceptable movement” and “Failure”.

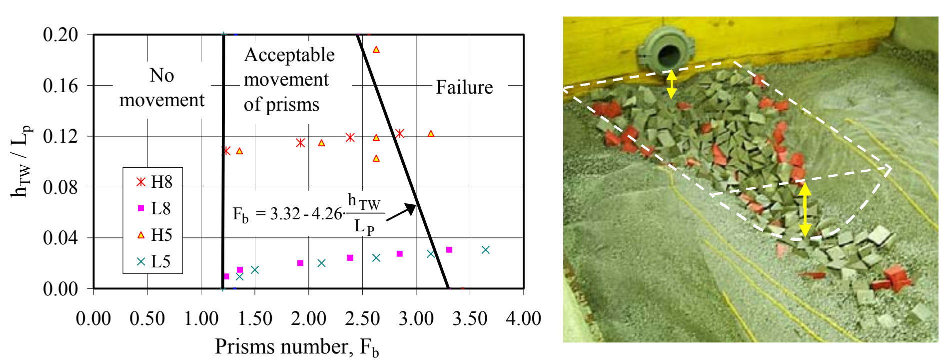

Figure 6: Failure diagram of prisms as a function of h_{TW}/L_P and prism number (left), Example of a failure at the protected area (right)

4.2.3 Formulas for calculating the scour hole geometry in the protected area

A linear regression with high correlation coefficients could be fitted through the data by using an equation of the form:

$y = a \cdot F_b + b$ where the prism number $F_b = u_0 \Big/ \sqrt{(\rho_b/\rho - 1) \cdot g \cdot V^{1/3}}$ (1)

The values of coefficients "a" and "b" were plotted versus $h_{TW}/V^{1/3}$ for the different dimensionless parameters of the scour hole. Interpolation lines were obtained for these values using the four tested tailwater depths. The equations with the form of "$a = f(h_{TW}/V^{1/3})$" and "$b = f(h_{TW}/V^{1/3})$" are summarized in Table 1. Scour hole dimensions can be estimated introducing the corresponding values of "a" and "b" in Eq. (1).

Table 1: Summary of coefficients of equation 1 for scour hole characteristics (valid for $0.10 < h_{TW}/V^{1/3} < 2.90$)

Scour hole characteristics	**Y**	**a**	**b**
Maximum scour depth	d_{sc} / D	$-0.01 \cdot (\frac{h_{TW}}{V^{1/3}}) + 0.87$	$0.38 \cdot (\frac{h_{TW}}{V^{1/3}}) - 1.00$
Scour depth at pipe outlet	d_{toe} / D	$-0.11 \cdot (\frac{h_{TW}}{V^{1/3}}) + 0.38$	$0.09 \cdot (\frac{h_{TW}}{V^{1/3}}) - 0.37$
Maximum scour width	W / D	2.00	1.50
Beginning of the scour hole	X_1 / L_P	$-0.27 \cdot (\frac{h_{TW}}{V^{1/3}}) + 0.09$	$0.88 \cdot (\frac{h_{TW}}{V^{1/3}}) - 0.29$
Distance of d_{sc} from pipe outlet	X_2 / L_P	$-0.07 \cdot (\frac{h_{TW}}{V^{1/3}}) + 0.36$	$0.62 \cdot (\frac{h_{TW}}{V^{1/3}}) - 0.50$
Maximum scour length	X_3 / L_P	$-0.25 \cdot (\frac{h_{TW}}{V^{1/3}}) + 1.13$	$1.00 \cdot (\frac{h_{TW}}{V^{1/3}}) - 1.45$
Required length of the protected area	L_{REQ} / D	$-0.37 \cdot (\frac{h_{TW}}{V^{1/3}}) + 3.63$	$0.39 \cdot (\frac{h_{TW}}{V^{1/3}}) + 0.38$

5 Conclusions

According to the tests results the following may be concluded:

- In the case of low tailwater depths, the scour hole formed close to the pipe outlet. The location of the scour hole moves downstream while increasing the tailwater level (Fig. 7).
- For similar values of the prism number F_b, the scour depth directly at pipe outlet was found approximately 3 times higher than for low tailwater depths.

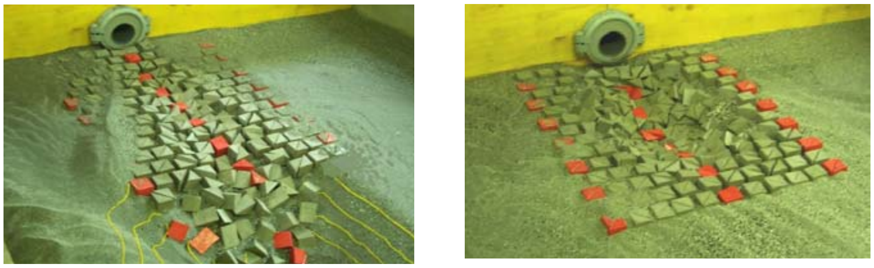

Figure 7: Location of scour hole as a function of tailwater level for Q = 12.5 l/s; high tailwater $h_{TW}/D = 1.1$ (left), low tailwater $h_{TW}/D = 0.2$ (right)

Comparison of the scour hole with and without using protection prisms led to the following results:

- For low tailwater depths ($h_{TW}/D < 0.2$), the location of the maximum scour depth from the pipe outlet with/without using the prisms was found the same but the maximum scour depth was 2.5 to 5 times smaller when using the protection prisms.
- For high tailwater depths ($h_{TW}/D > 1.1$), the distance of the scour hole from the pipe outlet increased when using the protection prisms. The location of the scour hole from the pipe outlet was found approximately 1.5 to 2.5 times farther in comparison to the scour hole location in a unprotected mobile bed. Furthermore, the protection prisms reduce the maximum scour depth by 35 to 70% compared to the case without protection.

By the systematic experimental study it could be shown that the protection prisms placed on mobile riverbeds reduce significantly the erosion and protect the downstream area next to diversion tunnel outlets in a very efficient way against scouring.

6 Design recommendations

The design discharge for checking the stability of the prisms is given by the risk analysis of the diversion system considering construction costs and damages during floods at construction site. The required size of prisms should then be determined by using a safety factor. For the design discharge a safety factor of $\beta = 1.3$ is recommended, which is applied on the prism number when using the failure diagram ($\beta \cdot F_b$). Furthermore the stability of the prisms should be checked for the safety discharge ($B \geq 1$).

For the range of application of the developed scour formulas ($0.10 < h_{TW}/V^{1/3} < 2.90$), the minimum required size of prisms $a_{b\ min}$ should be 45% of tailwater depth ($a_{b\ min} = 0.45 \cdot h_{TW}$). The required dimension of the prisms can be obtained by using the failure diagram (Fig. 6). The maximum spacing between prisms should not exceed 40% of the prism size ($0.40 \cdot a_b$). A minimum prism spacing of 0.50 m is recommended for construction reasons.

The prisms can be casted in place after excavation of the cube and creating the prisms with a lost diagonal formwork (Fig. 8 left). The alternate solution is to precast a reinforced formwork and fill it on site with mass concrete (Fig. 8 right).

Figure 8: Prisms construction methods, without using sides' formwork and reinforcement (left), precast formwork filled with mass concrete (right)

Notations

The following symbols are used in this article:

a, b constants
a_b length, width and height of prism (diagonally divided cube)
D diameter of the pipe
d_{sc} maximum depth of scour
d_{toe} scour depth at pipe outlet
d_{50} median particle size at which 50% of particles are retained
F_0 densimetric Froude number defined as $u_0 \big/ \sqrt{(\rho_s/\rho - 1) \cdot g \cdot d_{50}}$
F_b prism number defined as $u_0 \big/ \sqrt{(\rho_b/\rho - 1) \cdot g \cdot V^{1/3}}$
h_{TW} the difference in pipe invert elevation and elevation of tailwater level
L_P length of the protected area
L_{REQ} required length of the protected area to avoid any failure
Q discharge at pipe/tunnel outlet
u_0 velocity at pipe/tunnel outlet
$V^{1/3}$ equivalent volume of cube defined as $\sqrt[3]{(a_b^3/2)}$
W maximum scour hole width
X_1 distance of start of erosion from the pipe/tunnel outlet
X_2 distance of the maximum erosion depth from the pipe/tunnel outlet
X_3 scour hole length
β safety factor
ρ mass density of the fluid
ρ_s mass density of the bed material
ρ_b mass density of the concrete prisms

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Aknowledgment

The study was carried out as a diploma thesis of the postgraduate courses in hydraulic schemes under a scholarship of the Laboratory of Hydraulic Constructions of the Swiss Federal Institute of Technology in Lausanne, Switzerland.