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Riprap Sizing at Wing-Wall Abutment in a 90° Bend Based on Incipient Motion Criterion

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Abstract: Riprap is often used to protect abutment against scour. It is important to select riprap that is large enough to ensure stability under design flood conditions. In the past few studies have been performed about for sizing riprap to protect the bridge abutment in straight channel. For some reason, the bridge may cross a river bend. Since the flow patterns in river bend are different than in straight channel, this study was conducted. This paper presents observations and experimental results of incipient motion of riprap at 45° wing-wall abutment in a 90° channel bend. Tests were conducted using three different types of specific gravity of riprap and four different sizes of riprap. The incipient motion was considered reached when the first riprap element initially at the abutment is dislodged, either in the horizontal or in the vertical direction. Each riprap material conducted under four different discharges of 0.017, 0.020, 0.023 and 0.028 m^3/s. The size of riprap was correlated to the Froude number and tail water depth at the point of incipient motion.

Key words: Riprap · Abutment · 90° channel bend · Incipient motion · Scour

INTRODUCTION

Local scour is a natural phenomenon caused by the erosive action of the flowing stream on the sediment beds in the vicinity of piers or abutments [1]. In a study of 383 bridge failures, Richardson *et al.* [2] reported that 25 and 72% collapses involved pier and abutment damages, respectively. According to Sutherland [3], of the 108 bridge collapses surveyed in New Zealand during the period of 1960-1984, 70% of the expenditure on bridge collapses was spent on repairing or maintenance of abutment scour.

Riprap is often used to protect wing-wall abutment against scour. The riprap is placed to form a protective apron on the bed of the river channel adjacent to the vertical walls of the abutment structure. It is important to select riprap that is large enough to ensure stability under design flood conditions [4]. During past decades few studies have been conducted to present a formula for determination of riprap size at abutment in a straight channel. Some of the well known formula are listed in Table 1.

Most of the investigators have focused on scour mechanism in a channel bend, such as: Yen [8], Engelund [9], Kikkawa *et al.* [10], Odgaard [11] and Ghodsian and Mousavi [12] and few studies have been performed for the purpose of protection of structures within the channel bend such as bridge pier or abutment.

This paper presents observations and experimental results of incipient motion of riprap at 45° wing-wall abutment in a 90° channel bend. The aim of the experiments was the design of the size of riprap at abutment in a channel bend.

Dimensional Analysis: Stability of riprap at bridge abutment in a river bend depends on channel geometry, abutment characteristics, flow conditions, riprap and sediment properties and fluid parameters. Therefore for the median size of riprap D_{r50} one can write:

$$f\,(D_{r50},\ \theta, V_t, y_t,\ \rho_s, \rho_w,\ \mu, g) = 0 \qquad (1)$$

Where θ = location of abutment in the bend; V_t and y_t = mean velocity of flow and water depth at the

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Table 1: Equations for design of riprap size at abutment

Reference	Equation	Applicability	Symbols
Pagan-Ortiz[5]	$\frac{D_{r50}}{y}=\frac{1.05}{(S_S-1)^{0.81}}F_r1.62$		D_{r50} = Median size of the riprap
Austroads[6]	$\frac{D_{r50}}{y}=\frac{1.026}{(S_s-1)}F_r2$		y = Flow depth F_r = Froude number
Lagasse *et al.*[7]	$\frac{D_{r50}}{y}=\frac{1.02}{(S_S-1)}F_r2$	$Fr \leq 0.8$	S_s = specific gravity of the riprap material
Lagasse *et al.*[7]	$\frac{D_{r50}}{y}=\frac{0.69}{(S_S-1)}F_r0.28$	$Fr \geq 0.8$	

downstream straight of bend at riprap incipient motion point, respectively; ρ_s = density of riprap materials; D_{50} = median size of sediment grains; ρ_w = density of water; μ = viscosity of fluid; and g = gravitational acceleration. Using dimensional analysis, Eq. (1) can be written as:

$$D_{50} / y_t = f(F_{rc}, R_{ec}, \theta, S_s) \quad (2)$$

Where S_s = specific gravity of the riprap materials; F_{rc} and R_{ec}, = Froude number and Reynolds number at riprap incipient motion point, respectively. The Reynolds number in this study ranged from 23800 to 42700 is high enough in which have no effect on flow characteristics. By eliminating the Reynolds number from the above equation, one can have:

$$D_{50} / y_t = f(S_s, F_{rc}) \quad (3)$$

Equation 3 is a general form of formula at the point of incipient motion for rocks at the base of bridge abutment at a river bend. To determine the specific equation, experimental data are required which was obtained from the tests conducted as have been explained in the following sections.

Experiments

Flume: Experiments were carried out at the Model Laboratory of Shahid Chamran University, Ahwaz-Iran. The horizontal channel consisted of a 4.0m long upstream and a 2.0m long downstream straight reaches (Fig. 1). A 90° channel bend was located between the two straight reaches. The channel was of rectangular cross section 0.4m width, 0.7m height with 0.8m centerline radius of bend. The bed and sides of channel was made of plexi-glass supported by metal frame. Measurement of discharge was done by a triangular weir having vertex angle of 90°. A sluice gate was located at the end of the main channel to control the flow depth within the flume.

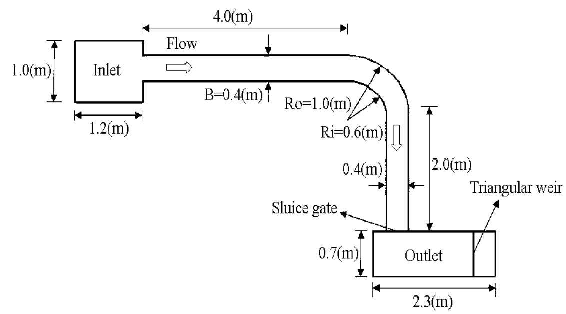

Fig. 1: Schematic top view of 90° flume

Sediment: Uniform sediment with specific gravity of 2.65, median size D_{50}=1.63mm and standard deviation σ_g was placed with a thickness of 0.36m and covered the total length of flume.

Abutment and Riprap Apron: A 45° wing-wall abutment having length L=4.0cm and height h=68.0cm from the flume bed was used for this study. The model had a b/L ratio of 4; where b=streamwise length of the abutment (Fig. 2). From the preliminary experimental tests, it was concluded that the maximum erosion at abutment is occurred at section 75° of the bend. To determine the extent of riprap apron at abutment located at section 75°, a test was conducted without riprap apron placement. During this 12-hour test, the scour hole around the abutment and the outer bank were measured by the point gage. The time development of scour depth versus time also was plotted. From this figure it was concluded that about 85% of the scour is occurred in the first two hours of testing. From the plotted bed topography, extend of scour hole was determined. This area was considered as the area to be protected by riprap material. Fig. 2 shows the dimensions of abutment and riprap apron.

The experimental tests were conducted using three types of riprap with specific gravity of 1.51, 2.05 and 2.65 and four different sizes of riprap (4.75, 9.52, 12.7 and

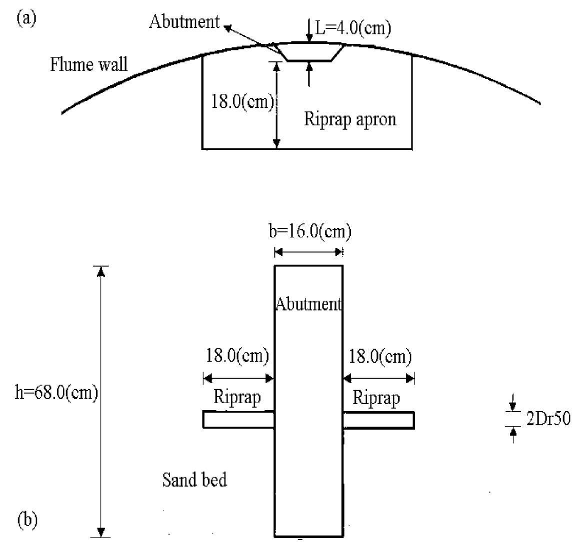

Fig. 2: (a) Schematic top view of abutment and riprap apron; and (b) schematic elevation of abutment and riprap apron

Table 2: Riprap properties used in this study

S_s	D_{r50} (mm)
2.65	4.75, 9.52, 12.70, 19.05
2.05	9.52, 12.70
1.51	12.70, 19.05

19.05mm). All riprap materials were angular, being obtained from crushed aggregate. The riprap properties are summarized in Table 2. The riprap elements were carefully placed at a thickness of $2D_{r50}$ [4]. According Unger and Hager [13], if these elements either protrude from the bed sediment or are lower than it, the riprap effect is reduced as compared with the optimum riprap setting so the surface of riprap elements was flush with the bed sediment surface (Fig. 2). In practice, a riprap is combined with a filter and the riprap may consist of various layers. The simplified and thus less safe riprap arrangement selected herein allows for some additional safety against failure [14].

Where S_s and D_{r50} have been defined previously.

Test Procedures: First the abutment was glued to the desire location of the bend and flume bed was filled with fine sand to the desire elevation. Then riprap were placed in the specified area. To avoid disrupting the bed and apron, the discharge was slowly increased up to the test value and flow depth was simultaneously adjusted by gradually opening of the tailgate. After the discharge was reach to the desired value, flow depth gradually was lowered in periods of fifteen minutes and carefully riprap was observed. The incipient motion was considered reached when the first riprap element located initially at the abutment had dislodged, either in the horizontal or in the vertical direction [14]. The flow depth at this time were recorded as riprap incipient motion depth (Table 3). Each riprap material were tested under four different discharges of 0.017, 0.020, 0.023 and 0.028 m^3/s. Fig. 3 shows after an incipient motion test.

Fig. 3: After a incipient motion test

Table 3: Incipient motion of riprap results

S_s	Q (m^3/s)	D_{r50} (mm)	y_t (m)	V_t (m/s)	F_{rc}
2.65	0.017	4.75	0.131	0.32	0.28
2.65	0.017	9.52	0.104	0.41	0.40
2.65	0.017	12.70	0.097	0.44	0.45
2.65	0.017	19.05	0.082	0.52	0.58
2.65	0.020	4.75	0.150	0.33	0.27
2.65	0.020	9.52	0.119	0.42	0.39
2.65	0.020	12.70	0.112	0.45	0.43
2.65	0.020	19.05	0.095	0.53	0.55
2.65	0.023	4.75	0.169	0.34	0.26
2.65	0.023	9.52	0.135	0.43	0.37
2.65	0.023	12.70	0.125	0.46	0.42
2.65	0.023	19.05	0.110	0.52	0.50
2.65	0.028	4.75	0.200	0.35	0.25
2.65	0.028	9.52	0.162	0.43	0.34
2.65	0.028	12.70	0.143	0.49	0.41
2.65	0.028	19.05	0.128	0.55	0.49
2.05	0.017	9.52	0.132	0.32	0.28
2.05	0.017	12.70	0.120	0.35	0.32
2.05	0.020	9.52	0.145	0.34	0.29
2.05	0.020	12.70	0.128	0.39	0.35
2.05	0.023	9.52	0.163	0.35	0.28
2.05	0.023	12.70	0.158	0.36	0.29
2.05	0.028	9.52	0.195	0.36	0.26
2.05	0.028	12.70	0.175	0.40	0.31
1.51	0.017	12.70	0.158	0.27	0.22
1.51	0.017	19.05	0.135	0.31	0.27
1.51	0.020	12.70	0.175	0.29	0.22
1.51	0.020	19.05	0.153	0.33	0.27
1.51	0.023	12.70	0.198	0.29	0.21
1.51	0.023	19.05	0.170	0.34	0.26
1.51	0.028	12.70	0.238	0.29	0.19
1.51	0.028	19.05	0.201	0.35	0.25

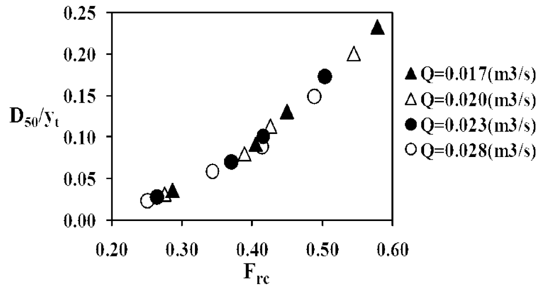

Figure 4. Variation of $F_{rc}$with D_{r50} /y_t for S_s = 2.65

Table 4:Comparison present paper with earlier studies

Reference	RMSE	R^2
Present paper	0.008	0.97
Lagasse *et al.* [7]	0.016	0.94
Austroads [6]	0.017	0.94
Pagan-Ortiz [5]	0.070	0.93

RESULTS AND DISCUSSION

Presentation of Data: After performing of experiments, for each measured tail water depth, mean velocity of flow and Froude number were calculated (Table. 3). In all the experimental tests it was observed that the first instability of the riprap begins near the downstream wall of abutment. Further decreasing flow depth, the location of first rock movement is shifted toward the upstream wall abutment. It was also observed that for each riprap, by increasing discharge the tail water depth at riprap incipient motion point increases. Also when discharge and specific gravity of the riprap are constant, by decreasing tail water depth the diameter of riprap increases. The comparison of tail water depths at riprap incipient motion point shows when discharge and size of riprap are constant, by increasing specific gravity of the riprap materials the tail water depth at riprap incipient motion point decreases.

Results of this research were also shown that for each three types specific gravity of riprap for each constant discharge, by increasing Froude number the ratio of D_{r50}/y_t increases. The variation of Froude number with D_{r50}/y_t for specific gravity of 2.65 and for various discharges at riprap incipient motion point is shown in Fig. 4. Also the range of D_{r50}/y_t in this study is 0.02 to 0.23.

Presenting New Relation: To develop a new formula for design of riprap at bridge abutment, the experimental data of all tests were analyzed according to the three non dimensional relation shown in Eq.3. The new equation which was obtained by regression analysis is as follow:

$$\frac{D_{r50}}{y_t} = \frac{1.63}{(S_s - 1)^{1.12}} F_{rc}^{2.54} \quad R^2 = 0.97 \tag{4}$$

In this Equation: R^2 = correlation coefficient and other variables have defined previously.

Comparison with Earlier Studies: The formula developed in this study, Eq. 4, was compared with formulas of earlier studies on riprap at abutment for straight channels. The root mean square error (RMSE) and correlation coefficient (R^2) of Eq.4 and equations of earlier studies are listed in Table 4.

The results of Table 4 are shown that the Lagasse *et al.* [7] and Austroads [6] equations have maximum consistency with the findings of this study. These equation predict the riprap size a little higher than the finding of this study. By using correction coefficient of 0.93 and 0.926 for Lagasse *et al.* [7] and Austroads [6]'s equations respectively, the results are more close to the present study. These correction coefficients are obtained from comparison of results of this paper with studies relations that were mentioned.

CONCLUSION

In this study, experimental tests were conducted to develop a formula for sizing of riprap at bridge abutment located in a 90° channel bend. This paper presents observations and experimental results of incipient motion of riprap at 45° wing-wall abutment in a 90° channel:

- In all the experiments it was observed that at first instability of the riprap begins near the downstream wall of abutment and by decreasing flow depth this location is shifted further upstream wall of abutment.
- For each riprap, by increasing discharge the tail water depth at riprap incipient motion point increases.
- When discharge and specific gravity of the riprap are constant, by decreasing tail water depth the diameter of riprap increases .
- The comparison of tail water depths at riprap incipient motion point shows when discharge and size of riprap are constant, by increasing specific gravity of the riprap materials the tail water depth at riprap incipient motion point decreases.
- New empirical equation for design of riprap size at bridge abutment in a 90° channel bend is presented.

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