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STABILISING CHANNEL BEDS AND BANKS USING ROCK CHUTES AND RIP-RAP

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A rock chute is a relatively short and steep section of the bed of a channel which has been armoured with rock. Rock rip-rap is the name given to rock protection, placed on banks to prevent erosion of the underlying material. For both, proper hydraulic design is very important to ensure that the geometry and rock size are matched with the site conditions and expected flow conditions such that the rock remains stable under all expected flow conditions. This paper summarises the theory for the proper hydraulic design of rock chutes and rock rip-rap and introduces spreadsheet-based computer programs to design and analyse the performance of these structures under a range of flow conditions.

1 Introduction

The stability of rivers and channels is often linked to the stability of the channel bed and banks. Channels may be de-stabilised by (for example) the draining of a downstream swamp, which can initiate an erosion head that, unchecked, will migrate upstream with substantial subsequent bank collapse.

A rock chute is a relatively short and steep section of the bed of a channel which has been armoured with rock. It is normally intended to either stabilize an erosion head, preventing it from moving upstream in the channel, or to reduce the overall grade of a channel by providing a weir within the channel bed. Rip-rap is the term given to loose rock armour, usually obtained by quarrying. It is widely used for bank protection. A major advantage of rip-rap protection is that it is very flexible. As a result, damage tends to occur gradually and, as stones move relative to each other, is, to some extent, self-healing.

Although the concept of a rock chute and riprap is simple, proper hydraulic design is very important to ensure that the geometry and rock size are matched with the expected flow conditions such that the rock remains stable under all expected flow conditions. In addition, appropriate rock chute design requires that the abutments are treated to prevent failure by outflanking of the crest and that the grading of rock sizes within the rock mixture minimizes the presence of voids.

This paper summarises the theory for the proper hydraulic design of rock chutes and rip-rap and introduces spreadsheet-based computer programs, CHUTE and RIPRAP, to design and analyse the performance of chutes and rip-rap under a range of flow conditions. The programs have been developed as part of the CRC for Catchment Hydrology toolkit program. (http://www.toolkit.net.au/)

In the following section, the essential hydraulic design elements of a rock chute and of rip-rap are discussed and the design theory summarized. In subsequent sections, the spreadsheet-based design programs are described, elements for good design practice are identified, and final conclusions drawn.

2 Hydraulic Design Elements and Design Theory

2.1 *Rock Chutes*

A typical rock chute is shown schematically in Figure 1, together with an illustration of the various terms used in describing and designing a rock chute. From a hydraulic point of view, the primary elements are the chute face and the apron, since these provide protection to the bed from the erosive forces of the water.

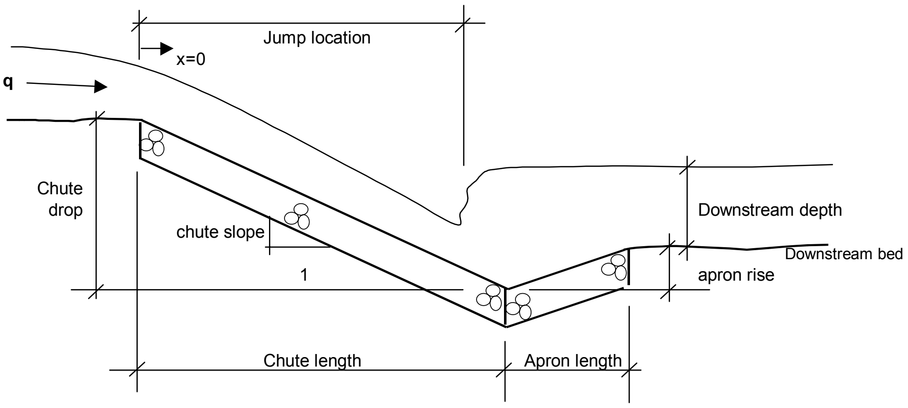

Figure 1. Schematic of a Typical Chute with Explanation of Terms

The primary design output is the rock size required to ensure a stable structure. Because the rock size is dependent on the bed shear stress, which, in turn, is dependent on the flow profile over the chute, a key element in the design process is the determination of the water surface profile.

Keller and Winston (2003) have discussed the three types of water surface profile that can occur. They demonstrated that the location of the point of maximum bed shear stress coincides with the point of minimum depth and is, in general, associated with a flow rate less than the maximum design flow in the river.

It follows that the chute design flow rate – that for which the required rock size is a maximum – will be lower than the channel design flow rate - that for which the required channel capacity is a maximum. This is a most important distinction in the design of a rock chute and receives further comment later in this paper.

From Shields Entrainment Function and Manning's Equation, Keller and Winston (2003) demonstrated that the required minimum stone size, D_{50}, on the face of a rock chute is given by:

$$D_{50} = \frac{0.97 F_S q^2 n^2}{0.047(S_s - 1) y^{7/3}} \tag{1}$$

where F_S is a factor of safety, q is the unit flow rate, n is Manning's roughness coefficient, S_S is the relative density of the bed material, and y is the depth.

The second stage of the hydraulic design of the chute is the determination of the chute bank angle. Again, Keller and Winston (2003) have demonstrated that:

$$D_{50} = \frac{0.75 yS}{0.047(Ss - 1)\cos\theta \sqrt{\frac{1}{F_S^2} - \frac{\tan^2\theta}{\tan^2\phi}}} \tag{2}$$

where S is the energy gradient, θ is the side slope angle, φ is the natural angle of repose of the rock material.

Equation (2) is used by the design program to determine the maximum allowable value of the side slope angle, θ, such that the value of D_{50}, required for stability on the side slope, is no greater than that calculated by Equation (1). In this way, rock stability is assured on both the bed and side slopes of the chute

2.2 *Rock Rip-rap*

A typical rip-rap application is shown in Figure 2. The figure shows the typical height of bank protected and shows alternative methods of treatment at the toe of the bank.

The theory is based on a fundamental force balance, requiring that, at the point of incipient particle motion, the disturbing forces on the particle (drag force exerted by the flow and weight component resolved down the slope) are balanced by the restoring forces (the product of the weight component resolved perpendicular to the bank and the tan of the natural angle of repose of the rip-rap material).

Keller and Winston (2004) have demonstrated that the minimum rock size required for stability is given by:

$$D_{50} = \frac{\left[\frac{0.75 yS \tan\phi}{0.047(S_s - 1)}\right]}{\sqrt{\left(\frac{\cos\theta \tan\phi}{F_S}\right)^2 - \sin^2\theta}} \tag{3}$$

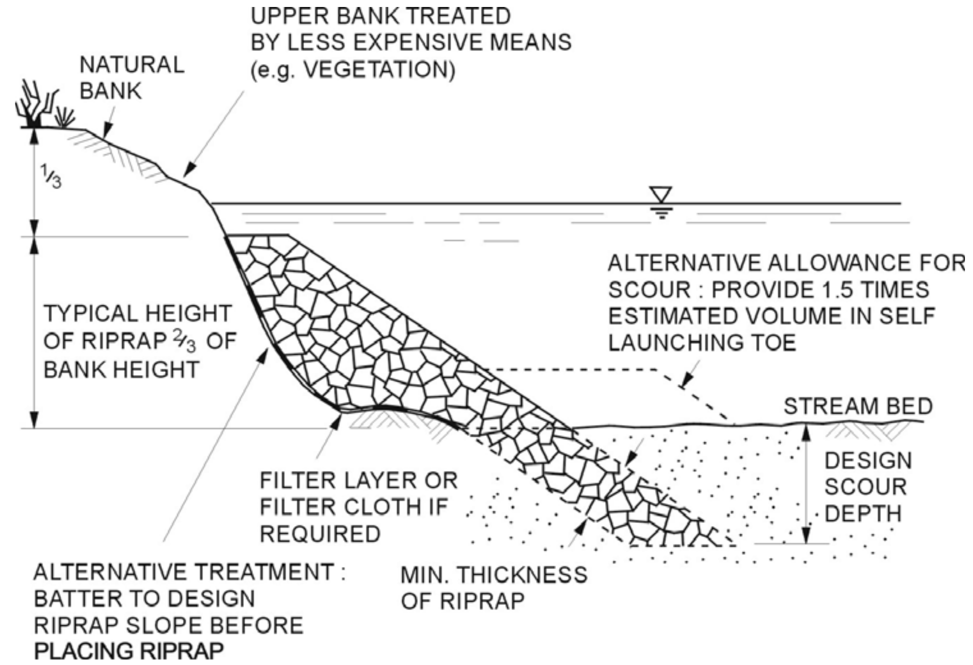

Figure 2. Typical Rip-rap Application

It is evident from the form of Equation (3) that a solution is only possible if $\frac{\cos\theta \tan\phi}{F_S} \geq \sin\theta$. Thus, the limiting bank slope is given by:

$$\theta_{\max} = \tan^{-1}\left[\frac{\tan\phi}{F_S}\right] \tag{4}$$

Equations (3) and (4) are solved by the program RIPRAP.

3 Design Programs

3.1 *CHUTE*

The design program is set up as a Microsoft Excel workbook, with separate sheets devoted to inputs, downstream channel conditions and results.

The program requires inputs that describe the structure and downstream conditions. These are as follows:

Structure Variables. With reference to the sketch in Figure 1, the following variables describing the dimensions of the proposed structure are entered into the input table:

Chute Drop, Chute Length. The vertical and horizontal distance respectively between the upstream lip of the chute and the lowest point,

Apron Rise, Apron Length. The vertical rise and horizontal length respectively of the downstream apron section.

Unit Flow Rate. The minimum and maximum flow rate per unit width specifying the range over which the program will calculate the D_{50} required.

Rock Variables. The angle of repose and the specific gravity of the proposed rock that will be used in the chute.

Downstream Conditions. The water surface profile on the chute is critically dependent on the tail water level. Several options are available.

The most reliable and exact option involves the specification of a rating table. However, this option requires the use of an external backwater program, such as HEC-RAS, to determine the tail water levels over a range of flow rates. Although other options, such as the specification of uniform depth, may be used for initial trials, a rating table should always be used as the final check. Pairs of Q and h values are entered in a table in the workbook marked “Rating Table”.

Once the required inputs have been entered by the user, the program initiates the running of a macro which reads the inputs from the relevant tables, checks all inputs for consistency then performs the required design calculations. Outputs are then placed directly into the results sheet, where embedded graphs display the results in a sensible form.

Figure 3 shows an example of a graph of the calculated value of D_{50} against the flow rate per unit width passing through the structure for typical inputs listed in Table 1.

For this example, the tail water conditions were based on uniform flow in the channel of bed slope 0.001, width 5m, and Manning’s coefficient of 0.03

The program also enters the values of water surface elevation, total energy level, velocity and friction slope into the results spreadsheet, but only for the flow at which the D_{50} was maximum. These data can be useful for error checking and are also plotted. Additionally, over the full range of flows, the program analyses and provides comment on the resultant flow conditions, location of the hydraulic jump and so on.

Table 1. Input parameters for example chute structure

Parameter	Value
Chute Drop	2
Chute Length	10
Apron Rise	0.5
Apron Length	3
Unit flow rate (max)	0.1
Unit flow rate (min)	4
Rock angle of repose	44
Specific gravity of rock	2.6
Factor of safety	1.2

Appropriate values for the factor of safety are discussed below

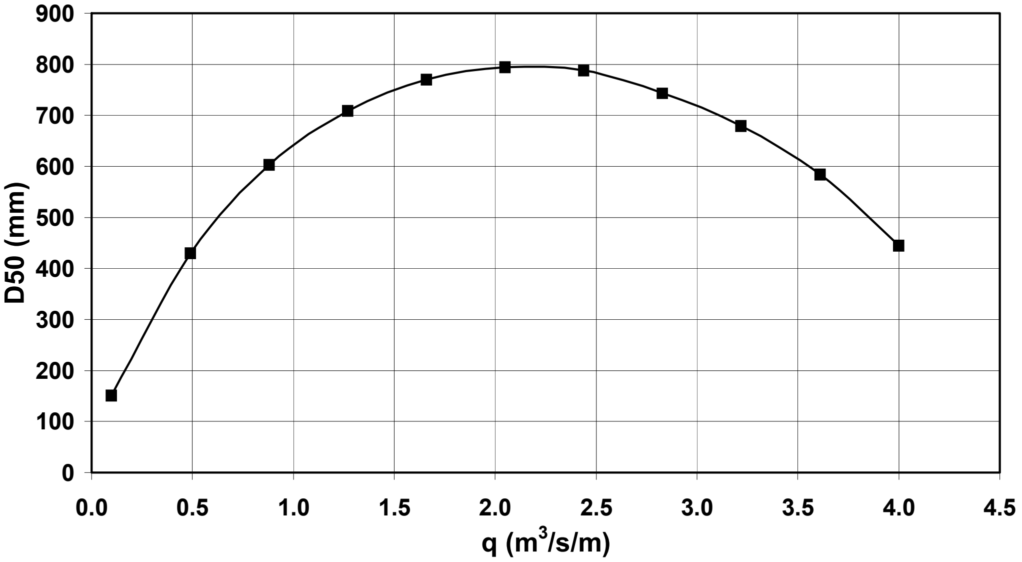

Figure 3. Plot of calculated D_{50} size against flowrate per unit width.

3.2 *RIPRAP*

The design program is set up as a Microsoft Excel workbook, with a single sheet containing both the input variables and tabulated output and a second sheet showing the graphed output. The required inputs include the following:

Natural angle of repose of the rip-rap - typically varies between about 30^0 and 43^0

Bank angle - angle (in degrees) of the finished rip-rap surface to the horizontal

Specific gravity of rip-rap rock

Local hydraulic energy gradient - the value adopted for this parameter is crucial to the accuracy of the computed required rip-rap size. Indeed, Equation (3) indicates that computed D_{50} values are directly proportional to the adopted energy gradient. The description of the hydraulic conditions, which dictate the forces on the rip-rap particle, is fully embodied in the value adopted.

Maximum depth and specific depth of interest - The user specifies the maximum depth for which data are required. The program splits the maximum depth into ten equal intervals and provides output at each interval of depth. In addition, the user specifies a specific design depth of interest – less than or equal to the maximum depth – for which output data are also generated. The generation of depth-dependant rip-rap size permits the specification of different rip-rap stone sizes at different depths, which may be appropriate on very large projects where cost is a substantial issue.

3.3 *Factor of Safety*

One important design input parameter for both programs CHUTE and RIPRAP is the factor of safety. Issues which govern the choice of value include the consequences of failure, the reliability of the input parameters, the quality and consistency of the available rock, the return period and likely duration of the design flood and the likelihood of eventual stabilisation by vegetation. The value adopted relies on the judgment and experience of the designer.

As a guide, values above 1.3 are appropriate where there are grave consequences of failure to property or assets. Values between 1.0 and 1.3 are applicable where the objective is general erosion control, where the risk of catastrophic failure is small, and where vegetation will eventually enhance the stability of the chute or riprap.

4 Design Elements

4.1 *Rock Chutes*

There are a number of other important details in the design of rock chutes. These include the specification of rock quality, grading, and thickness; details of filters and cutoff walls; and the treatment of abutments to prevent outflanking.

Rock quality, grading, and thickness issues; and the design of filters, are the same as those for riprap design (Hemphill and Bramley 1989). Cutoff walls are essential to minimise the risk of piping failures beneath the chute or through the abutments. Their importance increases with the permeability of the parent material, decreasing cohesion of the parent material, and the height and steepness of the chute. Abutments must be keyed into the banks of the channel. Rock riprap protection should be placed upstream and downstream of the chute to provide direct abutment protection.

4.2 *Rock Riprap*

Design considerations include a number of factors such as extent of bank protection (including length of bank to be protected and proportion of bank height to be protected), allowance for scour at the toe of the rip-rap, specification for rock quality and grading and thickness of layer and details of filters. Details of each of these issues are provided in (Keller and Winston, 2004).

5 Summary and Conclusions

This paper has summarised the theory for the hydraulic design of rock chutes and riprap and described spreadsheet-based computer programs, CHUTE and RIPRAP, which carry out the design and analyse the performance under a range of flow conditions. A factor of safety approach is used to modify the standard tractive force stability balance.

The design program CHUTE also calculates the flow profile over the chute structure throughout the flow range, identifying the type of profile and the location of the hydraulic jump. It is shown that the critical design flow rate with respect to rock size required, is less than the maximum design flow rate. The program identifies the critical design flow rate and carries out the hydraulic design.

The design program RIPRAP computes a table showing the design values of median rip-rap diameter for a range of bank angles and a range of depths. The ranges include the actual design bank angle and design depth as specified in the input to the program.

In addition to the hydraulic design, the succesful design of both rock chutes and riprap relies on a number of non-hydraulic issues such as the specification of rock quality, grading, and thickness; details of filters and cutoff walls; the treatment of abutments to prevent outflanking; extent of bank protection; and allowance for scour at the toe of the rip-rap.

Acknowledgments

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