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Some factors affecting erosion of bed channels protected with riprap

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Abstract This investigation is an experimental study of some factors responsible for the erosion process acting on the base material of a stream bed protected by riprap. Using a uniform material for the riprap and two graded sands as base material, a series of experiments was designed and conducted in the laboratory to verify the effect of the protection thickness and of the base material size distribution on the base erosion process. Based on the results of such experiments and of literature study, conclusions are drawn which permit the more confident design of riprap protection. Furthermore, a dimensionless description of the observed data is presented making it possible to estimate either the protective layer thickness or the erosion rate of the base material.

Agents qui affectent l'érosion du fond d'un canal protégé par "riprap"

Résumé Cette recherche est une étude expérimentale de facteurs qui régissent les érosions sous un perré (rip-rap) de protection du fond d'un canal. Employant un matériau uniforme pour le "riprap" et deux sables tamisés pour le tapis sous-jacent, on a executé plusieurs expériences pour vérifier l'effet de l'épaisseur du perré et de la granulométrie du matériau de base sur le processus de l'érosion sous-jacente. Appuyés sur des recherches bibliographiques, les résultats de ces essais permettent de dimensionner le perré avec plus de précision. Les résultats sont présentés sous forme adimensionnelle ce qui permet d'estimer l'épaisseur du perré ou le taux d'érosion du matériau sous-jacent.

INTRODUCTION

The design of stable channels for fine and noncohesive bed material commonly results in wide channels, that are inappropriate for practical applications. Two solutions are adopted in cases of problems of this nature: (a) channel linings consisting of materials possessing some cohesive force e.g. concrete lining, bituminous material, etc.; (b) channel protection by an assemblage of discrete particles known as riprap.

As regards the riprap protection, the amount of information about the stability of its particles, with respect to the incipient motion, is satisfactory (Graf, 1971; Simons & Şentürk, 1976; Wang & Shen, 1985). However, there is a limited number of studies about the erosive effect of the flow on the base material with respect to its size distribution, the riprap layer thickness and the riprap material size distribution (Anderson *et al.*, 1970; Paintal, 1971).

The purposes of this investigation are to amplify the amount of information about the riprap protection against leaching and to propose a model for estimating the erosion rate of the base material.

FACTORS AFFECTING THE BASE MATERIAL EROSION

Most of the models for evaluating the stable particle size at the riprap refers to the mean diameter d_{50} (particle size of which 50% is finer by weight). One would expect the riprap to be more stable if it consisted of a uniform material rather than a graded one, with regard to movement of individual particles. However, it is expected to be less efficient in the prevention against leaching.

For riprap consisting of uniform material the efficiency of the protection, with regard to leaching, is reduced when the relation between dr_{50} (the actual riprap mean diameter) and dm_{50} (the riprap minimum diamter, required for stability) is increased. This happens because the mean distance between particles is increased, facilitating the erosive action by the flow on the base material.

Because of the grain size variation of the base material a differential action is expected by the fluid on these grains. Fluid forces are more effective in leaching the smaller particles through riprap interstices. Thus, not only the mean diamater da_{50} of the base material should be considered in this analysis but also its uniformity coefficient Cu_a, given by the relation between the diameters da_{60} and da_{10} (particle sizes of which 60% and 10% are finer by weight, respectively).

The intensity of the mean shear stress (τ_b) on the riprap gives an idea of the degree of turbulence near it. This phenomenon is directly related to the base material erosion process. Increasing the mean shear stress an increase in the base material erosion rate is expected.

The riprap layer thickness seems to be the most significant parameter responsible for the bed protection against leaching of the base material through the riprap interstices. When the riprap thickness increases, the direct dislodgement by the flow is reduced because either the interstices between the particles are cut off or the path to the bed is lengthened.

EXPERIMENTAL APPARATUS

The hydraulic system illustrated in Fig. 1 is of the recirculating type and consists of: a steel rectangular flume 12 m long 40 cm wide and 50 cm deep with adjustable slopes by a hydraulic jack; a sand box in which the eroded material of the base was collected; a small basin at the outlet end of the sand box in which the water is collected and pumped back to the inlet end of the flume through two pipes. The discharge in the flume was measured with calibrated orifice plate located in each return line, and connected to vertical differential water-mercury manometers.

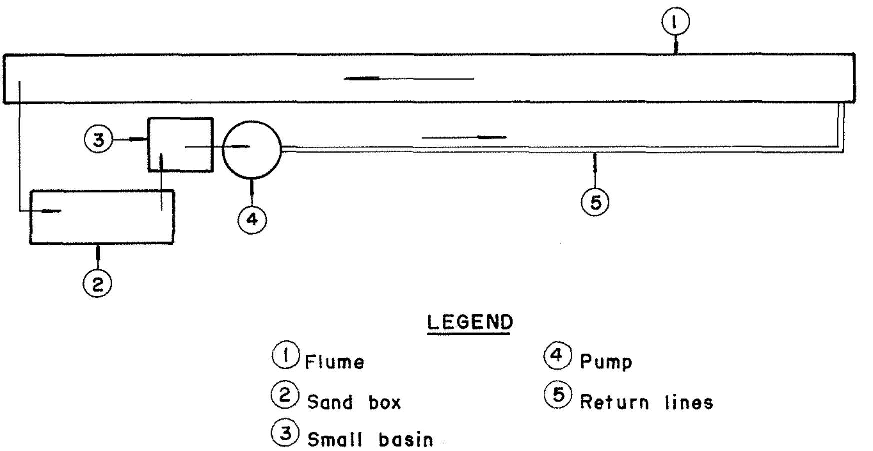

Fig. 1 Configuration of the hydraulic system components.

The elevation of the water surface was measured with a point gauge which could be read to one millimetre for sections located at 40 cm intervals along the flume centreline. Measurements of the bed elevation were obtained by attaching an equivalent 10 mm diameter circular plate to the point gauge.

EXPERIMENTAL PROCEDURE

For experiments under uniform flow conditions, the sand bed (or base) was located in the central reach of the flume which is 6.40 m long and 40 cm wide. One kind of uniform material was used as riprap and two graded sands were utilized as base material. Their size distribution curves are given in Fig. 2

In all, 12 runs were made and for each one, the following steps were necessary: the base and riprap preparation; the bed profile and the water surface elevation measurements; collection of the eroded sand from the test section of the flume. The data collected in each run were water discharge (Q), water surface slope (S_w), bed slope (S_b), flow depth (Y), and the base erosion rate (g_s). The mean shear stress estimate was made by using the Knight (1981) method, which eliminates the effect of the side wall.

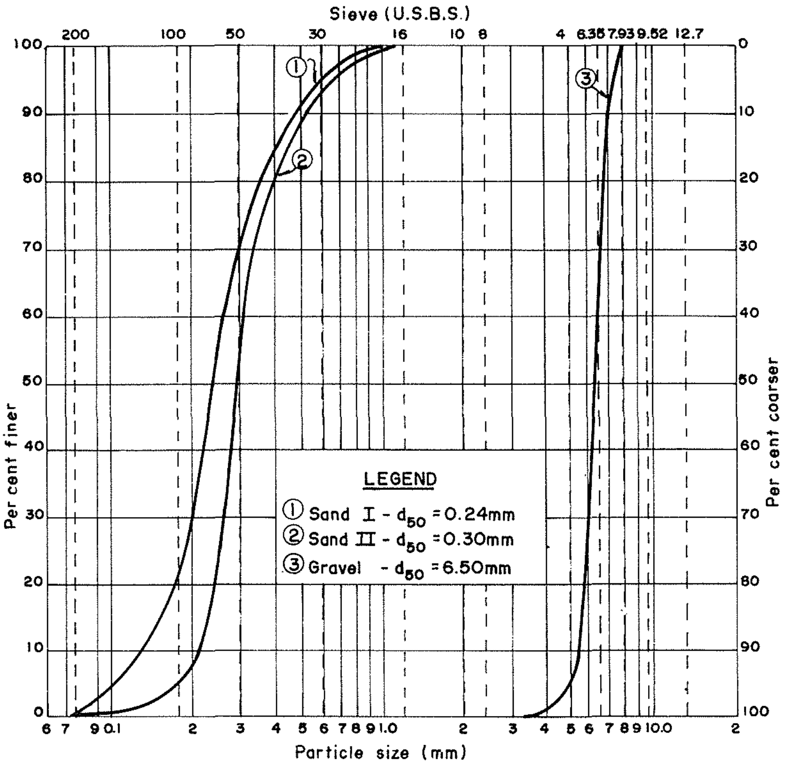

Fig. 2 Size distribution curves for the gravel used as riprap and for the sands utilized as base material.

EXPERIMENTAL VERIFICATION

Runs 1–9 were conducted to verify the behaviour of the base erosion with respect to the mean shear stress (τ_b) on the riprap and the riprap layer thickness (e). Their results are summarized in Table 1. Looking at the curves presented in Fig. 3 it can be noticed that the erosive effect of the flow at the base became more significant with increasing mean shear stress, and was strongly reduced as the riprap layer thickness increased.

The influence of the size distribution of the base material was firstly verified by the curves given in Fig. 4. It shows that the base material (curve 1) is coarser than the materials which were eroded in the runs 1 and 2 (curves 2 and 3) and collected in the sand box. This fact suggests that a differential erosion at the base material does take place, and in order to confirm it the sand used as base material in the runs 1–9 was replaced by a coarser one providing three more runs (10, 11 and 12). Their results are presented in Table 1.

The comparison between the curves given in Fig. 5, which refers to the results obtained by the runs 1–3 and runs 10–12, confirms the previously mentioned differential erosion occurring at the base material. However the effect of the riprap layer thickness on the base erosion process was more

Table 1 Influence of τ_b, e and the base material size on the base erosion process

Riprap(gravel): unit weight (γ_s) = 2 598 kg m^{-3}; dr_{50} = 6.50 mm
Base(sand): unit weight (γ_a) = 2 650 kg m^{-3}; da_{50} = 0.24 mm or 0.30 mm
Water: unit weight (γ) = 1 000 kg m^{-3}
kinematic viscosity (ν) = 1.011 x 10^{-6} m^2 s^{-1}
Flume width (L) = 0.40 m   e = n dr_{50}

Run	n	Q ($l\ s^{-1}$)	Y (m)	V ($m\ s^{-1}$)	F_r	S_b (%)	S_w (%)	S_e^* (%)	τ_b (kg m^2)	g_s (g m^{-2} h^{-1})
1	1	8.24	0.043	0.48	0.74	0.367	0.370	0.368	0.144	6.4
2	1	11.79	0.054	0.55	0.75	0.362	0.360	0.361	0.174	33.5
3	1	17.17	0.073	0.59	0.70	0.352	0.323	0.337	0.208	195.0
4	1	12.17	0.046	0.66	0.98	0.722	0.737	0.722	0.299	899.5
5	2	17.13	0.078	0.55	0.63	0.378	0.308	0.366	0.223	3.5
6	2	14.10	0.053	0.67	0.92	0.716	0.629	0.703	0.335	5.2
7	2	9.96	0.039	0.64	1.03	1.196	1.140	1.200	0.430	6.1
8	3	10.39	0.041	0.63	1.00	1.195	1.130	1.195	0.453	1.2
9	3	11.88	0.043	0.69	1.06	1.200	1.172	1.204	0.476	1.6
10	1	8.14	0.042	0.49	0.75	0.367	0.321	0.347	0.136	2.7
11	1	11.90	0.056	0.53	0.71	0.362	0.335	0.349	0.174	9.8
12	1	16.59	0.069	0.60	0.73	0.361	0.326	0.345	0.208	81.7

(*) $S_e = S_w - F_r\ (S_w - S_b)$; S_e = energy slope and F_r = Froude number.

For runs one to nine da_{50} = 0.24 mm

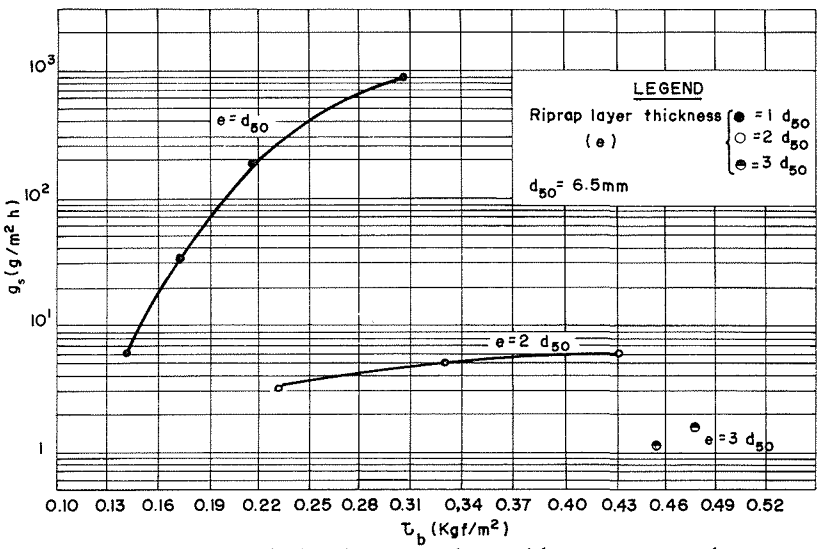

Fig. 3 Behaviour of the base erosion with respect to the mean shear stress (τ_b) and the riprap layer thickness (e).

significant than that of the base material size distribution.

The results of each verification here presented are in agreement with the results obtained by Anderson *et al.* (1970).

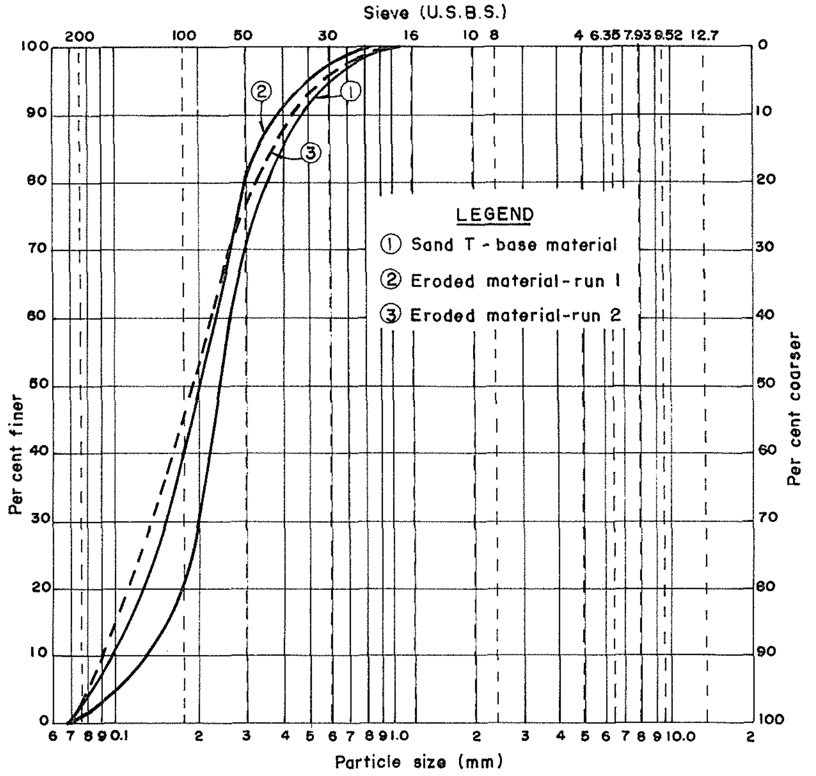

Fig. 4 *Size distribution curves for the eroded materials in runs 1 and 2.*

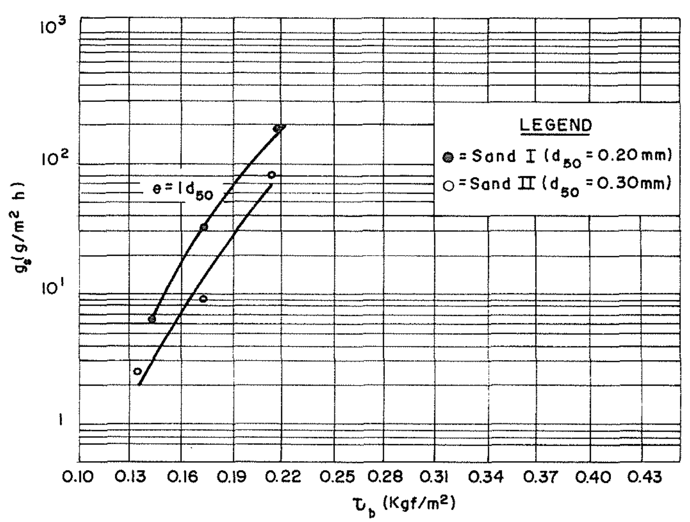

Fig. 5 *The effect of the base material size distribution on the base erosion process.*

A METHOD FOR ESTIMATING THE BED EROSION

The relevant variables e, τ_b, g_s, dr_{50}, da_{50}, da_{60}, da_{10}, γ. γ_s, γ_a, ν and gravitational acceleration g, related to the bed erosion process were combined in independent dimensionless groups, where the most significant ones are:

$$\phi_* = \frac{g_s'}{\gamma_a}\left[\frac{\gamma}{(\gamma_a - \gamma) g\, da_{50}^3}\right]^{1/2} \tag{1}$$

$$\tau_* = \tau_b/[(\gamma_s - \gamma_a)\, dr_{50}] \tag{2}$$

$$R_* = (dr_{50}/\upsilon)(\tau_b g/\gamma)^{1/2} \tag{3}$$

$$n = e/dr_{50} \tag{4}$$

$$E = dr_{50}/da_{50} \tag{5}$$

$$Cu_a = da_{60}/da_{10} \tag{6}$$

$$g_s' = L\, g_s \tag{7}$$

Figure 6 shows the relationship obtained between $\phi_*' = \phi_*/Cu_a$ and $\pi_* = \tau_* R_* E$ for each value of n, in which the corresponding data points were obtained from the 12 experiments previously mentioned.

For $n = 1$ the function $\pi_* = C_1(\phi_*')^{C2}$ was assumed as the relationship between π_* and ϕ_*' where the coefficients C_1 and C_2 were obtained by linear regression. The values of C_1, C_2 and the coefficient of determination (R^2) are respectively 561.5, 0.214 and 0.955.

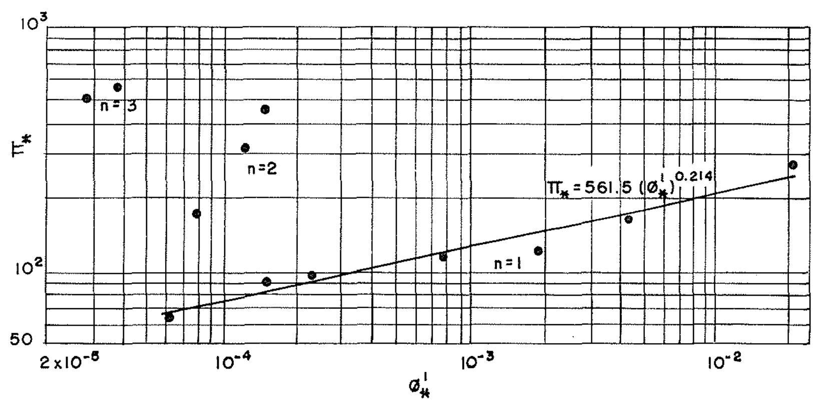

Fig. 6 Relationship between the dimensionless parameters π_* and ϕ_*' of the base erosion process.

Because of the small number of data points for n, two and three, no curve was drawn through them. However, looking at the data points for n = 2, the same form of function relating π_* and ϕ_*' is expected to be followed.

As not all possible combinations of parameter were considered in our experiments, by increasing the data points in the dimensionless diagram presented by Fig. 6, it should be possible to estimate either the riprap layer thickness corresponding to a maximum admissible rate of base erosion, or to know the base erosion rate for a given riprap layer thickness.

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