Bed-rock incision by streams: Summary

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INTRODUCTION

Bed-rock incision by streams involves bed-rock cutting and quarrying by the stream. The stream bed-rock–cutting mechanism is conceptually simple; it must be abrasion by entrained sediment except where solution or flow cavitation are acting. When a sediment particle strikes the bed, some of its kinetic energy may be expended in fracture and removal of bed material. Abrasion rate at a point is thus proportional to local stream sediment transport rate and will depend upon details of the fluid flow.

Generalization of the point abrasion model to the problem of stream incision requires integration over time-varying channel pattern and water and sediment discharges. Extensive exposed bed-rock channel reaches may develop morphologies which prevent hydraulic analysis at an appropriate scale. However, hydraulic and sediment transport parameters of predominantly alluvial streams may be analyzed even if short reaches of exposed bed rock act as local base levels. This paper describes a bed-load–abrasion stream-incision model developed from engineering sandblast-abrasion theory, and its application to incision by a stream flowing across tilted, layered rocks of variable resistance to abrasion.

BED-LOAD ABRASION MODEL

Bitter (1963a, 1963b) analyzed the effect of sandblasting on surfaces in terms of wear related to cutting by low-angle impacts, and to deformation and fatigue cracking by high-angle impacts. His model may be applied to a small locality of a stream bed by converting his volume erosion as a function of total mass of impinging particles to total abrasion rate $\dot{y}_t$ as a function of sediment transport per unit width g_s (Fig. 1):

$$\dot{y}_t = \dot{y}_d + \dot{y}_c ,$$

where the rate of elevation loss by deformation wear is

$$\dot{y}_d = \frac{1}{2} \frac{g_s}{\lambda} \frac{(v - K)^2}{\epsilon} ,$$

and the rate of elevation loss by cutting wear is

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$$\dot{y}_c = 2\frac{g_s}{\lambda}\frac{C(v-K)^2}{v^{1/2}}\left|\frac{U(v-K)^2\zeta}{v^{1/2}}\right]$$

In these equations, v and U are normal and downstream components of sediment impact velocity, respectively; ϵ and ζ are energy required to remove a unit volume of bed rock by deformation and cutting abrasion, respectively; λ is saltation distance,

$$K = \frac{\pi^2}{2\sqrt{10}}\left(\frac{R_i}{R_s}\right)^{3/2} z^{5/2}\rho_s{}^{-1/2}\left|\frac{1-q_1{}^2}{E_1}+\frac{1-q_2{}^2}{E_2}\right]^2 ,$$

$$C = \frac{0.288}{z}\left(\frac{\rho_s}{z}\right)^{1/2} ,$$

E is Young's modulus; ρ_s is particle density; z is bed-rock elastic load limit; q is Poisson's ratio; subscripts 1 and 2 refer to sediment particle and bedrock, respectively; R_i is minimum radius of curvature of the sediment particle; and R_s is radius of a sphere of the same mass as the sediment particle.

DISCUSSION

This model requires that the bed-rock surface undergoing abrasion be flat and parallel to the streamflow, and is not applicable without modification for a surface with small- or large-scale relief. Bitter (1963a) found experimentally that small ripples formed on abraded surfaces, although Finnie and Kabil (1965) found that ripples on hard materials such as rock had wavelengths that seldom exceeded a millimetre or two. The effect of these features on the abrasion rate could probably be accommodated in the model, as could that of larger features such as flutes, pits, and grooves. However, Shepherd and Schumm (1974) have found that these features enlarge and coalesce into deep, complex inner channels or "guts" even in homogeneous bed rock, suggesting some intrinsic instability in the incision process. These "guts" are of unpredictable morphology, so that past history or future development can rarely be determined even if present morphology is subject to hydraulic analysis. The abrasion model is thus not generally applicable to these channels.

Nonhomogeneous bed rock with tilted layers of varying resistance is more amenable to analysis. Resistant layers in the stream bed will tend to act as local base levels for the reach upstream. Faster erosion of less-resistant rock upstream is arrested by sediment deposition as the channel slope immediately upstream declines. As a result, upstream bed-rock incision can proceed only as fast as abrasion of the resistant layer. While bed topography across the resistant layer may be complex, channel geometry upstream is that of an alluvial channel. The alluvial channel cannot sustain the grooves or narrow "guts" of a bed-rock channel, and thus will have a more uniform cross section even in the immediate vicinity of the resistant ledge. It is plausible that, if the reach of channel occupied by the resistant layer is short compared with channel width, the essentially alluvial channel immediately upstream will inhibit formation of large-scale complexities in the resistant bed rock and the shape of the bed-rock channel will mimic that of the alluvial channel.

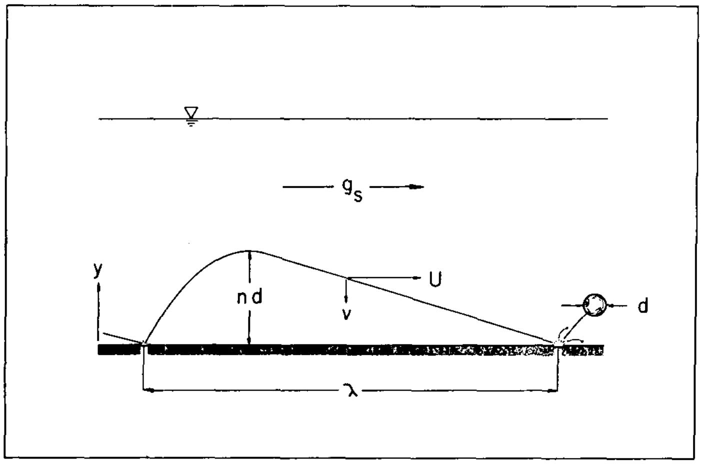

Figure 1. Bed-rock abrasion by bed-load particles of diameter d and mass transport rate per unit width g_s saltating n diameters above the bed with impacts at saltation intervals λ, vertical velocity v, and horizontal velocity U.

APPLICATION

Most geological stream-incision problems are not suitable for detailed analysis, because they involve poorly known changes of stream hydraulics, sediment-transport characteristics, and channel geometry over unknown periods of time. However, incision in bed rock that is initiated by stream diversion or stream capture can be analyzed if initial conditions and time of the event can be determined.

Application of the bed-load–abrasion model to an incision problem requires determination of bed-rock physical properties and a detailed time history of channel hydraulics, channel sediment-transport rate, and bed-load particle kinematics. Direct measurement is most accurate, but is rarely practical for all of the parameters. Indirect methods are available for evaluation of those parameters which cannot be measured directly. However, accuracy of the analysis suffers when indirect determinations are used.

The abrasion model was applied to the Dearborn River in Montana as an example of bed-rock incision in a report by Foley (1980a, 1980b), to illustrate how parameters may be determined indirectly and to assess the validity of the model. Extrapolated recurrence intervals from gaging station data were used with the abrasion model to estimate modern incision rate. The result, 0.006 to 0.06 cm yr^{-1}, has a large range because the extrapolated recurrence intervals have order-of-magnitude uncertainty for large discharges. However, the present rate of incision estimated for the Dearborn River from field data (Foley, 1980a, 1980b) is 0.05 cm yr^{-1}. This is within the range calculated with the abrasion model and suggests that the abrasion model has order-of-magnitude validity even when many parameters are determined indirectly.

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