Large bed element channels in steep mountain streams

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ABSTRACT The evolution of natural steep channels is a function of two factors in accordance with the principle of least action: flow distribution in the channel and terrain geomorphology. Large bed elements (LBE) occurring in the stream bed act on both factors. Stream flow in steep natural terrain occurs in two basic regimes: hydraulic and morphological. Velocity head upstream of an obstacle in the stream is related to the energy dissipation mechanism in a simplified two-dimensional setting. Simplification holds in a localized manner and requires further study to include the entire region around the LBE.

INTRODUCTION

Morphologic changes of natural steep channels result mainly from two factors: water and sediment flow distribution in the stream and existing channel geomorphology. Large bed elements (LBE) in the channel bed interact with both of them. These two factors, working in concert, modify the stream flow to comply with the principle of least energy action (Leopold, 1960). In this study, hydrogeomorphological processes are considered in two parts: 1) The dynamic processes of channel formation and evolution according to the theory of least energy and 2) the hydraulic processes of free surface flow.

Tumbling flow is the mode of occurrence of most water flow in steep natural streams, above a thin laminar sub-layer, due to friction at the stream bed. Mohanty and Peterson (Mohanty and Peterson, 1959) have defined "tumbling flow" as a condition of flow dominated by scattered regions of alternate acceleration and deceleration through critical flow over large bed elements. They have linked tumbling flow to the presence of large bed elements in the stream channel. Thus, tumbling flow appears to be characterized by a series of localized stationary hydraulic jumps.

Internal distortion, skin and spill resistance to flow characterize mountain steep LBE streams. Bed armoring of these streams occurs when cobbles or boulders above a certain size cannot be transported by open water flow. This
limiting size depends on stream conditions such as: slope, velocity, shear stress, channel geometry, and flow regime. Bed elements of this size and larger are referred to in this study as large bed elements (LBE).

At the level of the individual LBE, tumbling flow is highly unsteady. Turbulence that accompanies flow around the LBE results in energy dissipation. This energy is quantified as a function of time in two components: the water depth and the velocity head.

LITERATURE REVIEW

Idealized flume experiments of flow in steep, rough, fixed-bed, open channels conducted at Utah State university (Mohanty and Peterson, 1959) have led to the characterization of tumbling flow. For his experimental set-up he proposed three regimes: tranquil, tumbling and rapid. In the tranquil and rapid regimes, flow was dominated by subcritical and super-critical velocities, respectively.

In the tumbling flow regime, roughness elements induced super-critical flow over their crests followed by an overfall back into subcritical flow. Each roughness element acted as an overfall control. The result was alternate acceleration and deceleration from subcritical to super-critical velocities in a cyclical order. Spacing between two successive roughnesses marked the length of one cycle. And hydraulic jumps formed between them. Thus, the stream tended to flow at subcritical velocities between the roughnesses and at super-critical velocities over them.

In steep, rough, open channels, bed roughnesses came to be called "Large Bed Elements" or LBE's. However, it was Engel (Engel, 1960) who first recognized the need for determining the situations in which LBE's were bed roughness elements and those other situations in which LBE's were so large that they became cross-sectional changes in the stream channel. In the first case, Froude numbers could be independent of flow. While in the second case the Froude numbers were associated with the flow such that a deviation of the free surface might result.

As roll waves were observed (Mohanty and Peterson, 1959) at given spacings of roughness elements, excess energy developed by the stream during the tumbling regime would lead to a transition to the rapid regime. At Froude number values exceeding 1.5 the roll waves absorbed the excess stream energy. In an attempt to define the threshold at which the destructive roll waves developed, Mohanty (Mohanty, 1959) stipulated that in nature, where LBE's are variable in size and density they functioned as virtual weirs. However, flow through a virtual weir occurs at minimum specific energy. In such a virtual weir, the crest elevation might be represented by a statistical function describing roughness distribution and density. However,
relations proposed didn't account for roughness characteristics.

Virmani (Virmani et al, 1973) developed design methods for the use of LBE's as energy dissipators in steep channels. If they could prevent the formation of roll waves, energy could be safely dissipated in the stream by inducing tumbling flow. For energy dissipation, they considered tumbling flow in terms of discharge, slope, velocity distribution, drag force and boundary geometry. As tumbling flow oscillates around critical flow while it moves down the steep slopes, it keeps dissipating energy. The remaining stream energy is very close to the minimum specific energy for the specific discharge.

As velocity profiles were established (Marchand and Jarrett, 1984) for Colorado streams, water surface elevations were measured by transit stadia surveys twice at each site. Total horizontal distance of the slope measurements was normally about two and a half times the stream width. However, it was difficult to exactly locate the water surface level because of the greatly fluctuating water surface and occasional soft bottom conditions.

Tumbling motion in natural high-gradient streams possesses a single dominant direction with significant turbulent fluxes in directions transverse as well as collinear to this dominant direction of flow. Modelling such turbulence is simpler than for flows with recirculatory motion. A two-dimensional model will reasonably approximate such conditions.

**TURBULENCE**

According to the statistical theory of turbulence first proposed by Taylor (Taylor, 1938), velocity of fluid is a random continuous function of time and space. It is a random function because mean velocity does not relate to instantaneous velocity. If the instantaneous velocity \( v_i \) is considered the sum of a mean velocity \( v \), and a fluctuating velocity \( v' \), distribution of the fluctuating component, \( v' \) follows a Gaussian normal probability distribution.

High friction loss of turbulent flow is due to the exchange of momentum between fluid particles. If a fluid particle travels between two layers moving at different velocities, a momentum exchange results between the two layers. Slow particles entering the faster layer act as a drag on it. Subsequently, the mixing-length theory defines the mixing length, \( l \) as the distance a particle of fluid moves transverse to the mean flow before it loses its identity, and mingles with other particles.

The mixing-length theory finds extensive application in turbulent-flow problems where only the temporal mean of flow quantities is known. A knowledge of the fluctuations occurring during tumbling flow around large bed elements would add materially to the understanding of turbulence.
PROBLEM DEFINITION

As water tumbles around an obstacle in the high-gradient stream it is in full turbulence. The presence of the rock in the way of the supercritical flow results in dissipating energy through turbulent eddies. The supercritical velocities immediately upstream of the rock are no longer one-dimensional.

Because of main velocity gradients, turbulence is able to extract energy from mean flow. Thus turbulent motion is self-sustaining. The energy which sustains turbulence is obtained from the mean flow by shearing actions at the expense of additional pressure drop. This energy appears in the form of eddies.

![Diagram of the Jet Fan Around the Roughness Element](image)

Flow regime around the rock is characterized by local flow conditions around the rock. Tumbling flow due to the large bed roughness involves a dissipation mechanism immediately upstream of the large roughness. As supercritical velocities impact the rock, a fan forms upstream. In this region, main flow is no longer longitudinal. It is vertical as well as longitudinal. At the same time, turbulent fluctuations are observed in the longitudinal, vertical and transverse directions.

Direct observation indicates that flow around the rock takes the shape of a jet fan. Experimental procedures isolate the jet impact which causes the main flow to break and deflect in all directions. Main flow occurs in the longitudinal direction of the flume as well as in the vertical direction. At the mid-stream line, flow is reasonably well approximated by a two-dimensional dissipation process. Beyond eddies and turbulence, tumbling flow involves energy mechanisms at the upstream tip of the roughness element best described as:

(a) **Jet fan**, or the deflected jet. At the upstream tip of the rock, it results from the impact of the flow on the rock.

(b) **Eddy viscosity**. Resulting from turbulence dissipation by eddies, it is directly related to the Reynolds' stresses.

The portion of fluid involved in the jet motion is a direct function of the cross-sectional size of the obstacle, and
its frontal slope. Whereas the conditions of occurrence of each depends on the height of the obstacle, its width, its frontal slope, its side slopes, water depth, and water velocity immediately upstream of the obstacle.

DATA

For five rocks of different sizes, and for six discharges around each rock, the following measurements were made:
* Rock height, k.
* Rock width, w.
* Discharge, Q.
* Flow depth, y
* Jet height, h.
* Main and turbulent velocities, longitudinal and vertical at the tip of the jet fan, at two points in each direction, u, v, u', v'.

Rocks used to collect the data are of random shape. They all display smooth rounded corners. Velocity readings were obtained in terms of frequency of spinning of a propeller meter. The diameter of the propeller is 1 cm. Velocity readings were recorded every second for about one minute in every situation.

SOLUTION

The two-dimensional model determines the loss in velocity head as a function of the jet height. The difference between the velocity head and the potential energy displayed by the jet height is considered the amount dissipated at the mid-point of the upstream end of the LBE. Everywhere else transverse velocities involve three-dimensional energy mechanisms, which remain beyond the scope of this paper.

FIG. 2 Log-Log Correlation of the Jet Height Versus Point Velocity Upstream of the Jet Fan.
Tumbling flow around an LBE is almost always turbulent. Fluid motion is highly random, unsteady, and non-uniform. Problems in free turbulent flow are of a boundary layer nature. The region of space under consideration does not extend far in a transverse direction compared with the main direction of flow, but the transverse gradients may be large. The height of the jet is expressed in terms of the velocity components at the mid-stream line. This height value falls short of the kinetic energy value. The difference quantifies the amount of energy dissipated in deviating the flow upward over and around the obstacle at its middle section.

RESULTS

The two following points result from this study:

(a) Velocity readings at the upstream edge of the jet fan recorded higher values for the same discharge for a smaller size of the roughness element.

(b) For all sizes considered in this study, jet height showed a direct exponential correlation with the average values of point velocity recorded upstream of the LBE.

CONCLUSIONS

Respectively, two conclusions can be drawn from this study:

(a) Velocity profile upstream from the LBE is affected by the LBE size. Pressure waves upstream of LBE resulting from a horizontal pressure gradient slow the flow near the edges of the LBE and accelerate it along the middle line of flow immediately upstream of the fan edge.

(b) LBE size does not influence energy dissipation since the relationship between jet height and velocity is independent of the size. Velocity head drops between the upstream edge of the jet fan and the LBE. This results from a momentum transfer by turbulent stresses caused by impact and deflection of flow in all directions but mostly upward at the mid-section of the LBE.

REFERENCES


