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ORIGIN AND TRANSPORT OF LARGE BOULDERS IN MOUNTAIN STREAMS

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ABSTRACT

The means by which boulders of the order of metres in diameter appear in mountain stream beds is briefly reviewed. It is asserted that downstream translation under the action of direct fluid stress is unlikely. However, a combination of fluid stress and localized scour may effect small near-vertical displacements. Undermining of the stream bank upon which a boulder is perched has the potential to precipitate translation movements several diameters in extent, but the frequency of such incidents is probably not commensurate with the boulder's endurance to size reduction. It is therefore supposed that, as a rule, the net translation achieved by a large boulder during a streambed history of ordinary flood events can be measured in tens of metres. Where larger translations are in evidence this may indicate that catastrophic events, such as natural dam breaks or in-channel debris flows, have occurred.

INTRODUCTION

On the streambeds of the South Island high country, boulders are sometimes present that have a mean diameter an order of magnitude greater than the rest of the bed material. Both the origin of these large bed particles, and particularly the transporting mechanisms acting upon them, have received little attention from hydraulic engineers. Rather, researchers have concentrated on the initial movement and transport of gravels and sands, since these are the sizes normally

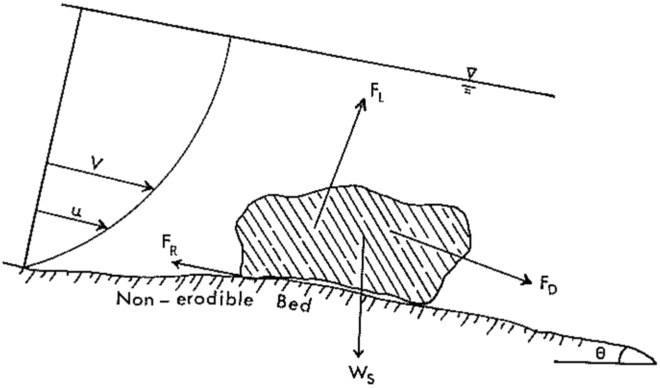

FIG. 1 – Forces acting on a large boulder in a mountain stream.

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present in riverbeds. The quantitative methods developed in this research may be applied in part, however, to an analysis of the movement of large bed particles.

Knowledge of the origin and the processes promoting the streambed transport of these large boulders has importance in general erosion studies, in civil engineering works and in the interpretation of ancient fluvial deposits (paleohydrology). Accordingly the aim of this paper is to describe how such boulders reached the streambed, and to examine the transporting mechanisms acting upon them so as to estimate their rate of progress downstream.

ORIGIN

The means by which larger boulders appear in the beds of mountain streams, although diverse, are relatively well understood in comparison with the problem of their channel transport. It is asserted that two major mechanisms operate: they may be exposed where a stream is degrading material containing large boulders, or they may fall to the channel from the valley walls or terraces. Included within the latter mechanism are all the various types of avalanches, falls, slides, and flows (see, for example, Varnes, 1968).

In the mountain streams on the western side of the Southern Alps, large boulders are numerous and appear to be derived in the main from landslides. The streams are now incised in these landslide deposits. On the eastern side, no such generalization can be made. But, apart from where reworking of glacial deposits occurs, supply to the streambed by rock falls and snow avalanches appears to dominate (T. Chinn and M. McSaveney, pers. comm.).

TRANSPORT

That some of the large boulders present in mountain streams are transported from time to time downstream is evinced by the lithological demand of separation of source, the lack of surficial staining normally acquired during burial in alluvium, and the absence of vegetation which commonly grows upon them if they remain stationary for long periods.

Gage (1953) reviewed four mechanisms whereby large boulders could be moved on valley floors or fans. Of these, he suggested that water traction by floods and intermittent progress by the rolling or sliding of a boulder into a depression excavated by the flow under its downstream side (Trowbridge, 1911) could be applied to channel transport. Gage suggested a further mechanism, namely, the undermining of a streambank and the consequent falling into the streambed of any boulder previously resting near the bank edge.

Water traction may be assessed quantitatively as follows where, to avoid confusion with the underside scouring process of Trowbridge, the case is taken of a boulder resting on a non-erodible bed. Following the general approach reviewed by Vanoni (1966), the threshold conditions of sediment motion can be viewed for the sliding case as a balance between forces assisting and resisting movement (Fig.1). If F_R is the sliding resistance, θ is the bedslope angle and μ is the coefficient of static friction then, at incipient motion

$$F_D + W_S \sin\theta = F_R = \mu\,(W_S \cos\theta - F_L) \tag{1}$$

Now

$F_D \approx \frac{1}{2} C_D \rho (\pi d^2/4) u^2$ = mean fluid drag

$F_L \approx \frac{1}{2} C_L \rho (\pi d^2/4) u^2$ = mean fluid lift

$W_S \approx \rho g (S-1)(\pi d^3/6)$ = immersed weight of the boulder

where C_L, C_D are the coefficients of lift and drag respectively, ρ is the fluid density, g is the acceleration of gravity, d is the mean diameter of the boulder, S is the specific gravity of the boulder, and u is the mean local fluid velocity. After the substitution of these expressions equation (1) may be written as:

$$u^2 \approx [(4/3) g d (S-1)(\mu \cos\theta - \sin\theta)] / (C_D + \mu C_L)$$

For the case described, the orders of magnitude* of the various terms are:

$$(C_D + \mu C_L), (\cos\theta - \sin\theta) = 0[10^{-1}]$$

$$(S\text{-}1) = 0(10^0)$$

Thus

$$u \quad 0(10^{1/2})\, d^{1/2} \text{ m/s} \qquad (2)$$

If the boulder tends to roll then equation (1) becomes

$$F_D M_1 + F_L M_2 + W_S \sin\theta\, M_3 = W_S \cos\theta\, M_4 \qquad (3)$$

in which M_i ($i = 1, 2, 3, 4$) are the respective moment arms about the point of turning. Since

$$M_i = 0(10^0)$$

equation (3) reduces to equation (2).

Whether the boulder rolls or slides is immaterial in this treatment; it can be easily determined, when the principal dimensions are known, by the inclusion of a shape factor in the analysis. Now in major floods (ordinary event), that is those having a return period of between 10 and 100 years, the maximum value of the mean fluid velocity V (Fig. 1) that has been measured in South Island mountain streams by Ministry of Works and Development staff is about 6 m/s.

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* if $x = 0(10^0)$, then $0.1 \leqslant x \quad 1$.

If $x = 0(10^{-1})$, then $0.01 \leqslant x \quad 0.1$.

If as a conservative estimate u is taken as being approximately equal to V, then the conclusion to be derived from equation (2) is that boulders larger than about 3.5 m diameter are likely to remain stationary in a major flood. This statement is in agreement with the extrapolated results* of Helley (1969, p. 11) which were based on field measurements ranging up to a mean particle diameter of around 0.5 m.

It must be emphasized that the above analysis concerns an average case and provides a rough estimate.

Thus, these large boulders are likely to remain in place and be reduced in size by chemical weathering and the abrasive action of sediment-laden flows (Hack, 1957, p. 83).

When a boulder is resting in alluvium its likelihood of moving is increased as other forces and processes which promote instability are present. For a partially submerged boulder these include a hydrostatic force due to a difference in upstream and downstream water levels, a virtual mass force due to the acceleration of flow around the boulder, a torque provided by the flow splashing up and over the particle (Leopold and Miller 1956), and a complex of vortex flows which, acting concurrently with the latter two mechanisms, erode the alluvium surrounding the boulder. Relative effects of these processes will be determined by the local hydraulic and sediment geometry.

For the fully submerged case some of the mechanisms will be absent or will have a small effect, but under the higher consequent velocities scouring action will be enhanced. In this connection Fahnestock and Haushild (1962) performed a series of flume experiments where cobbles were placed on a medium sand bed. Under steady subcritical flows a scour pocket was excavated on the upstream side. The submerged cobbles moved slightly upstream and into this pocket, eventually disappearing from sight below the bed surface. When the flow was supercritical the cobbles moved consistently downstream, presumably under the influence of the water traction mechanism examined previously. The author performed similar experiments, but with a gravel bed and a steeper slope. It was found that under subcritical flows* the submerged cobbles moved slightly downstream (less than $2d$) and into the bed but remained exposed. It is possible that the differences between these results and those of Fahnestock and Haushild are due to the reduced relative scour effected by the overriding influence of the larger bed material. Accordingly it is reasonable to assume that in mountain streams, where supercritical flow is localized because of the high boundary roughness, the downstream translation of large boulders during major floods is generally small – less than the several diameters envisaged by Trowbridge (1911).

Gage's mechanism of streambank undermining affords the opportunity of this degree of translational movement. Furthermore, as he points out, it would be repeated if a stream was corroding both laterally and vertically, thereby undermining successive terraces. The successive topplings of a boulder perched on these terraces would be halted only when the stream ceased to degrade. But

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* when the value $S = 2.65$ is used.

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* Details of flow conditions are given by Griffiths (1976, p E2)

the frequency of movement by this process would be low. In most cases a boulder would be reduced in size before it achieved any substantial translation (0×10^2 m). Translations of this order may be achieved, however, during catastrophic events such as natural dam breaks (Baker 1975) or debris flows moving down channel. Thorpe (1976) illustrates the ability of such flows to transport large boulders in the Waipawa River. An explanation of this process has been given by Rodine and Johnson (1976).

CONCLUSIONS

Large boulders appear in the beds of mountain streams either as a result of the excavation of earlier aggradational events or by gravitational means. Should they be positioned on bedrock they will, generally, not be moved if their mean diameter exceeds about 3.5 m. On the contrary, if they rest on alluvium very limited rolling or sliding movements may be achieved under the combined action of fluid stresses and localized scour – the boulder tending to progress down into the bed. Downstream translation of several diameters is possible when the bank upon which a boulder is sited is undermined by the stream. It is thought that although this mechanism, if repeated, could effect large displacements, such displacements are unlikely to occur owing to the more rapid action of size reducing processes.

The conclusion is that, in the absence of catastrophic events such as natural dam breaks or in-channel debris flows, the average downstream translation of a large boulder during its streambed history is $0(10^1)$ m or, conversely, where they are found to have travelled larger distances then emplacement by catastrophic means is probable.

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