STONE STABILITY UNDER NON-UNIFORM FLOWS

NGUYEN THANH HOAN

ROB BOOIJ, BAS HOFLAND, MARCEL J.F. STIVE, HENK JAN VERHAGEN

1Department of Hydraulic Engineering, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, the Netherlands
2WL | Delft Hydraulics, P.O. Box 177, 2600 MH Delft, the Netherlands

Abstract. The current research is aimed at finding a dimensionless stability parameter for non-uniform flow in which the effect of turbulence is incorporated. To this end, experiments were carried out in which both the bed response (quantified by a dimensionless entrainment rate) and the flow field (velocity and turbulence intensity distributions) are measured. A new stability parameter is proposed, which together with those of Shields [1], Jongeling et al. [2] and Hofland [3] was evaluated using the measured data. The focus of the evaluation is on the correlation of these stability parameters with the measured bed damage expressed in terms of the dimensionless entrainment rate. The experimental results confirm that the Shields stability parameter fails to predict bed damage for non-uniform flow conditions ($R^2 = 0.18$). In contrast, Jongeling et al. [2], Hofland [3] and our new proposed stability parameters give better damage predictions ($R^2 = 0.77÷0.81$). The results confirm the strong influence of the velocity and turbulence intensity distributions on the stability of bed material.

1. Introduction

In the design of bed protections the choice of stone sizes and weights to be used is essential. The Shields [1] formula was developed for uniform flow conditions and is widely used to determine the required stone sizes. In the Shields formula the near-bed shear stress is the only quantity representing the flow forces on the bed. Previous studies ([2], [3], [4], for example) have shown that not only the near-bed shear stress (or an estimate thereof based on the mean velocity) but also the turbulence influences the stability of the bed material in flowing water. Therefore, it is important to take turbulence effects into account, especially for the design of bed protections in non-uniform flow near hydraulic structures.
2. Governing variables

Flow forces. A stability parameter - expressed in the form of a dimensionless relation between hydraulic load \( \propto \rho u^2 d \) and bed strength \( \propto (\rho_s - \rho) g d \) - is often used to quantify the influence of hydraulic forces on the bed. Its general form can be expressed as \( \Psi = u^2 / \Delta gd \) where \( \Psi \) denotes a general stability parameter, \( u \) is a typical velocity scale, \( \Delta \) represents the specific submerged density of stone \( (= (\rho_s - \rho) / \rho) \), \( \rho_s \) is the density of stone, \( \rho \) is the density of water, \( g \) is the gravitational acceleration, and \( d \) denotes the stone diameter. For uniform flow Shields [1] used the shear velocity \( u_s \) to form the well-known Shields stability parameter \( \Psi_s = u_s^2 / \Delta gd \). In non-uniform flows, Jongeling et al. [3] proposed a stability parameter as follow:

\[
\Psi_{w,\alpha} = \left( \frac{\langle \pi + \alpha \sqrt{K} \rangle}{\Delta gd} \right)_m
\]

where \( k \) denotes the turbulence kinetic energy, \( \alpha = 6 \) is an empirical parameter, \( \langle \cdot \rangle_m \) is a spatial average over a distance of \( h_m \) above the bed, \( h_m = 5d + 0.2h \) and \( h \) is the water depth.

Hofland [3] proposed a stability parameter in which the maximum over the depth of the local values of \( \langle \pi + \alpha \sqrt{K} \rangle \) weighted with the relative distance \( \frac{L_m}{z} \) is used. The stability parameter, \( \Psi_{L_m} \), is expressed as (\( \alpha = 6 \)):

\[
\Psi_{L_m} = \max \left( \frac{\langle \pi + \alpha \sqrt{K} \rangle_{L_m}}{\Delta gd} \right) \frac{L_m}{z}
\]

where \( L_m \) denotes the Bakhmetev mixing length and \( z \) is the distance from the bed.

Bed response. Mosselman and Akkerman [4] distinguish two ways of defining the mobility of particles: i) the number of pick-ups (\( n \)) per unit time (\( T \)) and area (\( A \)) or ii) the number of particles that is transported through a cross-section per unit time. The former if expressed in terms of volume of entrainment is often called (volume) entrainment rate, \( E = nd/AT \). The latter is often called bed load transport, \( q_s \). The entrainment is linked to the bed load transport by: \( q_s = El \), where \( l_s \) is the displacement length. Both the entrainment rate and bed load transport can be used as bed damage indicators and are often expressed in dimensionless form as

\[
\Phi_s = E / \Delta gd \quad \text{and} \quad \Phi_s = q_s / \sqrt{\Delta gd^3}
\]
The use of $\Phi_s$ as a bed damage indicator is conventional for uniform flow. Paintal [5] found a strong dependence of $\Phi_i$ on $\Psi_i$:

$$\Phi_i = 6.56 \times 10^{18} \Psi_i^n \quad \text{for} \quad 0.02 < \Psi_i < 0.05 \quad (4)$$

For non-uniform flow Hofland [3] points out that $\Phi_i$ should be used as bed damage indicator because it is completely dependent on the local hydrodynamic parameters.

2.1. New stability parameter

In this section a new stability parameter is proposed which incorporates the influence of turbulence sources above the bed. A qualitative function is introduced which is quantified for the role of turbulence source away from the bed. The evaluation and final form of the new stability parameter will be made based on the analysis of the experimental data.

The instantaneous flow forces acting to move the stones are proportional to $\rho(\overline{u} + \alpha \overline{u'})^2 d^2$ where $\overline{u'}$ is the fluctuating part of the velocity ($\sqrt{\overline{u'^2}} = \sigma(u)$) and $\alpha$ is a turbulence magnification factor used to account for the dynamic characteristics of the forces due to the fluctuations. If we assume that the turbulence source near the bed has the largest influence on stone stability and that at a certain distance $H$ from the bed ($H \leq h$) the turbulence source has a negligible influence on stone stability, a weighing function can be used to account for the influence of the turbulence source at a distance $z$: $f(z) = (1 - z/H)^p$ where $\beta$ is an empirical constant. The force from the water column $H$ acting to move the stone can be averaged as follows:

$$F \propto \frac{1}{H} \int_0^H \rho(\overline{u} + \alpha \sigma(u))^2 d^2 x \left(1 - \frac{z}{H}\right)^p \, dz \quad (5)$$

By dividing the moving force to the resisting force ($\left((\rho_i - \rho)gd\right)$) a new stability can be obtained:

$$\Psi_{\text{new}} = \frac{\left\langle (\overline{u} + \alpha \sigma(u))^2 \times \left(1 - \frac{z}{H}\right)^p \right\rangle}{\Delta z d} \quad (6)$$

in which $\langle \ldots \rangle_H$ denotes an average over the height $H$ above the bed ($H < h$).

3. Experimental set-up and procedure

The experiment was carried out in a laboratory open-channel flume with an effective length of 13.30 m and an available width of 0.495 m. To decelerate the flow, an expansion was made near the end of the flume. Three set-ups with expansion angles of 3, 5 and 7 degrees were built and are shown in Figure 1.
To make the velocity measurable by a LDV-system both sides of the flume were made transparent. Real stones having a nominal diameter, $d_{n0}$, of 0.80 cm and $d_{n55}/d_{n15}$ of 1.27 were used to create a 4-cm-thick rough bottom. These stones are practically unmovable under the experimental flow conditions. To examine the stone stability, two-layer uniformly colored strips of artificial light stones were placed before and along the expansion. These stones are made of epoxy resin having densities in the range of 1320 to 2023 kg/m$^3$, mimicking shapes and sizes of natural stones. The artificial stones have $d_{n50} = 0.82$ cm and $d_{n55}/d_{n15} = 1.11$.

Twelve series with different flow conditions were conducted for each set-up. Each series consists of five runs. The water level and velocity measurements were carried out in the first run where the whole flume bottom was covered by real stones. The same flow condition was reproduced and repeated for the next four runs to measure stone entrainment. To this end, the uniformly colored strips of light artificial stones were placed at the designed locations. A 30-minute initial settling period was applied prior to the real test to remove loose stones that do not determine the strength of the bed. To start an entrainment test the flume was flooded slowly to the design condition. After two hours, the flow was stopped and the number of displaced stones was registered. The entrainment rates obtained from the four runs are averaged to get a statistically reliable entrainment rate for the series.

4. Results

A detailed analysis of the flow data [6] has shown that the turbulence intensity distributions deviate from the empirical curve reported for uniform flow. The flow is non-equilibrium and the ratio of turbulence intensities to the shear velocity cannot be expressed by any universal function. Therefore, the turbulence effect on the stability of stone should be modeled explicitly.
Correlation analysis between the available mobility parameters and the measured entrainment rate was presented in Hoan et al. [7]. In that analysis the shear velocity was determined based on the measured Reynolds stress distribution. As only two velocity components \((u -\) streamwise and \(w -\) upward) are available, the turbulence kinetic energy in Eqs (1) and (2) was approximated by assuming that 
\[
\frac{\sigma_v^2}{\sigma_u^2} = 1.9
\]

The approximation is based on the EMS measurement of the flow conditions where both \(u -\) and \(v -\)velocity components were measured. The analysis shows that virtually no correlation is found to exist between \(\Phi_u\) and \(\Psi\) for the non-uniform flow conditions \((R^2 = 0.18)\). In contrast, the Jongeling et al. and Hofland stability parameters are strongly correlated to the entrainment parameter:

\[
\Phi_u = 5.4 \times 10^{-13} \Psi_{WL}^{4.9} \quad \text{for} \quad 18 < \Psi_{WL} < 40 \quad (R^2 = 0.78) \quad (7)
\]

\[
\Phi_u = 1.2 \times 10^{-9} \Psi_{Lm}^{4.5} \quad \text{for} \quad 2.5 < \Psi_{Lm} < 5.5 \quad (R^2 = 0.77) \quad (8)
\]

A sensitivity analysis of \(\alpha\) in \(\Psi_{WL}\) and \(\Psi_{Lm}\) shows that \(\alpha = 3.5\) (for \(\Psi_{WL}\)) and \(\alpha = 3.0\) (for \(\Psi_{Lm}\)) give the best correlation \((R^2 = 0.81\) for both).

To evaluate the new stability parameter, a correlation analysis was made for various possible values of \(\alpha\), \(\beta\) and \(H\). The results are shown in Figure 2. The best correlation \((R^2 = 0.81)\) can be obtained when \(\alpha = 3\), \(\beta = 0.7\) and \(H = 0.7h\) are used. With \(H > 0.7h\) the correlation is high, showing that large-scale structures are connected to the entrainment of bed material, which is consistent with [3]. The insensitivity to \(H/h\) (above 0.7) and \(\beta\) leads to a choice of the final form of the new stability as follows:

\[
\Psi_{u_{0.5}} = \left\{ \left[ u + 3\sigma(u) \right] \frac{1}{\sqrt{1 - z/H}} \right\} \Delta gd
\]

Figure 2. a) Sensitivity analysis of \(H\), \(\alpha\) and \(\beta\). b) Vertical distributions of key parameters in Eq (9).

The correlation between the new stability parameter and the measured entrainment rate is shown in Figure 3. The entrainment curve found by regression analysis is given as

\[
\Phi_u = 9.6 \times 10^{-12} \Psi_{u_{0.5}}^{4.5} \quad \text{for} \quad 7.5 < \Psi_{u_{0.5}} < 18 \quad (R^2 = 0.81) \quad (10)
\]
5. Conclusions

The experimental results indicate that $\Psi_{WL}$, $\Psi_{Lm}$, and $\Psi_{u-\sigma}$ are properly representing for the flow forces on the bed and these parameters can be successfully used to predict bed damage while the conventional Shields mobility parameter can not predict the entrainment rate at all in non-uniform flow. The results confirm the strong influence of the velocity and turbulence intensity distributions on the stability of bed material.

References