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Dimensionless critical shear stress in gravel-bed rivers

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ABSTRACT

This paper first compiles critical shear stress values from 26 studies of gravel-bed rivers (GBRs) worldwide. The most frequently proposed value of the Shields criterion (θ_c) is 0.045, but three major groups with θ_c values ranging from <0.030 to >0.100 were identified.

Second, dimensionless critical shear stresses (the Shields criterion) were evaluated for 14 GBRs (18 sites) with watershed areas ranging from 12 to 3000 km^2. Different approaches were used to identify the initial movement of the bed material: painted and PIT-tag pebbles, sediment traps, and bedload samplers. The Shields criterion (θ_c) was estimated using the total shear stress (τ) and the grain shear stress (τ'). Several shear stresses were also estimated using shear velocities. For bedload transport, we obtained an average Shields criterion (θ_c) of 0.040. The values were higher in small rivers (>0.050) than larger rivers (<0.030) because of more significant bedform shear stresses. The Shields criterion (θ'_c) was lower when the grain shear stress (τ') was used and only reached 0.019. Different values are also proposed in relation to the type of mobilization: the θ_c value for partial transport was ~0.025 and exceeded 0.040 for full transport (usually reached in association with discharges with a 10-year return period). The values based on the results of sediment traps and a bedload sampler were greater than those obtained using tracers, but these differences are smaller than those usually reported in the literature.

1. Introduction

Although many parameters are used to estimate the mobilization of river bedloads such as critical erosion velocity (Hjulstrom, 1935; Sundborg, 1956; Costa, 1983; Williams, 1983), critical specific stream power (Gintz et al., 1996; Ferguson, 2005; Petit et al., 2005a; Gob et al., 2008, 2010; Parker et al., 2011; Houbrechts et al., 2015), and unit critical discharge (Bathurst et al., 1987; Ferguson, 1994; Lenzi et al., 1999; Rickenmann, 2001; Whitaker and Potts, 2007; Mao et al., 2008; Phillips and Deslosges, 2014), shear stress remains one of the most used parameters. Shear stress values permit the estimation of transported quantities, and this parameter is typically included in the most frequently used equations, such as the Meyer-Peter equation (Graf, 1971; Richards, 1982; Gob et al., 2005; Gao, 2011).

In addition, shear stresses can explain the shapes of river beds, particularly meandering beds (Dietrich et al., 1979; Lisle, 1979; Bridge and Jarvis, 1982; Jackson and Beschta, 1982; Petit, 1987; Clifford and Richards, 1992; Sear, 1996; Robert, 1997; Thompson et al., 1999; Milan et al., 2001). This parameter has also been used to explain the formation and destruction of pebble clusters (Storm et al., 2004; Piedra et al., 2012; Heays et al., 2014), the stability of step-pool systems (Zimmermann and Church, 2001; Wohl and Wilcox, 2005) and the evolution of other bedform patterns, such as bedrock patterns and cascades (Thompson and Croke, 2008).

The Shields criterion, which uses critical shear stress (the force needed to move an element of a given size), can be used to resolve protrusion and hiding effects using equations that include the relationship between the considered particle size and the median diameter of the bed (Parker et al., 1982; Andrews, 1983; Petit, 1994; Batalla and Martin-Vide, 2001). These equations lead to theories of equal mobility or, conversely, the theory of selective entrainment (Parker et al., 1982; Andrews, 1983). In addition, the Shields criterion can account for the effect of particle shape on the resistance to entrainment (Petit, 1989; Thompson and Croke, 2008).

Using shear stress values, it is possible to identify changes in bed morphology and sedimentology caused by embankments or the construction of dikes (Frings et al., 2009). This parameter was also used to highlight the incision of beds and thus the formation of paving in rivers in the Southern Alps (Liébault and Piégay, 2001).

Excess shear stress relative to the critical shear stress is used to assess the propagation velocity of the bedload and, consequently, the bedload discharge (Milan, 2013; Vazquez-Tarrio and Menendez-Duarte, 2014). The excess shear stress is also taken into account to estimate the long-term river bed incision rate in relation to tectonic movement (Lavé and Avouac, 2001).

Shear stress permits the estimation of the effects of aquatic microorganisms on the delay in movement initiation of particles that form the bed (Statzner et al., 1999; Statzner, 2012). Shear stress is also involved in the evaluation of the stability of different bank protection methods

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(Frothingham, 2008) and the stability of sedimentary units colonized by vegetation (Rodrigues et al., 2007).

The only limiting factor in the use of shear stress, as highlighted previously by several authors (Ferguson, 2005; Petit et al., 2005a; Parker et al., 2011), is that this parameter is more difficult to determine than the specific stream power because, in addition to knowing the width of the river, the depth of flow at the time of mobilization must be known, which may be difficult to obtain after the flow event, particularly in large rivers.

Another problem occurs when shear stresses are used. Indeed, several uncertainties remain regarding the critical shear stress values that affect the Shields criterion. As presented below, a wide range of values have been proposed in the literature. These differences result mainly from methodological aspects, which raise some questions considered below (for example, the definition of motion initiation and the method used in the estimation of shear stress).

This paper aims first to synthesize the values proposed in the literature and then propose Shields criterion values for 14 gravel-bed rivers (GBRs) (18 sites) mainly situated in the Ardennian massif. These values are obtained following the same methodology with a unique definition for the parameters (mobilization criterion and calculation methods for the total shear stress and the grain shear stress). For comparison, we have also included several values obtained from sediment traps and a bedload sampler (Helley-Smith).

2. Overview of the equations

In a uniform flow, the total shear stress (τ), expressed in N/m^2, originates from the product of the slope (s) multiplied by the hydraulic radius (R_h) and two constants (g is the acceleration caused by gravity and ρ_f is the density of the fluid) (Eq. (1)):

$$\tau = \rho_f g\, R_h s \tag{1}$$

The total shear stress (τ) can be divided into two components: the grain shear stress (τ') and the bedform shear stress (τ'').

The *grain shear stress* (τ') is the component of the total shear stress that intervenes only in the transport and movement initiation of the bedload. This parameter can be estimated in different ways but is generally obtained from the method recommended by Richards (1982), which has been successfully tested in flumes (Petit, 1989) and in natural rivers (Petit, 1990; Garcia et al., 2000; Latapie et al., 2014). This method is based on the Manning equation (Eq. (2)), which compares the total roughness coefficient (n_t) and the roughness coefficient caused by the resistance of the particles that form the river bed (n_o), as estimated by the Strickler equation (Eq. (2b)):

$$\tau' = (n_o/n_t)^{3/2}\tau \tag{2}$$

$$\text{with}\ \ n_o = 0.048{D_{50}}^{1/6} \tag{2b}$$

where D_{50} represents the median particle diameter (expressed in m).

Moreover, the shear stress can be estimated from the shear velocities (u_*):

$$\tau = {u_*}^2\rho_f \tag{3}$$

$$\text{with}\ \ u/u_* = 2.5\,\ln(y/y_0) \tag{3b}$$

where u is the velocity measured at a distance (y) above the bottom of the bed (but less than one-fifth of the total depth, or 0.2 d), and y_0 represents the roughness height, which depends on the size of the material constituting the river bed. The most commonly used descriptor of roughness height is D_{50}. Different relationships have been proposed for gravel-bed rivers (Hey, 1979; Petit, 1994), but most fall within the following range:

$$y_o = 0.20D_{50}\ \text{to}\ 0.25D_{50} \tag{3c}$$

In medium-sized rivers, the velocities can be measured directly at the marking sites even for high flow rates, but this process is difficult in larger rivers. However, the relationship between total shear stresses (Eq. (1)) and shear stresses based on shear velocities (Eq. (3)) can be estimated using velocity measurements from different cross sections.

Several relationships have been proposed to provide the critical value for movement initiation according to particle size (Miller et al., 1977). However, the most commonly used is the Shields function (θ) (Eq. (4)). The Shields function represents a dimensionless relationship among the shear stress τ (N/m^2), density of the sediment ρ_s, (kg/m^3), density of the fluid ρ_f (kg/m^3), particle diameter D (m), kinematic viscosity ν (m^2/s) and acceleration caused by gravity g (m/s^2).

$$\theta = \tau/\left(\left(\rho_s - \rho_f\right)gD\right) = fct(u * D)/\nu \tag{4}$$

The Shields entrainment function θ can be assigned a critical value (Shields criterion θ_c) to solve this equation for a given particle diameter. According to the well-known Shields diagram (Miller et al., 1977), θ_c varies with $(u_*\, D)/\nu$ (more commonly known as the particle shear velocity Reynolds number Re_*). However, for hydraulically rough beds, defined as $Re_* > 10^2$, θ_c becomes independent of the roughness conditions and tends to approach a constant value of 0.060 or 0.050 based on a movement initiation probability of 0.5 (Gessler, 1971).

3. Overview of dimensionless critical shear stresses

The value of the initially proposed Shields criterion is 0.060 (Shields, 1936; Miller et al., 1977), which leads to the equation $\tau_c = D$, where τ_c is expressed in N/m^2, and D, the diameter of the particles to be moved, is expressed in mm (Baker and Ritter, 1975). Most of the Shields criterion values have been estimated using total shear stress. We will clarify below how this criterion differs when grain shear stress or shear velocities are used.

Furthermore, some studies propose a single value, whereas others report more or less restricted ranges with various average values. Other studies present very wide ranges for which average values are not obvious. Furthermore, some papers suggest values for partial mobilization, whereas others suggest values for total mobilization, and still others do not provide any information on this point.

Select studies are presented in chronological order in Table 1 and are also illustrated in Fig. 1. Characteristics of the rivers, sediment sizes and data acquisition methods are summarized in Table 1 and sometimes developed in the text below.

Neill (1968) observed that isolated grains were set in motion when the Shields criterion was equal to 0.030 and that some movement was recorded at even lower values, provided that the observation time was sufficiently long. Values lower than 0.020 were proposed by Carling (1983). Similarly, Hammond et al. (1984), who used the shear velocities of tidal channels, documented θ^*_c values ranging from 0.015 to 0.031. By contrast, Parker et al. (1982) proposed a significantly higher θ_c value (0.088).

As a synthesis of studies performed by different laboratories, Komar (1987) proposed a θ_c value of 0.045, which was also recommended by Knighton (1998) and Robert (2003). Buffington and Montgomery (1997) performed a detailed synthesis of the issues and uncertainties in the assessment of movement initiation that included more than 600 values, but some of these values are also applicable to sandy beds or to Re_* values $<10^2$ when θ_c is not constant. The authors concluded that