ISSN 2047-0371

1.3.1. Measuring the shear strength of cohesive sediment in the field

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ABSTRACT: Shear stress is a fundamental driver of geomorphic change and is at the centre of a range of geomorphological processes including the deformation of glacier tills, mass movements on hillslopes, riverbank erosion and the stability of intertidal sediment. Consequently, measurements of a sediment's resistance to shear stress, i.e. shear strength, is essential in our field. Numerous techniques have been developed to quantify both surface and internal shear strength for soils and sediments, but most are limited to the laboratory. Measurements of shear strength, particularly for cohesive sediment, are best conducted in the field in the first instance, because the extraction, transport and storage of cores prior to analysis in the laboratory cause physical, chemical, and biological changes to the sediment characteristics that alter its shear strength. The handheld shear vane and the cohesive strength meter (CSM) are portable devices that can be used to measure internal and surface shear strength, respectively, in the field. The shear vane quantifies the undrained geotechnical shear strength of the sediment, i.e. resistance to deformation / fracture, and the CSM measures resistance to surface erosion by water. These tools can be combined with geomorphological mapping, stratigraphy, and sedimentological and biological analyses to support a range of investigations into geomorphological forms and processes.

KEYWORDS: shear vane, erosion threshold, erodibility, jet test, CSM

Introduction

Sediment is continually subjected to physical stress in the environment, whether from the crushing weight of a glacier, the scouring flows of water, or the relentless pull of gravity. Forces push, pull and manipulate sediment. When these forces are imposed parallel to the sediment surface, the stress generated is termed a shear stress (force per m^2; Pascal, Pa) (Figure 1).

Shear stress is of paramount importance to geomorphologists because it is a driver of geomorphic change. The term 'shear stress' is used in various ways in earth science, and a clarification is needed at this early point in the chapter (for more information, see Fookes et al. 2007, Ch. 3). Shear stress can describe forces applied parallel to the sediment surface (e.g. surface drag by flowing water) that result in a surface response (e.g. entrainment of surficial sediment) (Figure 1b). It can also be used to describe forces applied at the sediment surface (e.g. a moving glacier), but which are transmitted into the bed to exert internal shear stress that results in sediment deformation or fracture (Figure 1c). Finally, shear stress can be used to describe a force that acts upon the whole sediment bed (e.g. gravity) and which induces a shear stress that can result in sediment deformation or mobilisation (e.g. hillslope mass movement) (Figure 1d). In this chapter, I take an inclusive view of shear stress. Geomorphic processes in nature often involve a combination of stresses. A flowing glacier not only exerts a shear stress on the sediment bed, but the glacier's weight also imposes an extraordinary compressive stress normal to the sediment surface. Likewise, the erosion of a sediment bed in a river is linked not only to shear stress generated by fluid drag along the surface but also to small-scale unsteady flow events (e.g. bursts and sweeps) that impart forces normal to the sediment surface. Therefore, the chapter focuses on methods that quantify the shear strength of sediment as it relates generally to either internal shear stress or surface shear stress.

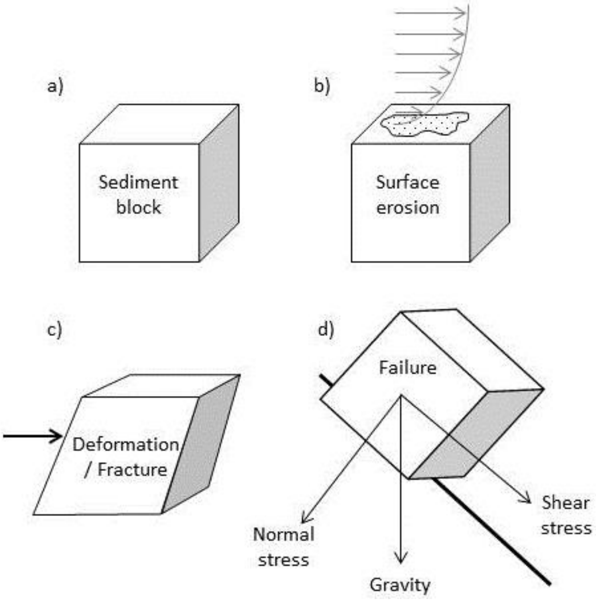

Figure 1: Shear stress imposed on a block of sediment resulting in (b) surface erosion, (c) sediment deformation / fracture, or (d) slope failure

Shear strength is a measure of a sediment's resistance to shear stress, or in other words it is a measure of the sediment's stability in space and time. When an applied shear stress exceeds the shear strength of a sediment, failure occurs and the sediment deforms, fractures and / or mobilises (Figure 1). Shear strength is an attribute of the sediment itself and is determined by the physical, chemical and biological characteristics that influence particle interactions within the sediment (cohesion, adhesion and friction).

Many excellent methods have been developed to quantify shear strength for soils and sediments. The most accurate of these are conducted within a laboratory using specialist equipment. However, cohesive sediment undergoes significant changes in sediment properties when it is cored, transported, stored and finally analysed in the laboratory, and these changes can significantly alter its shear strength (Knappett and Craig, 2012). Consequently, field approaches are recommended in the first instance for the quantification of *situ* shear strength of cohesive sediment.

This chapter provides an introduction to the *in situ* quantification of shear strength for cohesive sediment specifically with the geomorphologist in mind. It is divided into two sections. The first pertains to geotechnical shear strength, in which internal shear stress applied to sediment causes it to deform or fracture. The second section relates to stresses induced at the sediment surface specifically by flowing water and which results in erosion of the sediment surface. In each section, a single tool is presented in detail, one which is ideally suited for fieldwork by a geomorphologist. Complimentary techniques that can be applied in the laboratory are listed in each section.

Geotechnical shear strength

Many laboratory-based tests have been developed over the years to quantify the shear strength of soil and sediment, including the triaxial and direct shear tests. Detailed information on the theory and application of these approaches can be found in a soil engineering textbook (e.g. Terzaghi et al., 1996; Knappett and Craig, 2012) and the British Standard 1377.

Shear Vane

For *in situ* applications, the shear vane is the most reliable and readily-available device for measuring the undrained shear strength of cohesive sediment. It has been used extensively for the analysis of shear strength in soils (Serota and Jangle, 1972; Knappett and Craig, 2012), and has been applied to glacial till (e.g. Khan and Kostaschuk, 2011), riverbanks (e.g. Chen et al., 2012), and fine bed sediments in riverine (e.g. Grabowski, 2010) and marine environments (e.g. Hauton and Paterson, 2003).

Handheld shear vanes are compact, portable devices that can be easily carried into the field and used *in situ* (Figure 2). They typically come equipped with vanes of varying sizes to measure shear strength across a wide range of sediment bulk densities. For example, the Pilcon Hand Vane Tester (EDECO, England) has two vanes, a 19 mm diam. vane for use in consolidated sediment and a 33 mm diam. vane for softer sediment.

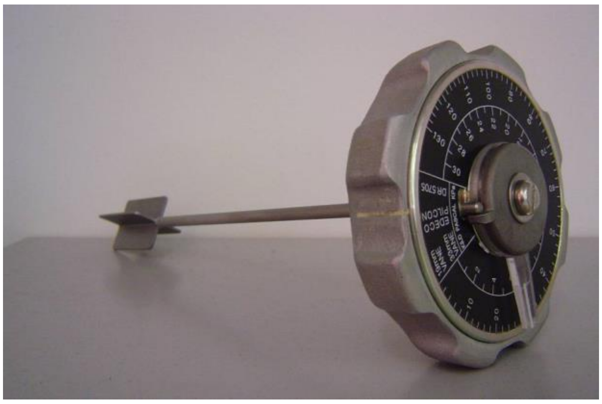

Figure 2: A shear vane tester equipped with a 33 mm diameter vane. The vane is inserted into the sediment, and the dial is rotated until the sediment fails, and the vane spins freely in the sediment.

To operate the device, the vane is inserted into the sediment perpendicular to the sediment surface, avoiding any lateral movement. Standard protocol for soil testing sets a minimum depth of insertion (70-80 mm for the Pilcon model); however the device can be inserted to a range of depths to investigate vertical changes in shear strength for cohesive sediment. The vane head is then rotated at a constant rate (e.g. 1 rev min^{-1}) until the sediment fails (i.e. the vane rotates freely in the sediment). The maximum shear stress (τ_v; kN/m^2) resisted by the sediment is a function of the torque (M) applied at failure and the size of the vane:

$$\tau_v = \frac{M}{K}$$

$$K = \pi D^2 \left(\frac{H}{2} + \frac{D}{6}\right)$$

where K is a constant that depends on the height (H) and depth (D) of the vane. Commercial shear vane testers will typically come calibrated for their standard size vanes so that τ_v can be recorded directly in the field. Several readings are recommended, and the mean used to characterize a sample. If τ_v differs substantially between readings for a sample, this may indicate that presence of a non-cohesive sediment lens or an obstruction (a large clast or root), and additional readings should be taken. For more information on conducting a shear vane test, see British Standard 1377 – Part 9.

Sediment samples should be collected for the analysis of sediment properties. At a minimum, sediment grain size distribution and water content should be measured.

It is important to remember that the shear vane is only recommended for use in cohesive soils and sediments. This does not mean that the sample must be composed entirely of clay and silt, though, as fine sediments with relatively low clay contents can classified as cohesive (van Ledden et al., 2004; Winterwerp and Van Kesteren, 2004; for a recent review see, Grabowski et al., 2011). As stated above, samples with highly heterogeneous sediment grain sizes can be problematic, due to the physical interaction of larger clasts. The presence of other types of material in the sediment, such as fine plant roots, is not as problematic as their tensile strength contributes to the shear strength of the sample (Gyssels et al., 2005). Grabowski (2010) found that the shear vane was able to detect differences in the shear strength of fine riverine sediment caused, in part, by differences in the amount of plant roots in the sediment, which would impact its susceptibility to fracturing and bulk erosion (Figure 3).

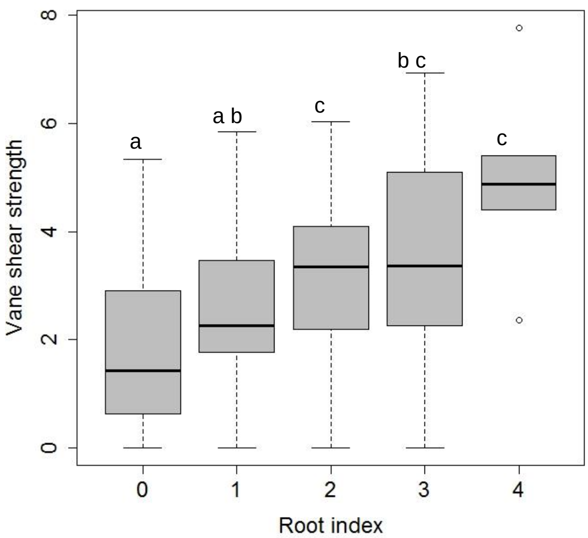

Figure 3: Vane shear strength for fine riverine sediment by root index category (0 = none, 1 = few, 2 = intermediate, 3 = abundant, and 4 = roots dominant) Bere Stream, Dorset, UK. (Kruskal Wallis, Mann-Whitney, $p < 0.05$) (Grabowski, 2010)

A final note about a related device. The pocket shear meter (e.g. Torvane) is similar in principle to the handheld shear vane, but the volume of sediment that is sheared is thinner and is limited to the surface of the sample. It is a useful tool to aid the visual classification of soil but is not suitable for the quantification of geotechnical shear strength of sediment (Head, 1994).

Resistance to erosion

The shear strength of sediment as related to erosion by flowing water is expressed as the shear stress required to initiate surface erosion, i.e. critical shear stress, or erosion rates once erosion has begun.

Flumes are considered the gold standard in this area of research. They generate steady water flows parallel to the sediment surface to impart consistent shear stresses. A wide range of flumes have been developed to quantify erosion resistance: unidirectional and oscillatory; straight and annular; recirculating and flow-through; and laboratory-based and field-deployable systems (e.g. Aberle et al., 2004; Amos et al., 2004; Bale et al., 2007; Droppo et al., 2007; Gerbersdorf et al., 2005; Roberts et al., 2003; Widdows et al., 1998).

Concerns over the impacts of extraction, transport and storage of sediment on sediment properties for laboratory investigations, combined with field evidence of significant spatial and temporal variations in erosion resistance has driven the development of field-deployable systems with small footprints, such as the Gust erosion chamber (Thomsen and Gust, 2000), EROMES (Schünemann and Kühl, 1993) and the cohesive strength meter (CSM) (Paterson, 1989). The CSM is the only system that is commercially available, and is the focus of this section. Whilst the CSM does not generate a shear stress *per se*, it quantifies sediment's resistance to erosion by water, and as was discussed in the introduction this process often involves both shear and normal stresses in nature. Furthermore, the forces generated by the CSM have been show to correlate with surface shear stress, at least at the lower range of the instrument (Grabowski et al., 2010).

Cohesive Strength Meter (CSM)

The CSM is a portable device that measures the *in situ* erosion resistance of surficial sediments. It is a modern, portable version of the laboratory jet test used by soil scientists for over 50 years to measure the shear strength of clayey soil samples (c.f. Paterson, 1989). Since its conception 20 years ago, the CSM has been increasingly used, particularly in the estuarine environment (e.g. Yallop et al., 1994; Tolhurst et al., 1999; Friend et al., 2005) but more recently in rivers (Grabowski et al., 2012).

The CSM is composed of a main instrument unit containing the computer and a reservoir of water pressurised by an external air cylinder, which is connected to a sensor head that is inserted into the sediment (Figure 4). The device is designed to be deployed *in situ* and the sensor head can be submerged under water. There is a maximum depth of deployment of the sensor head, which is dependent of the rigidity of the tubing, thus the use of core tubes in Figure 4. If the sensor head is being deployed sub-aerially, as is commonly the case for intertidal marine studies, the chamber must be filled with water gently using a syringe. To run a test, the CSM fires a jet of water downward onto the sediment surface within the sensor head chamber. Jet pressure is increased incrementally, and erosion is monitored based on sediment resuspension using an infrared transmissometer.

Figure 4: The cohesive strength meter (CSM) being used in the Bere Stream (Dorset, UK).

The initiation of erosion is typically identified by a 10% drop in light transmission within the test chamber (Figure 5). The CSM records the internal pressure (P_I) for each step in PSI, but the pressure of the impinging jet on the sediment surface (i.e. stagnation pressure, P_{stag}) is dependent on the specifics of the CSM model, the sampling routine, the length and diameter of tubing, and the height of the jet orifice above the sediment surface (Vardy et al., 2007). The conversion of P_l to P_{stag} allows erosion thresholds to be compared between different CSM units and models. To be able to incorporate these estimates of erosion thresholds into sediment transport models, P_{stag} must be converted to horizontal shear stress (τ). An empirical calibration was developed for the CSM by Grabowski et al. (2010) by comparing erosion thresholds generated in the CSM and annular flume using homogeneous sand/mud mixtures. For P_{stag} range of 30-110 Pa, critical shear stress was found to relate to P_{stag} as:

$$\tau_c = 0.0013P_{stag} + 0.047$$
$$(R^2_{adj} = 0.87,\ P < 0.01)$$

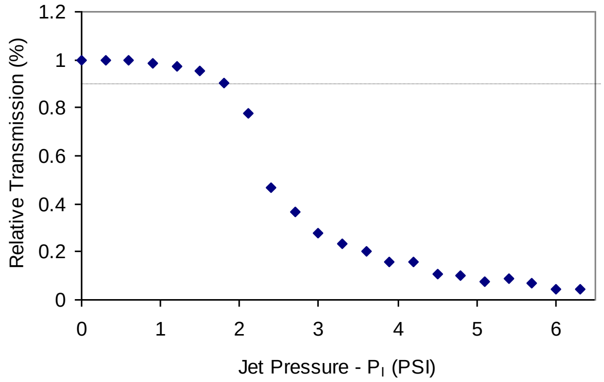

Figure 5: An example of a transmission curve from a cohesive strength meter run. A 10% reduction in transmission was used as the operation definition of erosion.

The cohesive strength meter, as the name suggests, should only be used to estimate erosion thresholds for cohesive sediment. This is primarily due to the method by which the CSM identifies erosion. A minimum clay/silt content is needed to ensure that erosion is synonymous with resuspension. For example, if the CSM was used to measure the erosion threshold of pure sand, the sand would need to be resuspended to a height of 1 cm off the bed to be registered by the transmissometer. In nature, sand grains would be entrained and transported as bedload at shear stress lower than necessary to suspend the sand grains to that height. The minimum clay/silt content will vary depending on the type and amount of clay. For pure kaolin the threshold minimum was found to be around 5% clay content (Grabowski et al., 2010), which is comparable to minimum content need to form a cohesive structural matrix in the sediment (4 – 10%) (Mitchener and Torfs, 1996; van Ledden et al., 2004). Grabowski et al. (2012) found that a minimum silt/clay content of 10% was appropriate for fine riverine sediment.

Finally, it is worth re-emphasising that the CSM measures only the erosion of the surficial sediment. It does not directly quantify erosion rates or depths of scours, though these could be obtained by an analysis of the rate of change in the slope of the transmission vs jet pressure plots (e.g. Figure 5; Tolhurst et al. 1999) and an empirical relationship between transmission and suspended sediment concentration, or by measuring scour depths after exposure to high jet pressures. A related device, the *in situ* jet test uses a depth-integrated approach to calculate critical shear stress based on the equilibrium scour depth at a set jet pressure. It has been used to quantify the stability of riverbanks (Hanson and Simon, 2001; Simon et al., 2006).

Conclusion

Numerous methods exist to quantify the shear strength of soils and sediments. The tools highlighted in this chapter, the shear vane and CSM, are two that are well suited to field geomorphological research. When used correctly, they generate shear strength readings that can support research in a range of geomorphological forms and processes.

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