



Estimating soil failure due to torsion via vane shear test by varying vane diameter and soil properties

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ABSTRACT

Soil–tool interaction poses an ongoing challenge to researchers, developers, and manufacturers. Numerous studies have focused on reaction forces, resistances, and associated soil failures during the penetration of tillage tools into soil or their surface movements. However, little research has been devoted to the interactions involved in the torsion failure of soil in agricultural tillage systems. To study the resistance of soil to failure due to torsion actions, this study develops a torsion-induced soil failure estimation model that is used to obtain relevant parameters based on in-situ experiments conducted in a soil bin by using soil with different physical properties (i.e., moisture content and soil density). Four vanes with various diameters but the same height (5 cm) were designed. The maximum torques at which soil failure occurred were then measured and analyzed. The results revealed a power function relationship between the soil failure due to torsion and the diameter of the vane, i.e., $T = \alpha D^\beta$ ($R^2 > 0.96$). The dimensionless parameters α and β of the estimation model were found to be related to the soil moisture ($P < 0.05$) and bulk density ($P < 0.05$), respectively. The values of both α and β varied nonlinearly with the soil moisture content, cone index, and bulk density. It was concluded that the power function can be applied to describe the relationship between the torque and the diameter of the vane; with the measurement device performing a torsion action in the soil layer, the torque at which soil failure occurs can be estimated by using the diameter of the vane along with the moisture content of the soil and its bulk density. When the height of the vane was constant, the torsion could be predicted by using the proposed power function model at certain soil conditions.

1. Introduction

The vane shear test has been one of the most widely used methods for the in-situ determination of the undrained shear strength of soil for many years. Bauer et al. (2007) discussed the capabilities of the vane test by highlighting its theoretical basis, its functioning principle (with some operational particularities), and certain applications for investigating the properties of fresh rendering mortar. Laskar and Bhattacharjee (2011) considered the resistances from underneath and above the vane in their study to examine the relationship between torque and rotation speed using a concrete rheometer with the vane geometry. Elaty and Ghazy (2012) studied the efficiency of a modified geotechnical vane shear test to assess the properties of fresh concrete. Nazari et al. (2013) built a three-dimensional (3D) vane rheometer model using a finite element method to calculate the isothermal flow parameters of standard Newtonian fluids (Brookfield). Their computational model was validated by comparing its results with those of experiments with a shaft torque conducted at different angular velocities.

Moreover, several researchers have investigated the yielding surface, the distribution of stresses, and the failure surface. For example, Skempton (1948) reported that the shear strength increases by 10% if the cylindrical shear surface has a diameter that is 5% greater than the width of the blade. Arman et al. (1975) found that the failure surface is circular at the cross section. However, Wilson (1964) noted that the failure surface is not circular but almost square on a plane when the torque reaches its maximum value. Furthermore, the vane configuration, geometry, operating conditions, and material properties are also controversial topics. The vanes applied in tests can have two, three, four, six, or eight blades, and their geometry can be rectangular, triangular, diamond-shaped, or conical (Keentok et al., 1985; Skempton, 1948; Pérez Foguet et al., 1999; Alderman et al., 1991; Yoshimura et al., 1987; Menzies and Mailey, 1976; Assaad et al., 2016; Elaty and Ghazy, 2012). In summary, most vane shear tests have been applied to civil engineering problems as a geotechnical method of investigation, where a majority of the investigations have focused on the following aspects: a) measuring material properties, particularly the shear

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Nomenclature

V_r	Constant angular velocity
R	Radius of the sheared cylinder
T_s	Torque due to lateral area of the vane
r_1	Radius of the shaft
T_{e1}	Torque due to upper area of the vane
d	Diameter of the shaft
T_{e2}	Torque due to lower area of the vane

σ	Shear yield stress
T	Torque, soil failure resistance
A, B	Equation coefficient and intercept
D	Diameter of the sheared cylinder (the diameter of the vane)
α	Power function coefficient
H	Height of the sheared cylinder (the height of the vane)
β	Power function exponent

strength; b) designing and optimizing the vane device; c) determining relationships among the shear strength, vane geometry, and material parameters; and d) developing prediction models for shear strength, which is a common stress index for the soil or the construction material. The purpose is to improve the measurement accuracy and standardize measurement devices.

However, several researchers have conducted in-situ vane shear tests used as an auxiliary research method in agricultural soil tillage systems. For example, Bachmann et al. (2006) measured the penetration resistance of soil and the vane shear strength to evaluate the state of compactness of three types of pasture soil 12, 50, and 150 years after the clearing of a secondary virgin forest. The results indicated that the duration of cattle grazing was easily detectable using penetration resistance data or shear strength data. Arvidsson and Keller (2011) compared penetrometer and shear vane measurements with the predicted and measured readings of a draft for a moldboard plow to examine the draught during plowing as a function of the soil strength and related the results to those of existing models. Shear vane measurements were used to derive the soil cohesion and predict the requirements of the draft. The results showed that neither shear vane nor penetrometer measurements are sufficient for predicting such requirements, so a simple yet reliable field method should be developed for such purposes. These investigations show that a vane shear test can be used to study the characteristics of soil–tool interaction, such as the reaction forces and failure-inducing actions in agricultural settings.

In the context of conventional tillage systems, the majority of studies have focused on reaction forces, or resistances, and the associated soil failures that occur when the tillage tools move horizontally through the soil layer. Tillage tools usually include a soil opener, plow, and subsoiler (Hasimu and Chen, 2014; Arvidsson et al., 2004; Celik and Raper, 2012). In traditional tillage systems, such tools are pulled in a passive manner using a tractor. The forces, resistances, and power consumption are usually obtained through measurements made during field experiments, soil bin experiments, and simulations, or they are predicted through mathematical models based on analytical approaches involving various assumptions and soil failure patterns during soil–tool interactions (Collins and Fowler, 1996; Mouazen and Neményi, 1999; Santo et al., 2010; Chen et al., 2013; Tagar et al., 2014; Karmakar and Kushwaha, 2006; Hettiaratchi and Reece, 1974; Godwin and O'Dogherty, 2007). Related soil failure patterns, or mechanisms, and soil disturbances are described using indices such as the disturbed soil geometry, the soil failure profile, the rate and path of cracks, soil translocation, the soil throw width, the soil cut width, the ridge-to-ridge distance, the ridge height, the after-plough depth, and the soil backfill (Godwin and Spoor, 1977; Jayasuriya and Salokhe, 2003; Karmakar et al., 2005; Solhjoui et al., 2012, 2013, 2014; Barr et al., 2016; Bögel et al., 2016; Manuwa, 2009). However, with the development of conservation tillage systems, new tillage tools have been designed to create the necessary environments; these include soil aeration, soil gashing, and root cutting devices (Maas and Bjorge, 2013; De Bree, 2013; You et al., 2012; Matin et al., 2016; He et al., 2016). These tools penetrate the soil intermittently or continuously while causing low disturbance, where the soil–tool interactions differ completely from those involving traditional tillage tools.

To explore these new soil failure actions and provide support for novel working devices, soil failure due to torsion after penetration has been considered. However, few studies on the reaction forces or the devices used in torsion-induced soil failure have been conducted in the backdrop of an agriculture tillage system. Similar studies can only be found in the domains of vane shear testing and tunnel exploration (Barnes and Nguyen, 2001; Hauton and Paterson, 2003; Shi et al., 2011; Zhang et al., 2014). In the latter domain, a shield construction technique has been widely applied to the construction of underground transport systems. The theoretical basis for its implementation was provided through accurate calculations of the load during the shield tunneling process. A common device for this purpose consists of a cylinder and cutterhead, which has a circular face, a frontal surface, a cutter, and an opening (Shi et al., 2011; Zhang et al., 2014). However, the shield has a large area of contact with the soil owing to its large dimensions. The special components and working methods of the shield render it different from the vanes used in vane shear testing in terms of the mechanism of interaction with the soil.

This study explores a novel mode of soil–tool interaction and estimates soil failure actions and its torsion resistance to provide support for new actions that induce soil failure and the design of related tillage devices. Considering the requirement of low soil disturbance during the penetration process and in light of the difference between vane shearing devices and shielding devices in terms of their dimensions and working principles, a device with a rectangular vane geometry was designed and used as a reference and prototype. The soil failure resistance due to torsion actions was then estimated and predicted using vanes with different diameters but the same height, and the related coefficients were investigated for soil with different properties.

2. Calculating the soil failure torque and assumptions

The in-situ vane shear experiment involves inserting a vane into the soil. It is then manually rotated at a slow, constant strain rate (constant angular velocity, V_r). The movement of the vane in the soil is shown in Fig. 1. When it is rotated, the surface and the upper and lower areas of the vane interact with the soil, and shear and failure behaviors are generated. The soil resistance is directly reflected in the torque applied to the vane. Thus, the failure resistance of the soil can be described by the torque of the vane.

The maximum torque (i.e., the soil failure torque or soil failure resistance; T) obtained in the experiment can be defined as the algebraic sum of the torque values exercised by the lateral area (T_s) and the upper and lower areas of the vane (T_{e1} and T_{e2} , respectively).

$$T = T_s + T_{e1} + T_{e2} \quad (1)$$

$$T_s = \pi DH\sigma R = \frac{\pi}{2} D^2 H \sigma \quad (2)$$

$$T_{e1} = \int_{r_1}^R 2\pi r dr \cdot \sigma \cdot r = \frac{2}{3} \pi \sigma (R^3 - r_1^3) = \frac{1}{12} \pi \sigma (D^3 - d^3) \quad (3)$$

$$T_{e2} = \int_0^R 2\pi r dr \cdot \sigma \cdot r = \frac{1}{12} \pi \sigma D^3 \quad (4)$$

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