Soil & Tillage Research 137 (2014) 58–66

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Soil failure patterns and draft as influenced by consistency limits: An evaluation of the remolded soil cutting test

A.A. Tagar [a,b], Changying Ji [a,*], Qishuo Ding [a], Jan Adamowski [c], F.A. Chandio [a,b], I.A. Mari [a]

[a] College of Engineering, Nanjing Agricultural University, Nanjing 210031, PR China
[b] Faculty of Agricultural Engineering, Sindh Agriculture University, Tandojam 70060, Pakistan
[c] Department of Bioresource Engineering, McGill University, Ste Anne de Bellevue, Quebec H9X3V9, Canada

ARTICLE INFO

Article history:
Received 2 May 2013
Received in revised form 3 December 2013
Accepted 5 December 2013

Keywords:
Sticky limit
Sticky point
Flat triangular shaped tool
Dry land soil
Paddy soil
Laboratory soil bin

ABSTRACT

Soil failure patterns play an important role in obtaining a better understanding of the mechanical behavior of soils. Despite the large number of studies over the past few decades, a better understanding of soil failure patterns and its relation to soil and tool parameters for particular soils such as dry land and paddy has not been developed. This study investigated soil failure patterns and related draft at sticky, plastic and liquid consistency limits and the sticky point of dry land and paddy soils. A soil cutting test rig was developed to perform soil cutting at three consistency limits (sticky limit, plastic limit and liquid limit) and the sticky point of soil, three rake angles (15°, 30° and 45°), and three operating depths (30 mm, 50 mm and 70 mm). A flat triangular shaped tool operating at a constant speed of 10 mm s^{-1} was used in all experiments. Soil failure patterns were observed and recorded using a digital camera, and draft per unit displacement was measured by load cells attached to the soil bin. A direct relationship between soil failure patterns or draft and the consistency limits of soil was found. Brittle failure was obtained at the sticky limit, chip forming failure was observed at 15° rake angle and 30 mm depth, and bending failure with little strains of elements at 30° and 45° rake angles and 50 mm and 70 mm depths at plastic limit, while flow failure was linked to the liquid limit of the soil. At the sticky point, flow failure was observed at an operating depth of 30 mm and 15° rake angle, while flow with considerable bending and no strains of elements occurred at 50 mm and 70 mm operating depths and 30° and 45° rake angles. However, bending was more prominent at 70 mm depth and 45° rake angle. The draft at the sticky limit, plastic limit and sticky point was cyclic in nature, whereas at the liquid limit it was comparatively diverse and fading. The highest draft was found at the plastic limit, and the lowest at the liquid limit. Since the soil failure patterns may change with moisture content, soil type and particle size distribution within the same textural class, consistency limits can provide clearer and more accurate definitions of soil failure patterns than moisture content levels alone.

1. Introduction

The proper design and selection of soil-engaging tools to achieve desired soil tilth depends largely on the mechanical behavior of the soils (Rajaram and Erbach, 1998). Soil failure patterns play an important role in obtaining a better understanding of the mechanical behavior of soils under varied soil and tool conditions. The variation in soil failure patterns can be attributed to the variations of mechanical behavior of the soil (Abo Al-kheer et al., 2011). Soil failure patterns can include collapse, fracturing (brittle), chip forming, and flow (Salokhe, 1986; Rajaram and Gee-Clough, 1988; Sharma, 1990). These failure patterns may vary with soil and tool parameters (Elijah and Weber, 1971; Godwin and Spoor, 1977; Stafford, 1981; Makanga et al., 1996).

Over the past couple of decades, numerous studies have been conducted to evaluate the effects of soil and tool parameters on soil failure patterns such as moisture content (Makanga et al., 2010; Rajaram and Gee-Clough, 1988; Wang and Gee-Clough, 1993), rake angles (Aluko and Seig, 2000), aspect ratio (Makanga et al., 1996) and operating speed (Stafford, 1979; Karmakar, 2005). Despite this large number of studies, a better understanding of the relationships existing between soil failure patterns and soil and tool parameters has not been elucidated. This is particularly true for dry land and paddy soils. This is likely mainly attributable to the complexity of soil genesis, textures, unique weather conditions, and the cropping systems associated with each soil under study.

* Corresponding author. Tel.: +86 25 58606571.
E-mail addresses: chyji@njau.edu.cn, chyji@yahoo.com (C. Ji).

0167-1987/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.still.2013.12.001

Although the importance of a better understanding of the true failure patterns of soils has been emphasized by a number of authors (e.g., Rajaram and Erbach, 1997, 1998), technical methods to quantify soil failure patterns are limited. Moreover, the numerical value of the moisture content does not show any direct relationship with changes in soil failure patterns in different soils (Jayasuriya and Salokhe, 2001). One potential indicator may relate to a soil's consistency limits. The consistency limits of soil or Atterberg limits (Atterberg, 1911) define the resistance of soils to deformation or rupture. The plastic limit refers to the minimum moisture content at which soil can be puddled (Lal and Shukla, 2004), the liquid limit is the minimum moisture content at which soil flows like a liquid (Dexter and Bird, 2001; SSSA, 2009), and the sticky limit is the moisture content at which soil has little or no stickiness/adhesion to a steel spatula (Lal and Shukla, 2004). These terms are commonly used for classifying cohesive soils for engineering purposes (McBride, 2008). To some extent, they may yield information on the mechanical behavior of soils (Keller and Dexter, 2012). Soil workability is clearly related to the consistency limits of soil (Mueller, 1985; Smedema, 1993; Müller and Schindler, 1998a; Dexter and Bird, 2001; Müller et al., 2003). Archer (1975) concluded that consistency limits can be used to classify soils for workability. Moreover, Yamamoto (1963) suggested that data on the consistency limits of soil can be used as a guide for tillage practices. The sticky point, defined as the moisture content at which soil has maximum stickiness/adhesion to a steel spatula (Braja, 2002), is also an important criteria of soil workability. According to Müller and Schindler (1998b) the stickiness of soil is the limiting factor for its workability.

Many studies have explored soil failure patterns (e.g., Makanga et al., 2010; Wang and Gee-Clough, 1993; Rajaram and Gee-Clough, 1988; Stafford, 1981; Elijah and Weber, 1971). All studies to date have been based on specific soil moisture content levels. Although a few moisture levels could be inferred to represent the agronomically important soil moisture contents at the permanent wilting point, field capacity and saturation (e.g., Makanga et al., 2010), the rationale for choosing specific moisture content values was not specified in these studies. However, some studies provided the plastic limit and liquid limit of their soils, but unfortunately the experimental soil moisture levels that were used did not correspond to moisture content levels at plastic limit or liquid limit. In contrast, our study explores for the first time the use of soil consistency limits to investigate soil failure patterns during soil cutting. In order to provide precise definitions of soil failure patterns, this study was designed to investigate: (i) the relationship between soil failure patterns and draft with consistency limits and (ii) failure patterns and draft at the sticky point, in both dry land and paddy soils.

2. Materials and methods

The experiments in this study were carried out in an indoor soil bin test rig developed at the Department of Agricultural Mechanization, College of Engineering, at Nanjing Agricultural University (NJAU) in China. The soils used in the experiment were dry land soil and paddy soil. These are yellow-brown soils according to the Chinese Soil Taxonomy and Halpudalf in the US classification scheme. China's yellow-brown soils, shown to have arisen through an independent soil genesis mechanism, are distributed across a wide swath of agro-ecological regions (27°33° N lat.), and have important implications for agricultural production. Consequently, an investigation of the general mechanical behaviors of these types of soil during cutting is warranted, particularly with respect to clearly defining its failure patterns. The paddy soil was used for a rice-wheat rotation on the university's Jiangpu Experimental Farm, while the farm's dry land soil was used to cultivate vegetables such as potatoes (*Solanum tuberosum* L., tomatoes (*Solanum lycopersicum* L.), eggplants (*Solanum melongena* L.) and chilies (*Capsicum* sp.).

2.1. Soil preparation

The experimental soil was air dried for two to three weeks, ground, and sieved through a 4 mm sieve. Composite soil samples were taken from the sieved soil to determine the moisture content in the soil, and then on the basis of existing moisture content a calculated amount of water was added to the soil (Eq. (1)) as a fine spray so as to attain the desired moisture content at the required consistency limit and the sticky point of the soil.

$$V_a = V_{req} - V_{ex} = (SMC_{req} \times W_s) - (SMC_{ex} \times W_s) \quad (1)$$

where, V_{req} is the volume of water which needs to be added to the soil in order to achieve the desired soil moisture content (ml), V_{ex} is the existing water present initially in the dry sieved soil (ml), SMC_{req} is the required moisture content (g kg^{-1}), SMC_{ex} is the moisture content of the dry sieved soil (g kg^{-1}), and W_s is the weight of soil (g).

It was then mixed well to obtain a homogenous soil specimen, covered with a polyethylene sheet to prevent evaporation, and left for 24 h to equilibrate to uniform moisture content. The soil was transferred to a metal-framed mold and compacted to the ideal bulk densities i.e., 1.22–1.4 mg m^{-3} for sandy clay loam soil (USDA, 1999) using a manually operated compactor. If this was not done, soil compaction could have had effects on soil failure patterns. Soil molds at the sticky limit were compacted to 1.22–1.25 mg m^{-3}. However, soil molds at the plastic limit, liquid limit and sticky point were compacted to 1.3–1.4 mg m^{-3} (Table 1). Because of high moisture content, it was not possible to compact soil molds at the required density with the compaction device. This is consistent with Smith et al. (1997), who concluded that when the moisture content is so high that all the soil pores are filled with water, the soil becomes less compressible. These soil molds (300 mm × 100 mm × 100 mm) were then transferred to the soil cutting test rig.

Table 1
The physical and mechanical properties of dry land and paddy soils at different consistency limits and the sticky point.

Consistency limit	Dry land soil					Paddy soil				
	Moisture content (g kg^{-1})	Dry bulk density (mg m^{-3})	Cohesion (kPa)	Angle of internal friction (Deg.)	Cone index (kPa)	Moisture content (g kg^{-1})	Dry bulk density (mg m^{-3})	Cohesion (kPa)	Angle of internal friction (Deg.)	Cone index (kPa)
Sticky limit	15	1.22	0.0012	26	106	17.7	1.25	0.001	29	109
Plastic limit	22	1.32	0.0005	16	104	32	1.4	0.0004	18	106
Liquid limit	36	1.3	0	4	11	45	1.4	0	4	13
Sticky point	32	1.4	0.00005	8	18	44	1.3	0	4	15