Journal of Asian Earth Sciences 77 (2013) 243–253

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

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

Study of preexisting shear surfaces of reactivated landslides from a strength recovery perspective

Deepak R. Bhat [a,*], R. Yatabe [b], N.P. Bhandary [b]

[a] Geo-Disaster Research Laboratory, Graduate School of Science and Engineering, Ehime University, 3 Bunkyo-cho, Matsuyama 790-8577, Japan
[b] Graduate School of Science and Engineering, Ehime University, 3 Bunkyo-cho, Matsuyama 790-8577, Japan

ARTICLE INFO

Article history:
Received 16 May 2013
Received in revised form 18 August 2013
Accepted 19 August 2013
Available online 7 September 2013

Keywords:
Reactivated landslide
Residual strength
Strength recovery
Preexisting shear surface soils
Ring shear test

ABSTRACT

Residual shear strength is generally considered in the design of preventive measures for slopes consisting of preexisting shear surfaces of large-scale landslides. Recent research suggests that the preexisting shear surface of a reactivated landslide can regain strength with the passage of time, which might also be considered in designing the slope stability measures. In this study, three reactivated landslide soils were tested in a ring shear apparatus for the discontinued shear periods of 1, 3, 7, 15, and 30 days with the following main objectives: (i) to understand the strength recovery behavior of landslide soils in a residual state of shear after as long as 30 days of discontinued shear, (ii) to understand the comparative pattern of strength recovery in highly plastic and less plastic soils, and (iii) to understand the mechanism involved in strength recovery at a residual state of shear. The results indicate that recovered strength measured in the laboratory is hardly noticeable after a rest period of 3 days, but recovered strength is lost after a small shear displacement. This paper primarily focuses on the effect of strength recovery from residual strength on preexisting shear surface soils and the mechanisms behind it.

1. Introduction

The shearing strength of a soil sample is defined as its maximum resistance to shearing forces (Skempton, 1964, 1985; Bishop et al., 1971; Lupini et al., 1981; Gibo and Egashira, 1992; Kalteziotis, 1993; Gibo, 1994; Watry and Lade, 2000; Wesley, 2009; Nakamura et al., 2010b; Stark and Hussain, 2010b, 2010c). The shearing strength of a soil is described in terms of peak strength and residual strength. When a soil sample has sheared, the shear stress normally reaches a peak value at a small shear displacement called the peak strength. When the shear displacement becomes large, it undergoes post-peak strength loss until a constant minimum value is reached. This is called residual strength (Skempton, 1964, 1985; Lo, 1972; Lupini et al., 1981; Bhat et al., 2012, 2013a,b,d,f). In the laboratory, the reversal direct shear test and torsional ring shear tests are used to measure the residual shear strength of soil specimens (Bishop et al., 1971; Chandler, 1977; Bromhead and Dixon, 1986; Stark and Eid, 1994; Wan and Kwong, 2002; Vithana et al., 2012a). The reversal direct shear test is widely used to measure the residual strength of soils in spite of several limitations (Stark and Eid, 1994; Wan and Kwong, 2002; Meehan et al., 2011). The primary limitation is that it can only shear the specimen in the forward and backward direction until a minimum shear resistance is measured. Each reversal of the shear box results in a horizontal displacement of less than 0.5 cm (Stark and Eid, 1994). As a result, the specimen is not subjected to continuous shear to large deformation in one direction; thus, a full orientation of the clay particles parallel to the direction of shear may not be obtained. Hence, the residual value measured by the reversal direct shear may not accurately simulate the field conditions in which large relative displacement occurs without a change in direction (Skempton, 1985; Stark and Eid, 1994). Residual strength values measured in the direct shear test, using the triaxial apparatus, were lower than the drained strength measured on polished slickensided surfaces (Christopher et al., 2011).

A torsional ring shear apparatus is now being widely used to measure the residual shear strength of a soil. The main advantage of the torsional ring shear apparatus is that it can shear the specimen continuously in one direction to obtain a large displacement; this method allows the clay particles to be oriented parallel to the direction of shear and to develop the true residual shear strength condition (La Gatta, 1970; Bishop et al., 1971; Bromhead, 1979; Tika, 1999, Bhat et al., 2013c,f). Another advantage of the ring shear apparatus is that no change occurs in the shear plane area during shearing (Tiwari and Marui, 2004; Vithana et al., 2012b). For the precise measurement of residual strength, a large deformation is applied to a specimen so that platy-clay minerals are oriented parallel to the shear plane (Skempton, 1985; Hong and Lade, 1989; Stark and Eid, 1994; Tana et al., 1998; Sassa et al., 2004; Jurko

* Corresponding author.
E-mail address: deepakrajbhat@gmail.com (D.R. Bhat).

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http://dx.doi.org/10.1016/j.jseaes.2013.08.023

and Sassa, 2008; Bhat et al., 2011, 2013c). The ring shear apparatus has been used frequently to measure residual shear strength.

The selection of shear strength parameters is integral to the design and repair of slopes containing preexisting shear surfaces in reactivated landslides (Stark and Hussain, 2010a). When a failure has already occurred in clay soils, any subsequent movement along the existing slope surface will be controlled by the drained residual strength (Skempton, 1964; Stark and Hussain, 2012). According to Skempton (1985), the field residual strength value for the slip surface soil should be identical to that calculated from the back analysis of the landslide in which movement has reactivated along a preexisting slip surface. Consequently, the back analyzed and lab-determined strength parameters must be the same as those of lab tests conducted under precisely similar in situ conditions. Bromhead and Curtis (1983), Mesri and Feng (1986), Stark and Eid (1994), Tika and Hutchinson (1999), Mesri and Shahien (2003), Stark et al. (2005) and Tiwari and Marui (2005) concluded that the drained residual shear strength measured with a ring shear apparatus is consistent with the back-calculated drained residual shear strength for a landslide slip surface.

Based on the back-analysis of an ancient landslide in cohesive colluvial soil in West Virginia, D'Appolonia et al. (1967) reported that the mobilized shear strength is greater than the drained residual strength of the slip surface material. Direct shear tests on undisturbed specimens containing the preexisting shear surface, obtained from shallow portions of the slip surface, show peak strengths greater than drained residual strengths. Researchers have suggested that the shear surface in the cohesive colluvial soil underwent "recovery", which caused an increase in shear strength beyond the drained residual value. Ramiah et al. (1973) investigated the strength recovery in remolded and normally consolidated kaolinite and bentonite in reversal direct shear tests, using rest periods of up to 4 days. Ramiah et al. (1973) found that the strength recovery for high plasticity soil (bentonite) is higher even with a short rest period. In the Bromhead (1979) ring shear apparatus, the shearing occurs at the top of the specimen, at the soil-to-top bronze porous stone interface. Angeli et al. (1996) use Bromhead (1979) ring shear tests to study the strength recovery mechanism in different clays, including London clay. Tests were performed on normally consolidated specimens. Angeli et al. (1996, 2004) concluded that there is an increase in the recovered shear strength with time during these direct and ring shear tests. Gibo et al. (2002) used a Bishop et al. (1971) type ring shear apparatus and concluded that a silt and sand dominated sample recovered its strength; however, the smectite dominated sample did not recover its strength. Stark et al. (2005) presented Bromhead (1979) type ring shear test laboratory results for two soils of different plasticity for rest periods up to 230 days. Stark et al. (2005) observed that the magnitude of recovered shear strength increases with increasing soil plasticity, but the recovered strength was lost with small shear displacement. Carrubba and Del Fabbro (2008) conducted Bromhead (1979) ring shear tests, similar to those performed by Stark et al. (2005), for aging times of up to 30 days and found more strength recovery in Montona flysch than in Rosazzo flysch. Strength recovery is negligible in kaolin clay after a 3-day rest period, but it is lost after a small shear displacement (Bhat et al., 2013d). Nakamura et al. (2010a) discussed the application of recovered strength in the stability analysis of reactivated landslides.

Residual shear strength is used for the design and repair of slopes containing preexisting shear surface of reactivated landslides. The basic design principle based on the lab-determined drained residual shear strength is consistent with the back-calculated drained residual strength for a landslide slip surface. If a preexisting shear surface recovers its strength at a residual state of shear in a short period of time, that recovered strength may be used as a remedial measure for the problematic layer. The recovered strength is greater than the residual shear strength, which increases the resisting force. Thus, the factor of safety increases, which reduces the cost of remedial measures. The study of the strength recovery from a residual state of shear is extremely important. However, before recovered strength can be used for design and repair of the problematic layer, strength recovery mechanisms and the influencing factors should be studied. Tokiwa et al. (2013) have reported that it is essential to understand the fracture formation mechanisms and the relation with the preexisting shear surface.

The Bishop et al. (1971) type ring shear apparatus is best suited for investigating the strength recovery in the laboratory because the shear is confined and occurs at a soil-to-soil interface. Gibo et al. (2002) used a Bishop et al. (1971) type ring shear apparatus to first observe the strength recovery effect on soil samples obtained from two different reactivated landslides. Gibo et al. (2002) concluded that the strength recovery effect should be considered in the stability analysis of a reactive landslide dominated by silt and sand particles at an effective normal stress less than 100 kN/m^2. However, the use of normally consolidated specimens and the short test duration (i.e., 2 days) may not be sufficient to reach this conclusion. The strength recovery observed for a normally consolidated Xuechengzhen specimen (i.e., silt and sand dominate) may have been caused by the presence of silt or sand particles along the shear surface; these particles may have penetrated the shear surface or zone during secondary compression of the ring shear specimen and provided some additional shear resistance. However, Gibo et al. (2002) concluded that the Kamenose specimen (i.e., smectite dominated) did not exhibit any strength recovery. This result contradicts the findings of Ramiah et al. (1973), which indicated that bentonitic soils exhibit higher strength gain. The Xuechengzhen specimen strength gain may have been more pronounced if Gibo et al. (2002) had used a longer rest period. The residual shear strength in preexisting landslides is more common in over consolidated soil, and rest periods longer than 2-days are necessary to simulate field conditions.

In this study, three preexisting shear surface soil samples are tested using the Bishop et al. (1971) type ring shear apparatus for rest periods of 1, 3, 7, 15, and 30 days. This paper describes the ring shear strength recovery laboratory test procedure and the observed strength recovery behaviors of three soil samples. The main objectives of this study are as follows: (i) to test the soil strength recovery from the residual state of shear during the long rest period (i.e., up to 30 days) by first using the Bishop et al. (1971) type ring shear apparatus, (ii) to compare the strength recovery of high plasticity soils and low plasticity soils, and (iii) to understand the strength recovery mechanisms at the residual state of shear.

2. Study areas

2.1. Krishnabhir landslide

The country of Nepal consists of over 80% mountainous topography (Bhandary et al., 2011). Geologically and tectonically, Nepal is divided into five tectonic zones: Terai, Sub-Himalaya (Siwaliks), Lesser Himalaya, Higher Himalaya, and Tibetan-Tethys Himalaya. Several major Himalaya thrusts and faults, namely, South Tibetan Detachment System (STDS), Main Central Thrust (MCT), Main Boundary Thrust (MBT), and Main Frontal Thrust (MFT), separate these tectonic zones. In the Lesser Himalaya zone of central Nepal, there are many reactivated landslides because of the steep mountain slopes and dynamic geological conditions (Yatabe et al., 2005). Krishnabhir landslide is a major reactivated landslide located in the Lesser Himalaya zone (Dahal et al., 2009; Hasegawa et al., 2009). The location of the Krishnabhir landslide is shown in