Residual Shear Strength Measured by Laboratory Tests and Mobilized in Landslides

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Abstract: Drained residual shear strength measured by multiple reversal direct shear or ring shear tests has been successfully used for over four decades for stability analyses of reactivated landslides in stiff clays and clay shales; A body of literature has accumulated in recent decades, claiming that "healing" or "strength regain" is realized in time on preexisting slip surfaces already at residual condition. In other words, the shear stress required to reactivate a landslide is claimed to be larger than the drained residual shear strength determined using laboratory tests. This article presents (1) a comparison of secant residual friction angle determined from laboratory tests and secant mobilized friction angle back-calculated for reactivated landslides; (2) explanations that field evidence used to claim "healing" can be attributed to alternative factors, and the laboratory evidence on "strength regain" upon reshearing is the result of either the testing apparatus or testing procedure, or is inapplicable to stiff clays and shales; and (3) laboratory aging test results, which show no "strength regain" on preexisting shear surfaces at residual condition. **DOI: 10.1061/(ASCE)GT.1943-5606.0000624.** *© 2012 American Society of Civil Engineers.*

CE Database subject headings: Clays; Shale; Residual strength; Landslides; Slope stability; Laboratory tests.

Author keywords: Clays; Shales; Residual strength; Landslides; Slope stability.

Introduction

Following Skempton (1964, 1985), drained residual shear strength measured by laboratory tests has been successfully used for stability analyses of reactivated landslides (e.g., Skempton and Petley 1967; Hutchinson 1969; James 1970; Palladino and Peck 1972; Blondeau and Josseume 1976; Morgenstern 1977; Chandler 1976, 1977, 1984; Bromhead and Dixon 1986; Terzaghi et al. 1996). Mesri and Shahien (2003) have summarized laboratory and field experience to show that drained residual shear strength from laboratory tests is mobilized on the entire slip surface of reactivated landslides and on the nearly horizontal lithological and structural discontinuity segment of first-time slope failures. Stability analyses by Huvaj-Sarihan (2009) for additional reactivated landslides support these conclusions (Fig. 1).

The most commonly used method for determining drained residual shear strength of stiff clays, shales, and mudstones is by drained multiple reversal direct shear tests or by drained ring shear tests, using either undisturbed or reconstituted specimens (e.g., Bishop et al. 1971; Chandler 1977; Bromhead and Dixon 1986; Stark and Eid 1994). For direct shear tests, the best procedure is to start with precut specimens, sometimes cut from intact undisturbed samples, but more often prepared from reconstituted samples (Mesri and Cepeda-Diaz 1986).

A body of literature has accumulated in recent decades claiming that "healing" or "strength regain" is realized with time on preexisting slip surfaces already at residual condition. In other words, the shear stress required to reactivate a landslide is claimed to be larger than the drained residual shear strength determined using laboratory tests. The objective of this article is to (1) present a comparison of secant residual friction angle determined from laboratory tests and secant mobilized friction angle back-calculated for reactivated landslides, and laboratory aging test results that show no "strength regain" at residual condition; and (2) explain that field evidence used to claim "healing" can be attributed to alternative factors, and the laboratory evidence on "strength regain" upon reshearing is the result of either the testing apparatus or testing procedure, or is inapplicable to stiff clays and shales in which residual condition is encountered.

Relation of Residual Strength to Effective Normal Stress

To provide an explanation for the behavior observed in the field and laboratory, it is useful to return to the definition of drained residual shear strength condition, and to note the relationship between secant residual friction angle and effective normal stress during shear to residual condition. According to Mesri and Shahien (2003), drained residual shear strength represents the face-to-face alignment and interaction of plate-shaped clay particles that are predominantly oriented parallel to the direction of shearing to the *maximum extent possible* for that composition. Secant residual friction angle depends on the nature of the particles and on effective normal stress because the latter determines arrangement of particles during consolidation and shear. Secant residual friction angle decreases with effective normal stress because the maximum extent possible for particle reorientation and face-to-face interaction improves with the increase in effective normal stress during shear. In other words, residual strength fabric at any effective normal stress is determined by compression or swelling involved to reach that effective normal stress, followed by sufficient shear displacement to reach residual condition.

These concepts and their implications to the so-called "strength regain" are illustrated and explained in terms of drained ring shear

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Note. This manuscript was submitted on April 11, 2011; approved on August 24, 2011; published online on April 16, 2012. Discussion period open until October 1, 2012; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Geotechnical and Geoenvironmental Engineering***, Vol. 138, No. 5, May 1, 2012. ©ASCE, ISSN 1090-0241/2012/5-585–593/$25.00.

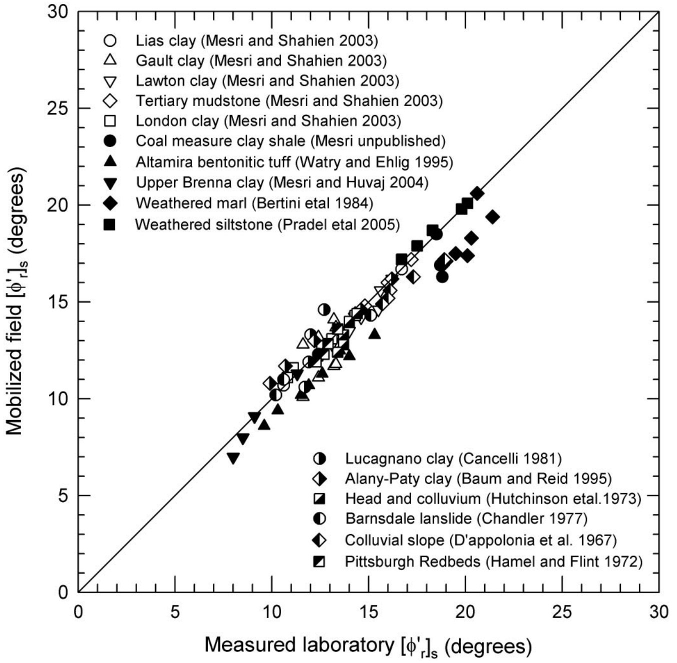

Fig. 1. Mobilized field secant friction angle back-calculated for reactivated landslides compared with residual secant friction angle measured by drained laboratory multiple reversal direct shear or ring shear tests (Huvaj-Sarihan 2009; printed with permission)

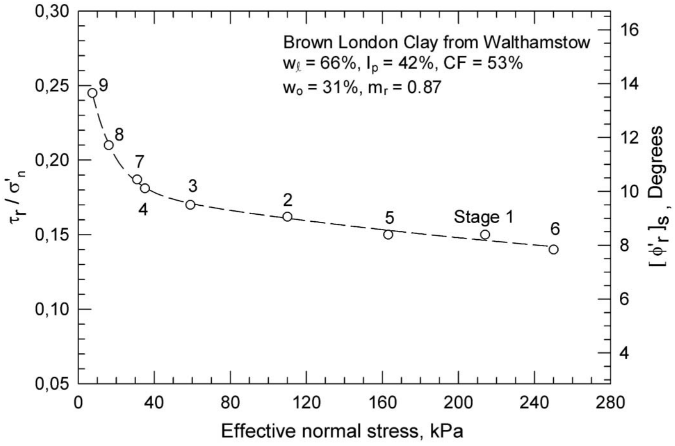

Fig. 2. Drained ring shear tests on London clay conducted at different effective normal stresses, showing the nonlinear shape of the residual shear strength envelope, and relationship of secant residual friction angle to effective normal stress (data from Bishop et al. 1971)

tests data in Figs. 2 and 3, respectively, on London clay (Bishop et al. 1971) and Lias clay (Chandler 1977). As has been pointed out by Bishop et al. (1971), "… residual strength is independent of stress history since the points fall on a unique curve dependent only on the magnitude of effective normal stress." A residual shear strength independent of stress history was also observed by Bishop et al. (1971) for Weald clay from Arlington with natural water content, liquid limit, plasticity index, and clay size fraction, respectively, 25, 65, 33, and 52%.

Slip Surface at Residual Condition Subjected to Changes in Effective Normal Stress

Reinitiation of movement on a slip surface that has reached residual condition under a certain effective normal stress may occur after an elapsed time during which effective normal stress has (1) remained unchanged, (2) increased, or (3) decreased. Only condition (1), which is the subject of next section, may provide information on possible "healing" of the residual condition. Implications of conditions (2) and (3) are explained next.

The residual shear strength data in Fig. 2 were obtained by Bishop et al. (1971) on brown London clay from Walthamstow, with natural water content, liquid limit, plasticity index, and clay-size fraction, respectively, 31, 66, 42, and 53%. During the ring shear test, residual condition was reached under nine different effective normal stress stages ranging from 6.9 to 250.5 kPa. The total shear displacement was 96.5 cm and the total duration of the test was 110 days. After residual condition under one effective normal stress was reached, the motor was stopped and a new normal stress was applied. The sample was then allowed to consolidate or swell under the new load before shearing restarted. Preconsolidation pressure of London clay and Lias clay are significantly greater than the maximum effective normal stresses in Figs. 2 and 3; therefore, it is safe to assume that at all effective normal stresses, the slip surface remained within the gap between upper and lower confining rings in the Imperial College/Norwegian Geotechnical Institute ring shear apparatus.

At the reinitiation of shear movement under a reduced effective normal stress, a peak was first observed before the new residual condition. The difference between the peak and residual strengths increased as the effective normal stress decreased. However, when the normal stress increased, no peak occurred at the reinitiation of shear movement. The peak that was observed under reduced effective normal stress, and further displacement that was required to reach a new residual condition, are attributed to disruption of slip surface resulting from the swelling of the London clay sample (containing 17% montmorillonite at a liquidity index of 0.17). As expected, the magnitude of swelling and disruption and associated difference between the peak and the residual strength increased as the effective normal stress decreased. The absence of a peak after an increase in effective normal stress is explained in terms of small recompression of London clay. For the London clay and particular pressure increments, improvement in clay particle orientation

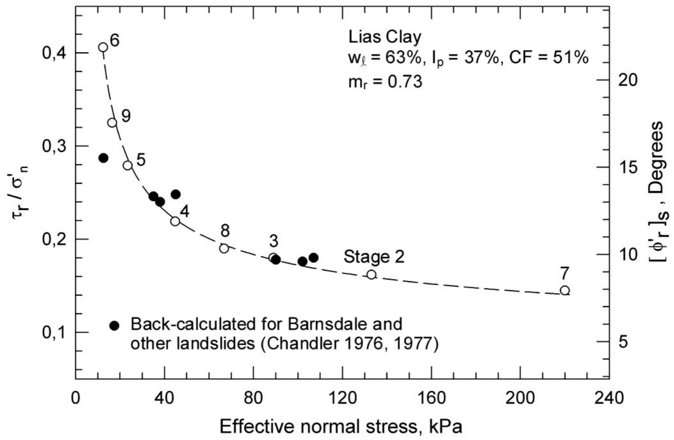

Fig. 3. Drained ring shear tests on Lias clay conducted at different effective normal stresses, showing the nonlinear shape of the residual shear strength envelope, and relationship of secant residual friction angle to effective normal stress (data from Chandler 1977)

during recompression apparently cancelled the need for particle reorientation during shear to the new residual condition.

To examine whether the observed peak, in drained ring shear tests following changes in effective normal stress on shear surfaces at residual condition, is of any practical significance and provide a reserve of strength for the field situation, Chandler (1977) conducted a drained ring shear test using the Bishop et al. (1971) apparatus on a Lias clay sample with liquid limit, plasticity index, and clay-size fraction, respectively, 63, 37, and 51%. First, the sample was subjected to effective normal stress of 177 kPa and sheared until residual condition was reached. The sample was then subjected to a number of changes in normal stress, allowing adequate time for consolidation or swelling before shearing to new residual condition. The secant residual friction angle for these tests is shown in Fig. 3. The parameter m_r, reported in Figs. 2 and 3, defines the curvature of residual strength envelope (Mesri and Shahien 2003).

The normal stress was reduced and the ring shear sample was allowed to swell while the shear stress was left on the sample. Then, upon reinitiation of shearing, a small peak was observed before residual condition was reached under the reduced effective normal stress. Chandler (1977) explained the small peak in terms of disturbance to the fabric of the shear plane produced by reverse shear displacement during swelling as a result of the relaxation of the proving rings used to measure shearing force. When shear stress was removed before swelling, no peak was observed upon reinitiation of shearing.

The residual condition fabric that is reached at a given effective normal stress, plus shearing displacement, does not necessarily represent the residual condition fabric at any other effective normal stress plus shearing displacement; the fabric is less well ordered at lower effective normal stress and more well ordered at higher effective normal stress. Therefore, small peaks in shear stress versus displacement curves following changes in effective normal stress represent work needed to establish the residual condition under the new effective normal stress. For example, in the Chandler (1977) tests, the most significant initial peak before new residual was observed after loading from 12.4 kPa to 220 kPa. A shear displacement of 30 mm was required to change the less well ordered residual condition fabric at 12.4 kPa ($[\phi'_r]_s = 22.1°$; only somewhat modified by recompression from 12.4 to 220 kPa) to a much more well ordered fabric at 220 kPa ($[\phi'_r]_s = 8.3°$).

Chandler (1977) considered the practical significance to the field situation of small peaks that may be observed following changes in normal stress, assuming minimal shear displacement during construction (e.g., increase in effective normal stress produced by drainage or toe-weighting), concluding that "This reserve of strength will be small and since movements are likely to occur on the landslide shear surface during construction, even if the factor of safety is quite high, it is considered unwise to place any reliance on this reserve of strength for design purposes."

Mobilized shear strength back-calculated by Chandler (1976, 1977) for Barnsdale and other landslides in Lias clay are plotted in Fig. 3 and show remarkably good agreement with residual shear strength from laboratory tests.

Literature on Aging of Residual Condition

On the basis of back-analyses of reactivated landslides and laboratory measurements, a residual shear strength independent of time, under constant normal and shear stress conditions, has been repeatedly proposed. Skempton and Petley (1967) concluded that there is no evidence that the strength on principal slip surfaces may increase with time after shearing movements have ceased, and this result appears to hold good even when there has been no renewal of movement during the past 10,000 years or more. According to James (1970), when the residual condition has been reached the slope remains, in general, with its factor of safety at unity. It is unlikely that any "healing" occurs along the slip plane because these slopes at the residual can remain meta-stable for centuries and be reactivated by relatively minor modifications to their geometry such as trimming at the toe. Morgenstern (1977), referring to numerous examples in the literature (e.g., Early and Skempton 1972), concluded that after clay soil has been subjected to large shear strains the strength is reduced to the residual value and it is generally agreed that only residual strength is available if movement is renewed along the preexisting slip surface. According to Brooker and Peck (1993), a mass that is actively moving or has moved but now appears stable can be reasonably assumed to have a factor of safety near unity and to be mobilizing its residual angle of friction at all points on the failure surface. Mesri and Shahien (2003) analyzed data for 42 reactivated slides in 11 stiff clays and shales, concluding that on reactivated slip surfaces of landslides in stiff clays and clay shales the residual condition has been reached, and the mobilized shear strength is equal to the residual shear strength from laboratory reversal direct shear or ring shear tests, independent of time after initial failure.

Bishop et al. (1971) tested an undisturbed blue London clay specimen from Wraysbury, with natural water content, liquid limit, plasticity index, and clay-size fraction, respectively, 28.7, 72, 43, and 57%, in the Imperial College-Norwegian Geotechnical Institute ring shear apparatus. The blue London clay was composed of 30% quartz, 15% kaolinite, 10% chlorite, 35% illite, and 10% montmorillonite. After the residual condition under an effective normal stress of 204 kPa had been reached, the test was stopped for two days at a displacement of 9.9 cm to see if the London clay was capable of "healing". "No gain in strength was observed when shearing was restarted." During the two days, no change in specimen thickness was recorded. For a series of drained ring shear tests on Studenterlunden clay from Norway, with mineralogical composition of 22% illite, 1–2% hornblends, and 1% organics, Bishop et al. (1971) reported that in some cases, the test was stopped overnight or at weekends, but this made no observable difference.

Hamel and Flint (1972) back-analyzed "ancient landslides" with slip surfaces in Pittsburgh Redbeds claystone (natural water content, liquid limit, plasticity index, and clay-size fraction, respectively, 17–31%, 27–41%, 8–13%, and 14–29%), reactivated by excavation of the toe. They concluded that the friction angles calculated are in excellent agreement with the measured residual friction angles of failure surface, and "It is believed that the failure surfaces did not heal following the ancient landslides and that residual or near residual strengths existed along the failure surfaces when slope excavation began."

Bromhead and Dixon (1986) carried out a detailed comparison of residual shear strength of London clay determined from shear box tests on natural slip surfaces, ring shear tests on reconstituted samples using the Bromhead (1979) apparatus, and back-analyses of reactivated landslides. They reported good agreement between slip surface tests and ring shear data and excellent correlation between residual shear strength back-calculated and residual shear strength determined from laboratory tests. Bromhead and Dixon (1986) concluded that the magnitude of the likely porewater pressure change, and effect of this on the shear strength, make a discussion of a degree or so in the residual angle of shearing resistance of second-order importance.

Nevertheless, a body of literature accumulated during recent decades has been claiming "healing" or "strength regain" on shear surfaces at residual condition.

A shear strength mobilized on an "old sliding surface" greater than the residual strength from laboratory tests was first hypothesized by D'Appolonia et al. (1967). They concluded, on the basis of field observations of behavior of a colluvial slope together with interpretation of laboratory test results and stability analyses, that "healing" of slickensides has occurred. Considering that most of the subsequent studies of "healing" of the residual condition represent further examination of this hypothesis, we have carried out a detailed reevaluation of the evidence used by D'Appolonia et al. (1967). In summary, neither the laboratory test results, nor stability analyses together with observations of slope movement at Weirton, West Virginia (Huvaj-Sarihan 2009), provide convincing evidence for "healing" of residual condition, first hypothesized by D'Appolonia et al. (1967). Furthermore, severe desiccation of shear zone, which may in the rare case of very shallow slip surfaces contribute to the disruption of residual condition, is not a "healing" phenomenon.

De Beer (1967), while studying the residual shear strength of the overconsolidated Boom clay, speculated on the "recovery of strength." Assuming that the residual condition was properly defined in the Ghent tests on Boom clay reported by De Beer (1967), the difference in the residual friction angle of 15° in Ghent tests and 11° in Danish tests can be partly explained by the lower effective normal stresses used in the Ghent tests. It is also possible that the precut plane, which was produced in the Ghent tests before consolidation in the ring shear, after consolidation had moved down into the lower confining ring. In summary, the tests reported by De Beer (1967) provide no evidence to support "… recovery of strength in the shear zone … due to the reforming of bonds …." In fact, De Beer (1967) concluded that practical evidence obtained in Belgium shows that the residual shear box angle on previously cut samples is relevant for new slides along old sliding surfaces. Referring to the De Beer (1967) idea of "reforming of bonds," Morgenstern (1967) explained that this healing is not compatible with known field behavior, and the discrepancies discussed by De Beer may be a question of testing technique.

In a laboratory study of "Thixotropic effects on residual strength of remolded clays," Ramiah et al. (1973), normally consolidated in a direct shear apparatus, remolded specimens of a bentonite ($w_\ell = 400\%$, $I_p = 354\%$, $CF = 71\%$) and a kaolinite ($w_\ell = 66\%$, $I_p = 23\%$, $CF = 11\%$) to effective normal stress of 30, 60, and 100 kPa, sheared to residual condition by multiple reversal shear, and then allowed to rest for up to 96 hours. The study by Ramiah et al. (1973) may not be relevant to residual shear strength condition, which is encountered in the field in stiff clays and shales with a liquidity index commonly less than or near zero. It is unlikely that: (a) residual condition—orientation of particles in the direction of shear to the maximum extent possible—actually developed at every reversal within the fresh soil that came in from top half of the sample; and (b) shearing to residual condition completely arrested secondary compression of bentonite samples normally consolidated from a liquidity index of 1.85 to 30, 60, or 100 kPa. Ramiah et al. (1973) appear to have been aware of the limitations of their testing program as they noted that most stiff clays and shales have natural water contents at or near plastic limit, and a rest period following the residual condition may not show any significant strength increase at high consolidation pressure.

Nieuwenhuis (1991) describes a series of ring shear tests carried out in connection with the La Mure landslide in the French Alps, with slide planes at approximately 4-m depth and ground water level that drops to levels at or below the slide planes (Van Genuchten and Nieuwenhuis 1990). In the Utrecht State University ring shear device, the gap between the upper and lower confining rings is sealed by O-rings and inner and outer steel rings to control porewater pressure. One ring shear test on a varved clay is described in detail; however, a general conclusion is reached on "regain in shear strength due to stopping the rotation."

Serious problems exist with the ring shear test and interpretations of Nieuwenhuis (1991), briefly including the following: the O-rings and inner and outer steel rings assembly packed with extruded soil could result in a "jump of 7% in shear strength … after stopping the rotation for a number of hrs" and restarting, reporting that "… the sample is pushed through the gap between upper and lower rings and loss of soil through the gap continuing during the whole test." For the La Mure landslides, if in fact a "strength gain" over residual strength from laboratory tests has been back-calculated (not reported by Nieuwenhuis 1991) following severe dry-wet seasons, it could be caused by disruption of slip surface at residual condition by nonuniform desiccation and consolidation swellings (i.e., increase and decrease in effective normal stress).

In a series of articles, Angeli et al. (1996, 1999, 2004) employ "strength regain" to interpret observations of groundwater-level changes and slope movements for the 1-km-long Alvera mudslide with preexisting slip surfaces. It is deduced, assuming infinite slope behavior, that the mobilized shearing resistance required to stop movement is equal to the drained residual shear strength on the basis of conventional laboratory tests, whereas the mobilized shearing resistance that must be overcome to reinitiate movement is larger by 1 kPa for the slip surface at 5-m depth. In a comprehensive update on measurement and field application of residual shear strength, Skempton (1985) concluded that there can be little doubt that the tests and back-analyse are measuring the same strength, and stability analyse and laboratory tests cannot be expected to yield results with an accuracy better than approximately $\pm 10\%$.

Angeli et al. (1996) examined "strength regain" by means of drained direct shear tests (1996) and ring shear tests using the Bromhead apparatus (2004). The peaks observed following rest periods in direct shear tests, apparently normally consolidated to 71 kPa, resulted from vertical movement, during the rest period, of the slip surface into the lower half of the shear box. Part of the slip surface had to be reformed on reinitiation of shearing, resulting in the observed peaks.

The Bromhead smear-type ring shear device is a simple and inexpensive practical apparatus for measuring residual shear strength of clay compositions (Bromhead 1979; Bromhead and Curtis 1983; Salt 1988; Stark and Eid 1994). In the Bromhead ring shear device, using a remolded specimen of initial 5-mm thickness, the shear strains are concentrated at the top of the sample, and a slip surface [0.5 mm in thickness according to Salt (1988)] forms next to the upper platen, which is serrated to prevent slip at the platen/soil interface. For this reason, the Bromhead ring shear device is not suitable for examining the plausibility of "strength regain" at residual condition. Any vertical movement (measured in microns) of soil into or out of the serrations, as a result of compression or swelling during the rest period, is expected to disrupt the preexisting slip surface. Upon reshearing, the slip surface is reformed at thousands of points on the plane next to the upper platen. Therefore, the observed peaks do not represent "strength regain" on a preexisting slip surface already at residual condition. For the same reason, the peaks are lost only after a few mm of shear displacement. This type of boundary condition effect is not expected in field situations.

The rocks that have produced the Alvera mudslide are rich in calcite and other soluble minerals. In the field, especially when the shallow landslide is nearly "stationary," precipitation of calcite in the shear zone, in addition to the decrease and increase in effective normal stress, could produce a peak at the reinitiation of shearing (e.g., Hawkins and Privett 1985). Angeli et al. (2004) concluded that the precise mechanism responsible for strength regain must remain an open question, and its application into engineering of stabilization measures should be approached with great caution. Finally, the slight difference interpreted by Angeli et al. (1996, 2004) between the shearing resistance that was overcome to reactivate slope movement, and shearing resistance that was mobilized to stop movement, may be attributed to displacement self-stabilization where geometry allows (Salt 1988; Skempton et al. 1989).

Gibo et al. (2002) examined strength recovery from residual condition in reactivated landslides using a new ring shear apparatus with shear surface within soil at the gap between the upper and lower confining rings. Remolded samples from the Kamenose landslide ($w_\ell = 114\%$, $I_p = 64\%$, $CF = 73\%$; 77% smectite—Ca and Mg montmorillonite, 14% quartz), and Xuechengzhen landslide ($w_\ell = 32\%$, $I_p = 14\%$, $CF = 10\%$; 25% chlorite, 30% mica, 33% quartz, 11% feldspars) were used in the ring shear tests. After normally consolidating the remolded Kamenose samples to 50, 100, 200, and 300 kPa, and shearing to residual condition (shear displacements of 970 to 2,300 mm were required because remolded intact specimens were used), shearing was stopped and the soil was consolidated for two days without allowing displacement by shear. Upon reshearing, no peak and no change in residual shear strength was observed. The values of $[\phi'_r]_s$ before and after the rest period were 13.3, 10.8, 8.8, and 7.0°, respectively, at 50, 100, 200, and 300 kPa effective normal stress. Gibo et al. (2002) concluded that the strength recovery from the residual state rarely occurs in the Kamenose sample.

Remolded samples of Xuechengzhen material were normally consolidated to 30, 60, 100, and 200 kPa, sheared to residual condition (after 95 to 110 mm displacement for 30 and 60 kPa effective normal stress, and after 225 to 264 mm displacement for 100 and 200 kPa), and allowed to rest for two days. Upon reshearing, practically no change in shear strength was observed at 100 and 200 kPa effective normal stress. However, some increase in shear strength was observed at effective normal stress of 30 and 60 kPa. For Xuechengzhen material with a plasticity index of 14%, residual shear strength was only slightly smaller than the fully softened shear strength, especially at effective normal stresses less than 100 kPa. For example, at $\sigma'_n = 60$ kPa, $[\phi'_{fs}]_s = 32°$ and $[\phi'_r]_s$ before aging was 29°, and after aging it was 31°. In other words, for the Xuechengzhen mineralogical composition, residual condition defined by plate-shaped particles highly oriented in the direction of shear, is hardly applicable.

Strength gain on the basal shear surface was postulated by Bromhead and Clarke (2003) to explain basal incorporation in coastal landslides. According to Bromhead and Clarke (2003), moisture content changes in mudslide mass down to and including the basal shear surface—slope dries out. Drying and wetting (compression and swelling) of basal shear surface disrupt residual condition fabric and require shearing displacement to return to the residual condition. The strength gain from desiccation and wetting may be enhanced by accumulation of salt (from coastal salt sprays) in the basal shear zone and cation exchange and chemical bonding by calcite and iron compounds (Moore and Brunsden 1996; Moore 1991; Kenney 1967; Anson and Hawkins 1998; Tiwari et al. 2005). For a coastal mudslide at Dorset, England, the porewater concentration along the basal shear surface was 75 meq/l, compared with 50 meq/l for in situ ground water (Moore and Brunsden 1996). For shallow landslides in arid conditions, strength gain resulting from desiccation, accumulation of salt, or precipitation of cementing agents, offers no evidence to support the "healing" that allegedly takes place on slip surfaces at constant external conditions.

Ring shear tests were carried out by Carrubba and Del Fabbro (2008) using the Bromhead apparatus on a reconstituted sample of Cormons flysch from northern Italy to study "strength gain at the reactivation of displacements along aged sliding surfaces" because "back analyses of reactivated landslides have outlined that mobilized in situ strength along preexisting sliding surface may be slightly greater than laboratory residual strength."

Reconstituted samples of Cormons flysch ($w_\ell = 45 - 51\%$, $I_p = 23$–27%, $CF = 25$–40%, $w_o = 21$–26%, $\phi'_{fs} = 27$–$28°$) were normally consolidated from an initial water content 1.5 times the liquid limit, to 25, 50, or 100 kPa, sheared to residual condition, and then aged for up to 30 days. Carrubba and Del Fabbro (2008) concluded that "the self-healing process causes an increase of shear strength above the residual value, and may lead to shear strength close to or greater than [the fully softened], although affected by considerable brittleness" (i.e., the strength increase observed at reinitiation of movement was lost in less than 1 or 2 mm of shear displacement). Carrubba and Del Fabbro (2008), using a power law, extrapolated their laboratory measurements to report after 1 year of aging an increase in "shear strength angles at reactivation" of 9.0 to 10.0° at $\sigma'_n = 25$ kPa, and 4.5 to 5.0° at $\sigma'_n = 100$ kPa. Even more unreasonable and misleading friction angles were reported by Carrubba and Del Fabbro (2008) for 10 and 100 years of aging. These are hardly "slightly greater than laboratory residual strength."

One useful aspect of Carrubba and Del Fabbro (2008) was their reports of large compressions that took place during the aging at residual condition in Bromhead apparatus. As explained for the tests by Angeli et al. (2004), the movement of the Cormons flysch into the roughened upper platen of the Bromhead apparatus disrupted the slip surface and residual condition fabric, leading to a shear strength "close to or greater than" the fully softened strength. Such a "healing" is not expected on preexisting shear surfaces in the field.

The "healing" tests reported by Stark et al. (2005) were carried out using the Bromhead ring shear apparatus and suffered from the same problems described for the tests by Angeli et al. (2004) and Carrubba and Del Fabbro (2008).

Tests to Examine Aging of Residual Condition

A series of drained multiple reversal direct shear tests was carefully planned and conducted to examine aging of the residual condition. A key requirement was to minimize vertical movement of the slip surface at residual condition so that throughout the entire test, the slip surface would remain within the gap between upper and lower halves of the shear box. A Wykeham Farrance direct shear device with 60 × 60 mm inside dimensions was used.

Tests on Beaumont Clay

A sample of Beaumont clay from Houston ($w_\ell = 73\%$, $I_p = 50\%$, $CF = 70\%$) was air-dried and pulverized for the entire sample to pass a No. 200 U.S. standard sieve. Distilled water was added to obtain a water content near the liquidity index of 1.5 and the sample was allowed to hydrate for at least one week. Then, the water content was decreased to 49.2% by gradually air-drying and mixing. A precut direct shear specimen was prepared using the procedure described by Mesri and Cepeda-Diaz (1986). The two halves of the reconstituted precut specimen were separately consolidated inside the top and bottom halves of the direct shear box. Each face of the shear surface was consolidated against a Tetko Polyester screen (HD7-6) supported by a smooth and flat Teflon plate. These specimens were consolidated in increments to a maximum effective normal stress of 2,700 kPa, unloaded in decrements to 100 kPa, and then reloaded to 300 kPa.

The two halves of the shear box were rapidly unloaded, and the two flat and smooth surfaces were assembled together. An adjustable spacer below the lower porous stone was set to produce, upon reapplication of normal stress, a 1 mm lift of the lower half of the specimen to ensure that the precut slip surface remained throughout the test within the gap between upper and lower halves of the shear box. The effective normal stress of 300 kPa was reapplied and a compression of less than 0.5 mm was measured in one day. The upper and lower halves of the shear box were disconnected and separated by approximately 1 mm. After two complete forward and two complete reverse shearing at the rate of 3.3×10^{-4} mm/min, during the residual condition of the third forward shear ($[\phi'_r]_s = 7.0°$ at 300 kPa), the motor was turned off and residual condition fabric was aged for 7.5 days. On reinitiation of shearing, no peak and no increase in residual shear strength was observed. During shearing under effective normal stress of 300 kPa, the liquidity index of the specimen was zero, and total compression of the specimen was 0.12 mm (Fig. 4).

Then the lower half of the shear box was brought back to its original position and the two halves were screwed together, and normal stress was reduced to 200 kPa. Rebound was observed to complete primary swelling and some secondary swelling in approximately one day. The screws were removed, the upper and lower halves of the shear box were separated by 1 mm, and shearing was resumed under an effective normal stress of 200 kPa. After one forward and one reverse shear, shearing was stopped during the second forward shear ($[\phi'_r]_s = 7.4°$ at 200 kPa) for 7.5 days. Upon reshearing, no initial peak and no increase in residual shear strength was observed. During this unloading and shearing process, the total rebound of the specimen was 0.11 mm (Fig. 5).

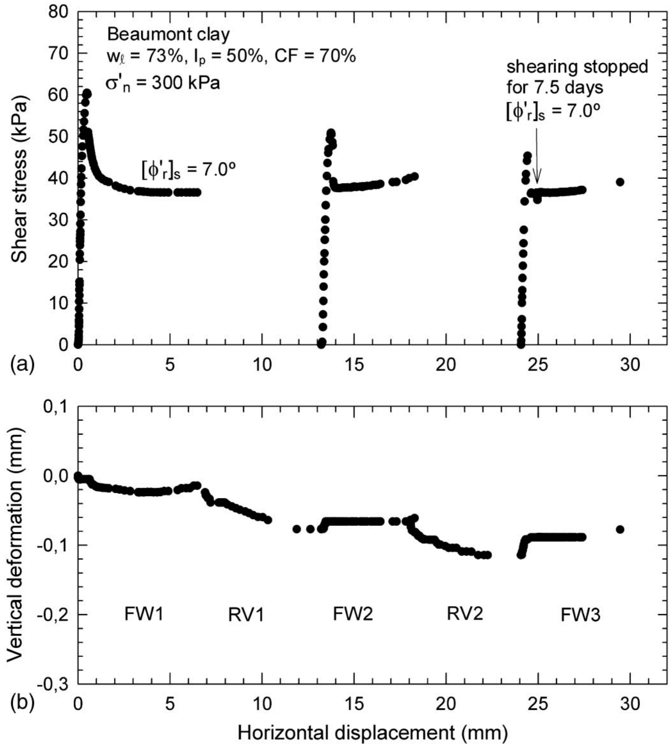

Fig. 4. Drained multiple reversal direct shear test on precut reconstituted Beaumont clay to examine possible aging of residual condition at $\sigma'_n = 300$ kPa

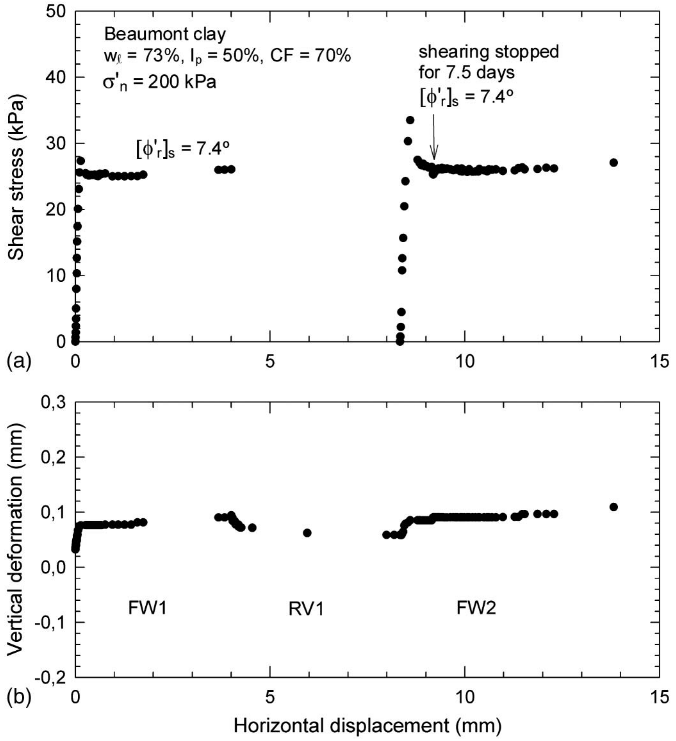

Fig. 5. Drained multiple reversal direct shear test on precut reconstituted Beaumont clay to examine possible aging of residual condition at $\sigma'_n = 200$ kPa

The lower half of the shear box was brought back to its original position and the two halves were screwed together, and normal stress was increased to 400 kPa. After primary recompression and some secondary compression in approximately one day, the screws were removed, the upper and lower halves of shear box were separated by 1 mm, and shearing was resumed. Aging of residual condition for 7 days was allowed during the second forward shear ($[\phi'_r]_s = 6.6°$ at 400 kPa). Upon reshearing, no initial peak or increase in residual strength was observed. (After almost 60 mm of cumulative shear displacement, some extrusion had taken place, and no further shearing was contemplated.) The total vertical compression of the precut specimen starting from shearing under 300 kPa, unloading and shearing under 200 kPa, and then reloading and shearing under 400 kPa, was 0.45 mm (Fig. 6).

Tests on Brenna Clay

A second series of drained multiple reversal direct shear tests was conducted on a reconstituted precut specimen of Brenna clay from Grand Forks, North Dakota, with liquid limit, plasticity index, and clay-size fraction, respectively, 91, 53, and 87% (Mesri and Huvaj 2004). The specimen preparations for the direct shear test and consolidation history up to 300 kPa were identical to those for Beaumont clay in the first series of tests. The precut specimen was subjected to two forward and two reverse shearing, reaching residual condition after 26 mm shear displacement under effective normal stress of 300 kPa. The lower half of the shear box was brought back to its original position and the two halves were screwed together and normal stress was reduced to 100 kPa and then to 50 kPa. Under both normal stress decrements, complete primary swelling and some secondary swelling was allowed. The screws were removed, the upper and lower halves of the shear box were separated by 1 mm, and shearing was resumed under an effective normal stress of 50 kPa. After one forward and one

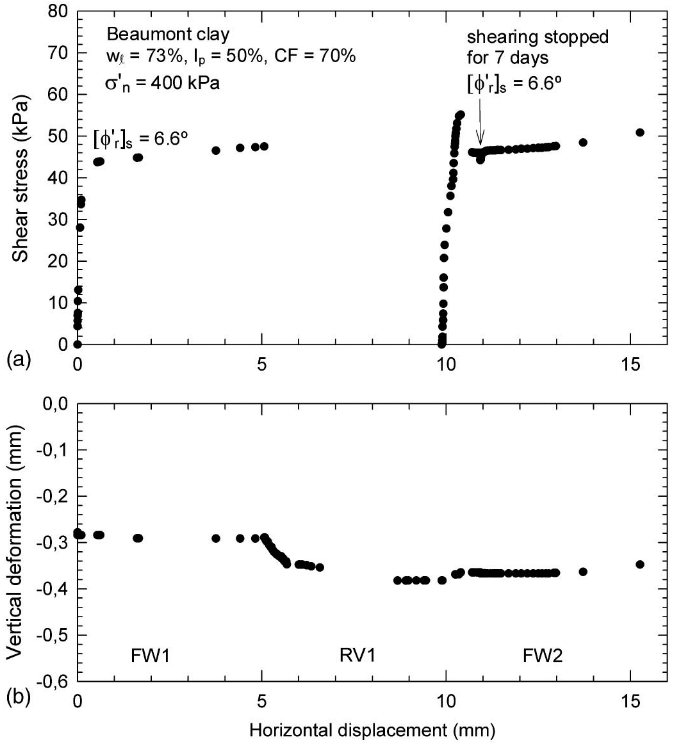

Fig. 6. Drained multiple reversal direct shear test on precut reconstituted Beaumont clay to examine possible aging of residual condition at $\sigma'_n = 400$ kPa

reverse shear, residual condition was reached under effective normal stress of 50 kPa. During the third forward shear and at cumulative shear displacement of 60 mm, shearing was stopped for 7 days. Upon reshearing, no increase in residual shear strength was observed. Shearing was continued and during the fourth forward shear and cumulative shear displacement of 72 mm, shearing was stopped for 30 days. When shearing commenced, no initial peak and no increase in residual shear strength was observed. The drained reversal direct shear test results on the Brenna clay, during the last three forward shears, including the two aging periods, are shown in Fig. 7.

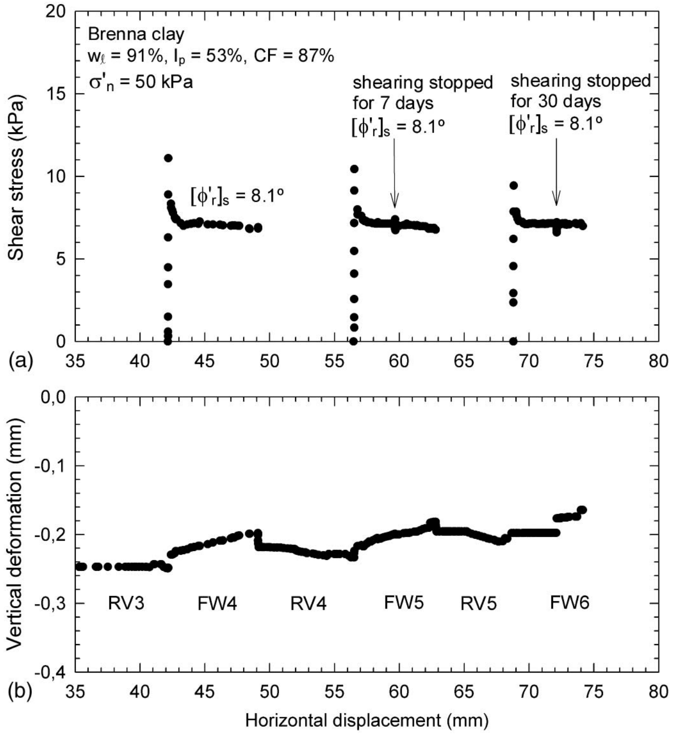

Fig. 7. Drained multiple reversal direct shear test on precut reconstituted Brenna clay to examine possible aging of residual condition at $\sigma'_n = 50$ kPa

In summary, no "healing" or "strength regain" was observed in these tests. The five examinations of aging of residual condition using the direct shear apparatus were successful because throughout the shearing and aging periods, the slip surface remained within the gap between the upper and lower halves of the shear box. Upon dismantling, a flat, highly polished, and slightly striated slip surface was observed for both the Beaumont and Brenna clays. The value of m_r is 0.87 on the basis of the secant residual friction angles at three values of effective normal stress for Beaumont clay and at two values of effective normal stress for Brenna clay.

Summary and Conclusions

The stability, even the movement (e.g., Skempton et al. 1989), of reactivated landslides has been successfully evaluated and interpreted using the assumption that shear strength mobilized on the slip surface of a landslide is equal to the residual shear strength on the basis of laboratory drained multiple reversal direct shear, or ring shear tests, independent of the time after reaching the residual condition. Landslides with a slip surface at residual condition, on a long-term basis, rarely remain stationary and may move at the rate of approximately 2–50 mm/year (e.g., Skempton and Hutchinson 1969; Skempton et al. 1989). As pointed out by Skempton (1985), stability analysis and laboratory tests cannot be expected to yield results with accuracy better than approximately $\pm 10\%$.

Residual condition on a slip surface is reached when, upon shearing, plate-shaped clay particles become oriented face to face and parallel to the direction of shearing to the maximum extent possible under the operating effective normal stress. The secant residual friction angle is a function of effective normal stress under which the residual condition is reached through shearing; as effective normal stress increases, a higher degree of particle orientation and alignment becomes possible, and thus $[\phi'_r]_s$ decreases.

When effective normal stress on a shear plane at residual condition is increased or decreased, after compression or swelling, further shearing is required to reach the residual condition under the new effective normal stress. Depending on the magnitude of the change in effective normal stress, and the nature of the compression or swelling, a peak may be observed before reaching the new residual condition. This peak is often lost after small shear displacements, and in the field changes in effective normal stress resulting from the fluctuations of groundwater pressure may have some effect on short-term movement of the slope; however, it is unwise, as Chandler (1977) pointed out, to place any reliance on this peak strength for long-term movement and stability of landslides.

Numerous examples in the literature confirm, as pointed out by Morgenstern (1977), that residual strength is only available if movement is renewed or accelerated along the preexisting slip surfaces. No gain in strength has been observed following the aging of residual condition in reliable ring shear tests (Bishop et al. 1971; Gibo et al. 2002) in which the slip surface remained within the gap between upper and lower confining rings. The laboratory data suggesting "healing" or "strength regain" in terms of a peak observed upon reshearing, have primarily originated from (1) drained reversal direct shear tests, especially on normally consolidated specimens in which the slip surface, if any, most likely moved down into the lower half of the shear box, creating an initial resistance and associated peak as a new slip surface was being formed; and (2) drained ring shear tests in the Bromhead apparatus in which the slip surface forms next to upper platen, which is serrated (artificially roughened) to prevent slip at platen/soil interface. Any vertical movement of soil into or out of the serrations, during aging at residual condition, disrupts the residual condition fabric at numerous points and upon reshearing leads to a brittle peak. The peak is lost after a few millimeters of shear displacements as the slip surface at residual condition is readily reformed by shear strains concentrated at the top of the specimen.

In the drained multiple reversal direct shear tests reported here, every effort was made to keep the slip surface at residual condition within the gap between the upper and lower halves of the shear box. No peak and no increase in residual strength was observed upon reshearing, following aging times in the range of 7 to 30 days under five different effective normal stresses for two different clay compositions.

In certain special field conditions, changes in a number of external factors may contribute to an increase in shearing resistance on a preexisting shear surface. The shear strength may increase as a result of penetration and reinforcing action of tree roots, especially in the case of shallow slip surfaces (e.g., thin colluviums). The so-called "root cohesion" is generally less than 7 kPa (Fleming and Johnson 1994; Turner 1996; Sidle and Ochiai 2006); however, values as high as 94 kPa have been reported (Schmidt et al. 2001). The shear strength of the shear zone may also increase as a result of chemical changes, including accumulation of salt especially in coastal areas, precipitation of carbonates and iron compounds, and exchange of lower valence to higher valence cations (Kenney 1967; Chandler 1969; Hutchinson 1965, 1969, 1970; Hawkins 1988; Moore 1991; Hawkins and McDonald 1992; Anson and Hawkins 1998, 2002; Tiwari et al. 2005). For shallow landslides, suction resulting from drop of groundwater level below the slip surface is expected to temporarily increase shear strength. Ignoring suction in stability analyses is expected to lead to an underestimation of actual factor of safety (Brand 1985; Au 1998; Bromhead and Clarke 2003; Bromhead 2004; Cornforth 2005). Severe desiccation and nonuniform swelling may also disrupt the slip surface and lead to a temporary increase in shear strength on preexisting shear surfaces.

The possible effect of tree roots, chemical changes, suction, desiccation, and groundwater level fluctuations on the stability of a landslide should not be overlooked in favor of "healing" or "strength regain" under constant conditions. These external changes can lead to a temporary increase in factor of safety of a landslide; however, their contribution to long-term stability has not been conclusively established by a significant body of field evidence.

Acknowledgments

Nejan Huvaj-Sarihan was supported by a Department of Civil and Environmental Engineering Teaching Assistantship during part of her graduate study at the University of Illinois at Urbana-Champaign. The direct shear test on Brenna clay was conducted by graduate student Mohammad Moridzadeh.

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