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Clay Shear Strength Rate Dependency and the Available Strength Along Earth Slides Rupture Surfaces

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ABSTRACT

Earth slide movements are affected by the shear behavior of the material in their shear zone. In many cases, the earth slide shear zones are made of weak clay layers. Traditional geotechnical laboratory testing utilizes standard loading rates for determining the shear behavior of clay. When an earth slide movement creates field shear rates that are faster or slower than the typical laboratory test ranges, the available shear strength along the rupture surfaces can differ from the laboratory predicted strength. The effect of the clay viscosity on observed behavior of earth slides founded on clay beds is examined in this paper. This paper demonstrates how some of the earth slides characteristics can be explained by considering the rate dependency of the shear strength of clay. This paper provides a review of available clay shear strength within an earth slide shear zone from pre-failure to failure conditions. The pre-failure peak and residual shear strength rate are reviewed. The residual strength during failure and its dependency on the clay content, pore fluid chemistry, and stress history is discussed. In general, the lower shear rate results in smaller available shear strength along a rupture surface. Both peak and residual shear strength reduce with slower shear rate prior to the failure. After full development of the rupture surface, the shear strength increases nonlinearly with the shear rate increase. The non-linear increase in the clay strength during failure is due to the clay viscosity shear thinning characteristics. The clay viscosity depends on the clay mineralogy, pore fluid chemistry, and liquidity index. This paper discusses that by correlating the clay viscosity with the stress history, clay mineralogy, and clay content; an estimation of the available shear strength of clay beds and order of magnitude of rate of movement are possible.

RÉSUMÉ

Les mouvements de glissement de terrain sont affectés par le comportement de cisaillement des matériaux à la zone de cisaillement. Dans de nombreux cas, les zones de cisaillement des glissements de terrain sont constituées par les couches faibles d'argile. L'approche traditionnelles des essais au laboratoire géotechniques utilisent des taux de chargement standard pour déterminer le comportement de cisaillement de l'argile. Lorsqu'un mouvement de glissement de terrain crée des taux de cisaillement sur le terrain qui sont plus ou moins rapides que la gamme d'essais laboratoire spécificité, la force disponible de cisaillement au long des surfaces rompus peut être différent de la résistance prévue au laboratoire. L'effet de la viscosité de l'argile sur le comportement observé des glissements de terrain trouvés sur les couches d'argile est examiné dans cet article. Cet article montre que certains des spécificité des glissements de terrain peuvent être expliquées en considérant le taux dépendance de force cisaillement de l'argile. C'est aussi, une révision de la résistance disponible au cisaillement de l'argile disponible dans une zone de cisaillement de glissement de terrain, de la pré-rupture aux cours de la rupture. Le pic de pré-rupture et le taux de résistance au cisaillement résiduel sont examinés. La résistance résiduelle pendant la rupture et sa dépendance à la teneur d'argile, à la chimie des fluides interstitiel et à l'historique des contraintes sont discutées. En général, le taux plus faible de cisaillement peut avoir pour une résistance au cisaillement disponible plus petite le long d'une surface de rupture. La résistance au cisaillement maximale et résiduelle diminue avec un taux de cisaillement plus lent avant la rupture. Après le développement complet de la surface de rupture, la résistance au cisaillement augmente de manière non linéaire avec l'augmentation du taux de cisaillement. L'augmentation non linéaire de la résistance de l'argile pendant la rupture est à cause de propriété fine de la viscosité d'argile au cisaillement. La viscosité de l'argile dépend de la minéralogie de l'argile, de la chimie du fluide interstitiel et de l'indice de liquidité. L'objectif de ce travail est d'étudier la relation de la viscosité d'argile avec la tension antécédent, la minéralogie de l'argile et le contenu d'argile, une estimation de la force disponible de cisaillement des couches d'argile et de l'ordre de grandeur de la vitesse de déplacement est faisable.

1 INTRODUCTION

Earth slides are significant ground hazards threatening infrastructures (Hungr et al. 2005). Despite traditional landslide engineering efforts to predict and prevent failure of earth slopes, in reality, prevention of all earth slides is neither practical nor economical. Therefore, the earth slides impose risks to many human activities from linear infrastructures (i.e., roads, pipelines, railways) to open-pit mine slopes. These infrastructures bear the effects of earth slides that vary from loss of life due to rapid earth slide movements to regular maintenance requirements related to continuous or continual movements of slower earth slides. The earth slide types vary from translational earth slides, controlled by weak layers in the foundation, to rotational earth slides in more homogeneous soil, to flow slides. Reactivation of earth slides may occur along previously developed rupture surfaces due to natural causes or human activities (Cruden and Varnes, 1996) (Hungr et. al. 2014).

Regardless of the triggering mechanism, the consequence of earth slides failure is a direct function of the rate of movement of the earth slide. This paper focuses on parameters that affect the post-failure movement rate of an earth slide.

2 EARTH SLIDES MOVEMENT

Earth slides go through pre-failure deformation, failure, and post-failure displacement (Skempton and Hutchinson 1969). Cruden and Varnes (1996) classified the slides into seven velocity classes based on their movement rate (Table 1).

Table 1. Landslide Velocity Scale (Cruden and Varnes, 1996)

Velocity Class	Description	Velocity (mm/sec)	Typical Velocity
7	Extremely Rapid	$>5X10^{3}$	> 5 m/sec
6	Very Rapid	$5X10^{1}$ - $5X10^{3}$	5 m/sec to 3 m/min
5	Rapid	$5X10^{1}$ - $5X10^{-1}$	1.8 m/hr to 3 m/min
4	Moderate	$5X10^{-1}$ - $5X10^{-3}$	13 m/month to 1.8 m/hr
3	Slow	$5X10^{-3}$ - $5X10^{-5}$	1.6 m/year to 13 m/month
2	Very Slow	$5X10^{-5}$ - $5X10^{-7}$	16 mm/year to 1.6 m/year
1	Extremely Slow	$<5X10^{-7}$	<16 mm/year

Depending on the movement rate, the ability to respond to the earth slides varies. Typically, there is no time to react to landslides with velocity classes 6 and 7, there might be time for evacuation for landslide velocity classes 4 and 5, and maintenance measures are possible for landslide velocity classes 1, 2 and 3. Therefore, a prediction of an order of magnitude of landslide movement rate is useful for risk management purposes. Despite continuous effort from geotechnical engineers, prediction of movement rates in various stages of the earth slides has been a challenge.

3.1 Pre-failure Deformation

Following a triggering event, the earth slide movement initiates with an elastic deformation stage in the sliding body followed by three phases of plastic strain development of the potential shear zone, namely primary, secondary and tertiary movement phases before full failure (Varnes 1978) (Figure 1). The primary movement stage is associated with progressive development of the shear zone. Plastic shearing of the shear zone continues with a secondary creep phase with constant shear stress. Eventually, the entire shear zone material strains beyond the strain corresponding to the peak shear strength. At this stage, the shear strength at the entire shear zone drops from the peak to critical state (CS) shear strength. With further movement, the rupture surface is fully developed to a residual shear strength along the shear zone, and the earth slide accelerates to the final failure stage (tertiary movement stage).

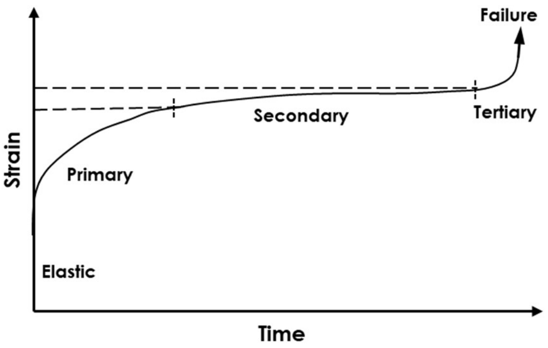


Figure 1. Typical Pre-failure movement stages of an earth slide

Geotechnical engineers commonly use an empirical approach to estimate the time to failure (Federico et. al. 2012). These widely used empirical correlations estimate the time to failure based on the inverse velocity method (Fukuzono, 1990). The method is based on the inverse rate methods that were previously introduced for the prediction of volcanic eruptions (Voigth, 1988).

3.2 Failure

After full development of the rupture surface, the earth slide can accelerate beyond the movement rate present during the pre-failure stage.

At this stage, the earth slide mass movement may change to a flow slide (i.e., fast liquid-like shear movement within the superficial layers) or move on a distinct shear zone (i.e. rupture surface) (Vulliet and Hutter, 1988) (McDougall 2017). The flow slides typically develop in homogeneous natural deposits or manmade earth fills (i.e. waste rock dumps). The flow slides normally occur in material with higher than their typical water content, access to water, or the possibility of skeleton collapse. In many cases, the existence of weak layers at the base of the earth slide concentrates the movement in a shear zone within the weak layer. This usually results in a translational earth slide on the weak layer. In some cases, translational movements are not limited to only one rupture surface. They frequently slide on rupture surfaces at several depths. These earth slides may be regarded as a set of blocks, one sliding over the other (Eshraghian et a. 2008, Vulliet and Hutter, 1988).

3.3 Post-Failure

After full development of the rupture surface, the driving forces from gravity and water pressure are larger than the resisting forces that are generated by the base and internal shearing. At this stage, the earth slide mass accelerates until a new balance between the resisting force and the driving force is achieved; the moving slide mass reaches an equilibrium velocity. The earth slide mass can continue moving with this velocity until either the driving force reduces, for example, with a change in geometry to a flatter overall slope or a reduction in the groundwater level, or increase in resisting force, for example, by reaching another earth mass at the toe.

The relationship between the driving force larger than the equilibrium resisting force (F_D-F_0) and equilibrium velocity is non-linear (Figure 2). In simple terms, the movement rate (v) is essentially negligible as long as the earth slide is in static equilibrium in which driving force (FD) is less than the minimum resistance force to start the movement (F0). The limit equilibrium force analysis simply checks if the summation of the driving forces is smaller than the summation of the resisting force. In this method, the resisting drag force along a sliding plane is estimated based on solid friction angle ignoring the strains, so the limit equilibrium methods do not consider the velocity field. The base resisting force is defined with considering the drainage condition (i.e., drained for slower loading and undrained for fast loading).

For earth slides with velocity slower than 10 to 100 m/hr, the inertia term in the movement equation does not play a significant role in the post failure stage (Vulliet and Hutter, 1988). In these situations, the equation of linear momentum reduces to the quasi-static equilibrium equations, and that stress can be determined (Vulliet and Hutter 1988). The dynamic equilibrium for most earth slides is therefore achieved when the driving force is equal to the dynamic shear resisting force which is a nonlinear function of velocity (i.e. soil viscosity).

Vulliet and Hutter (1988) demonstrated that the base resistance force is essentially a viscous fluid resistance. The limit equilibrium resistance (frictional resistance at static case) is essentially a subcase of general viscous shear resistance in which the static resistance is simply the yield strength of the viscous soil before the start of shearing.

Eshraghian et al. (2007) showed that the reactivation movement rate of earth slides is sensitive to the pore pressure changes on the earth slides rupture surfaces (Figure 3). With effective stress being a direct function of the pore pressure on the shear zone, the shear resistance can linearly decrease with an increase in pore pressure. As a result, the earth slides movement rate increases nonlinearly with increase of the This results in a non-linear correlation between the pore pressure in excess of the pore pressure at the start of movement and the earth slide movement rate.

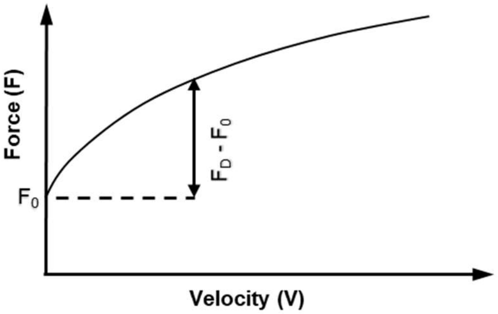


Figure 2. Typical Earth Slide Velocity versus Driving Force Relationship

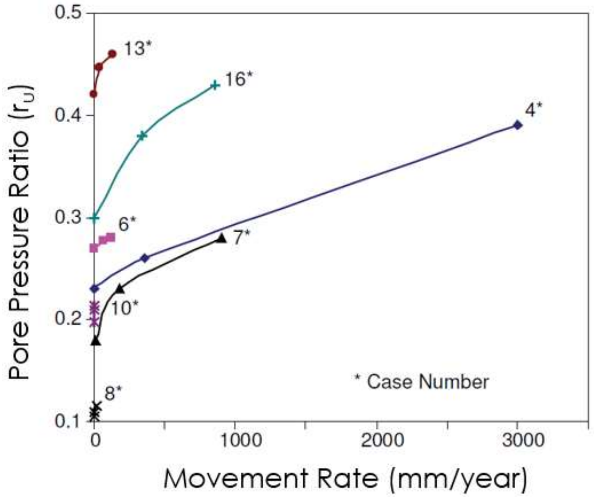


Figure 3. Reactivated Earth Slide Movement Rate versus Pore Pressure Ratio (r_u) (Eshraghian et al. 2007)

The pore pressure ratio at the start of movement (r_{u0}) is essentially the pore pressure ratio that causes a drop of the Factor of Safety to a value lower than unity. With pore pressure ratios (r_u) higher than r_{u0}, the slope starts moving. Eshraghian et al. (2007) demonstrated the non-linear relationship between translational earth slides velocity (V) and pore pressure ratio (r_u). They also showed that this non-linear relationship was correlated with plasticity index of the material within the shear zone and depth of the shear zone. The more plastic material and deeper shear zone resulted in a steeper slope of the non-linear curve (slower movement with the same change in pore pressure ratio r_u). These correlations can be best explained in terms of the shear zone soil viscosity.

3 SHEAR STRENGTH

Shear strength of a natural soil is a function of many factors, including its void ratio, gradation, clay fraction and activity, stress history, temperature, strain, strain rate, and structure. Many of these parameters are interrelated. Therefore, the normal practice is to test the soil samples under controlled environments as close as possible to the actual expected site conditions and loading history and only allow for some of these parameters to change during testing. Most of our knowledge on shearing strength of soil is developed based on controlled rate shear tests. These tests show three different levels of strength with change of strains as the peak strength (τ_{peak}) the critical state strength ($\tau_{critical\ state}$), and the residual strength ($\tau_{residual}$) envelope (Figure 4).

In dilative soils, highly overconsolidated fine grained soils or dense granular material, the shear strength increases to a peak value. The peak strength in a natural deposit is a result of microstructures (i.e., bonding between particles). Among the general factors that affect the peak shear strength of clays, overconsolidation and drainage conditions seem to be the most obvious influential factors. At the same stress level, overconsolidated clays show higher peak shear strength in comparison to normally consolidated clays. This difference is due to different compactness and water content during shearing.

After passing the peak shear strength, the rupture surface is formed, and the soil arrives to a critical state with constant volume shearing. The shear strength reduction from peak to critical state is associated with the breakage of bonds between particles and the change in void ratio. At this stage, the soil within the shear zone is completely restructured, therefore, the critical state shear strength and void ratio are independent of stress history and only depend on the current stress condition at the post shear state. From this stage, the volume of soil in the shear zone is constant (i.e. a constant void ratio and water content).

With further strain, the soil strength may reduce to a residual strength value associated with oriented particles at large displacement along the slip surface. The strength reduction after critical state to residual is more pronounced in soils with platy particles (i.e. clay).

The shear strength reduction from peak to yield strength (i.e. to critical state or residual strength) releases an extra energy to the earth slide mass, and therefore, affects the post-failure movement rate of the earth slides. This sudden extra energy available to the earth slide mass can be best presented by the brittleness index (Bishop 1967) or a generalized brittleness index (D'Elia et al. 1998). The generalized brittleness index defines the rate at which the strength decreases from the peak to the ultimate strength (Hight and Leroueil, 2003). The generalized brittleness is associated with a given stress path; therefore, it is not a fundamental soil characteristic. In general, the brittleness index decreases with decrease in the soil overconsolidation ratio. This brittle shearing can develop in overconsolided clays, cemented soils, quick clays, and dense sands. The generalized brittleness is close to zero for normally consolidated soils (OCR=1). Therefore, a soil high overconsolidation ratio can indicate the possibility of sudden movement acceleration for the earth slides in undisturbed deposits (i.e. not in a reactivated earth slide). Post failure shear strength is affected by the soil viscosity as discussed in the following section.

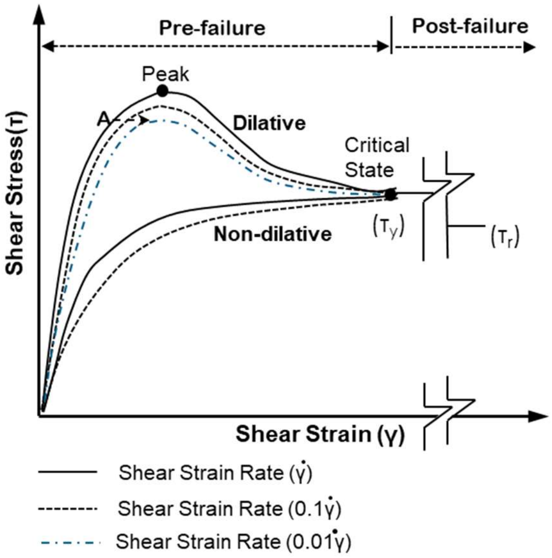


Figure 4. Typical Shear Strain Test on Dilative and Non-dilative Clays

4 SOIL VISCOSITY

The viscous behavior of soil affects the earth slides both before and after the full development of the rupture surface.

4.1 Creep Before Failure

Before full development of the rupture surface, the stress-strain behavior and the peak strength of soils are affected by the shear strain rate (Figure 4).

Although the effect of the shear strain rate on small strain range is not significant (the early part of the stress-strain curves), the shear stress-strain curves with various strain rates increasingly deviate from each other in higher strains. The peak shear strength is also a function of the strain rate, indicating that the failure envelope is a rate dependent surface (Hight and Leroueil, 2003). For an aged natural clay, the slower stress change can lead to a lower peak shear strength. Therefore, if loading brings the stress state close to the peak (point A on Figure 4), the creep can create more strain and bring the stress state to the peak at a lower strain rate envelope. The strain rate does not significantly affect the critical state line, but because the soil is following a smaller limit state envelope with a slower strain rate, the failure strength is also reduced. The effect of the rate of shearing on residual strength is small, smaller than 3% per logarithm cycle of rates, for rate of movement smaller than 1 mm/minute (Hight and Leroueil, 2003).

4.2 Post-Failure Viscous Behavior

After full development of the rupture surface and start of the failure, the shear strength may further drop to a residual shear strength due to realignment of the soil particles.

After reaching the critical state, the volume, and therefore the water content, of the shear zone is constant. The constant water content and constant volume shearing after failure cause a semi-liquid behavior within the shear zone in that the shear strength is primarily a function of the shear strain rate. The effect of the semi-liquid behavior on the shear zone shear strength is best described by the soil viscosity.

Viscosity is the result of the flow resistance created by internal friction of particles within the shear zone. Although the shear resistance within the shear zone (τ) increases with an increase in the shear strain rate ($\dot{\gamma}$), soils generally show a shear-thinning viscosity with a yield point (Mezger 2014) (Figure 5). In material with shear-thinning viscosity, the rate of increase in the shear resistance decreases with an increase in the shearing rate. The yield point at the start of viscous shearing is the large strain shear strength (i.e. residual strength) at the end of the rupture surface development (Figure 5). If the summation of external driving shear forces is smaller than the resistance that can be provided by the yield shear strength, the soil in the shear zone will still act as a soft solid, and there is no shear movement. When the driving shear forces are larger than the resisting force from the shear yield, the movement starts. In Newtonian Fluids, the rate of increase in shear strength with increase in shear strain rate is a constant, but in soil, with shear-thinning behavior, the rate of increase in the shear strength becomes smaller with the shear strain rate increase, although the actual shear strength increases with shear strain rate (compare viscosity η_1 and η_2 in Figure 5).

Soil viscosity values were reported by a few researchers (Widjaja and Lee, 2013, Locat and Demers, 1988, and Jeong et. al. 2010). Viscosity was found to be a function of the soil liquidity index (LI) (i.e. liquid limit (LL), plastic limit (PL) and natural water content (WC)). An increase in LI decreases the viscosity. The liquid limit and plastic limits of soils are related to the clay content and activity. Widjaja and Lee (2013) demonstrated that for the same clay mineralogy, the viscosity (η) increases with an increase in clay fraction (CF).

After reaching the critical state, the volume of the shear zone material does not change. The constant volume shearing results in a constant liquidity index after full development of the rupture surface and failure. The critical state void ratio depends on the stress level and drainage during shearing. Thefollowing section discusses some practical implications of soil viscosity on the post-failure movement rate of earth slides.

5 PRACTICAL IMPLICATIONS

Using the soil viscous behavior, some of the earth slides pre-failure and post-failure movement characteristics can be explained qualitatively.

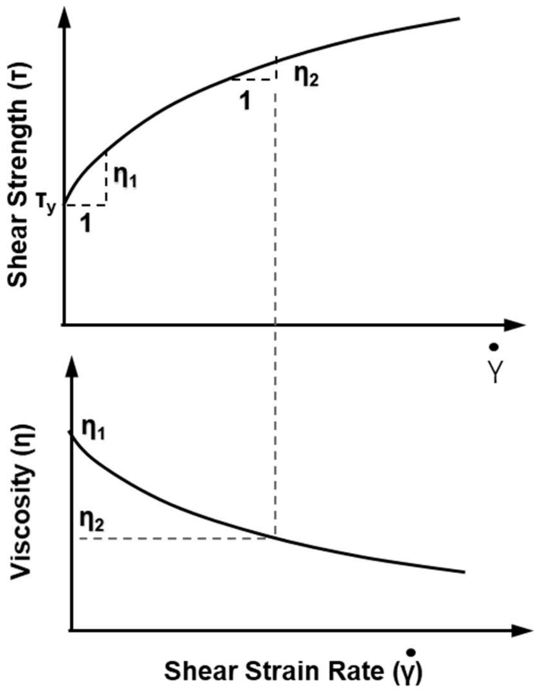


Figure 5. Typical Shear strength (τ) and viscosity (η) versus shear strain rate ($\dot{\gamma}$) for a specific liquidity index

5.1 Effect of Clay Fraction

Figure 6 presents a schematic change of viscosity and shear strength of two soils with the same clay mineralogy but different clay contents of CF1 and CF2 (CF1<CF2).

The higher the clay fraction or clay activity, the lower the yield strength, but the higher the viscosity (Figure 6) (Widjaja and Lee, 2013). Consider two earth slides with the same geometry but one on the shear zone from soil CF1 and another with rupture surface in soil CF2. With the same amount of additional force beyond the yield point (with Factor of Safety less than unity) ($\delta\tau$), the earth slide with shear zone in soil with lower clay content (CF1) must have a higher shear strain rate to achieve dynamic equilibrium. Therefore, higher clay fraction in the shear zone of the earth slide (e.g. slide with shear zone in CF2 soil) may have lower shear strain rate and possibly rate of movement (i.e. more ductile movement) with the same change in shear stress despite an easier start of failure in comparison to an earth slide with the same geometry but with lower clay faction (CF1) in its shear zone.

5.2 Effect of Stress Level

The stress level on the shear zone of an earth slide generally depends on its average depth.

The viscosity of the soil increases with decrease in liquidity index (LI). Therefore, for soil with specific LL and PL, a decrease in water content causes an increase in viscosity. Consider two earth slides A and B that are controlled by the same weak layer of normally consolidated soil. Now assume earth slide A has a deeper shear zone in comparison to earth slide B. Assuming that the shear zone material is normally consolidated (to eliminate the stress history effect), an average state condition for these two slides can be represented by points A1 and B1 along the Sedimentation Compression Line (SCL) on the water content (and LI) versus stress graphs as shown in Figure 7. Because the stress level A1 is larger than the stress level B1, the water content at point A1 is smaller than water content at Point B1. If both of these earth slides fail in undrained shear condition, at the critical state, water content of slide A is still less than water content of slide B (stress path A1 to A2 and stress path B1 to B2 in Figure 7). If the failures follow a drained condition, the void ratio of the normally consolidated soil in the shear zone decreases during shearing but after reaching the critical state, the water content of the deeper material is still smaller than the water content of the shallower material (Stress paths A1 to A3 and B1 to B3).

Therefore, the liquidity index of the deeper slide is most likely to be smaller than the liquidity index of the shallower slide during failure. As a result, the viscosity of the deeper slide is larger than the viscosity of the shallower earth slide. If these two slides are subject to the same average shear force along their slip surface, the dynamic equilibrium is achieved with a faster shear strain rate in the shallower earth slide in comparison to the deeper earth slide. If both slides have the same shear zone thickness, the shallower slide must go through a faster shear straining than the deeper slide. In many cases, the thickness of the shear zone is controlled by the thickness of the weak controlling layer in the foundation and an estimation of the actual movement rate is possible. In reactivation of earth slides, previous movements show the possible shear zone thickness for future movements.

5.3 Effect of Stress History and Loading Rate

Depending on the drainage boundary condition and the loading rate during development of the shear zone, the shearing may develop with minimal drainage and change in water content (i.e. undrained shearing) or with full drainage of shear induced excess pore pressure (i.e. drained failure). The drainage can affect the change in the water content before full development of the shear zone. Also, the stress history of the shear zone material affects the volumetric change during shearing, and therefore, the water content during shearing.

Consider a soil that has completed its self-weight consolidation to a stress state represented by Point A1 in a critical state diagram (Figure 8). Now assume that the unloading processes (e.g., by erosion of overburden) remove some of the load unevenly at the site resulting in different stress states at the location of two earth slides with the same geometry to current stress states of C0 and D0. As a result, the shear zone at one site is at a lightly overconsolidated state (C0) and at the other site at a heavily overconsolidated state (D0). If the failure in both cases is drained, the stress paths for these two shear zones are C0-C1-C2 and D0-D1-D2.

The undrained failure stress paths are C0-C3-C4 and D0-D3-D4. As shown in Figure 8, at the critical state, the heavily overconsolidated shear zone has a higher water content in comparison to the lightly overconsolidated shear zone (WD2>WC2 and WD4>WC4). As a result, the heavily consolidated shear zone has a higher LI in comparison to the lightly overconsolidated shear zone.

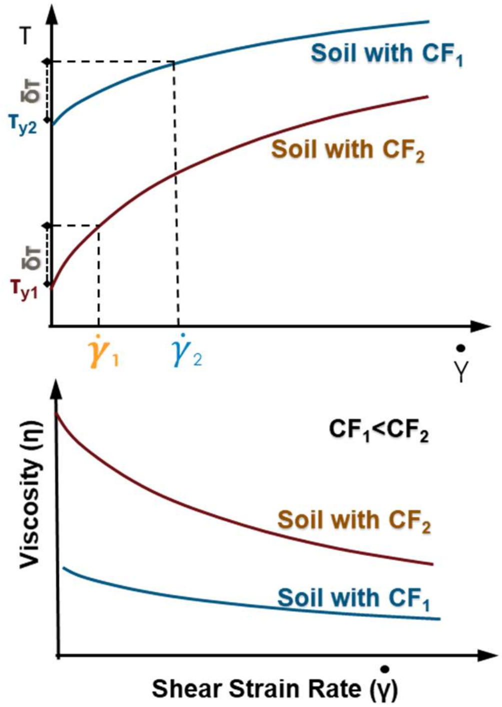


Figure 6. Change of viscosity and shear strength with clay faction

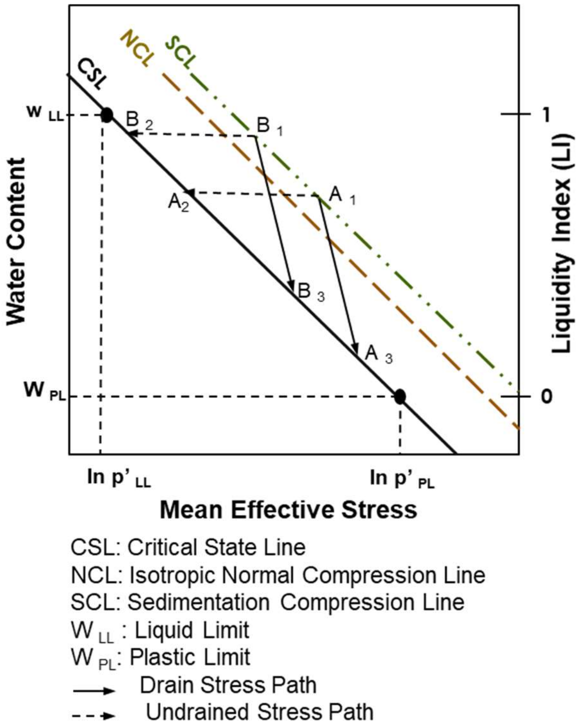


Figure 7. Effect of Stress Level on Critical State Water Content and Liquidity Index

Therefore, the viscosity of the heavily overconsolidated shear zone is smaller than the viscosity of the lightly overconsolidated shear zone.

Assuming the same geometry and unbalance force for the two earth slides, the earth slide with the heavily overconsolidated shear zone shall have a faster shear strain rate in comparison to the earth slide with lightly overconsolidated shear zone to achieve dynamic equilibrium. If the shear zone thickness is the same for these two earth slides, the earth slide with heavily overconsolidated shear zone must move faster than the slide with lightly overconsolidated shear zone.

As discussed in Section 3, overconsolidation may also increase the brittleness of the shearing in the first-time failure in soils. The sudden release of energy with brittle shearing and shear strength drop from peak to residual value can cause additional acceleration of the earth slide. Overconsolidation may also affect the shear zone thickness due to shear localization. This effect is discussed in the next section.

6 OTHER ASPECTS OF EARTH SLIDE SHEAR ZONE

In addition to soil viscosity, other aspects of the shear zone may affect the earth slide movement rates.

6.1 Shear Zone Localization

Because the actual earth slide velocity depends not only on the shear strain rate but also the shear zone thickness, knowledge or ability to estimate the shear zone thickness is essential to estimate the possible movement rate of the earth slide. The shear zone thickness needs to be measured from previous movements at the site or estimated by comparison with similar earth slides.

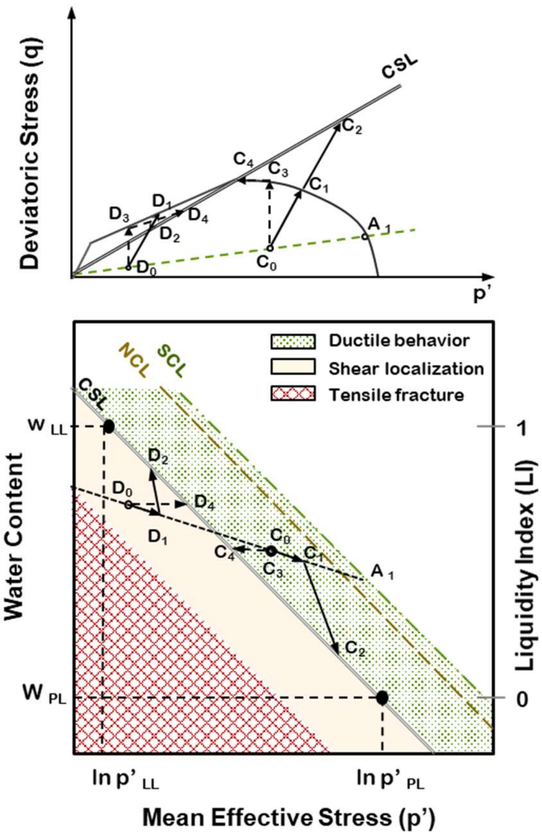
Shearing localization depends on the stress history of the shear zone. The shearing is ductile in shear zones within normally consolidated or slightly overconsolidated soils unless undrained shearing and liquefaction cause a sudden drop in shear strength values with strain. The shear zone can develop as a gradual uniform shearing within the uniform soil (Figure 8, ductile behavior zone). In uniform soil deposits, the shear zone can develop to the soil surface and the entire earth slide mass can become the shear zone. In earth slides with normally consolidated strata with limited thickness, the shear zone may be limited to the weak zone only.

The shear zone localization may occur in earth slides with heavily overconsolidated shear zones (Shear localization zone in Figure 8). In these cases, the shear zone may be thinner than the weak layer thickness.

In extremely overconsolidated soils, the failure can be controlled by tensile failure (tensile fracture zone in Figure 8). Shear failure and viscosity cannot be used for qualitative evaluation of the post-failure rate of movement in the tensile failure cases.

6.2 Entrapped Water in Shear Zone

Sometimes with available water sources to the earth slide surface or the sliding path, the water content of the sliding mass can even increase to values higher than LL. In these cases, the water can be entrapped within the shearing zone. Very high water content in the shear zone results in the development of a flow slide.



CSL: Critical State Line
NCL: Isotropic Normal Compression Line
SCL: Sedimentation Compression Line
W_{LL} : Liquid Limit
W_{PL}: Plastic Limit
⟶ Drain Stress Path
- - → Undrained Stress Path

Figure 8: Effect of Stress History and Shearing Drainage on Critical State Water Content and Liquidity Index

6.3 Reactivation of Earth Slides

Earth slides with intermittent movements have stable stages between the movement. During these rest times between movements, restructuring of the soil microstructures (aging) can occur. Restructuring of the shear zone can affect the shear strength to rupture for subsequent movements.

6.4 Pore-Water Chemistry

Soil water chemistry can affect the void ratio and the viscous behavior of the soil (Jeong et al. 2010). As the viscosity and water content can change with pore-water chemistry, shear strength and post failure rate of movement can be affected by pore-water chemistry.

7 CONCLUSIONS

Previous studies of earth slide movements showed nonlinear increase in the rate of movement with increase in the unbalance force. The post failure movement rate was found to be correlated with the plasticity of the material in the shear zone and the average depth of the shear zone (Eshraghian et al. 2007).

It is shown here that qualitative estimation of order of magnitude of earth slides post-failure movement rate is possible by considering the viscosity of the soil within the earth slide shear zone. In many cases, the experiences from the previous earth slide movements in a region can be used in prediction of earth slide movements for other earth slides in the region or other areas with similar conditions. This paper predicts that generally, earth slides with shallower shear zones, lower clay content, and higher overconsolidation ratio may accelerate to a higher post-failure movement rate in comparison to their counterparts with deeper shear zones, higher clay content, and lower overconsolidation ratio. Pre-failure brittle behavior of shear zone, shear band localization, water chemistry, and water entrapments in the shear zone may also change the rate of movement of the earth slides, in some cases to a flow sliding mode. Local site experiences can provide invaluable information on the shear zone thickness and possibility of changing of earth slide to other types of failure with a higher rate of movement.

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