Prediction of Static Liquefaction Landslides

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Prediction of Static Liquefaction Landslides

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ABSTRACT
Static liquefaction failure of sloping grounds has resulted in significant damages to built structures and even loss of lives. The principal aim of this research is to relate static liquefaction behavior of cohesionless soils to a measurable threshold from the field. Based on a very large number (893) of undrained laboratory shear tests on cohesionless soils collected from the past literature, a threshold triggering excess pore water pressure is introduced in this study above which static liquefaction failure occurs. The effect of variations in the direction and relative magnitudes of principal stresses associated with different modes of shear and ground slopes on static liquefaction failure of cohesionless soils is characterized by empirical relationships of the triggering excess pore water pressure ratio with these variables. The triggering pore pressure ratio can be employed as a more precise criterion for detecting liquefaction triggering and landslide warning in instrumented slopes of saturated cohesionless soils.

RÉSUMÉ
L’échec de la liquéfaction statique des sols en pente a provoqué des dommages importants aux structures construites et même des pertes de vies humaines. Le but principal de cette recherche est de relier le comportement statique de liquéfaction de sols sans cohésion à un seuil mesurable du terrain. Sur la base d’un très grand nombre (893) d’essais de cisaillement en laboratoire non drainés sur des sols sans cohésion, relevés dans la littérature antérieure, un seuil déclenchant une pression interstitielle en excès est introduit dans cette étude, au-dessus duquel se produit une défaillance de liquéfaction statique. L’effet des variations dans la direction et les amplitudes relatives des principales contraintes associées à différents modes de cisaillement et de pentes du sol sur l’échec de la liquéfaction statique de sols sans cohésion est caractérisé par des relations empiriques du rapport de déclenchement de la pression de l’eau dans les pores excédentaire avec ces variables. Le rapport de pression interstitielle de déclenchement peut être utilisé comme critère plus précis pour détecter le déclenche de la liquéfaction et l’avertissement de glissement de terrain sur les pentes instrumentées de sols saturés et sans cohésion.

1 INTRODUCTION
Most landslides in steep slopes are triggered by increasing of excess pore water pressure (generated by a seismic event, heavy rainfall, rapid snowmelt, tidal fluctuations, water waves, pile driving, or rapid changes in water level), leading to an undrained static liquefaction failure and strain-softenning. During this phenomenon, rise in pore water pressure reduces soil’s effective stress and thus shear resistance, and eventually leads to a slope failure. This can develop into a catastrophic flow slide failure if the post-liquefaction strength of the soil drops below the static driving shear stress beneath the slope. The sudden nature and the large shear displacements attained rapidly following flow liquefaction events have made static liquefaction one of the most catastrophic mechanisms in the failure of natural slopes, man-made dams, and mine tailings embankments.

Despite considerable advances in understanding landslide mechanics and the employment of landslide monitoring systems, these phenomena continue to cause significant damages throughout the world. For example, the deadliest landslide disaster in the United State’s history occurred on the 22th of March 2014 in Oso, Washington (USA) after three weeks of intense rainfall. The Oso landslide mass obliterated more than 50 homes, claimed 43 lives, injured 10 people, and buried portions of a major state highway resulting to an estimated capital loss of at least $50 million. The failure occurred in a loose sandy colluvial material susceptible to static liquefaction (Keaton, et al., 2014). Even more recently, the Fundão iron mine tailings dam (Brazil) failed due to static liquefaction on November 5th, 2015. Static liquefaction failure resulted from a clogged drainage and the subsequent increase in pore water pressure (Morgenstern et al., 2016). Although some studies have proposed empirical rainfall thresholds, such thresholds can be often misleading and erratic without proper consideration of the mechanisms of failure and the role of pore water pressure.

Previous experimental studies of flow slide failures indicate that the initiation of liquefaction flow failure is essentially associated with the build-up of excess pore water pressure ($u_r$) and the corresponding reduction in effective stress and soil resistance (Anderson and Sitar, 1995; Eckersley, 1990; Take, et al., 2013). With a sufficient increase in $u_r$, a saturated sandy slope can undergo undrained strain-softenning and static liquefaction. Accordingly, an analysis of the threshold $u_r$ required for static liquefaction failure can be effectively used to predict the occurrence of a flow failure. However, just how much $u_r$ is required to produce a flow slide has not yet been resolved. This study attempts to relate static liquefaction behavior to an experimentally-verifiable threshold of pore water pressure above which liquefaction occurs. A practical framework for predicting the onset of static liquefaction is presented based on a minimum triggering $u_r$ required to
induce undrained strain-softening in a saturated cohesionless soil.

2 THRESHOLD EXCESS PORE PRESSURE RATIO

Figure 1 presents undrained triaxial compression shear tests on Illinois River and Toyoura sand specimens in terms of consolidation relative density ($D_{rc}$) and excess pore pressure ratio ($r_u$). Several studies (Ishihara, 2008; Vaid and Chern, 1983) have found that the major principal stress at the time of consolidation ($\sigma_{1c}$) largely controls liquefaction and shearing behavior of cohesionless soils. Accordingly, $r_u$ is defined here as the shear-induced excess pore water pressure ($u_r$) normalized by $\sigma_{1c}$. Static liquefaction and undrained strength reduction is triggered when the applied monotonic shear load exceeds soil’s peak undrained strength, $s_u$ (yield). Strain-softening subsequently follows the initiation of liquefaction until a reduced post-liquefaction undrained strength, $s_u$ (liq) is mobilized.

According to Figure 1, with increasing $D_{rc}$ the amount of strength reduction from $s_u$ (yield) to $s_u$ (liq) and $r_u$ decrease until $D_{rc} = 34\%$ and $31\%$ neither of the sands display strain-softening and liquefaction behavior. The maximum $r_u$ ($r_u$ max) developed in specimens which exhibit even the slightest strain-softening behavior are all greater than 0.64 for both Illinois River and Toyoura sand specimens. Whereas, those at respectively $D_{rc} = 34\%$ and 31% for Illinois River and Toyoura sands undergo strain-hardening behavior with $r_u$ max < 0.64. These suggest that the occurrence of static liquefaction in a saturated cohesionless soil is closely related to $r_u$ max.

Although $r_u$ max = 0.64 is inferred from Figure 1, field liquefaction behavior and pore water pressure generation in a soil beneath a sloping ground can be more complicated than an isotropically-consolidated specimen. Figure 2 illustrates a hypothetical failure plane beneath a sloping ground. Different modes of shearing, ranging from compression at the crest of the slope, to simple shear, and extension at the toe can exist on a failure plane. As illustrated in Figure 2, a transition in mode of shearing occurs as the angle of the failure plane with the horizontal varies and the associated principal stress ($\sigma_{1}$, $\sigma_{3}$) directions rotate (Yoshimine, et al., 1999). Different modes of shearing are approximately assigned along the failure plane in Figure 2 based on the counter-clockwise angle of the failure plane to the horizontal ($\theta$), with $\theta > 15^\circ$, $-15^\circ \leq \theta \leq 15^\circ$, and $\theta < -15^\circ$ attributed as compression, simple shearing, and extension modes of shear, respectively. The relative magnitudes of the initial (consolidation) principal stresses ($\sigma_{1c}$, and $\sigma_{3c}$) under a sloping ground also change, which produces different principal stress anisotropy characterized by the principal stress ratio, $K_c = \sigma_{3c}/\sigma_{1c}$.

As demonstrated in Figure 3, $r_u$ max developed in a cohesionless soil is largely affected by differences in triaxial compression (TxC), direct simple shear (SS), and triaxial extension (TxE) modes of shear as well as $K_c$ and $D_{rc}$. Accordingly, for a precise prediction of $r_u$ required to trigger static liquefaction ($r_u$ max) it is necessary to account for the variation in principal stress directions associated with different modes of shearing and their relative magnitudes ($K_c$) beneath a sloping ground. Based on a large database...
of laboratory shear tests collected from past studies, this study explores a threshold \( r_u \) (\( r_{u,\text{tr}} \)) beyond which static liquefaction could occur in a cohesionless soil. The effects of \( K_c \) and differences in mode shearing on \( r_{u,\text{tr}} \) are also studied.

3 DATABASE OF LABORATORY SHEAR TESTS

A large database of 873 triaxial compression shear, TxC (Castro, 1969; Chen, 1984; Chu, 1995; Dawson, et al., 1998; de Gregorio, 1990; Dennis, 1988; Di Prisco, et al., 1995; Doanh, et al., 1997; Durham and Townsend, 1973; Finge, et al., 2006; Fourie and Tshabalala, 2005; Gajo and Piffer, 1999; Gassman, 1994; Higher and Tobin, 1980; Higher and Valvee, 1980; Hird and Hassona, 1990; Hyodo, et al., 1994; Jefferies and Been, 2006; Kato, et al., 2001; Konrad, 1993; Konrad and Pouliot, 1997; Kramer and Seed, 1988; Lavigne, 1988; Lee, 1965; Leong and Chu, 2002; Murthy, et al., 2007; Omar, 2013; Riemer, 1992; Sadrekarimi, 2009; Sasitharan, 1994; Sasitharan, et al., 1994; Skirrow, 1996; Sladen, et al., 1985; Sladen and Handford, 1987; Stiber, 1992; Takeshita, et al., 1995; Tsomokos and Georgiannou, 2010; Vaid, et al., 2001; Verdugo, 1992; Wanatowski and Chu, 2007; Wang, 2005; Wride and Robertson, 1997a; Wride and Robertson, 1997b; Yoshimine, 1995; Zhang, 1997), torsional simple shear, TSS (Alarcon-Guzman, et al., 1988; Keyhani and Haeri, 2013; Nakata, et al., 1998; Sivathayalan and Vaid, 2002; Wride and Robertson, 1997a; Yoshimine and Ishihara, 1998; Yoshimine, et al., 1999), and triaxial extension shear, TxE (Been, et al., 1991; Chung, 1985; Doanh, et al., 1997; Gajo and Piffer, 1999; Hyodo, et al., 1994; Lade, et al., 2006; Riemer, 1992; Shahsavar, 2012; Vaid, et al., 2001; Vaid and Thomas, 1995; Yoshimine, et al., 1998; Yoshimine, et al., 2001; Yoshimine, et al., 1999) tests on cohesionless soils are collected in this study which cover a very wide range of non-plastic silt contents, SC (0 to 60%), consolidation void ratios, \( e_c \) (0.261 to 1.287), major consolidation principal stresses, \( \sigma'_c \) (29 to 60,000 kPa), specimen preparation techniques (AP: air pluviation; WP: water pluviation; MT: moist tamping), and consolidation principal stress ratios, \( K_c \) (0.33 to 1.0). The wide range of \( K_c \) (0.33 to 1.0) allows the modeling of different sloping ground initial conditions. Principal stress directions continuously rotate in TSS tests or undergo an abrupt 90° rotation in TxE shearing of anisotropically consolidated specimens, while the principal stress directions remain the same in TxT tests. Note that shear stress is applied in TSS tests by torsion, while TxT and TxE samples undergo shearing on the failure plane as a result of a deviator stress.

As shown in Figure 1, \( s_u(yield) \) and \( s_u(liq) \) respectively describe the liquefaction triggering condition and the subsequent behavior after liquefaction occurs. Following the triggering of liquefaction, the mobilized undrained strength reduces from \( s_u(yield) \) to \( s_u(liq) \). The normalized difference between \( s_u(yield) \) and \( s_u(liq) \) is used here to quantify the degree of strain-softening and determine the occurrence of static liquefaction. This is often defined by the undrained brittleness index, \( I_B \) as below (Bishop, 1971):

\[
I_B = \frac{s_u(yield) - s_u(liq)}{s_u(yield)}
\]

\( I_B \) ranges from 0 to 1, where \( I_B = 1 \) indicates a very brittle soil behavior associated with an extremely low \( s_u(liq) \), while \( I_B = 0 \) occurs in non-brittle or strain-hardening soils where no strength reduction occurs during undrained shear.

In the following, the liquefaction behavior of cohesionless soils is characterized in terms of \( I_B \) and \( r_{u,\text{max}} \) for the 873 laboratory shear tests collected in this study. Note that \( s_u(yield) \) includes the initial shear stress (\( \tau_\text{c} \)) resulting from anisotropic consolidation, as well as the additional shear stress applied to cause strain-softening and liquefaction. The post-liquefaction undrained strength, \( s_u(liq) \) is chosen at the end of the tests where a critical state of constant effective stress and shear stress is attained following strain-softening behavior. Whereas, for specimens exhibiting a limited liquefaction the minimum undrained strength prior to strain-hardening is more relevant to flow...
failures and stability analysis and this is adopted here as $s_u(\text{liq})$.

4 RESULTS AND DISCUSSION

Figure 4 presents $l_B$ versus $r_{u,\text{max}}$ for each mode of shear based on the large database of laboratory shear tests. While $l_B$ and the amount of strain-softening increase with increasing $r_{u,\text{max}}$ for all modes of shearing, these plots show greater $r_{u,\text{max}}$ in compression and simple shearing modes than when a soil is subject to an extension mode of shear. The plots of Figure 4 further indicate that increasing anisotropic consolidation (decreasing $K_c$) promotes strain softening and increases $l_B$.

![Figure 4](image-url)

Figure 4. Undrained brittleness ($l_B$) and maximum excess pore water pressure ratio ($r_{u,\text{max}}$) data for (a) TxC, (b) TSS, and (c) TxE shear tests.

An interesting feature of Figure 4 is that the $r_{u,\text{max}} - l_B$ data fall on a distinct trendline for each $K_c$, inferring that $r_{u,\text{max}}$ is primarily affected by $K_c$ and the mode of shearing for saturated granular soils. The small scatter at a given $K_c$ for each mode of shear possibly emerges from differences in SC, specimen preparation method (i.e., soil fabric), $e_0$, and $\sigma'_{1c}$, besides inaccuracies in laboratory shear testing of loose sands at large shear strains (e.g., membrane resistance, bedding errors, boundary effects, non-uniform stress distribution associated with specimen bulging in TxC and necking in TxE). It follows that a state of $r_{u,\text{max}} = 1.0$ ($\sigma'_3 = 0$) is only possible for isotropically consolidated soils ($K_c = 1$), while for anisotropically consolidated cohesionless soils ($K_c < 1$) severe strain-softening and $l_B \approx 1$ could ensue at $r_{u,\text{max}} < 1.0$.

For each mode of shearing in Figure 4, the average $r_{u,\text{max}} - l_B$ trendline for each $K_c$ resembles that of $K_c = 1$ which is translated both horizontally (decreasing $r_{u,\text{max}}$) and vertically (increasing $l_B$) in proportion to its $K_c$ value. Accordingly, modified $l_B^*$ and $r_{u,\text{max}}^*$ parameters are used to shift these data onto the $K_c = 1$ trendline in Figure 5. Figure 5 further presents specific correlations between $l_B^*$ and $r_{u,\text{max}}^*$ for each mode of shear which include the effects of $K_c$. Despite the wide ranges of testing parameters ($e_0$, SC, $\sigma'_{1c}$, $K_c$, specimen preparation methods), correlations shown in Figure 5 display a relatively narrow range of variations and the average relationships exhibit high coefficients of correlation ($R^2$) indicating their accuracy.
liquefaction behavior as well as the threshold $f_u$ ($r_{u,tr}$) above which a saturated cohesionless soil will liquefy ($I_s > 0$). The relationships shown in Figure 5 can thus be used to estimate the ranges of $r_{u,tr}$ corresponding to the initiation of static liquefaction ($I_s \geq 0$) for each shearing mode.

At any given $K_c$, a range of $I_s$ is obtained from its relationship with $I_u$ as shown in the abscissa of Figure 5 for each mode of shearing and sweeping $I_u$ from 0 to 1.0. Based on the fitted correlation between $I_u$ and $r_{u,tr}$ for each shearing mode, $r_{u,tr}$ is then calculated from $r_{u,tr}$ using the corresponding equation between $r_{u,tr}$ and $r_{u,tr}$ shown in the ordinates of Figure 5. The variation of $r_{u,tr}$ with $K_c$ is subsequently demonstrated in Figure 6 for each mode of shearing. According to this figure, $r_{u,tr}$ increases with increasing $K_c$ for compression and simple shearing modes. In other words, the potential for static liquefaction failure would increase (i.e. failure occurs earlier at a lower $r_{u,tr}$) with increasing ground slope. Griffiths et al. (2011) and Eichenberger et al. (2013) report similar trends respectively for saturated cohesive soils and volcanic ash in finite element simulations. In extension however, since anisotropic consolidation pre-shearing ($K_c$) and undrained extensional shearing occur in different directions, shear stress reversal occurs on the failure plane in TxE tests, and thus $r_{u,tr}$ exhibits a brief increase with decreasing $K_c$ followed by a more or less constant $r_{u,tr} = 0.136$. Accordingly, in order to obtain more accurate estimates of $r_{u,tr}$ for triggering analysis it is imperative to consider the appropriate $K_c$ corresponding to the operating mode of shear and the in-situ stress condition. Note that although $r_{u,tr}$ seems to be independent of $D_c$, this can be considered by measuring the in-situ $r_u$ as $D_c$ affects a soil’s ability to develop excess pore pressure and attain $r_{u,tr}$ for instigating liquefaction.

Figure 5. Unified relationships based on modified $I_s^*$ and $r_{u,tr}$ data for (a) TxC, (b) TSS, and (c) TxE shear tests.

5 TRIGGERING OF STATIC LIQUEFACTION

Static liquefaction could trigger when a soil is no longer able to sustain the applied shear stress and hence undergoes strain-softening ($I_u \geq 0$). Therefore, $I_u = 0$ would represent the minimum condition to instigate static liquefaction.

6 APPLICATION FOR STATIC LIQUEFACTION PREDICTION

It is proposed that $r_{u,tr}$ can provide a refined criterion for examining field stress paths and determining the proximity of an in-situ stress state to instability. The proposed method can be employed as a pragmatic triggering method.
criterion in landslide warning and in-situ monitoring systems for enhanced prediction of flow slide failures resulting from static liquefaction. This would require warning pore water pressure thresholds to be set with respect to $r_{u,br}$ for the corresponding mode of shear and stress anisotropy ($K_c$). A drained limit equilibrium analysis of the pre-failure slope geometry should be first performed to identify the probable critical sliding surface (with the lowest factor of safety) and establish the pre-failure (consolidation) shear ($\tau_{c'}$) and normal ($\sigma_{nc}')$ stresses along the sliding surface. The magnitude of $K_c$ along a potential failure plane can be determined from the following equation (Ishihara, 2008):

$$K_c = \frac{\sigma_{3c}'}{\sigma_{1c}'} = \frac{\sigma_{nc}' - \tau_c'/\cos \theta + \tau_c \tan \theta}{\sigma_{nc}' + \tau_c'/\cos \theta + \tau_c \tan \theta} \quad [6]$$

An infinite slope is a special case of Equation [6] in which the sliding plane is parallel to the ground slope ($\alpha = 0$), and thus $K_c = (1 - \sin \alpha)/(1+\sin \alpha)$ beneath an infinite slope of an angle $\alpha$.

Similar to Figure 2, approximate modes of shear can be assigned based on the inclination of the failure plane from the horizontal ($\theta$) with $\theta > 15^\circ$, $-15^\circ \leq \theta \leq 15^\circ$, and $\theta < -15^\circ$ corresponding to compression, simple shearing, and extension modes of shear, respectively. Relationships shown in Figure 5 can then be employed to calculate $r_{u,br}$ on the failure plane and predict liquefaction-induced landslides. The critical sliding surface (determined from a limit equilibrium analysis) can be used as a preliminary guideline for the installation of piezometers for measuring $u_e$ along the probable failure surface. An ideal field monitoring system would be automated with sufficient measurement points to examine the pattern of pore water pressure generation and identify the most critical pore pressure regime on a real-time basis. The strength of the proposed method is that the in-situ $r_i$ is directly measured by piezometers, and there is no need for expensive soil sampling or the determination of in-situ density of cohesionless soils. The key contribution of this method is that the fundamental effects of mode of shearing and $K_c$ are considered in predicting static liquefaction and $r_{u,br}$.

Note that the proposed method is only applicable when a slope has become fully saturated. In an unsaturated soil, suction among soil particles imparts additional confining stress which could create steep slopes ($\alpha \geq 30^\circ$). If saturated (e.g., by a rainfall, tidal fluctuation, snowmelt), the decrease of soil suction and the increase of soil unit weight (as water infiltrates soil) can produce a rapid accumulation of shear strain and positive $u_e$. Due to steep slopes (high $K_c$), $r_{u,br}$ required to instigate static liquefaction failure could be quickly attained.

7 CONCLUSIONS

This study suggests a certain threshold of pore water pressure ratio ($r_{u,br}$) required to trigger static liquefaction and produce undrained strain-softening behavior. The threshold excess pore water pressure ratio defines a boundary between liquefaction and non-liquefaction behaviors based on a large number of high-quality laboratory shear test results. The laboratory test results indicate that excess pore pressure equal to the total overburden pressure (i.e., $ru = 100\%$) is not necessarily required for static liquefaction triggering, and failure could occur at a much lower $r_{u,br}$. It is further observed that $r_{u,br}$ mobilized in compression and simple shearing modes decrease with increasing initial stress anisotropy (decreasing $K_c$). Whereas for extension shearing, $K_c$ has a relatively reduced effect on $r_{u,br}$.

Based on the premise that $r_{u,br}$ is developed just before the occurrence of static liquefaction, an empirical approach is developed in this study for estimating $r_{u,br}$. The concept of triggering pore pressure recognizes that pore pressure is central to liquefaction and flow failures, and it is based on the principles that stress anisotropy and mode of shearing determine liquefaction potential and $r_{u,br}$ produced in a cohesionless soil subject to a monotonic shear load. The results of this study provide the possibility to develop more precise early warning systems based on the measurement of pore water pressure required for triggering liquefaction-induced landslides. Soil characteristics such as relative density, silt content, or fabric are indirectly considered by measuring and monitoring of the in-situ $r_i$, while slope geometry is accounted for through $K_c$.

8 REFERENCES


