laboratories for the study of landslides due to liquefaction, erosion, (Doanh et al, 1997; Darve and Laouafa, 2000; Muir Wood et al, 2007; Erdin et al, 2009).

Fig. 1 compares the differences of grain size distribution for Houston sand and the sand sample of this study.

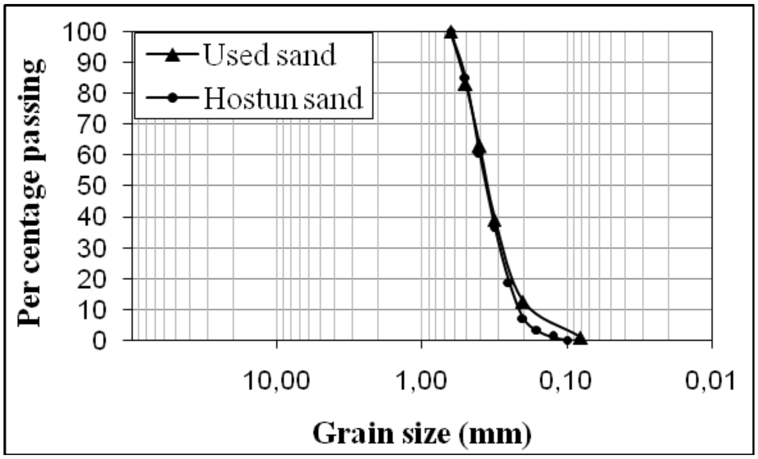


FIG. 1. Sieve curves (used sand and Hostun sand).

The used Marl is taken from the region of Tizi-Ouzou (Algeria). It is green marl, with following characteristics: Atterberg limits; liquid limit (LL = 23.0 %); plastic limit (PL = 15.12) and the plasticity index (PI = 7.88). The moist density ($\rho = 1.8$ g/cm^3); specific gravity ($G_s = 2.16$); dry density ($\rho_d = 1.59$ g/cm^3). The mineralogical study showed that: the organic mater content (OM) was 2.12% and the carbonate content ($CaCO_3$) was 55.085%.

EXPERIMENTAL DEVICE AND SAMPLE PREPARATION

APPARATUS

The used apparatus is a monotonic triaxial (Digital Triest 100), equipped with sensors measuring axial strain, axial force, confining pressure, back pressure, volume change or pore pressure, as the test is drained or undrained. The data are acquired by an Acquisition Data Unit (ADU), and then analyzed by Data System 7 software (DS7). The latter allows the pilot of each accessory of triaxial apparatus and presents procedures for the achievement of various testing stages. It finally groups the tests results in tables and curves report.

SAMPLE PREPARATION

The samples were prepared by sand and marl layers, they have a cylindrical form, with 70 mm in diameter and 140 mm in height. To control moisture of each layer; sand and marl are moistened with optimum water content, then compacted in successive layers by compactive energy about 15 blows per layer. This allows getting samples of medium density. The performed samples with different combinations of sand and marl layers in plane or inclined dispositions are as follows:(Marl/Sand, Sand/Marl, Sand/Marl/Sand, Marl/Sand/Marl), these allows to represent natural cases of (sand-marl) multi-layers existing in the region of Tizi-Ouzou (Algeria), which are often affected by landslides.

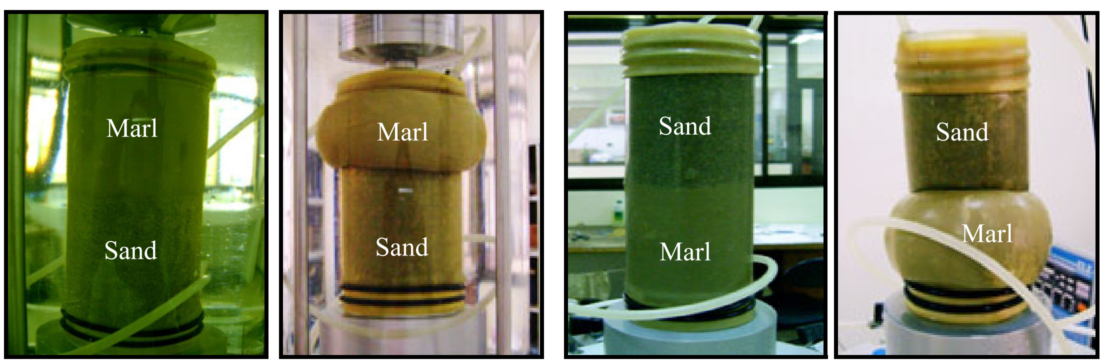
The samples were then subjected to unconsolidated undrained triaxial tests (UU), under a confining stress of 100 kPa. It is a stress adopted by several researchers in their works on landslides (Darve and Laouafa, 2000; Ishihara, 2003; Arab, 2009). It represents the state of moderately dense soils frequently affected by landslide problems.

To reproduce landslides caused by rapid loading as volcanoes, earthquakes and explosions, we chose a shear rate of 2.5 mm/min. This allows the development of significant pore pressures during test (Sassa et al, 2007).

The quality of saturation is evaluated by measuring the Skempton coefficient B which is equal to ($\Delta u/\Delta\sigma$). For this study, the saturation has been followed until B $\geq$ 90%, approaching the real rate saturation of natural soils.

TESTING RESULTS AND ANALYSIS

Samples in plane layers are generally characterized by settlement of marl; it represent a plastic failure in marl layers. These are then punched by the sand layers whatever their positions in the multilayer sample. The sand layers remain practically intact as shown in Fig. 2 and 3.

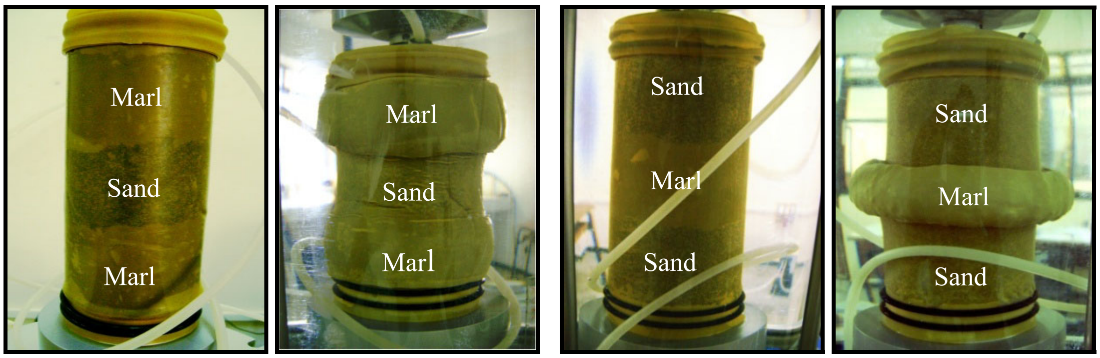


(a) M/S (before failure) **(b) M/S (after failure)** **(c) S/M (before failure)** **(d) S/M (after failure)**

FIG. 2. Samples with two layers (plane layers).

The marl layer undergoes initially all deformations. The sand layers begin to deform only after total deformation and puncture of marl layers as shown in Fig. 4. The sliding failure appears clearly in the case of samples with 2 or 3 inclined layers, especially in the case of (S/M) and (S/M/S) samples, as shown in Fig. 5 and 6. Unlike plane layers samples where the failure is purely plastic in marl layers; the sliding failure is very apparent in the case of inclined layers samples (for both 2 and 3 layers), especially for (S/M/S) sample. Thus, the inclination of layers strongly influences landslides, especially when the marl is situated between two layers of sand as shown in Fig. 6.

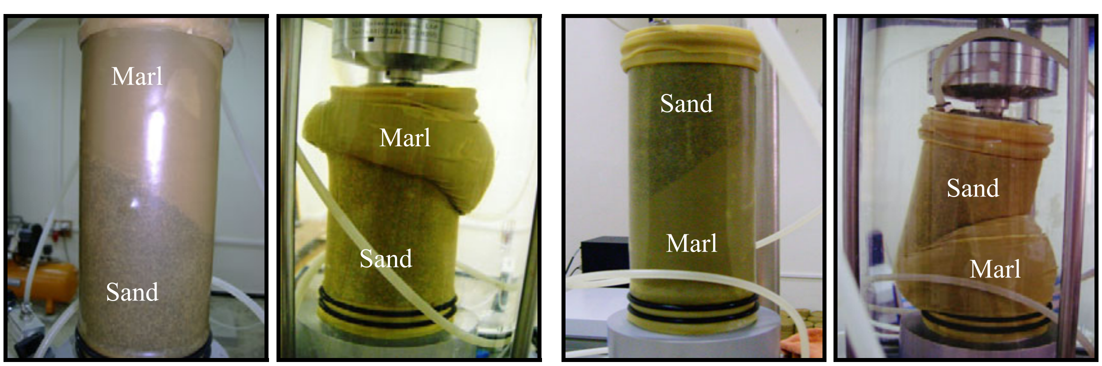
The failure plan by sliding follows the same inclining plan of layers. The sliding plane doesn't locate exactly at the interface between sand and marl layers. However, a thin layer of marl adheres to both sides with sand layers and the sliding plane (shear plane) appears within layers of marl, nevertheless, it is near the sand-marl interfaces as shown in Fig. 7. In all cases, the point of failure is located in the marl layer. This shows that the marl becomes still a weak area in contact with water which facilitates failure by sliding.



(a) M/S/M (before failure) **(b) M/S/M (after failure)** **(c) S/M/S (before failure)** **(d) S/M/S (after failure)**

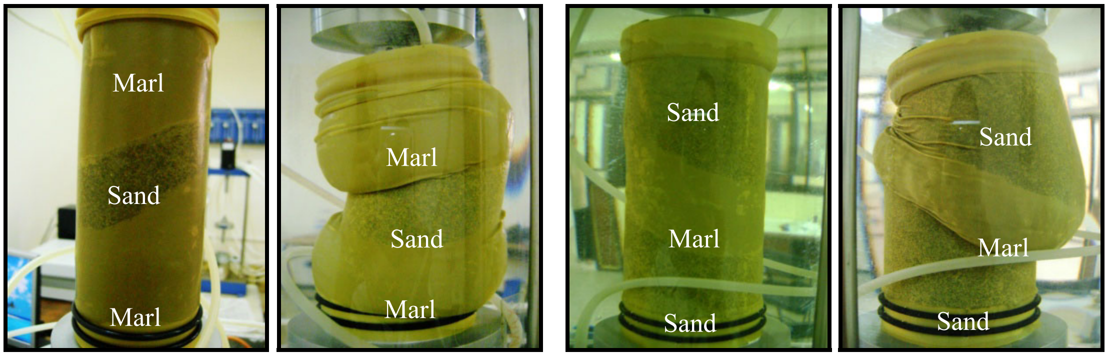
FIG. 3. Samples with three layers (plane layers).

FIG. 4. Deformation of sand layers after total deformation and punching of marl layer.



(a) M/S (before failure) **(b) M/S (after failure)** **(c) M/S (before failure)** **(d) S/M (after failure)**

FIG. 5. Samples with two layers (inclined layers).



(a) M/S/M (before failure) (b) M/S/M (after failure) (c) S/M/S (before failure) (d) S/M/S (after failure)

FIG. 6. Samples with three layers (inclined layers).

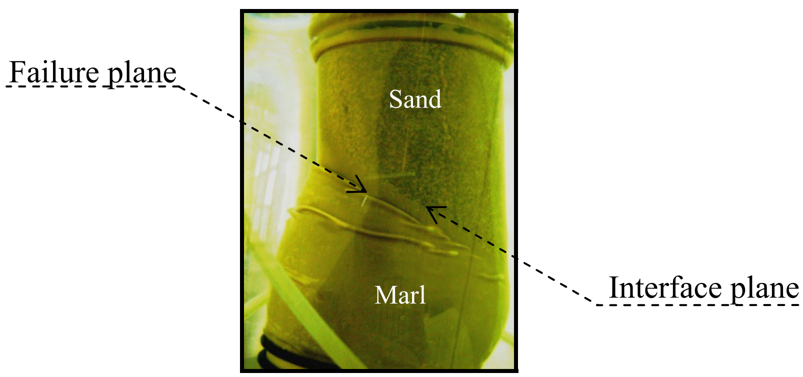


FIG. 7. Position of failure plane relatively to the interface plane.

EVOLUTION OF PORE PRESSURE DURING THE TRIAXIAL TESTS

The pore pressure is slightly influenced by the inclination of the layers; it evolves practically with the same manner in plane and inclined layers, as shown in Fig. 8. While, the pore pressure is strongly influenced by the order of layers, it is then strongly influenced by the position of marl and sand in the sample as shown in Fig. 9. The pore pressure is directly related to the proportion of marl existing in the sample. The developed pore pressure is greater in the case of (M/S/M) sample, where the proportion of marl is about 70%. However, it is smaller in the case of (S/M/S) sample, where the proportion of marl does not exceed 30%.

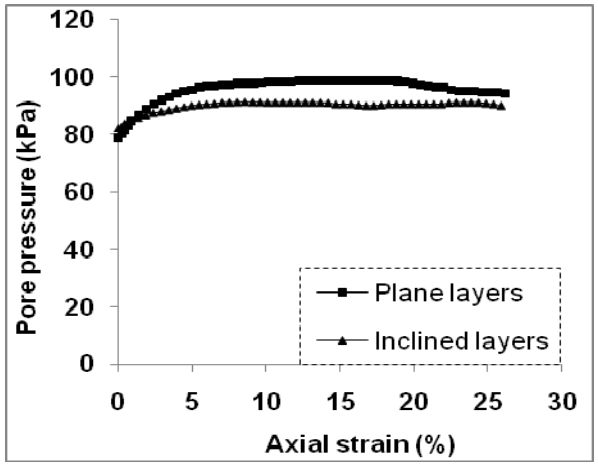


FIG. 8. Evolution of pore pressure in relation to the inclination of layers.

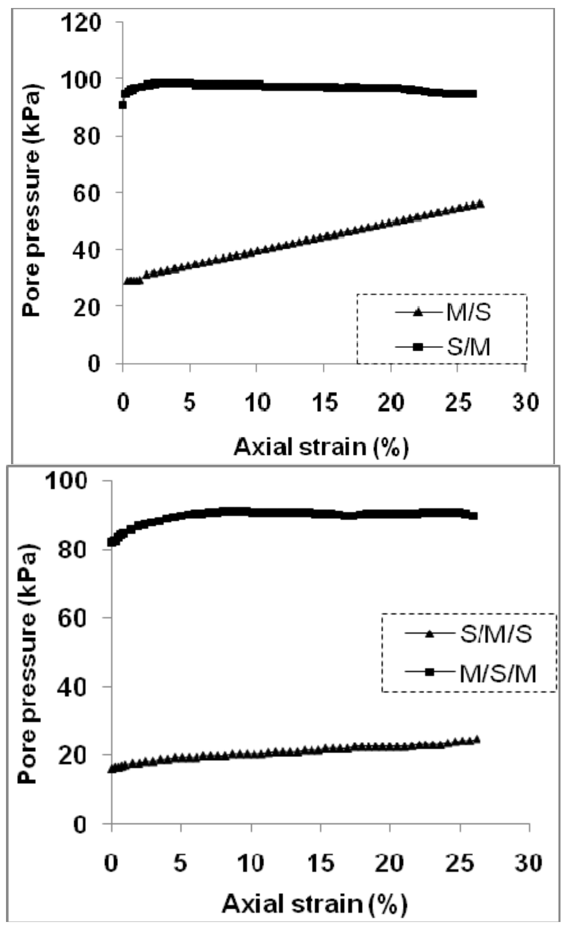
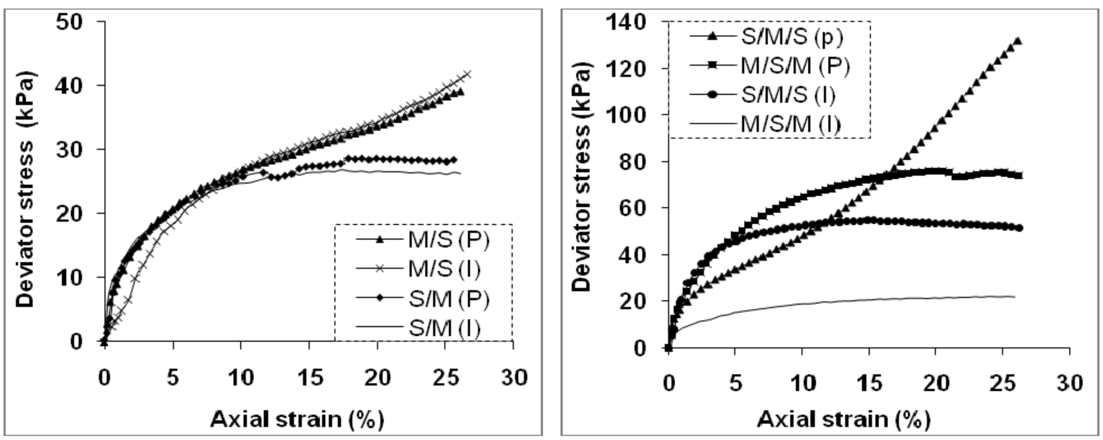


FIG. 9. Evolution of pore pressure in relation to the order of layers.

EVOLUTION OF DEVIATOR STRESS DURING THE TRIAXIAL TESTS

In the case of samples with two layers, the arrangement of the layers influences slightly the deviator stress, while, the latter is virtually not influenced by the inclination of layers. The curves representing the samples in plane or inclined layers have exactly the same shape, and evolves with the same way, as shown in Fig. 10.

In the case of samples with two layers, the deviator stress is greatly influenced by the inclination of layers and their arrangement. It is directly related to the proportion of sand present in the sample. The curve representing the (S/M/S) sample with plane layers as shown in Fig. 10 illustrate a particular evolution of the deviator stress. The proportion of sand exceeds 70% in this sample. After punching the marl layer which is not exceeding 30%, the sand undertakes all of the vertical force and develops a new important resistance. The curve representing the (M/S/M) sample with inclined layer as shown in Fig. 10, illustrates the lowest deviator. The proportion of marl in this case exceeds 70%. It constantly deforms under applied stress. The sand layer in this sample with the proportion not exceeding 30% doesn't take virtually any effort especially with inclined layers.



(a) Samples with two layers **(b) Samples with three layers**

FIG. 10. Evolution of deviator stress in relation to the order and the inclination of layers.

CONCLUSION

This experimental study shows the behavior of multilayer of sand-marl type, depending on the nature, the inclination and the disposition or the order of the different layers. It is based on experimental triaxial tests, conducted in the laboratory on samples, representing the real case of natural multilayer affected by sliding in the region of Tizi-Ouzou, Algeria. The obtained results are very important; they show clearly the mode of deformation and fracture of different layers under the effect of applied forces. They show the precise position of the failure plane by sliding relatively to the interface layers. The sliding plan follows the same inclining plan of layers. It does not locate exactly at the interface (sand-marl), but it is near the interface on the marl layer, which becomes still a weak area in contact with water.

The sliding is very apparent in the samples with inclined layers, and it is more evident in (S/M/S) inclined multilayer when the marl layer is situated between two sand layers. When vertical force is applied, the grains of sand are rearranged and remove water existing in the voids; the removed water fed to both sides (below and above) the marl layer; the latter loses strength rapidly in contact with water and constitutes a weak area. Under the weight of the upper layer of sand and the applied force, it slides along the direction of inclination of the sample layers and lead sample to failure.

The results show also the evolution of deviator stress and pore pressure curves, depending on the nature, the arrangement and inclination of layers which are important parameters to know, in the study of landslides.

REFERENCES

Arab, A. (2009). "Comportement monotone et cyclique d'un sable limoneux." *Comptes Rendus Mécanique.* Elsevier., Vol. 337 (8) : 621-633.

Bromhead, E.N. (2005). "The stability of slopes", Taylor & Francis e-Library, 2nd Edition, London.

Closson, D., et al. (1999). "The use of the soil map of Belgium in the assessment of landslide risk." *Biotechnol. Agron. Soc. Environ* : 165-172.

Darve, F. and Laouafa, F. (2000). "Instabilities in granular materials and application to landslides." *Mechanics of cohesive-frictional materials*. John Wiley & Sons, Ltd., Vol. 5 : 627- 652.

Doanh, T., et al. (1997). "Undrained instability of very loose Hostun sand in triaxial compression and extension.", *Mechanics of cohesive-frictional materials*, Vol. 2 : 47-70.

Duncun, J.M. and Wright, S.G. (2005). "Soil strength and slope stability." Wiley, Canada : 213-247.

Erdin, I., et al. (2009). "Time-dependent behaviour and static liquefaction phenomenon of sand." *Geotech Geol Eng*., Vol. 27 : 181-191.

Glade, T., et al. (2005). "Landslide hazard and risk." Wiley, Chichester,U.K.

Ishihara, K. (2003). "Soil behaviour in earthquake geotechnics." Clarendon press, Oxford, U.K : 241-281.

L.C.T.P, (2004). " Étude géotechnique d'urbanisation des POS A1 et A5 Azazga." *Laboratoire Central des Travaux Publics,* Dpt études/ R.B / B.B / R.M.

L.C.T.P, (2006). " Étude géotechnique d'urbanisation des POS D1 et D2." *Laboratoire Central des Travaux Publics,* Dpt études S.K/ B.B/ R.M.

Muir Wood, D., et al. (2007) "Deviatoric stress response envelopes from multiaxial tests on sand." Soil Stress-Strain Behavior: Measurement, Modeling and Analysis, *Geotechnical Symposium in Roma,* The Netherlands : 253-262.

Sassa, K. et al. (2005). "Landslides Risk Analysis and Sustainable Disaster Management." *Proceedings of the first general assembly of the international consortium on landslides.* Springer-Verlag, Berlin, Germany : 127-139.

Sassa, K et al. (2007). "Progress in Landslide Science.", Springer-Verlag, Berlin, Heidelberg, Germany.

Study of Interparticle Ultimate Shear Stress in Soils

Jeffery C. Chang[1], Jason Y. Wu[2], M. ASCE, P.E. and Mingshu Lee[3]

[1]General Manger, CUC Engineering Consultant Co., Ltd., 2B, No.11, Li-Ming Road, Hsin-Tien, Taipei County, Taiwan, ROC 23155, Jeffery@mail.cuc.com.tw
[2]Associate Professor, Department of Civil Engineering, Chung Hua University, 707 Wufu Road, Hsinchu, Taiwan, ROC 30012, jasonwu@chu.edu.tw
[3]Manger, C & M Hi-Tech Engineering Co., Ltd., 2B, No.11, Li-Ming Road, 231 Hsin-Tien, Taipei County, Taiwan, ROC 23155, Leems@mail.cuc.com.tw

ABSTRACT: The plus sign in the Mohr-Coulomb's equation conceals an inherent hypothesis. According to the principle of superposition of forces in physics, it expresses that the shear stresses contributed by the cohesions and the frictions are occurring on a shear plane simultaneously. However, such assumption has never been questioned since the application of this equation in 1776. This paper proposes that before the combination of any two types of shear stress, they shall be examined if they are identical physical events with the same spacetime coordinates. This research conducts a series of stress-controlled and strain-controlled direct shear tests to verify this assumption. Test results have shown that both cohesion and frictional resistance occurred neither simultaneously nor in the same space. In conclusion, for a given failure plane of a soil, it is likely to occur only one type of shear stress under a physical spacetime.

INTRODUCTION

Mohr-Coulomb's Failure Criteria

Soil strength is vital to the safety of virtually all aspects of soil stability. Therefore, promised accuracy of shear strength parameters for geotechnical analysis and design is essential. The Mohr-Coulomb's equation as shown in Eq. (1) is by far the most widely used for strength determination. It was originated by Coulomb in 1776 based on his experimental observations and later combined with Mohr's failure theory to consider the functional relationship of ultimate shear stress and the normal stress on the failure plane.

$$\tau_f = c + \sigma_f \tan\varphi \qquad (1)$$

where τ_f is the shear stresses at failure, σ_f is the normal stress on the failure plane, c is the cohesion intercept, and φ is the friction angle. The use of Mohr-Coulomb's equation is simple and convenient for the determination of interparticle shear stress on a shear plane. However, the simplicity conceals an inherent hypothesis indicating the cohesion and frictional resistance are simultaneously acting on the same shear plane to conform to the principle of superposition of forces. Such assumption has never been questioned since the use of Mohr-Coulomb's equation.

This paper evaluates the base hypothesis of the equation and explores if the cohesion and the friction concurrently applied on the same shear plane. An experimental program was designed to observe the occurrence of spacetime of these two types of shear stresses and to determine whether they meet the criteria of identical shear stress events and conform to the principle of superposition of forces

PHYSICAL CONCEPTS FOR FORCE MEASUREMENTS

Principle of Superposition of Forces

Physical experiments show that when two forces $\vec{F}_1$ and $\vec{F}_2$ act at the same time at a point of a body, the force effect on the body is the same as if a single force $\vec{R}$ were acting equal to the vector sum of the original forces as shown in Eq. (2):

$$\vec{R} = \vec{F}_1 + \vec{F}_2 \qquad (2)$$

More generally, any numbers of forces applied at a point on a body have the same effect as a single force equal to the vector sum of the forces. This important principle is called superposition of forces (Young and Freedman, 2008).

Relativity of Simultaneity

In a given frame of reference, an event is an occurrence that has a definite position and time. Space is the boundless, three-dimensional extent in which objects and events occur and have relative position and direction. However, space and time have become intertwined and therefore, modern physics considers the time (t) and the three dimensions (*x,y,z*) of space collectively as a four-dimensional entity called spacetime and using (*x,y,z,t*) as the spacetime coordinates of an event.

In physics, the relativity of simultaneity is the concept that simultaneity - whether two events occur at the same time - is not absolute, but depends on the observer's reference frame. According to the special theory of relativity, it is impossible to say in an absolute sense whether two events occur at the same time if those events are separated in space. Measuring forces with times or time intervals involve the concept of simultaneity. Any two forces can be considered as the same events if they have relativity of simultaneity, in other word, the same spacetime coordinates, and can be combined together according to the principle of superposition of forces (Woodhouse, 2003; Young and Freedman, 2008).

CRITERIA FOR MEASURMENTS OF SHEAR STRESS

Hypothesis of Superposition for Two Types of Interparticle Shear Stresses

According to Coulomb's observations, with each applied normal stress, the stress-controlled direct shear test obtains its corresponding peak shear stress and leads to an approximate linear result. When the regressive straight line does not pass origin, it will cut off y-axis and produce a cohesion intercept (c) as shown in Eq. (1). However, as described in physics, if this equation holds true, one must assume that the cohesion (c) and the friction ($\sigma_f \tan\phi$) occur simultaneously on the same spacetime to satisfy the principle of superposition of forces and the concept of simultaneity as defined in physics (Young and Freedman, 2008). Thus, they can be summed up and obtain the unique value of shear stress at failure (τ_f) for a given soil.

Criteria of Measured Scale

The requirement of Mohr-Coulomb's equation is the principle of superposition of forces. However, this hypothesis has never been verified and properly documented. As described above, to combine any numbers of forces, they must fulfill the following requirements:

1. Identical physical measurements.
2. Identical spacetime of occurrence.

To validate Mohr-Coulomb's equation, the cohesion and the friction must be identical physical events and satisfy the following conditions:

1. Identical counts of shear stresses: the physical measurements of the occurrence must be the interparticle shear stress of the same shear plane.
2. Identical spacetime of occurrence: the spacetime of the occurrence of cohesion and friction must have identical spacetime coordinates.

EXPERIMENTAL PROGRAM

The experimental program was designed to observe the spacetime coordinates of ultimate shear stresses caused by the cohesion and the friction for cohesive specimens using stress-controlled and strain-controlled shear tests. In addition to the regular shearing performances, one group of the cohesive specimens were subjected to repeated shearing after failure for stress-controlled shear tests to observe the peak shearing stress. For strain-controlled tests, the cohesive specimens were measured for peak shearing stress at failure and the residual stress after failure under constant rate of shearing. The observed spacetime of ultimate interparticle shear stress contributed by cohesion and friction were compared and evaluated carefully for evidences of identical physical events.

Tested Materials

To minimize the complexities of testing material, ASTM D1556 Ottawa standard sand was used for the experiment. It was first oven-dried at 105°C for 24 hours and