Estimate the In-situ Earth Pressure in a Thrust Fault Zone by Vertical Cut

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Abstract

The tension crack appears at the ground surface acompanied by excavations in soils. The development of tension crack is depended upon the horizontal earth pressure exerted on the soils. For a normally-consolidated level ground, the tension crack depth of a vertical cut can calculate according to Rankine's active earth pressure theory. The critical height of a vertical cut can stand without lateral supports is twice as deep as the tension crack depth. However, in this paper a large tension crack depth observed for a vertical cut in fault zone. This tension crack depth and critical height of vertical cut are applied to estimate the in-situ horizontal earth pressure of fault zone at rest.

Keywords: In-situ earth pressure, Fault zone, Vertical cut, Tension crack, Critical height

1. Introduction

For the normally consolidated deposit soils, the vertical overburden pressure σ_{v0} is the maximum pressure that the soil mass in its history. The in-situ horizontal earth pressure at rest that no deformation in the lateral direction is $\sigma_{h0} = K_0\sigma_{v0}$ as shown in Fig.1(a). The coefficient of at-rest earth pressure (see Fig.2) at a depth z in the level ground is defined as $K_0 = \sigma_{h0} / \sigma_{v0}$. The coefficient of K_0 is depended upon the stress history of the soils, such as soil deposition process and geological history.

For a vertical cut in an infinite half deposited space, the in-situ horizontal stress at rest is decreasing due to the soils expand in lateral direction (McCarthy, 1993). At the state of shear failure, the at-rest horizontal stress decreases to reach the so-called 'active' stress state (see Fig.2). The active horizontal pressure at failure that remained in soils based on Rankine's active earth pressure theory for cohesive granular ($c-\phi$) soils is expressed as,

$$\sigma_A = \gamma z \tan^2(45-\frac{\phi}{2}) - 2c\tan(45-\frac{\phi}{2}) \quad (1)$$

The magnitude of the horizontal pressure σ_A is the minimum and will exert on a retaining structure. During the vertical cut, the released horizontal pressure that acts on soil mass from at-rest stable state to active failure state (see Fig.2 and Fig.3) is,

$$\Delta\sigma_h = K_0\gamma z - K_A\gamma z \quad (2)$$

The coefficient of active earth pressure is designed as, for example in cohesionless soils $K_A = \tan^2(45-\phi/2)$ and $K_0 = 1-\sin\phi$.

From the variation of $\sigma_h (= \sigma_A)$ with depth z in Eq.(1) shown in Fig.1(b), it shows that at the ground surface the tension stress is a maximum. The negative lateral earth pressure takes place within the depth of $2c/\gamma\tan(45+\phi/2)$ due to the soil cohesion. If the tensile strength of soils is very close to zero, it remains customary to estimate the maximum depth of tension crack z_c expresses as,

$$z_c = \frac{2c}{\gamma}\tan(45+\frac{\phi}{2}) \quad (3)$$

Terzaghi (1943) suggested the tension crack depth does not exceed one-half the critical height H_c of a vertical cut that may stand without lateral supports (Kutschke and Vallejo, 2011). This indicates that the horizontal tension force and compression force acting on the cut wall is in force equilibrium (see Fig.1). This suggestion indicates that the critical self-stand height of a vertical cut without supports is

$$H_c = 2z_c \tag{4}$$

Thorne and Abt (1993) also supported that if no specific data for the depth of tension crack are available, 0.5 may be used as the default value of tension crack ratio z_c/H_c. The above statement is supposed that the horizontal stress only caused by soil gravity effect. This does not consider for a faulting process that the in-situ horizontal stress can be much greater than that caused by gravity effect of soil mass.

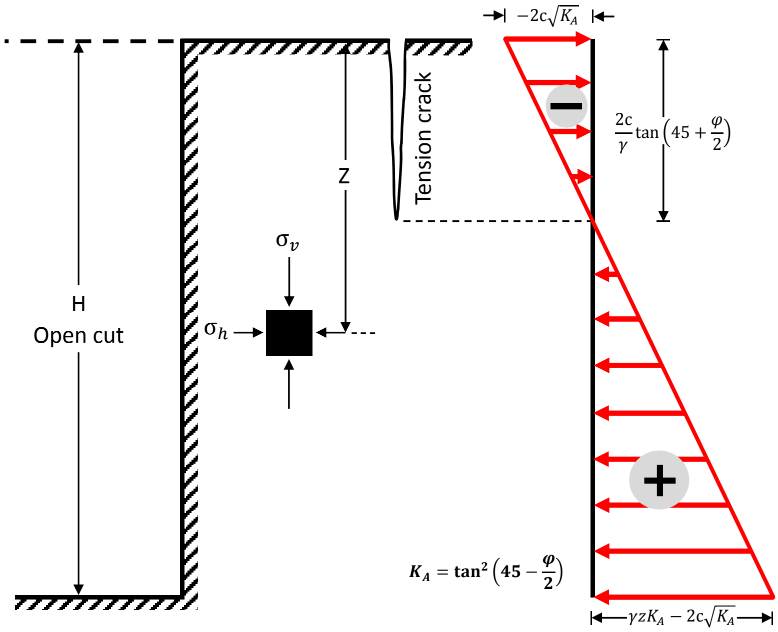


Figure 1. The development of lateral earth pressures and tension crack due to vertical cut.

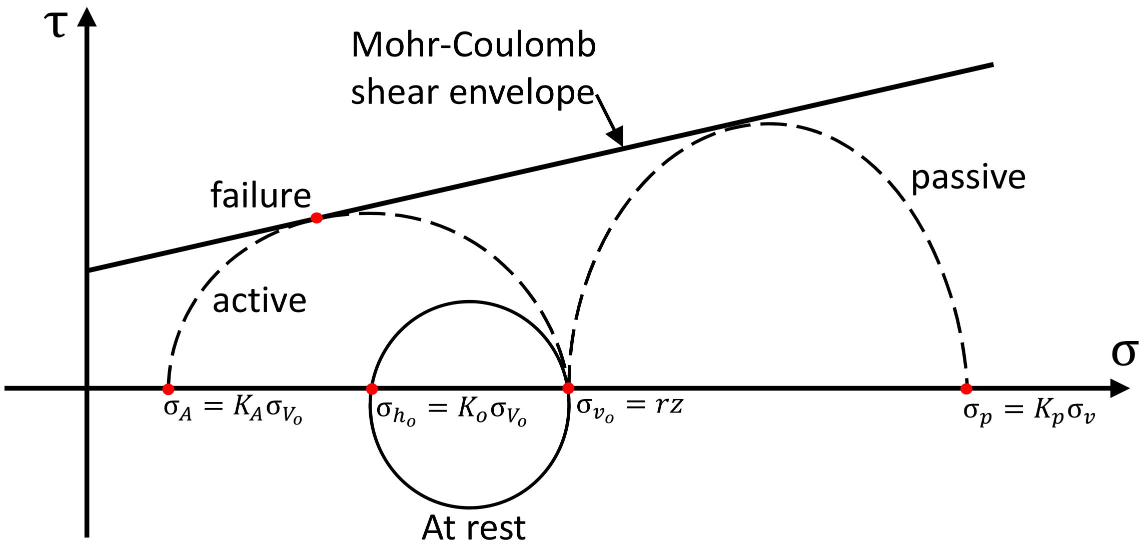


Figure 2. The in-situ horizontal earth pressure decreases from at-rest state to active shear failure due to ground movement.

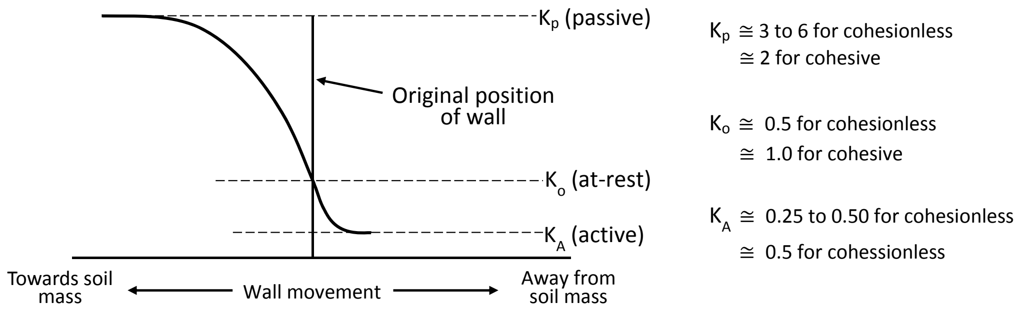


Figure 3. The coefficient of earth pressure decreases from K_0 to K_A due to ground movement.

A shallow excavation to 5m depth in fault zone in Taiwan causes a rapidly lateral slope movement. Several tensile cracks appeared in the upper slope surface extend to 80m far away from the slope cut (Yang et al., 2006). The field displacement measurements of inclinometers show that the possible shear slip surface is limited within a certain distance, but not a circular failure surface. This indicates that the in-situ stresses in fault zone is different to the sedimention deposite. This paper aims to estimate the in-situ stresses by the observation of critical excavation height in fault zone related to the developed tension crack depth.

2. Site condition and material property

A vertical cut in 3m depth with no lateral support will be carried out to observe the tension crack development in a 40m-thick fault zone (see Fig.4). The test site in Taiwan is located in a slope land with the inclination less than 6 degree. Actually, this site of open cut is within the hanging wall of a thrust fault. The fractured material in faulted zone mainly is the mudstone/siltstone occasionally with sandstone interlayers. The foot wall material with a high pressured groundwater from measurement mainly is the gravelly formation. Before the test of open cut, a 5m-depth slope cut in the field was done and a retaining wall with anchorage installed.

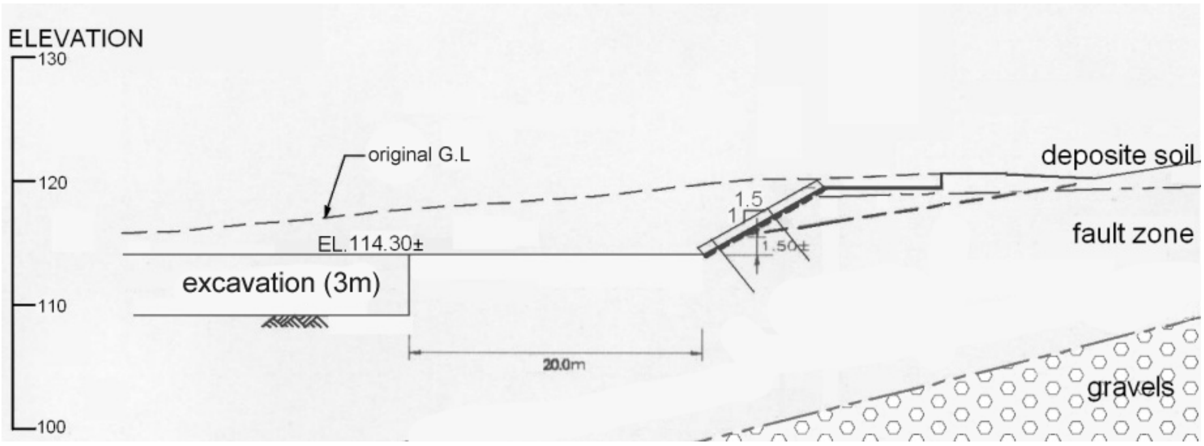


Figure 4. The profile of open cut and previous slope cut in the fault zone.

The unit weight of faulted mudstone/siltstone with natural water content of 8%~12% in the fault zone is 23 kN/m^3. The Atterberg limits of mudstone are obtained as: Liquid Limit LL=24, Plastic Limit PL=13, and Plastic Index PI=11. It is noticed that the natural water content of 8% is less than PL. This property makes this mudstone like the stiff clay by air dried. Several conjugate micro-fractures, such as the Reidel shear fractures are observed in the mudstone/siltstone sample (see Fig.5) cored from the fault zone. The clay-sized material in the shear fractures reveals the high water absorbability.

(a)micro-fractures in mudstone sample (b)case of excavation with supports

Figure 5. The appearance of faulted mudstone block and excavation cases in the fault zone.

The uniaxial compression strength of mudstone samples with natural water content ranges from 2.8 kg/cm^2 to 5.5 kg/cm^2. The deformation modulus is 120 kg/cm^2 (120~960 kg/cm^2). The fracture pattern after peak strength is split fracture or fracture (see Fig.6). The shear strength parameters by direct shear tests are: the average frictional angle $\phi = 25^o(\pm 8.5)$ and cohesion C=0.4 kg/cm^2. The ratio of E/Su used in clayey soil analysis is roughly estimated as 300~2400. It is noticed that the residual frictional angle for remolded samples of mudstone (siltstone/shale) with 20% water content is seriously decreasing to 7.2 degree (see Fig.7). The behavior at natural water content ω=10% shows more brittle in shear failure than that at ω=20%.

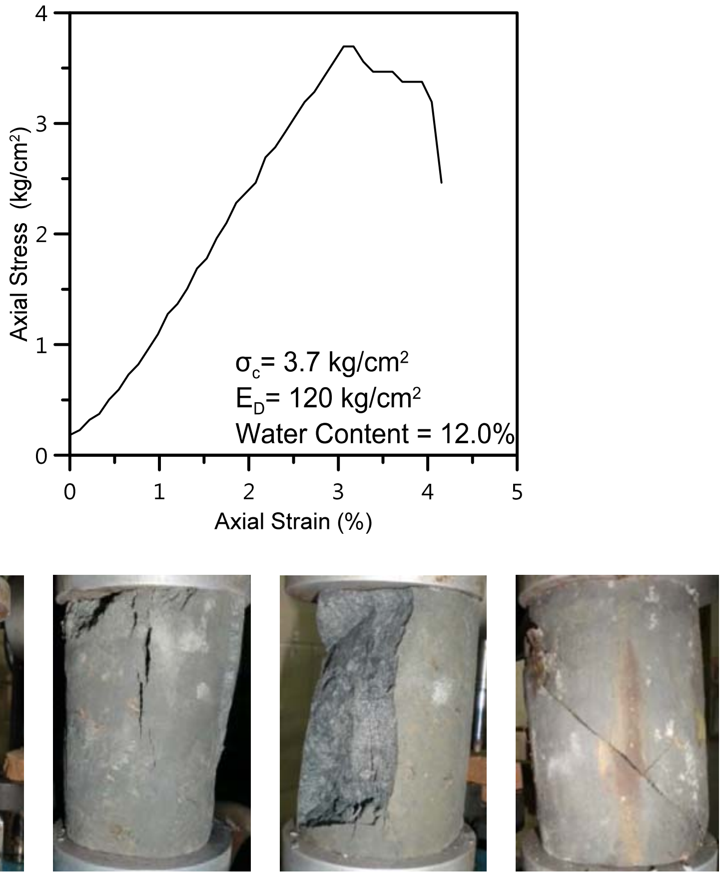
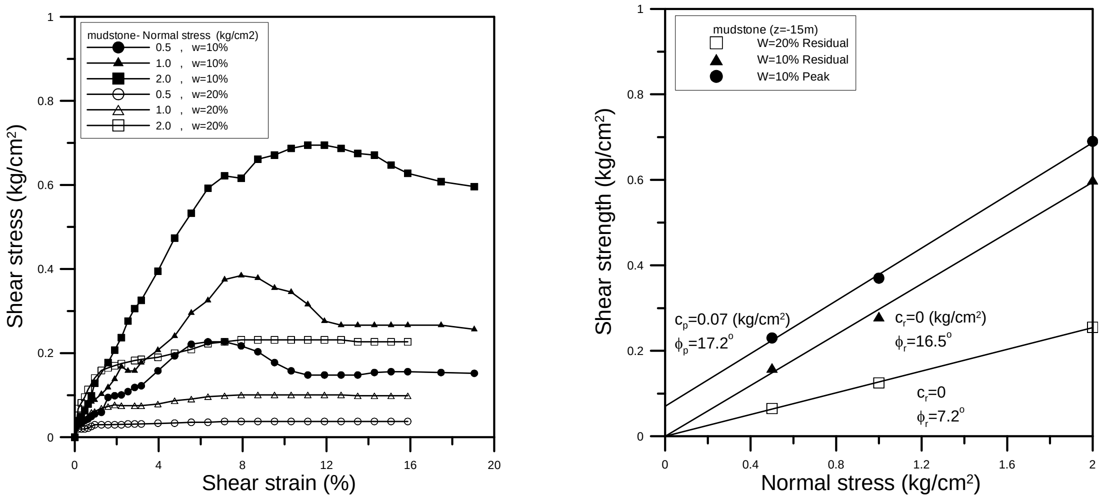


Figure 6. The typical stress-strain behavior of mudstone and fracture mode under compressive test.



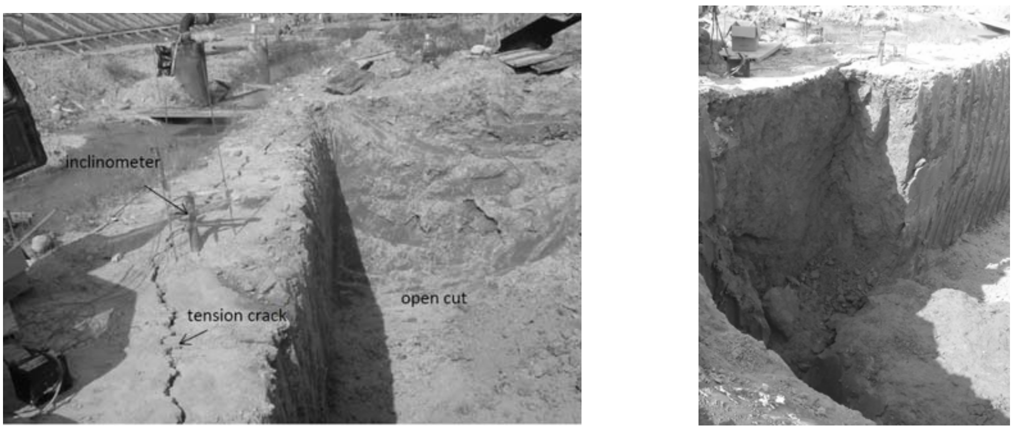
(a)shear stress-strain curve (b)strength envelope

Figure 7. The shear behavior and strengths of faulted mudstone at ω =10% and 20%.

3. Vertical cut without lateral support

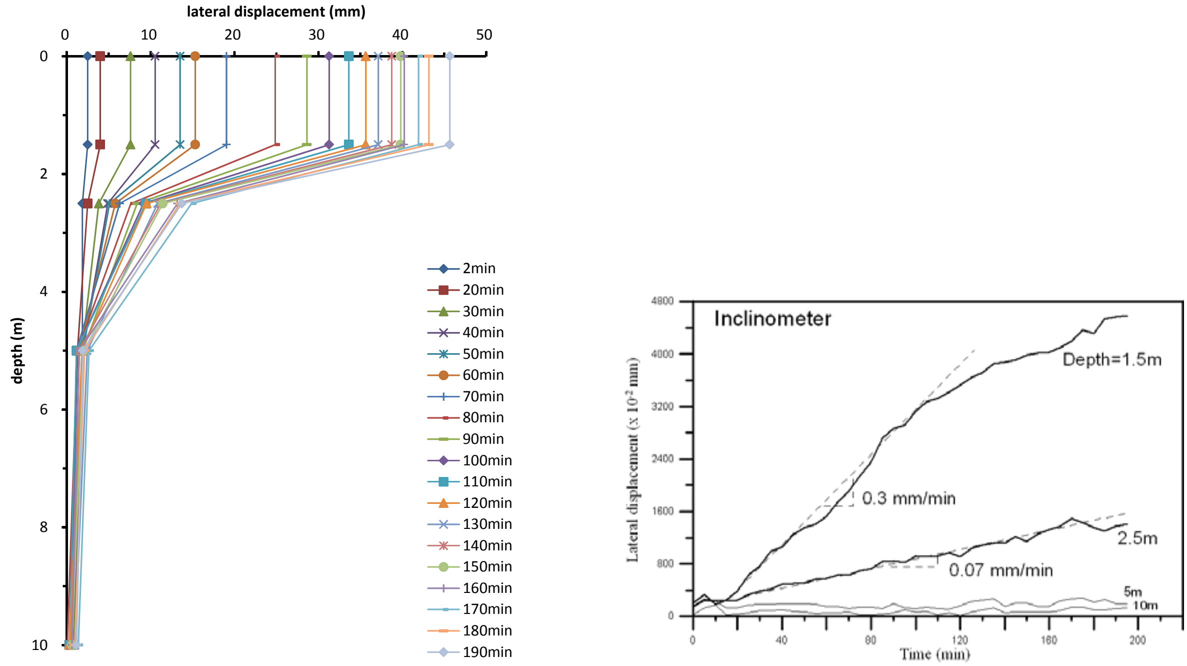
A vertical open-cut to 2.5m depth (with 10m in length and 4m in width) is performed in the field. This test aims to measure the lateral movement of ground by open cut. In order to measure the lateral displacement close to the cut wall of excavation, the inclinometer is setup near to the cut wall in 50cm before excavating (see Fig. 8). No lateral support is applied to this test excavation that we can measure the free displacement of the field ground. Four automatic measurement sensors are setup at the depth of 1.5, 2.5, 5 and 10m to record the lateral displacement. The interval of taking lateral displacement data is 5 minutes.

Figure 8(a) shows a tension crack appears at the ground surface in 2 hours after excavating. The maximum opening of the tension crack reaches 5cm. Due to the confinement of corner effect in a three-dimensional excavation, the tension crack is in a circular shape at the ground surface. However, the tension crack is vertically extended. A mudstone block in 0.8m thick was cut apart and pushed over. That is similar to the toppling failure. The base of the block observed is failure by shear. This ensures the Terzaghi's theory is applicable for this case. The surface characteristic of tensile fracture shown as Fig.8(b) is very rough. The tension crack depth is 2.4m in the 3m vertical open-cut. The lateral displacement measured by inclinometer as shown in Fig.9 for determining the slide plane is good agreed to the crack depth. At depth of 1.5m, the ground movement rate is 0.3 mm/min and total lateral displacement is up to 45mm in three hours.



(a)tension crack at ground surface (b) crack surface characteristic

Figure 8. A tension crack accompanied with the vertical open cut and the tension crack surface.

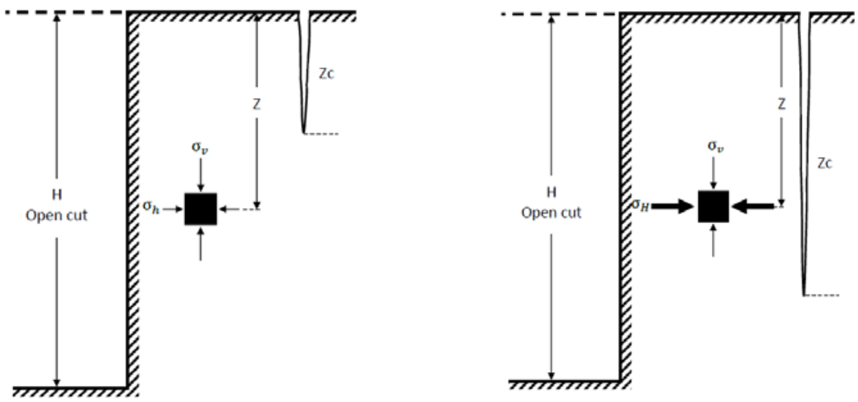


(a)lateral displacement of cut wall (b)movement rate at different depth

Figure 9. The lateral displacement and movement velocity measured by inclinometer.

4. Estimate the horizontal in-situ pressure

The critical height of vertical excavations in $c-\phi$ soil theorectically is to be twice as deep as the tesnsion crack depth according to Terzaghi's observation. That is, $H_c=2z_c$. At this vertical open- cut in the thrust fault zone, the tension crack depth (z_c) at failure observed is 2.4m. The critical height of open cut without supporting theoretically is estimated as $H_c=2z_c$ =4.8 (m). However, in this site the critical self-stand height only comes to H_c=2.5m. This means, see Fig.2, that excavations into this fault ground results in a large horizontal pressure released to soil mass. This large released horizontal pressure enhances the tension crack quick developing. The allowable critical height of excavations to keep self-standing is much less than that for the normally-consolidated deposition soils.



(a)normally-consolidated ground (b)fault zone

Figure 10. The difference in tension crack depth due to two in-situ earth pressure condtion.

Therefore, in the fault ground the in-situ horizontal pressure at rest σ_{H0} (see Fig. 10) should be different to that at-rest σ_{h0} in sedimention ground. That is, this released horizontal pressure $(\sigma_{H0}-\sigma_A)$ in fault zone (see Fig. 2) during the vertical cut to push the ground is more larger than $(\sigma_{h0}-\sigma_A)$ in normally-consolidated deposition. According to the difference in self-stand excavation height, the ratio of released stress ($\sigma_{H0} - \sigma_A$) to $(\sigma_{h0} - \sigma_A)$ can estimate as the ratio of critical excavation height ($4.8/2.5 = 1.92$). That is,

$$(\sigma_{H0} - \sigma_{A0}) = 1.92(\sigma_{h0} - \sigma_A) \cong 2(\sigma_{h0} - \sigma_A) \tag{4}$$

Therefore, the in-situ horizontal at-rest earth pressure in fault zone can express as,

$$\sigma_{H0} \cong 2\sigma_{h0} - \sigma_A \tag{5}$$

where the σ_{h0} is the horizontal at-rest earth pressure and σ_A is the active earth pressure for normally-consolidahereted deposition soils. This means that the in-situ horizontal stress at rest σ_{H0} in fault zone is directly related to the stresses in normally-consolidated deposite soils. Therefore, Eq.(5) is rearranged into

$$\sigma_{H0} \cong 2K_0 \times \gamma z - (\gamma z \times K_A - 2c\sqrt{K_A}) \tag{6}$$

That is,

$$\sigma_{H0} \cong \gamma z[2K_0 - K_A] - 2c\sqrt{K_A} \tag{7}$$

The in-situ horizontal earth pressure at rest in fault zone can estimate using the emperical formula those adopted in normally-consolidated depostion. For example, we get $K_A = \tan^2(45 - \phi/2) = 0.28$ and $K_0 = 1 - \sin\phi = 0.57$ using $\phi = 28^\circ$. The vertical earth pressure is $\sigma_{v0} = \gamma z$. This horizontal earth pressure at rest in fault zone is calculated by Eq.(7) as

$$\sigma_{H0} \cong 0.86\gamma z + 0.56c \qquad \text{[for this fault zone]} \tag{8}$$

However, the in-situ horizontal earth pressure at rest in the normally-consolidated deposition soils is

$$\sigma_{h0} = 0.57\gamma z \qquad \text{[for NC deposite]} \tag{9}$$

It is found that the σ_{H0} in fault zone is close to the vertical earth pressure σ_{v0}. Fig. 11 shows the variation of σ_{v0}, σ_{h0} and σ_{H0} using c=0.4 kg/cm^2 and $\phi = 28^\circ$. This indicates the in-situ horizontal earth pressre in fault zone is greater than that in normally-consolidated deposite soils. However, that K_A and K_0 formula may be different for various ground condition depended upon the soil properties and geological histroy.

5. Conclusions

The Rankine's active earth pressure theory in soil mechanics is derived according to Mohr-Coulomb shear failure criterion. The soil is tensile cracking at where the horizontal earth pressure is negative in excavations. The tension crack depth of $c - \phi$ soils by vertical cut can be approximately estimated. Terzaghi suggested from experimental observations that the critical height of vertical excavations with no lateral supports is twice as deep as the tension crack depth. However, in this paper a vertical cut without lateral supports in fault zone shows that the critical self-stand height of excavations by Terzaghi's formula is over-estimated. This implies that a large horizontal earth pressure is released from the faulting materials. According to the ratio of critical self-stand height between the fault zone and normally-consolidated deposite soils, we estimate the in-situ horizontal earth pressure in this fault zone is $\sigma_{H0} \cong \gamma z[2K_0 - K_A] - 2c\sqrt{K_A}$. This in-situ horizontal earth pressure in fault zone can be estimated directly by the coefficients of earth pressure at rest and at active state in normally-consolidated deposition.

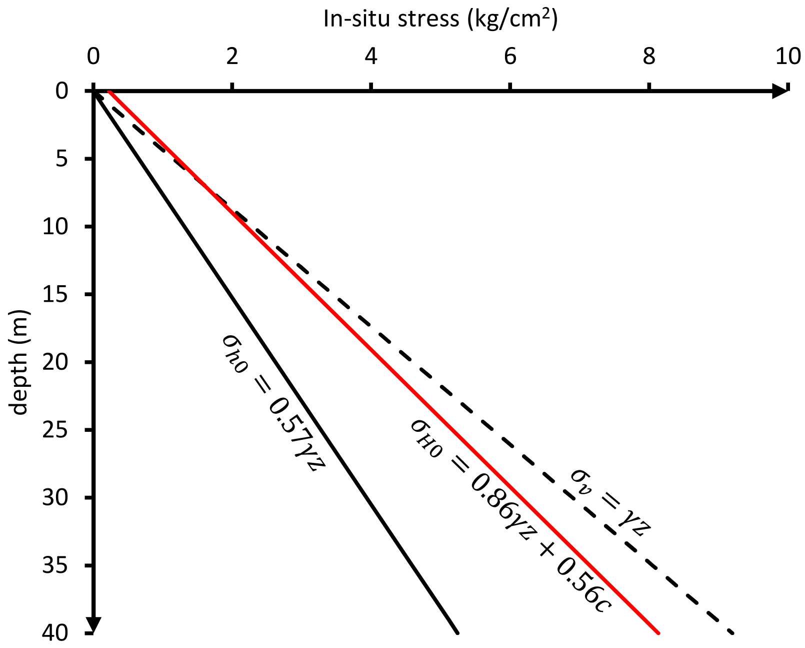


Figure 11. The variation of in-situ horizontal stress σ_{h0} in normall-consolidated deposite soils and σ_{H0} in thrust fault zone.

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