A case study on the determination of the excavated trench depth in unsaturated soil constructed by trench method without supporting structures

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Abstract: Together with the excavated width, the depth of trench play a vital role in stability as well as economics effectiveness of a trench constructed by open trench method. It is widely recognized that a steeper angle of an open trench, a smaller amount the excavated soil required; however, the trench is unstable. In this case, an external supporting structure system is obliged to prevent the trench from falling into the excavation zone. In addition, an open trench is normally located above the water table, hence under unsaturated condition. One of the most important characteristics of unsaturated soil is negative pore water pressure which brings about the matric suction, higher negative pore water pressure, higher matric suction; consequently, higher shear strength of soil. On the other hand, there is a few theories and research works have been reported on the method of determining a suitable depth of a trench under unsaturated condition. Previous works tend to assume that the distribution of matric suction is either constant or linear with depth; as a result of this, the designed results are often overestimated compared to practical results. In this paper, the effect of distribution of matric suction was taken into account to propose an equation to estimate the depth of a trench that can be applied without supporting structure. Finally, an example of numerical calculation of a depth of the open trench was described.

1 Introduction

One of the most important parameters need to be considered when dealing with the stability of underground construction constructed by open method such as traffic tunnel, cable tunnel (power electricity cable, communication cable), sub-pavement tunnel, even some path of railway tunnel, are that the magnitude of the depth (H), and width (L) of open trench. In other words, the L/H ratio must be met both the stability of underground structure requirement and economic effectiveness. The L/H ratio controls the angle of the open trench, hence amount of excavation work required. The smaller the value of β (as shown in the Fig 1) is, the higher stability of the open trench can be obtained; however, the larger the amount of excavation work need to be done. Economically side speaking, once the value of β equals to 90^0 the amount of excavation work required is lowest, hence the highest of effectiveness of economic. In spite of this, the stability of the open trench must be taken into account. It is widely observed that under this condition β=90^0, some external supporting structures (known as the temporary structure) ought to be applied such as earth anchor, retaining wall, struts, sheet pile,. As a result of this requirement, some shortcoming might be seen as follows:

- Due to the existence of the temporary structures, the construction area of underground construction is reduced;
- It is costly since the temporary structures used;
- Progress of construction work is highly affected, even much longer as compared to that in case of without using temporary structures.

Based on these problems, this paper aims to determine the applicable depth of the open trench without supporting structures under the condition that the angle of the open trench,β, equals to 90 degree.

2 Required depth of an open trench

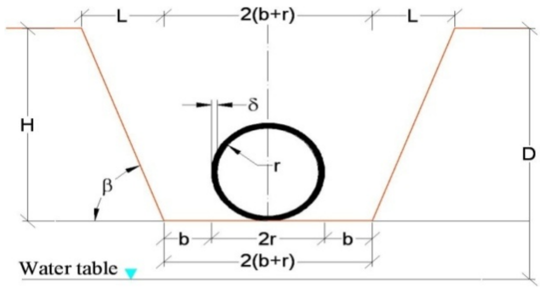

Fig 1. A typical cross section of an open trench

Where: δ is the thickness of structure, (mm); r is the inner radius of circle-structure (or half of width of rectangular shape), (cm); β is the angle of the open trench (degree);

It's widely recognized that the open trench is constructed in somewhere that is normally located above the water table, hence under unsaturated condition. Thus, in order to find out the applicable value of the depth of the open trench,H, without supporting structures with the angle of open trench of 90 degree, the depth of water table is assumed to be D (m) (Fig 1), the type of soil is classified as cohesionless soil and under unsaturated condition.

According to Kartozia B.A.1983, the required depth, H must be fulfilled the following conditions:

$$H \geq (2 \div 5)2r = (4 \div 10)r \tag{1}$$

and, $$D > H + m \tag{2}$$

Where: m is the thickness of backfill soil layer which used to resist the water penetration under high pressure, this parameter can be defined as below Terzaghi K. 1941:

$$m \geq \frac{h}{(\frac{\gamma_s}{\gamma_w} - 1)} \tag{3}$$

Where γ_s, γ_w are the density of soil, and water respectively (kN/m^3);h is the height of pressurized water once groundwater seepage into the open trench.

3 Matric suction in unsaturated soil

One of the most important characteristic of unsaturated soil is the negative pore water pressure. In other words, the pore water pressure due to capillarity is negative (suction), it is defined as a function of the size of the soil pores and the water content. At the groundwater level, the pore water pressure is zero and decreases (becomes negative) once the capillary zone goes up. As the result of the negative pore water pressure, the effective stress increases. To specify, for the capillary zone, z_c, the pore water pressure at the top is -$z_c\gamma_w$, hence the effective stress (Fredlund 2014; Fredlund et al. 2012; Fredlund et al. 1996) stated that profile of matric suction in a horizontally layered unsaturated soil generally depends on several factors; especially the soil properties as given by soil water characteristic curve and the soil permeability, environmental factors including infiltration due to precipitation or evaporation rates and boundary drainage conditions including the location of groundwater level. The matric suction profile will come to equilibrium at a hydrostatic condition when there is zero net flux from the ground surface. If moisture content is extracted from the ground surface such as evaporation, the matric suction profile will be drawn to the left (matric suction increases). If moisture enters at the groundwater surface such as infiltration, the matric suction profile will be drawn to the right (matric suction reduces).

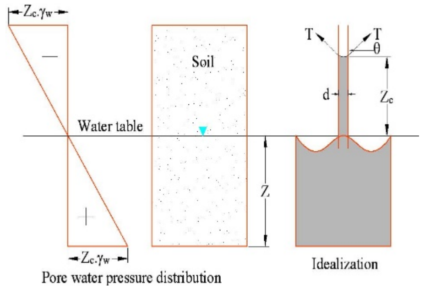

Fig 2. Simulation of capillary in soil (Budhu 2000).

Under steady state, the water flux in and out of the soil reaches the balance. If the magnitude of water flux is the same as the hydraulic conductivity of the saturated soil, the magnitude of the pore-water pressure is constant (Fig 3).

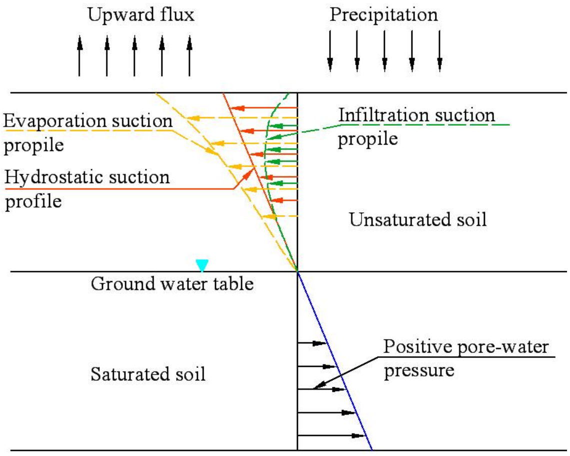

Fig 3. Matric suction profile in horizontally layered unsaturated soil profiles under various surface flux boundary condition ((Fredlund 2014; Fredlund et al. 1996)

From the distribution of matric suction, it's found that the matric suction profile varies with depth and linearly reduced from surface to the water table; however, once the boundary drainage conditions change is due to either upward flux or precipitation, the distribution of matric suction is not linearly. Therefore, in this paper the change in the distribution of matric suction is assumed as a function of the third order polynomial and expressed as below:

$$F_{hd}(y) = a + by + cy^2 + dy^3 \quad (4)$$

Where y is the considered depth of open trench; F_{hd} is the function of matric suction varies with depth. The equation (11) must be met the following conditions:

$$y = 0 \rightarrow F_{hd}(y) = \max = k\gamma_n gD$$

$$y = D \rightarrow F_{hd}(y) = 0$$

By considering and comparing with the practical condition, the Eq (4) can be rewritten as:

$$F_{hd}(y) = \frac{A}{D}\left(D^2 - 2y^2 + y^3 / D\right) \quad (5)$$

Or $F_{hd}(y) = AD\left(1 - y^3 / D^3\right)$ (6)

Where $A = k\gamma_n g$, k is the pore water pressure coefficient, which varies with the slope of hydrostatic pressure (or hydrostatic suction profile); g is specific gravity. Taking a look into the Eq (12a, b), the magnitude of matric suction is decrease from a value of AD = $kD\gamma_n g$ (at y=0) to zero (at y=D). The istribution of matric suction is showed in the Fig 4.

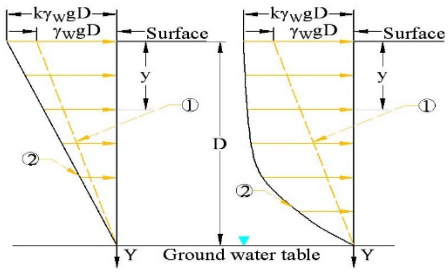

Fig 4. The distribution of matric suction with depth. (1) represent the surface of hydrostatic suction; (2) the distribution line of matric suction.

4 Determination of depth of open trench without supporting structure

4.1 Earth pressure

The horizontal pressures act to the wall of open trench is caused by the active earth pressure, p_a, which can be determined as follow(Bang 1985; Terzaghi 1941; Terzaghi et al. 1996; Wang 2000):

$$p_a = (\sigma_n - u_a) = (\sigma_đ - u_a)\cot g^2(\frac{\pi}{4} - \frac{\varphi'}{2}) - 2C.\cot g(\frac{\pi}{4} - \frac{\varphi'}{2}), \quad (7)$$

Where : $\sigma_đ = \gamma_đ.g.y$, (8)

C is the total cohesion stress which consists of two components, one is the effective cohesion, C'; the other is suction force: $(u_a - u_w)tg\varphi_b$. In other words:

$$C = C' + (u_a - u_w)tg\varphi_b \quad (9)$$

Combination of Eq (9) and (7):

$$p_a = (\sigma_n - u_a) = (\sigma_d - u_a)\cot g^2(\frac{\pi}{4} - \frac{\varphi'}{2}) - 2(C' + (u_a - u_w)tg\varphi_b)\cot g(\frac{\pi}{4} - \frac{\varphi'}{2})$$
$$= (\sigma_d - u_a)\cot g^2(\frac{\pi}{4} - \frac{\varphi'}{2}) - 2C'\cot g(\frac{\pi}{4} - \frac{\varphi'}{2})$$
$$- 2(u_a - u_w)tg\varphi_b.\cot g(\frac{\pi}{4} - \frac{\varphi'}{2}), \quad (10)$$

Substitute Eq (5) into Eq (10):

$$p_a = (\sigma_n - u_a) = (\sigma_d - u_a)\cot g^2(\frac{\pi}{4} - \frac{\varphi'}{2}) - 2C'\cot g(\frac{\pi}{4} - \frac{\varphi'}{2})$$
$$- 2tg\varphi_b.\cot g(\frac{\pi}{4} - \frac{\varphi'}{2}).\frac{A}{D}[D^2 - 2y^2 + y^3 / D] \quad (11)$$

Substitute Eq (8 into Eq (11):

$$p_a = (\sigma_n - u_a) = (\gamma_d gy - u_a)\cot g^2(\frac{\pi}{4} - \frac{\varphi'}{2}) - 2C'\cot g(\frac{\pi}{4} - \frac{\varphi'}{2})$$
$$- 2tg\varphi_b .\cot g(\frac{\pi}{4} - \frac{\varphi'}{2}).\frac{A}{D}[D^2 - 2y^2 + y^3 / D] \quad (12)$$
,

The total magnitude of active earth pressure acts to the retaining wall with its height of H_t, p_a, can be defined as:

$$P_A = \int_0^{H_t} p_a dy \quad (13)$$

4.2 Determine the magnitude of depth of open trench

The distribution of active earth pressure can be divided into two regions, one is tensile region, the other one is compressive region. Two these regions are separated at a depth of y_k. In the tensile region (from the surface to depth of y_k), the active earth pressure is negative, which causes soil mass behinds retaining wall tends to move away from the retaining wall. The magnitude of y_k may be estimated by combination Eq (10) and Eq (5, 6), together with a condition of $p_a = 0$ and $u_a = 0$:

$$\sigma_d \cot g^2(\frac{\pi}{4} - \frac{\varphi'}{2}) - 2C'\cot g(\frac{\pi}{4} - \frac{\varphi'}{2}) - 2tg\varphi_b .\cot g(\frac{\pi}{4} - \frac{\varphi'}{2}).\frac{A}{D}[D^2 - 2y^2 + y^3 / D] = 0 \quad (14)$$

After working out the Eq (14), the value of y_k can be found.

If total active earth pressure Pa acts to the retaining wall is completely dissipated, the corresponding depth under that condition will be the one that can be applied without supporting structure. In other words, the magnitude of depth of the open trench, y_{kc}, can be determined by solving the following equation:

$$P_A = \int_0^{y} p_a dy = 0 \quad , \quad (15)$$

By substituting Eq (11) into Eq (15), and working out the Eq (15) with y is the variable, the y_{kc} can be derived, and its value is a function of

$$y_{kc} = f(\varphi', \varphi_b, u_a, \sigma_d, D, A) \quad (16)$$

5 Numerical caculation

The physico-chemical properties of the studied soil was obtained from a construction site located in the Southeast of Vietnam is described in the Table 1.

Table 1. Soil parameters used in this paper

Description	Symbol	Unit	Value
Unit weight	γ	kN/m3	18
Effective cohesion	c'	kPa	50
Effective friction angle	φ'	Degree	22

Effective friction angle associated with matric suction	φ^b	Degree	14
Pore-water pressure coefficient	k	-	1.5
Other parameters			
Pore air pressure	u_a	kPa	0

5.1 Effect of level of ground water table

By changing the level of groundwater table, D, the relationship between depth of the open trench without supporting structure and D, can be found (Table 2), and (Fig 5).

Table 2. Relationship between k_{kc} and level of groundwatertable

Description	Unit	Values						
Depth of groundwater table, D	m	7	8	9	10	11	13	15
k_{kc}	m	4.38	4.97	5.25	5.83	6.19	7.18	7.34

5.2 Effect of effective friction angle (Fig 6)

Table 3. Relationship between k_{kc} and effective friction angle

Description	Unit	Values						
Effective friction angle,φ'	degree	10	14	18	22	26	30	35
k_{kc}	m	4.85	4.55	4.34	4.21	3.87	3.57	3.32

5.3 Effect of effective cohesion (Fig 7)

Table 4. Relationship between k_{kc} and effective cohesion

Description	Unit	Values						
Effective cohesion, c'	kPa	20	40	50	60	70	75	85
k_{kc}	m	3.71	4.09	4.23	4.31	4.39	4.45	4.63

5.4 Effect of pore water pressure coefficient (Fig 8)

Table 5. Relationship between k_{kc} and pore-water pressure coefficient

Description	Unit	Values				
Pore-water pressure coefficient, k	-	1.0	1.2	1.5	1.7	2.0
k_{kc}	m	3.22	3.69	4.23	4.52	4.98

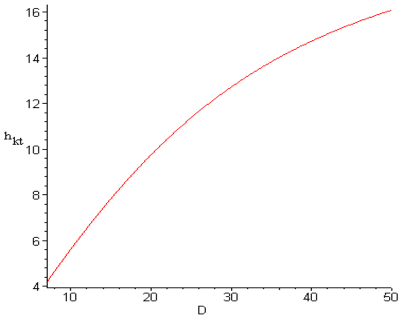

Fig 5. Relationship between k_{kc} and level of groundwater table

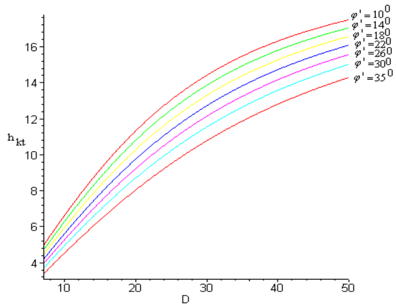

Fig 6. Relationship between k_{kc} and effectivefriction angle

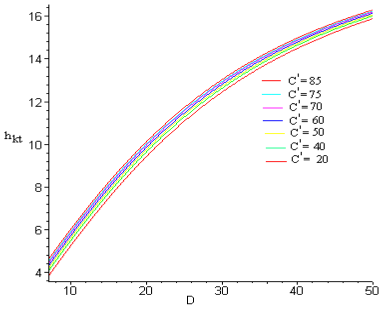

Fig 7. Relationship between k_{kc} and effective cohesion

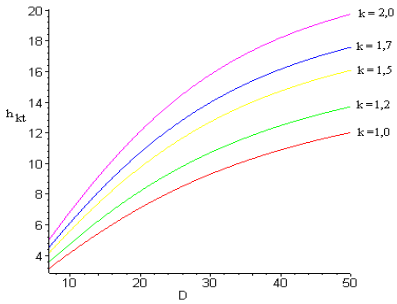

Fig 8. Relationship between k_{kc} and pore-water pressure coefficient

6. Conclusion

♦ Due to the existence of negative pore-water pressure, the total cohesion forces increases. Also, the loss of soil mass which located behind the retaining wall induces the crack. This is a point that can be used to consider whether the open trench needs to be strengthened at a certain depth or not;

♦ Previous works assumed that the distribution of the matric suction is linearly decreased with the depth; consequently, the tolerances are normally higher than those in reality;

♦ In this paper, the distribution of matric suction is assumed to be third order polynomial for determination of the depth of open trench without supporting structure;

♦ As can be seen from numerical calculation:

- The magnitude of k_{kc} is nonlinearly increased with the level of groundwater table; however, once the level of groundwater reaches the certain value, the value of k_{kc} almost constant and tends to reach the critical value;

- Under the same conditions:

+The value of k_{kc} decreases with an increase of effective friction angle;

+The value of k_{kc} does not significantly increase as the effective cohesion goes up;

+The value of k_{kc} is notably increased as the pore-water pressure coefficient, k, increases.

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