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Deformations assessment in expansive clays

An approche au calcul de déformations en argiles gonflées

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ABSTRACT

A procedure for deformations assessment of expansive clays is presented. Constitutive equations for compression due to external loads and for deformations due to changes in suction values are developed. The movements of a foundation in expansive clay are the algebraic sum of the compression produced by external loads and the deformation produced by suction changes. Examples for assessment of soil properties and deformations in expansive clays are presented

RÉSUMÉ

Ce travail propose une méthode de calcul de déformations en argiles gonflées. Une loi de comportement a été développée pour prendre en compte les charges et les variations de succion lesquelles provoquent la déformation du sol. Il faut noter que les déformations d'une fondation sur argiles gonflées sont la somme algébrique de deux termes: les déformations provoquées pour les charges extérieures et pour les changes de succion. L'application de la méthode proposée se fait au moyen d'un problème pratique.

Keywords : expansive clay, suction, constitutive equations, deformations assessment, soil properties

1 INTRODUCTION

When expansive clay is overloaded by the construction of a civil engineering structure, it suffers a compression. Moreover, when this clay undergoes a change in soil suction magnitude, it swells or it shrinks.

Therefore, deformation of swelling clay is the algebraic sum of compression due to external load increments plus deformations caused by soil suction variations.

In this paper, a procedure for the prediction of soil movements due to both phenomena is presented. Examples of soil properties and deformation assessments are included.

2 DEFORMATIONS ASSESSMENT

2.1 Constitutive equations

Deformations of unsaturated clay are due to: (1) stress increments caused by the load of a structure, and (2) suction variations in subsoil. Strains due to loads of a structure are calculated with the tools of soil mechanics. Decrease of suction magnitude causes an increment in the double layer of the particles of soil and, in some cases, water molecules move into clay particles.

Therefore, soil deformation is the algebraic sum of deformation due to external load increments plus deformation due to changes in soil suction.

2.2 Deformation due to external load increments

Consider a soil element subjected to load due to weight of soil. Initial confined pressure is

$$p_{co} = \frac{p_{vo} + p_{ho} + p_{ho}}{3}$$

p_{vo} = vertical normal stress

p_{ho} = horizontal normal stress

But $p_{ho} = K_o p_{vo}$, then

$$p_{co} = (1/3)(1 + 2K_o) p_{vo}$$

If soil is cemented and is subjected to soil suction p_s , the initial confinement pressure p_{beo} is (figure 1a)

$$p_{beo} = p_{cie} + p_{co} + b_5 p_a (p_s/p_a)^n \quad (1)$$

p_{cie} = internal pressure due to cementation; p_s = soil suction magnitude, $b_5 \approx 1$, p_a = atmospheric pressure = 101.3 kPa

A civil engineering structure causes over a soil element the load increments σ_z , σ_x and σ_y shown in figure 1b.

Let p_{beo} be constant for a while. Strain of soil element is

$$\epsilon_z \cong (1/A) [\sigma_z - \nu (\sigma_x + \sigma_y)]^f \quad (2)$$

A = rigidity modulus of soil

ν = Poisson modulus

Consider a small thickness element Δz_o . Then

$$a_1 = \sigma_x / \sigma_z \quad a_2 = \sigma_y / \sigma_z \quad (3)$$

$$\sigma_x = a_1 \sigma_z \quad \sigma_y = a_2 \sigma_z \quad (4)$$

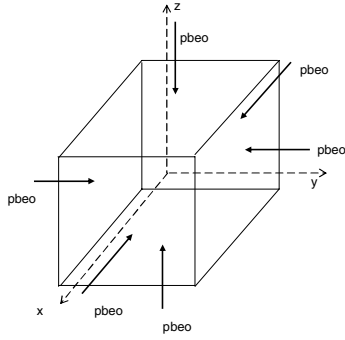
Substitute equations 4 in equation 2

$$\epsilon_z \cong (1/A) \{ \sigma_z [1 - \nu (a_1 + a_2)] \}^f \quad (5)$$

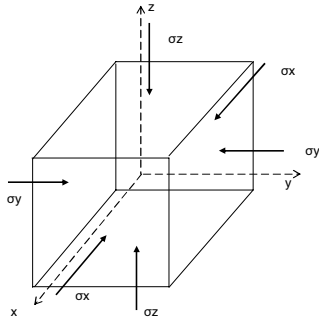
Let

$$f = 1 - \nu (a_1 + a_2) \quad (6)$$

$$\epsilon_z \cong (1/A) (f \sigma_z)^f \quad (7)$$



(a) Initial confinement pressure



(b) Stress increments due to presence of an engineering structure

Figure 1. Loads over a soil element

Consider now the action of confining stress. For the stress state shown in figure 1, confining pressure is

$$p_{be} = p_{beo} + \Delta p_{be}$$

$$\Delta p_{be} = (1/3) (\sigma_z + \sigma_x + \sigma_y)$$

$$\Delta p_{be} = b_1 \sigma_z + b_2 (\sigma_x + \sigma_y) \quad (8)$$

where $b_1 = 1/3$ and $b_2 = 1/3$.

Substitute equations 4 in equation 8

$$\Delta p_{be} = c \sigma_z \quad (9)$$

$$c = b_1 + b_2 (a_1 + a_2) \quad (10)$$

$$p_{be} = p_{beo} + c \sigma_z \quad (11)$$

We propose the following constitutive equation for the calculation of strain in the soil element of figure 1b (Deméneghi 2003)

$$\frac{d(\Delta z)}{\Delta z} = -\frac{1}{A} \frac{\left(\frac{f\sigma_z}{p_a}\right)^r d\left(\frac{f\sigma_z}{p_a}\right)}{\left(\frac{p_{beo} + c\sigma_z}{p_a}\right)^s} \quad (12)$$

A, r and s are soil properties. For practical purposes we can take in cohesive soils $r = 0$ and $s = 1$. Integrate equation 12: for σ_z varying from 0 to σ_z , element thickness changes from Δz_o a Δz_f . Then

$$\int_{\Delta z_o}^{\Delta z_f} \frac{d(\Delta z)}{\Delta z} = -\int_0^{\sigma_z} \frac{1}{A} \frac{d(f\sigma_z)}{p_{beo} + c\sigma_z}$$

$$\frac{\Delta z_f}{\Delta z_o} = \left(\frac{p_{beo} + c\sigma_z}{p_{beo}} \right)^{-f/cA} \quad (13)$$

But (figure 2)

$$\Delta z_f = \Delta z_o + \Delta w, \quad \Delta z_f/\Delta z_o = 1 + \Delta w/\Delta z_o \quad (14)$$

$$\Delta w/\Delta z_o = \Delta z_f/\Delta z_o - 1 \quad (15)$$

Let $\delta_z = -\Delta w$

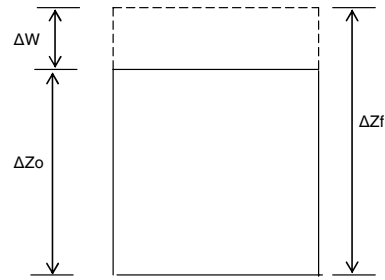


Figure 2. Deformation of a soil element

$$\delta_z = \left[1 - \left(\frac{p_{beo} + c\sigma_z}{p_{beo}} \right)^{-f/cA} \right] (\Delta z_o) \quad (16)$$

In expansive clays the state stress is at the recompression line or at the normally consolidation line. Then

For recompression line

$$\delta_z = \left[1 - \left(\frac{p_{beo} + c\sigma_z}{p_{beo}} \right)^{-f/cAs} \right] (\Delta z_o) \quad (17)$$

For normally consolidation line

$$\delta_z = \left[1 - \left(\frac{p_{beo} + c\sigma_z}{p_{beo}} \right)^{-f/cAvr} \right] (\Delta z_o) \quad (18)$$

2.3 Strain due to adsorption of water molecules in soil particles

In clayey soils water molecules are introduced into the solid grains; when a molecule of water introduces into two platelets of a soil particle, its electric charges are pulled apart, becoming more dipolar and attracting other water molecules; additionally, the electric charges on the surface of the platelets also concentrate, pushing away other platelets and increasing the number of molecules between them, resulting in the increase of the volume of the particles (Alonso et al. 2008). Moreover, when suction decreases the double layer of the particles

increases. Therefore, soil suffers volumetric changes from suction variations. For computation of this strain we propose the following constitutive equation

$$\frac{dV}{V} = -\frac{1}{B_a} \frac{d(b_4 p_s)}{p_c + b_4 p_s} \quad (19)$$

V = soil element volume, $b_4 \approx 1$, B_a = soil property

$$p_c = p_{co} + \sigma_c \quad (20)$$

$$\sigma_c = (1/3) (\sigma_z + \sigma_x + \sigma_y) \quad (21)$$

When suction changes from p_{so} to p_{sf} ($p_{so} < p_{sf}$), soil element thickness diminishes from V_o to V_f . Then

$$\int_{V_o}^{V_f} \frac{dV}{V} = \int_{p_{so}}^{p_{sf}} -\frac{1}{B_a} \frac{d(b_4 p_s)}{p_c + b_4 p_s}$$

$$\frac{V_f}{V_o} = \left(\frac{p_c + b_4 p_{sf}}{p_c + b_4 p_{so}} \right)^{-1/B_a} \quad (22)$$

Let ϵ_{va} be the volumetric strain

$$\epsilon_{va} = \Delta V/V_o = (V_o - V_f)/V_o = 1 - V_f/V_o$$

$$\epsilon_{va} = 1 - \left(\frac{p_c + b_4 p_{sf}}{p_c + b_4 p_{so}} \right)^{-1/B_a} \quad (23)$$

Equation 23 gives volumetric strain of soil element. If ϵ_{va} is positive, the element contracts, but if ϵ_{va} is negative, the element swells. For practical purposes $b_4 \approx 1$.

In engineering practice we need compute vertical strain ϵ_{za} . This value is obtained with the following procedure

$$\epsilon_{va} \equiv \epsilon_{xa} + \epsilon_{ya} + \epsilon_{za}$$

If there are no cracks in the subsoil: $\epsilon_{xa} \equiv \epsilon_{ya} \equiv 0$ and $\epsilon_{za} \equiv \epsilon_{va}$

If there is a crack pattern in one direction: $\epsilon_{ya} \equiv 0$, $\epsilon_{xa} \equiv \epsilon_{za}$ y $\epsilon_{za} \equiv \epsilon_{va}/2$

If there are two crack patterns: $\epsilon_{xa} \equiv \epsilon_{ya} \equiv \epsilon_{za}$ y $\epsilon_{za} \equiv \epsilon_{va}/3$

Magnitudes of suction are measured using field or laboratory essays.

In approximate way, we can assess the value of suction in the field with an oedometer test. The essay consists to add water into soil specimen and then apply loads when the soil is fully saturated (figure 3). Then

$$\Delta p_{cs} = b_5 p_a (p_{so}/p_a)^n, \quad so$$

$$p_{so} = p_a (\Delta p_{cs}/b_5 p_a)^{1/n} \quad (24)$$

and

$$B_a = -\frac{\ln\left(\frac{p_{co}}{p_{co} + b_4 p_{so}}\right)}{\ln\left(\frac{1 + e_A}{1 + e_o}\right)} \quad (25)$$

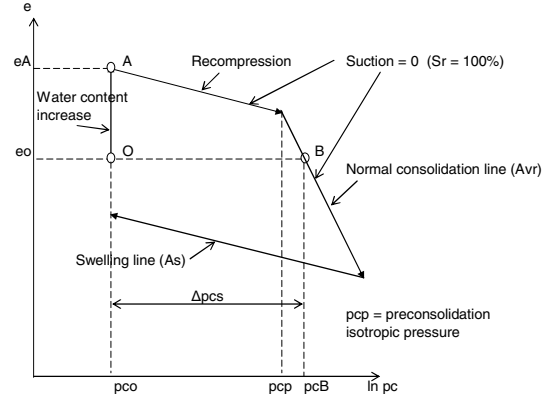


Figure 3. Oedometer test

Modulus A_s is obtained in the swelling branch, considering as is usual in expansive clays that $p_{cie} = 0$. Let (p_{c1}, e_1) and (p_{c2}, e_2) be two points in the swelling line ($p_{c2} > p_{c1}$). Then

$$A_s = -\frac{3(1 - K_o)}{1 + K_o} \frac{\ln\left(\frac{p_{c2}}{p_{c1}}\right)}{\ln\left(\frac{1 + e_2}{1 + e_1}\right)} \quad (26)$$

A_{vr} is obtained in a similar way.

As we have commented, deformation of expansive clay is the algebraic sum of settlement due to external load increments plus deformation due to absorption of water molecules in the soil particles.

3 EXAMPLES

3.1 Soil properties assessment

In an oedometer test the following results were obtained: $p_{vo} = 12.26$ kPa, $e_o = 1.208$, $e_A = 1.449$, $p_{vB} = 186.39$ kPa, $e_B = 1.2$, $p_{vp} = 88.29$ kPa.

In the swelling line {Point (p_v [kPa], e): 1 (58.17, 1.041), 2 (119.39, 1.023)}. In the normal consolidation line: 1 (272.42, 1.146), 2 (578.59, 1.002).

Calculate initial suction magnitude and properties B_a , A_s and A_{vr} .

Consider $K_o = 0.7$, $b_4 = b_5 = 1$, $n = 0.75$, $p_a = 101.3$ kPa.

Solution

$$p_{co} = (1+2K_o) p_{vo} / 3 = (1+2(0.7))(12.26)/3 = 9.808 \text{ kPa}$$

$$p_{cB} = (1+2K_o) p_{vB} / 3 = (1+2(0.7))(186.39)/3 = 149.112 \text{ kPa}$$

$$\Delta p_{cs} = p_{cB} - p_{co} = 149.112 - 9.808 = 139.304 \text{ kPa}$$

Substitute in equations 24 and 25

$$p_{so} = 101.3 (139.304/(1)(101.3))^{1/0.75} = 154.91 \text{ kPa}$$

$$B_a = -\frac{\ln\left(\frac{9.808}{9.808 + (1)154.91}\right)}{\ln\left(\frac{1 + 1.449}{1 + 1.208}\right)} = 27.23$$

In the swelling line (equation 26)

$$A_s = -\frac{3(1-0.7)}{1+0.7} \frac{\ln\left(\frac{119.39}{58.17}\right)}{\ln\left(\frac{1+1.023}{1+1.041}\right)} = 42.97$$

In normal consolidation line

$$A_{vr} = -\frac{3(1-0.7)}{1+0.7} \frac{\ln\left(\frac{578.59}{272.42}\right)}{\ln\left(\frac{1+1.002}{1+1.146}\right)} = 5.74$$

3.2 Deformation predictions

A structure rests on a foundation slab of 8 per 16 m in plan, with a uniform load transfer to subsoil of 25 kPa. Construction of structure is in dry season, when suction in clay has a magnitude ($u_a - u_w$) = $p_s = 820$ kPa. At the end of the rainy season suction decreases to 60 kPa. Subsoil stratigraphy is shown in figure E-1. Soil properties are: $A_s = 39.8$, $A_{vr} = 5.2$, $B_a = 31.7$, $n = 0.75$, $OCR = 8$, $K_o = 0.68$, $b_4 = b_5 = 1$, $v = 0.40$, $p_{cie} = 0$, $p_a = 101.3$ kPa, $p_{vp} = 90$ kPa.

Compute the movements of foundation slab from dry to rainy season.

Solution

Initial vertical soil pressure, at the middle of clay stratum is

$$p_{vo} = 18(0.6) + 15(0.3) = 15.3 \text{ kPa}$$

Normal stress increments, at the middle of clay stratum are

$$\sigma_z = 24.88 \text{ kPa}$$

$$\sigma_x = 17.50 \text{ kPa}$$

$$\sigma_y = 16.77 \text{ kPa}$$

Substitute in equations 10 and 6

$$c = \frac{1}{3} + \frac{1}{3} \frac{17.50 + 16.77}{24.88} = 0.792$$

$$f = 1 - 0.4 \frac{17.50 + 16.77}{24.88} = 0.449$$

$$p_{co} = \frac{1 + 2(0.68)}{3} (15.3) = 12.036 \text{ kPa}$$

$$p_{cp} = \frac{1 + 2(0.68)}{3} (90) = 70.8 \text{ kPa}$$

Maximum compression occurs at the end of rainy season, when soil suction is 60 kPa. Using equations 1 and 21

$$p_{beo} = 0 + 12.036 + (1)(101.3) (60/101.3)^{0.75} = 80.43 \text{ kPa}$$

$$\sigma_c = (24.88 + 17.50 + 16.77)/3 = 19.72 \text{ kPa}$$

$$p_{beo} + \sigma_c = 80.43 + 31.54 = 100.15 \text{ kPa}$$

In view that $p_{beo} + \sigma_c > p_{cp}$, settlement caused by external load increments occurs in the normal consolidation line. Using equation 18

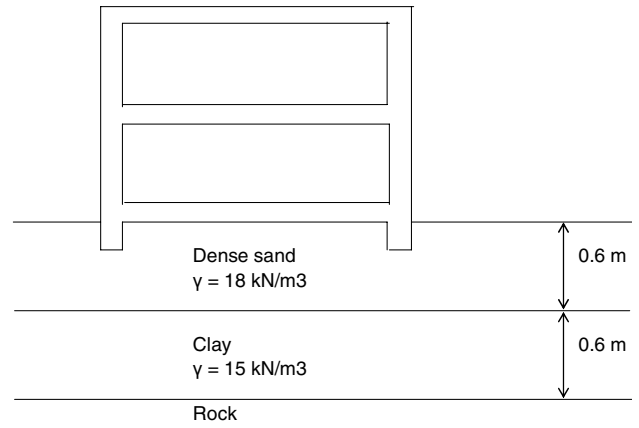


Figure E-1. Deformation of an expansive clay

$$\delta_z = \left[1 - \left(\frac{8043 + 0.792 (2488)}{8043} \right)^{-0.449/0.792(5.2)} \right] = 1.42 \text{ cm}$$

Deformation due to absorption of water in soil. When suction decreases from 820 to 60 kPa, it follows an expansion of clay. Using equations 21, 20 and 23:

$$\sigma_c = 19.72 \text{ kPa}$$

$$p_c = 12.036 + 19.72 = 31.756 \text{ kPa}$$

$$\varepsilon_{va} = 1 - \left(\frac{31.756 + (1)60}{31.756 + (1)820} \right)^{-1/31.7} = -0.0728$$

If there are no cracks in the subsoil:

$$\varepsilon_{za} \equiv \varepsilon_{va} = -0.0728$$

Expansion due to absorption of water molecules is

$$\delta_{za} = -0.0728(60) = -4.37 \text{ cm}$$

At the end of the rainy season, the movement of foundation slab is the algebraic sum of settlement caused by external load plus deformation originated by absorption of water, *i e*:

$$\delta_z = 1.42 - 4.37 = -2.95 \text{ cm}$$

4 CONCLUSIONS

Taking into account that deformations of expansive clay are the algebraic sum of the compression due to external load increments (caused by the construction of a civil engineering structure) plus deformations produced by suctions changes in the soil, a procedure was presented for the calculation of both movements.

Compression caused by external load increments is computed using equation 17 or equation 18, while deformations produced by soil suction variations are predicted utilizing equation 23.

Examples for soil properties assessment and calculus of movements of a slab foundation in expansive clay are included.

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