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The process of soil cracking and faulting

Le process du crevasement et faille de sols

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ABSTRACT
Ground fissuring is a recurrent problem in many countries where water extraction surpasses the natural recharge of aquifers. Due to differential settlements, the soil layer undergoes deformations and cracks with serious consequences for civil infrastructure. Here an approximate analysis of the fissuring process that can be used to predict the location of cracks is proposed. To that purpose, the ground loss theory is applied to highly compressible sediments overlying a sinusoidal shaped graben. This analysis shows the existence of tensile zones where tension cracks are more likely to appear.

RÉSUMÉ
Le crevassement du sol est un problème qui existe dans beucoup des pays où l'extraction de l'eau depasse la recharge naturelle de l'aquifère. Les tassement difèrentielles provoquent l\apparition des crevasses qui ont des conséquences sevères sur les ouvrages du gènie civil. Ici on propose un anlyse approché qui peut ètre utilisé pour definir la location des nouvelles crevasses. Das ce sans, la théory de la perte volumetrique est appliqué au cas des sols compressibles qui se trouvent sur un graben de gèometry sinusoidal. Cet analyse montre l'existence des zones de tension où les crevases pourrait apparaitre.

1 INTRODUCTION

Ground fissuring has been extensively studied by different authors, for example Heindl and Feth, (1955), Pashley (1961) Robinson and Peterson (1962), Winikka, (1964), Holtzer (1976 and 1984) and Sandoval & Bartlett (1991) which related this phenomenon to water extraction and/or differential settlements. Holtzer (ed.) published in 1984 a compendium of papers dealing with several aspects of ground subsidence, including those caused by groundwater withdrawal in semi-arid regions.

2 SUBSIDENCE ANALYSIS

2.1 *Effective stress increment*

The effective stress (σ) is defined as that controlling the strength and volumetric behavior of soils. For the case of saturated soils it can be obtained from Terzaghy's effective stress equation: $\sigma = \sigma^T - u_w$, where (σ^T) represents the total stress and (u_w) the pore water pressure inside the soil mass. If the water table declines a quantity Δh, while the total stress keeps constant, then the pore pressure decreases a quantity $-\Delta u_w = \Delta h\,\gamma_w$, where γ_w represents the volumetric weight of water. In such case, the effective stress increment on the soil mass will be $\Delta\sigma' = -\Delta u_w$.

If it is assumed that the soil mass is isotropic and homogeneous, that the water table initially parallels the soil surface and also that the aquifer is completely depleted at the end of the process, then the ratio between the final (σ_f) and initial (σ_i) vertical effective stresses at a point located at a depth y is given by

$$\frac{\sigma_f}{\sigma_i} = \frac{(\gamma_n - \gamma_w)y}{(\gamma_n)y} = \frac{\gamma_n - \gamma_w}{\gamma_n} \tag{1}$$

That is to say, this value keeps constant at any depth and equals the ratio between the specific weight of the submerged (γ_n- γ_w) and dried (γ_n) soil. If, it is considered that the dewatering process is well represented by the one-dimensional consolidation phenomena with a constant compression index C_c, defined as

$$C_c = e_0 - e_f / \log\left(\frac{\sigma_f}{\sigma_i}\right) \tag{2}$$

where e_0 and e_f represent the initial and final voids ratio respectively, then the volumetric strain of an homogeneous and isotropic soil that compresses due to water extraction, should be a constant given by

$$\varepsilon_v = \frac{C_c}{1+e_0}\log\frac{\sigma_f}{\sigma_i} = C_f \tag{3}$$

where C_f represents the compression factor defined as

$$C_f = \frac{C_c}{1+e_0}\log\frac{\gamma_n - \gamma_w}{\gamma_n} \tag{4}$$

Accordingly, the vertical displacement v of a soil column of thickness h during a one-dimensional consolidation (i.e. horizontal displacements are null) is given by

$$v = C_f h \tag{5}$$

2.2 *Subsidence analysis by ground loss*

The stress increment triggers the consolidation phenomenon in the compressible soil layers. If the rock basement is irregular, not only vertical but also horizontal displacements occur and therefore tension stresses may appear on the soil mass. In order to accurately define the position of the tensile zones, both vertical and horizontal strains should be known. These strains can be obtained by means of a displacement analysis using the ground loss theory as described below.

Sagaseta (1987) proposed an approximate solution to determine the displacement field owing to ground loss. With this procedure it is possible to obtain the displacement vectors in an isotropic homogeneous incompressible soil when part of it is extracted at shallow depth, and the surrounding particlesl displaces to completely fill the void. Sagaseta solves the case for the extraction of a finite volume of soil v at a depth h from the surface. For the plane case, the ground loss is defined by the volume per unit length of an equivalent circle of radius a. This analysis involves the following steps:

a) The displacements caused by ground loss are obtained from a sink located in an infinite medium.

b) A free surface is introduced by considering a virtual source (i.e. a sink with negative sign) symmetrically placed to the sink.

c) The shear stresses appearing on the free surface due to the inclusion of a negative image, are determined and the related strains are subtracted from the solution.

Initially, the existence of a free surface is ignored and therefore all displacements are directed towards the center of the sink. For the case of small displacements, the following equation is proposed

$$u_r = \frac{a}{2}\left(\frac{a}{r}\right) \tag{6}$$

where u_r represents the radial displacements and

$r = \left[(x - x_0)^2 + (y - y_0)^2\right]^{1/2}$ the radial distance of the point (x, y) to the center of the sink (x_0, y_0). In the second step, the addition of a negative image lead to the following horizontal (u) and vertical (v) displacements

$$u = -\frac{a^2}{2}\left(\frac{x}{r_1^2} - \frac{x}{r_2^2}\right), \quad v = -\frac{a^2}{2}\left(\frac{y-h}{r_1^2} - \frac{y+h}{r_2^2}\right) \tag{7}$$

where h represents the depth of the sink placed vertically to the origin and r_1 and r_2 are the radial distances from the considered point (x, y) to the sink and its negative image, respectively. Next, the complete elimination of the remaining stresses on the soil surface is obtained by integrating Cerutti's solution (Westergard, 1940) for a point load in the surface, resulting in the equations

$$u_\tau = -a^2 \frac{x}{r_2^2}\left[1 - 2\frac{y(y+h)}{r_2^2}\right], \quad v_\tau = a^2 \frac{y}{r_2^2}\left(1 - 2\frac{x^2}{r_2^2}\right) \tag{8}$$

The addition of Equations 7 and 8 represents the solution to the displacements produced by a single sink in a semi-space. When the displacements are produced by tunneling or pile extraction, these equations should be integrated for the complete volume loss to compute the total displacements induced into the soil mass.

This analysis can also be applied to soil consolidation due to water extraction. Here, the volume of ground loss is represented by the volumetric reduction of the voids of the soil during consolidation (Eq. 2). Therefore, it suffices to multiply relations 7 and 8 for the compression factor C_f and integrate for the entire mass being consolidated. This analysis would be valid for the primary volumetric strain arising while the soil remains saturated. Inclusion of secondary consolidation or/and further drying of the soil requires a more sophisticated analysis to determine a general compression factor.

When the soil mass is confined by a horizontal smooth rock basement (where vertical displacements are null), this new boundary can be introduced into the analysis by considering a symmetric positive image. Additionally, this positive image has to be examined with its corresponding negative image symmetric to the soil surface in order to maintain the free surface condition. Furthermore, this negative image requires its positive counterpart symmetric to the incompressible boundary, and thus maintain a non-vertical displacement condition at this zone. Therefore, this mechanism evolves into an infinite series of positive and negative images each time getting farther from the origin. These series take the following form for horizontal and vertical displacements:

$$u = -a^2 \sum_{i=1}^{\infty} \frac{1}{2}\left(\frac{x - x_{0i}}{r_{1i}^2} - \frac{x - x_{0i}}{r_{2i}^2}\right) + \frac{x - x_{0i}}{r_{2i}^2}\left[1 - 2\frac{(y - y_{0i})(y - y_{0i} + h_i)}{r_{2i}^2}\right]$$

$$v = -a^2 \sum_{i=1}^{\infty} \frac{1}{2}\left(\frac{y - y_{0i} - h_i}{r_{1i}^2} - \frac{y - y_{0i} + h_i}{r_{2i}^2}\right) - \frac{y - y_{0i}}{r_{2i}^2}\left(1 - 2\frac{x - x_{0i}}{r_{2i}^2}\right) \tag{9}$$

where sub-index i refers to the i-th sink with its corresponding negative image. In most cases, enough precision is obtained when three or four elements of this series are considered. This analysis can be applied for parallel boundaries or even when the free surface and the incompressible boundary form an angle (Figure 1). During the addition of displacements, the rotation of the reference frame for the inclined boundary should be taken into account.

For the case of an irregular basement, the non-displacement condition at the boundaries can be introduced by considering flat virtual surfaces at the vertical and horizontal projections of the point being analyzed (Figure 2). These virtual boundaries move with the considered point and their addition approximates the shape of the irregular basement. Even though this analysis is only approximate, important conclusions about the displacements and strains into the soil mass can be gathered. The procedure outlined above is applied in the following section to obtain the displacements and strains of a consolidating soil mass bounded by an incompressible rock basement of sinusoidal shape.

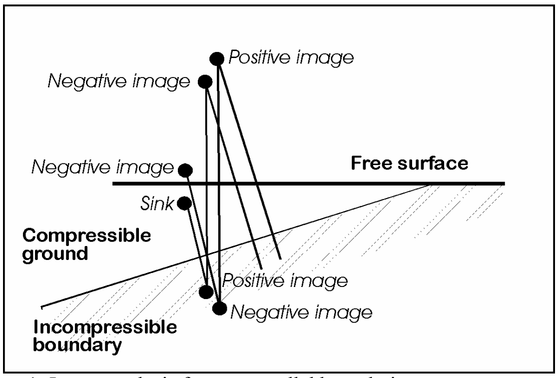

Figure 1. Image analysis for non-parallel boundaries

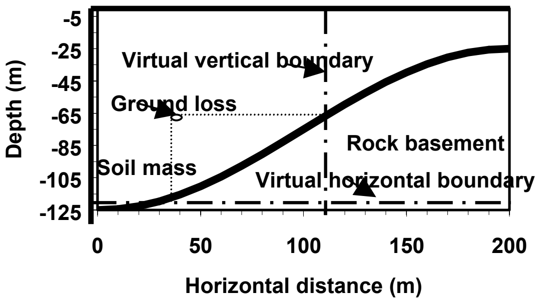

Figure 2. Virtual horizontal and vertical boundaries for an irregular basement.

3 BEHAVIOR OF A SINUSOIDAL BASEMENT

If it is assumed that the rock basement shows a sinusoidal shape with maximum depth h and maximum width $2a$, then the displacements into the soil mass should verify the following conditions:

a) Horizontal displacements u at the axis of symmetry of the rock basement should be null. Therefore, vertical displacements v at this same axis should be close to the condition of one-dimensional consolidation (Eq. 5);

b) Both, horizontal and vertical displacements (u, v) should be null at the rock basement;

c) Volumetric strains into the complete soil mass should be equal to the consolidation factor C_f (Eq. 4).

Both, vertical and horizontal displacements for a particular geometry ($h = 100$, $a = 200$) and for a particular compression factor $(C_f = 0.08)$ were obtained with the procedure described in the previous section. This compression factor was chosen as it represents a typical value of alluvial soils in central Mexico. With these displacements, their corresponding strains can be readily obtained. Curves of equal horizontal strains for this graben are shown in Figure 3. This Figure shows in dark colors two large tension zones in the soil mass. The first appears at the shoulder of the graben showing high tension strains with a maximum value located at approximately 160 m from the deepest zone. The second appears left of the inflection point with moderate tension strains and with its maximum value located at about 50m. Depending on the mechanical characteristics of the soil and local heterogeneities, the soil may crack at any point inside these zones; however, for a homogeneous soil, the most probable location of cracks coincides with the maximum tension strain.

A slightly different shape of graben is represented by a double-sinusoidal rock basement. Figure 4 shows the horizontal strains obtained for this case. Three tension zones are identified; The first is associated with the shoulder of the graben; and the other two relate to the inflection points ($x = 100\,m$ and $x = 300\,m$). Also in this case, the maximum tension strain occurs at the shoulder of the graben, indicating that this zone will be the first to crack.

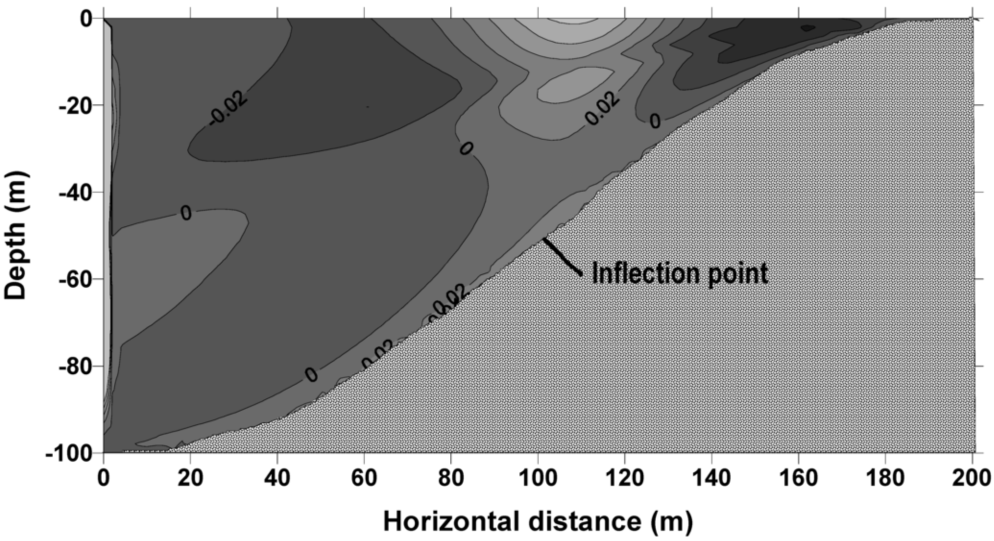

Figure 3. Horizontal strains due water depletion (*a* =200 m, *d* = 100m)

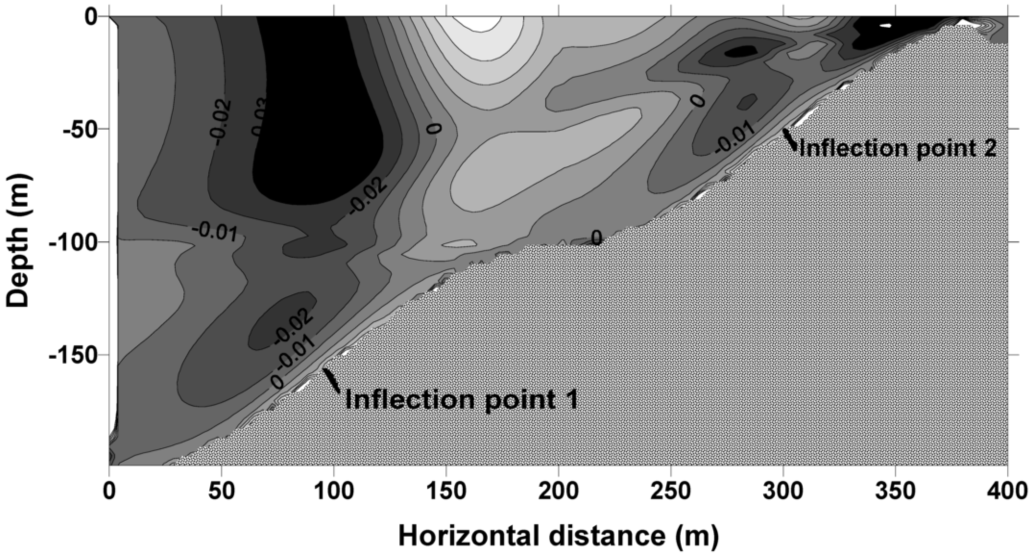

Figure 4. Horizontal strains for a double sinusoidal graben

4 CONCLUSIONS

The process and evolution of soil cracks due to water depletion has been studied by means of the ground loss theory applied to a compressible soil over an irregularl rock basement. With this procedure vertical and horizontal displacements as well as strains of the soil mass due to water withdrawal can be obtained.

Even though, the results reported here represent only an approximation mainly due to the irregular shape of the basement and the approximation of the infinite series, the theoretical results widely agree with the field observations and analytical results reported by other authors.

This analysis shows that cracks on the soil surface may develop when the following conditions are fulfilled:

a) The rock basement is highly irregular
b) Important water table declines are taking place
c) Soil sediments show medium to high compressibility and low plasticity.

The analysis also shows that, for a sinusoidal buried graben, surface cracks are more likely to appear close to the inflexion point. When a crack has completely developed from the soil surface to the rock basement, and the water table decline continues, the phenomenon may evolve into a faulting process evidenced by the presence of a growing step on the soil surface. The evolution of the step depends on the thickness, the compression factor and the plastic index of the soil layers as well as on the water extraction rate.

When a faulting process triggers, new faults, essentially parallel to the previous, are likely to develop towards the center of the graben.

Finally, this analysis could be very helpful for delimiting potential cracking zones in the valleys where water is being depleted.

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