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INITIAL CRACKS IN SATURATED SWELLING SOILS

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ABSTRACT

Shrinkage cracks in swelling soils determine their transport properties. An available model of shrinkage cracks in a brittle medium, is used for the description of crack growth in water saturated soils undergoing desiccation. The main objective of the work is to validate the model by available data. Available data justify use of the constant elastic, strength, diffusivity, and shrinkage properties of a clay soil. A key point is the existence of a minimum crack capable of developing on the conditions under study. A developing crack passes stages of delay, jump, stable growth at approximately constant velocity, and quick slowing down untill stopping. Relations between the minimum crack dimension and some other characteristic dimensions of soil structure are discussed. The concept of the minimum quasi-brittle crack capable of developing at shrinkage leads to two possible types of shrinkage cracks in clay soils. Checking the model predictions based on the available data shows satisfactory agreement between them.

KEYWORDS

Saturated swelling soil, drying, shrinkage, cracking.

INTRODUCTION

Shrinkage cracks are observable even in saturated clay soils under desiccation in restrained conditions [1-3]. A model of the development of an isolated shrinkage crack under the action of shock drying was earlier considered in the frame of linear elastic fracture mechanics [4]. The objective of this work is to show that the model is in agreement with the available data [1-3] for drying in restrained conditions, but staying saturated was considered to be suddenly placed $\theta = \theta_o$ clay soils. A body with the initial (gravimetric) water content, . The simplest condition of water exchange on the $\theta = \theta_1 < \theta_o$ in a medium with (gravimetric) water content , was assumed. It was supposed that there exists a crack of length *l* going into $\theta = \theta_1$ boundary of the body, the depth of the body along the *z*-axis perpendicular to its boundary (the *y*-axis). The maximum shrinkage (reached on the boundary at *z*=0) was [4] σ_* stress

$$, \quad (1)\ \sigma_* = \frac{E\alpha}{3(1-\nu)}(\theta_o - \theta_1)$$

where *E* is Young's modulus; ν is Poisson's ratio; α is the shrinkage coefficient. Dependence of the length *l* $\beta >> 1$ (*D* is the hydraulic diffusivity). For $\beta = l/2\sqrt{Dt}$ on the time *t* was expressed using a parameter

$$(2) \qquad l = \frac{\pi^3 \beta^2}{4} l_*, \qquad t = \frac{\pi^6}{64} \frac{\beta^2 l_*^2}{D} = \frac{\pi^3 l_* l}{16D} \qquad (l_* = \frac{1}{\pi}\left(\frac{K_{Ic}}{\sigma_*}\right)^2)$$

, and l_* l is close to $\beta << 1$ is the critical stress-intensity factor). For K_{Ic} (

$$. \qquad (3)\, t = \frac{l_*^2}{4D\beta^2} = \frac{16}{\pi^3 D} \frac{l_*^4}{(l - l_*)^2}, \qquad \frac{l - l_*}{l_*} = \frac{8\beta}{\pi^{3/2}}$$

represents the Griffith's formula and is the length of the crack for which the body would fracture if it was l_* . The form of the relation *t*(*l*) is given by Fig.1 (except the σ_* loaded by the uniformly distributed stress (Fig.1) will not $l < l_*$ it follows that a crack with l_*). From the meaning of the quantity $l > z_*$ range) after a definite delay time the crack $l > l_*$ (at l_* develop. When the length of the initial crack is close to with a jump goes over into a new moving equilibrium state and further will increase continuously and with time goes into the regime of propagation with a constant velocity. Equalizing asymptotic dependencies *t*(*l*) to the right (Eqn. 2) and to the left (Eqn. 3) of the minimum (Fig.1) one can estimate the minimum as

$$. \qquad (4)\, l_\tau \cong 1.43 l_*, \qquad \tau \cong 2.77 l_*^2 / D$$

(Fig.1) [4]. $l_* < l_0 < l_\tau$ The initial depth of a quasi-brittle crack developing by jump is in the range Accounting for Eqn. 4 an average initial depth of cracks capable of developing by jump is

$$. \qquad (5)\, l_{av} = 1.22 l_*$$

L_{av} (Fig.1) and then from Eqn. 2 average crack depth after jump T_{av} From Eqns. 3 and 5 it follows

$$. \qquad (6)\, L_{av} \cong 5.72 l_*, \qquad T_{av} = 11.10 (l_*^2 / D)$$

PROPERTIES OF SATUATED CLAY SOIL AS FUNCTIONS OF WATER CONTENT

). However, at saturated θ_1 and θ_0, *D*, and α can vary in dependence on water content (at given K_{Ic} *E*, *ν*, - shrinkage limit) the fracture toughness of the studied clays [5-7] changes with water content $\theta > \theta_S$ state (very little if at all. The same is related to *E* and *ν*. The soil water diffusivity of disaggregated clays, *D* is $\alpha = (1/V)(dV/d\theta)$ nearly constant with soil water content [8]. The shrinkage coefficient α is defined as)). The derivative is at cm^3/g where *V* is the specific volume of a clay soil (per unit mass of oven-dried soil (a constant pressure. For soils with high clay content the dependence between *V* and θ is linear [9] and is the water ρ_W is the clay particle (or solid phase) density, and ρ_S where $\alpha = (1/\rho_W)/(1/\rho_S + \theta/\rho_W)$ if the absolute value of a relative deflection $\theta'' < \theta < \theta'$ value is considered as constant in a range α density. does not surpass 0.1, *i.e.* α'' and α' of corresponding $\bar{\alpha} \equiv (\alpha' + \alpha'')/2$ of the average, $(\alpha'' - \alpha')/(\alpha' + \alpha'') < 0.1$

OF AN ACTUAL CASE $(\theta_0 - \theta_1)$ THE WATER CONTENT DIFFERENCE

decreases (Fig.2) means the $\theta_1 = \theta(0,t)$ surface The fact that the actual water content at the soil existence of small water content differences between the soil surface and a certain superficial layer. To (Fig.2) as a $\Delta\theta \equiv \theta_o - \theta_1 << (\theta' - \theta'')$ estimate these differences one can formally consider a small interval and a θ_o constant small difference between a higher (decreasing) water content within the superficial layer, where $3\delta\theta$ should not surpass $\Delta\theta$. The difference θ_1 lower (decreasing) water content at the soil surface, limit the $\delta\theta$ value [10]. Statistical fluctuations θ is a statistical (thermodynamic) fluctuation of the $\delta\theta$ values from [2, 3, 11] is ~0.001. Therefore in θ value measurements. Absolute error of θ accuracy of is used. $\delta\theta = 0.001$ practical estimation in the following the value

COMPARISON BETWEEN THE MODEL PREDICTION AND THE AVAILABLE DATA

Works [2, 3, 11, 12] were dedicated to studying the different aspects of cracking of intact Saint-Alban sensitive marine clay (80 km west of Quebec City in the Saint Lawrence Valley, Canada) undergoing , $\nu = 0.3$ desiccation and shrinkage in saturated state under restrained conditions. Two sets of data: *E*=4MPa, [3] give the model prediction of $K_{Ic} = 1.6\text{kPa}\cdot\text{m}^{1/2}$, $\nu = 0.5$ and *E*=6MPa, $K_{Ic} = 1.35\text{kPa}\cdot\text{m}^{1/2}$. One can conduct a number of comparisons between the model prediction and the data [2, $l_* = 2.00 \pm 1.04\text{cm}$ 3, 11, 12]. It can be shown that: a/ the observable values of the crack length before and after jump, estimate; b/ the model l_* [3] are in agreement with Eqns. 2 and 3 and the $l_j = 8-11\text{cm}$, $l_o = 3-4\text{cm}$ =3-4cm l_o estimate, and Eqn. 4; c/ values of l_* [3], the $l_o = 3-4\text{cm}$ is fulfilled with $l_* < l_o < l_\tau$ inequality estimate confirm Eqn. 5 for the average initial depth of cracks before jump; d/ crack length l_* [3] and the =17hours [3] T_j [3] and the observable time before jump, $l_j = 8-11\text{cm}$, $l_o = 3-4\text{cm}$ before and after jump, estimate and Eqn. 3. l_* are in agreement with the

RELATIONS BETWEEN l_* AND SOME CHARACTERISTIC DIMENSIONS

$l_* >> \Delta$ Because the crack development is described by the linear elastic fracture mechanics the condition should be carried out, where *Δ* is the dimension of the structure inhomogeneity (the maximum value of *Δ* is and the maximum value of l_* the maximum dimension of sand grains in the soil). The above estimate of mm [11] show that the condition is fulfilled. $\Delta \cong 2$

l_* The mean dimension of (surface) cracks developing by the merging of smaller initial cracks of dimension is the critical value of the ratio of the mean linear dimension of an area that one K_* [13] where $(K_* + 1)l_*$ is [14]). In connecting $K_* \cong 5$ initial (surface) crack takes over to the mean crack dimension proper (for soils should coincide $(K_* + 1)l_*$ these enlarged surface cracks and forming the network their mean dimension (data for Saint-$S_o = (K_* + 1)l_* \cong 6l_*$, *i.e.* l_* between initial cracks of dimension S_o with the mean spacing, value). Then, using the l_*=20-24cm [2] do not contradict this relation at the estimated S_o Alban clay, [15] connecting the thickness of the intensive-cracking layer at the quasi-steady state, $z_o \cong S_o / 2$ relation . Then, $z_o \cong 3l_*$ between initial cracks, one can get an estimate of S_o [13] and the mean spacing, z_o $z_m \cong 30l_*$ [13] (Fig.1) one can get an estimate for the maximum crack depth $z_o \cong 0.1z_m$ accounting for that) and L_{av} estimate, the mean depth of primary cracks after jump (S_o . According to Eqn. 6 and the above $L_{av} \cong S_o$) are of the same order of magnitude, S_o their mean spacing at the surface (

. The $z_0 < l(t) \le z_m$ and $l(t) \le z_0$ ranges The depth of an actual growing crack, l can be in the passes, on the average, stages (Fig.1) of delay (or forming an z_m development of cracks reaching the depth), and quick $L_{av} \cong< l < z_*$), quasi-stable growth ($l_\tau < l <\cong L_{av}$), crack jump ($l_* < l \le l_\tau$ initial crack) ( ). The first three stages can be described quantitatively based on the $z_* < l \le z_m$ slowing-down and stop (model [4].

TWO POSSIBLE TYPES OF SHRINKAGE CRACKS IN A SWELLING SOIL

The major model concept of the minimum quasi-brittle crack capable of developing at shrinkage, enables one to assume that in saturated clay soils there are cracks of depth $l < l_*$ incapable of developing in dimension in desiccation, and cracks reaching dimension $l > l_*$, that are initial in developing large shrinkage cracks. Observations show, that the network of shrinkage cracks actually consists of larger seasonal macrocracks [16-18] and smaller quasi-steady interaggregate microcracks [19-22].

CONCLUSION

Results of the work demonstrate: a/ the applicability of the linear elastic fracture mechanics for the description of quasi-brittle cracking even in such visco-plastic materials as water saturated swelling clay soils; b/ the connections between the minimum dimension of a quasi-brittle crack capable of developing at shrinkage and other characteristic dimensions of a crack network in a swelling soil; and c/ two possible types of shrinkage cracks in swelling soils.

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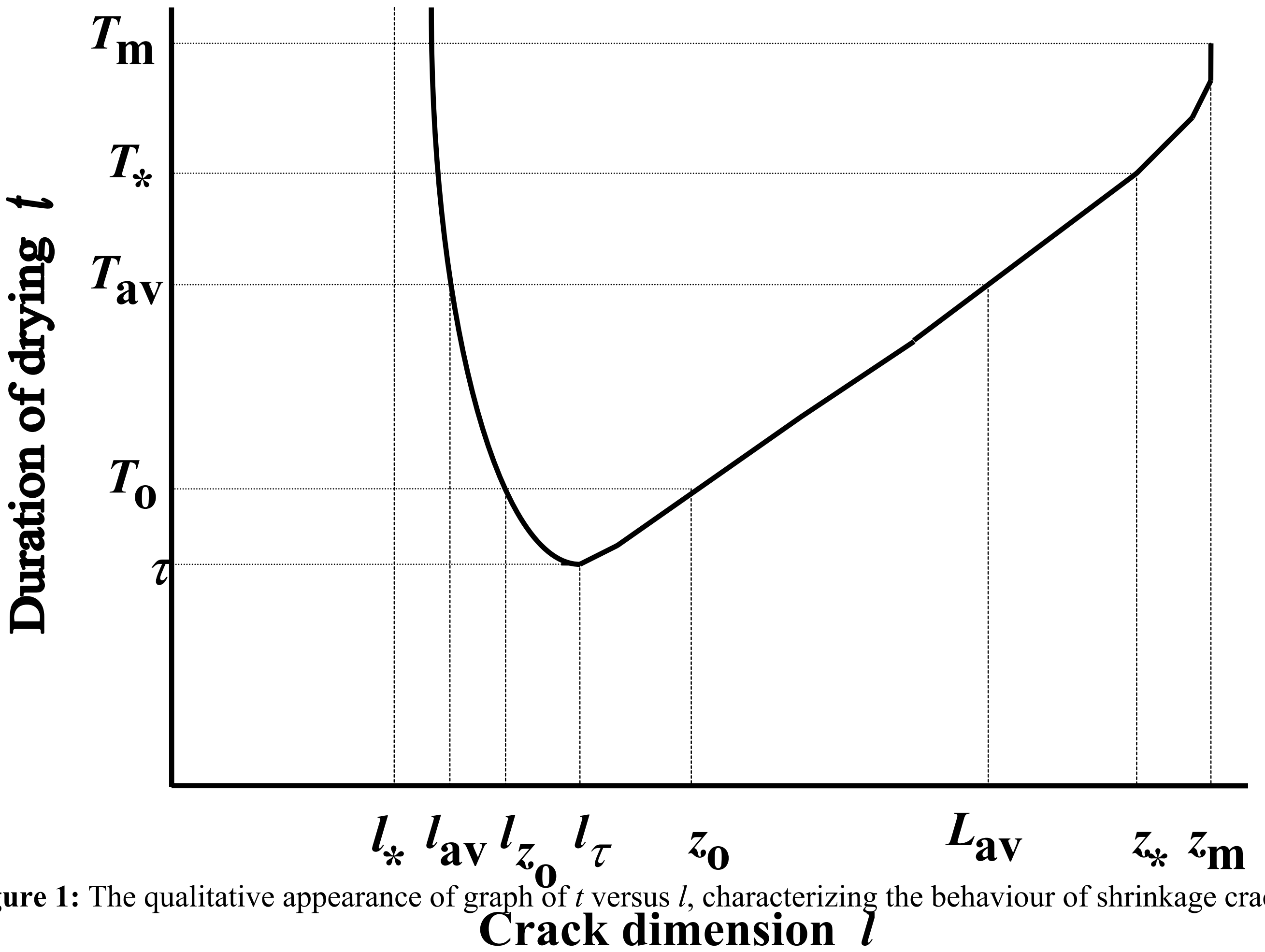

Figure 1: The qualitative appearance of graph of *t* versus *l*, characterizing the behaviour of shrinkage crack.

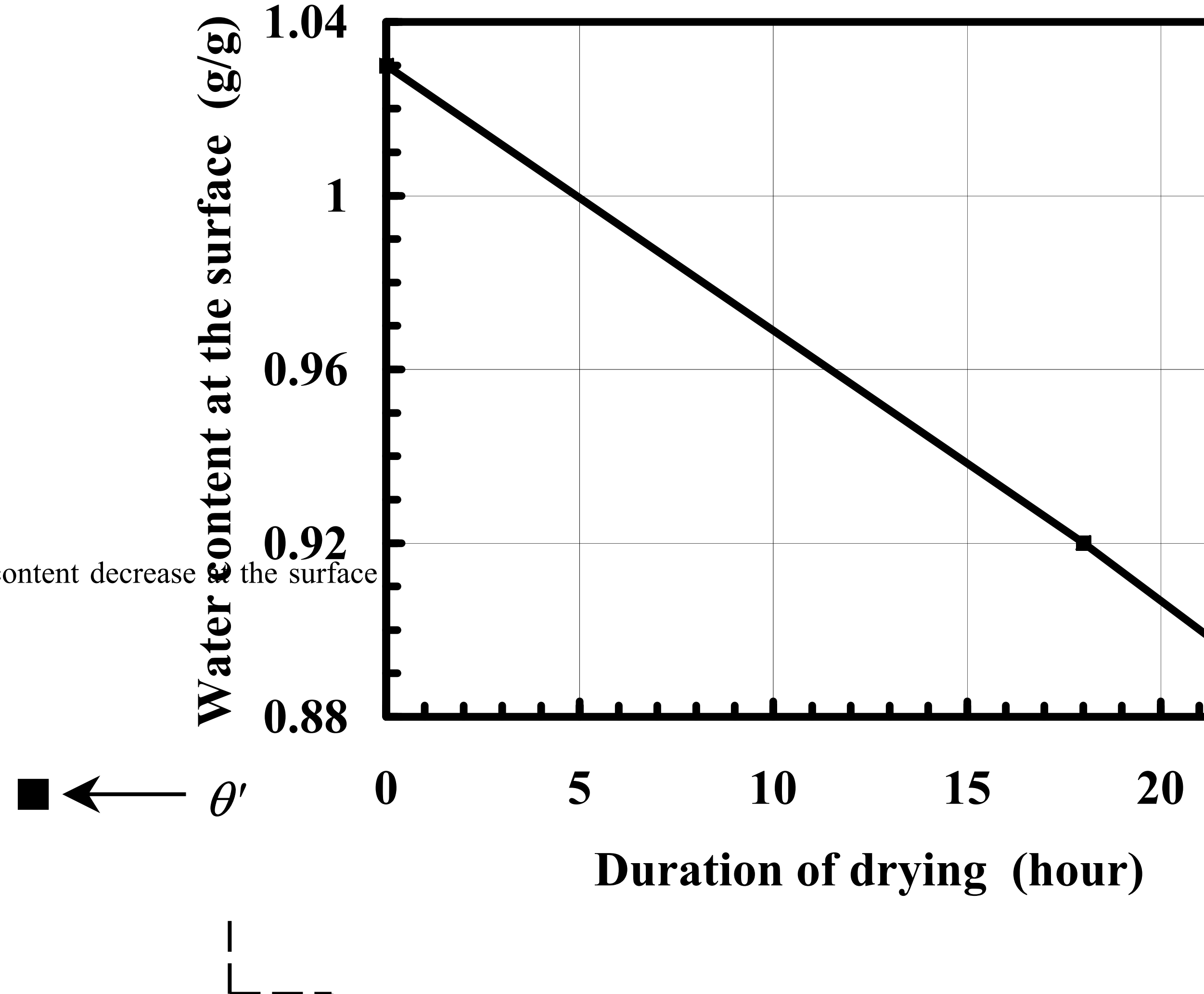

Figure 2: Water content decrease at the surface