THE EFFECT OF SHRINKAGE CRACKS ON THE SOIL SURFACE MICRORELIEF

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ABSTRACT

There is the specific form of a microrelief of swelling clay soils, called gilgai. The relief consists of mounds, depressions, and even sections of the surface. Existing models of the phenomenon do not account for the role of horizontal shrinkage cracks and are qualitative. The objective of this work is to propose a quantitative model of possible interconnections between the formation of shrinkage cracks, vertical and horizontal, and the gilgai microrelief. Preliminarily, a summary is given of available models of the vertical and horizontal shrinkage cracks in soils. A proposed mechanism of the gilgai formation is based on a width increase of the air-filled horizontal cracks during a wetting season. Some simple relations are considered between the gilgai microrelief and vertical and horizontal shrinkage cracking. The analysis results of available data on geometrical gilgai characteristics favor the feasibility of the model.

1 INTRODUCTION

A microrelief of heavy clay soils with a high shrink-swell capacity in a horizontal or weakly inclined clay plain frequently consists of alternating microelevations (mounds), micro-depressions (depressions), and even sections (shelves) and is called gilgai (the term introduced by Australian soil scientists) (Edelman and Brinkman [1]; Russell and Moore [2]; Paton [3]; Knight [4]; Wilding and Tessier [5]; Klich et al. [6]; Goodie et al. [7]; White [8]). There are several forms of gilgai (Wilding and Tessier [5]), the most frequent being the round gilgai. The typical dimensions of the gilgai are as follows: the mean distance between mounds (or depressions) is up to several meters; the mean mound diameter is up to ~2m; the maximum vertical interval "mound to depression" is up to several tens of centimeters. The important feature accompanying a gilgai microrelief is the development in dry season of the vertical ground surface cracks with a mean surface width up to several centimeters, a depth (by limit of probe penetration) up to several tens of centimeters, and a length of surface crack segment up to 3m (Knight [4]). During wet periods the cracks close, but not totally. Many subhorizontal cracks are also observed in photos of the vertical subsoil sections (Knight [4]).

The condition diversity of gilgai observation suggests different possible mechanisms for gilgai origin. A brief review of corresponding models was given by Knight [4] as well as Wilding and Tessier [5]. The models are based on differential loading and soil movements along shear planes (slickensides) after the failure of soil material near vertical cracks as a result of swelling and the falling of the surface soil into the cracks. On the whole these models are qualitative. Except for that the models do not take into account the potential role of horizontal shrinkage cracks at gilgai formation.

The objective of this work is to propose a quantitative model of possible interconnections between the formation of vertical and horizontal shrinkage cracks on the one hand and round gilgai on the other hand, as well as to validate the model using available data. The model to be proposed is based on the previous modeling of vertical (Chertkov and Ravina [9]) and horizontal (Chertkov and Ravina [10, 11]) shrinkage crack networks in swelling soils. For reader's convenience we preliminarily give a brief summary of the models.

2 SUMMARY OF MODELING THE VERTICAL AND HORIZONTAL CRACKS IN SWELLING SOILS

According to a model of vertical shrinkage cracks (Chertkov and Ravina [9]) the knowledge of the maximum crack depth, z_{m}, the thickness of an upper intensive-cracking layer, z_{o}, and the variation with depth of the horizontal surface shrinkage, $\delta(\mathrm{z})$ (from the water content profile and the shrinkage curve of the soil matrix) allow one to find in succession the average spacing between crack intersections with a straight line, $d(z)$, the mean specific length of crack traces per unit area of a horizontal cross-section, $L(z)$, the width of vertical cracks at a depth z, $R(z,h)$ (where h is crack-tip depth, $h > z$), and the total specific volume of vertical cracks at depth z, $V_{\mathrm{v}}(z)$. The model was verified by experimental data on crack volume from Zein el Abedine and Robinson [12], Yaalon and Kalmar [13], Dasog et al. [14], and Bronswijk [15].

The model of horizontal shrinkage cracks (Chertkov and Ravina [10, 11]) determines the key parameter to be the maximum vertical size of gilgai (see below). For this reason the summary of the model will be in more detail. The model assumes that thin layers of drying soil along vertical-crack walls tend to contract but the moist soil matrix hinders this. This causes development of horizontal cracks (or close to them) starting from the walls of vertical cracks. The model also assumes that, on the average, the distribution of volume (and width) of horizontal cracks is similar for any vertical profile.

Linear shrinkage, $\varepsilon_{\mathrm{o}}(z)$ of the soil matrix at a depth z is connected with surface shrinkage, $\delta(z)=\varepsilon_o(2-\varepsilon_o)$. Linear vertical shrinkage at a point on the wall of a vertical crack, $\varepsilon(z,h)$ depends on the crack depth, h and the depth of the point on the wall, $z \le h$. At crack walls $\varepsilon(z,h) \ge \varepsilon_o(z)$. Below the crack tip ($z > h$) the linear shrinkage coincides with $\varepsilon_{\mathrm{o}}(z)$. The value, $\Delta S(z,h)$

$$\Delta S(z,h)=\begin{cases}\int\limits_z^h \left(\varepsilon(z',h)-\varepsilon_o(z')\right)\mathrm{d}z', & z \le h \le z_{\mathrm{m}} \\ 0, & h < z \le z_{\mathrm{m}}\end{cases} \tag{1}$$

is defined as the *potential relative subsidence* at depth z of a vertical profile containing a vertical crack of depth h. The value $\Delta S(z,h)$ at depth z, averaged on all depths h of vertical cracks, $z \le h \le z_{\mathrm{m}}$, $\overline{\Delta S}(z)$ is defined as the *mean potential relative subsidence* (MPRS)

$$\overline{\Delta S}(z)=\frac{1}{\delta(z)}\int\limits_z^{z_{\mathrm{m}}}\Delta S(z,h)R(z,h)\mathrm{d}L(h) \tag{2}$$

where functions $\delta(z)$, $L(h)$, and $R(z,h)$ determine the weight factor in the averaging.

Available experimental data allow for the following approximation of linear shrinkage at the crack wall

$$\varepsilon(z,h)=\begin{cases}\varepsilon_o(0), & 0 \le z \le R(0,h) \\ \varepsilon_o(z'), & R(0,h) \le z \le h\end{cases} \tag{3}$$

where the relation between points z and z' is determined by the condition

$$(z-R(0,h))/(h-R(0,h))=z'/h \qquad (R(0,h) \le z \le h \text{ and } 0 \le z' \le h). \tag{4}$$

The total specific width of the horizontal ruptures on the walls of vertical cracks (per unit length of vertical profile) is equal to ($-\mathrm{d}\overline{\Delta S}(z)/\mathrm{d}z$). Considering all vertical profiles to be similar, the total specific volume of the horizontal cracks, $V_h(z)$ is equal to the total specific width of the horizontal ruptures

$$V_h(z)=\begin{cases} -\dfrac{d\overline{\Delta S}(z)}{dz}\cdot(1-\delta(z)), & \text{if } \dfrac{d\overline{\Delta S}(z)}{dz}<0 \\ 0, & \text{if } \dfrac{d\overline{\Delta S}(z)}{dz}\geq 0 \end{cases} . \qquad (5)$$

The multiplier, $1-\delta(z)$ excludes from the total volume $V_h(z)$ a volume at the intersections with vertical cracks that is already included in their volume. Replacement of $(1-\delta(z))$ by $d(z)$ in eqn (5) gives an expression for the mean width of horizontal cracks at a depth z, $R_h(z)$. The cumulative mean width, $\overline{W}(z)$ of horizontal cracks upwards from depth z_m (or cumulative specific volume of the cracks per unit surface area) is

$$\overline{W}(z)=\int_z^{z_m} V_h(z')\,dz' \quad , \qquad 0\leq z\leq z_m \; . \qquad (6)$$

According to an estimate from Chertkov and Ravina's [10] Fig.6 the mean value of $\overline{W}(0)\cong 0.002\,\text{m}$.

3 A CONCEPTUAL MODEL OF GILGAI FORMATION ASSOCIATED WITH A SHRINKAGE CRACKS NETWORK

We assume that before gilgai formation a dry soil contains both subvertical and subhorizontal cracks (Fig.1a) with width, depth, spacing, and volume distributions that are described by the above models (Chertkov and Ravina [9-11]). It is worth noting that shear cracks (slickensides) can also be present. However, their volume is assumed to be negligible compared to that of the vertical and horizontal cracks.

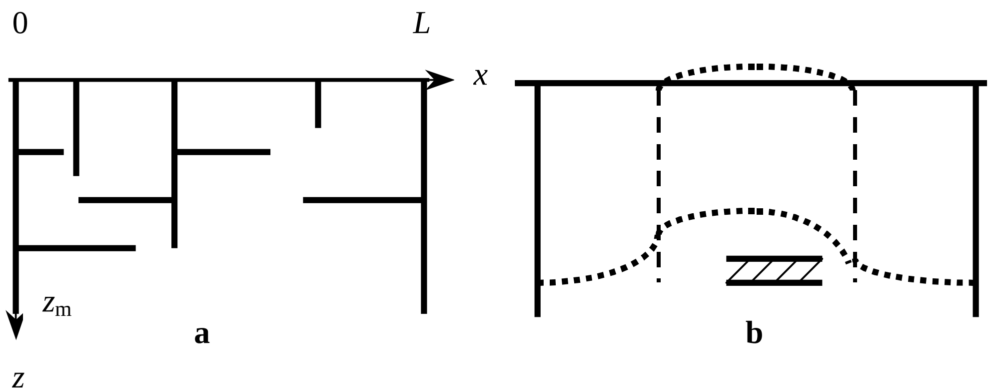

Figure 1: Scheme of mound formation. a. Vertical and horizontal shrinkage cracks after the dry season (*L* is a spacing between the deepest cracks of depth z_m). b. The lower dotted line is the vertical cross-section of an interface between imbibed water and air in shortening and widening horizontal cracks (see a shaded slit). The upper dotted line is a mound of diameter *D* and height *H*.

During the wet season water infiltrates through the soil surface and vertical-crack walls. As a result of soil swelling the vertical cracks close except for the some of the largest - those of depth z_m (Fig.1). The latter also close, but not totally. In addition, closing of the relatively short vertical cracks as well as swelling of wetted soil layers along walls of the largest vertical ones lead to sealing of the horizontal shrinkage cracks that go out of the vertical-crack walls. Movement of a boundary (interface) between imbibed water and air entrapped within the horizontal cracks (Fig.1b) lead to shortening of the cracks in horizontal directions (Fig.1b). However, we assume that due to the softness of the upper wetted soil a volume of air-filled horizontal cracks is approximately retained when moving the boundary. Therefore, the width of the dry parts of air-filled horizontal cracks should enlarge (Fig.1b) and lead to a mound formation. An equilibrium position of the boundary (interface) (Fig.1b) corresponds to the equality between the forces of air pressure in horizontal cracks, the weight of mound soil, and the overburden pressure. A dry clay soil is rather more rigid than a wet one. Therefore, during the following dry season the mounds can be kept due to the dry-soil rigidity.

4 SOME SIMPLE RELATIONS BETWEEN GEOMETRICAL GILGAI CHARACTERISTICS AND THOSE OF CRACKS IN THE FRAME OF THE MODEL

We enter S as a spacing between the mounds and L as a spacing between the deepest vertical cracks (of depth z_m) (Fig.1a). Both S and L are random values that vary in the ranges

$$S_{min} \le S \le S_{max} \;, \quad \text{and} \quad L_{min} \le L \le L_{max} \;, \tag{7}$$

According to the conceptual model every mound is between two of the deepest cracks. However, in general $S \ne L$ since with the sufficiently small L value a mound does not develop between the corresponding deepest cracks. For the same reason

$$S_{min} > L_{min} \;, \tag{8}$$

$$S_{max} > L_{max} \;, \tag{9}$$

and

$$S_{min} \le L_{max} \;. \tag{10}$$

Equations (8)-(10) should be tested using experimental data and Chertkov and Ravina's [9] model.

According to the conceptual model the vertical interval "mound to depression", H is a difference between the cumulative widths of horizontal cracks, W and W', before and after wetting, respectively,

$$H = W' - W \;. \tag{11}$$

Except for that the model assumes that the air-filled horizontal-crack volume before and after wetting is approximately constant, i.e.,

$$S^2 W \cong D^2 W' \tag{12}$$

where D is a mound diameter. From eqns (11) and (12) we have

$$H \cong (S^2 / D^2 - 1) \cdot W \;. \tag{13}$$

All values entering eqn (13) are random. It is clear that $H_{min} = 0$. For H_{max} eqn(13) gives

$$H_{max} \cong (S_{max}^2 / D_{min}^2 - 1) \cdot W_{max} \;. \tag{14}$$

Equation (14) should be tested using experimental data and Chertkov and Ravina's [10-11] model.

According to the conceptual model, mounds are between the deepest cracks, but shelves and depressions are in the vicinity of the cracks. That is, the mean spacing between mounds and that between depressions (or shelves) should approximately coincide. This result should be tested. Tensile shrinkage stresses at the soil surface near the deepest cracks are rather smaller than the stresses between the deepest cracks. Therefore, the density of sufficiently shallow vertical cracks (per unit area) on the surface of mounds should be essentially higher than on the shelves or in depressions. This result should also be tested.

5 DATA USED IN THIS WORK AND THEIR ANALYSIS BASED ON THE MODEL

We used data from Knight [4] and the $\overline{W}(0)$ estimate from Chertkov and Ravina [10] that are presented in Table 1. In the table $\overline{S} \pm \delta\overline{S}$, $\overline{S}_d \pm \delta\overline{S}_d$, $\overline{D} \pm \delta\overline{D}$, $\overline{z}_o \pm \delta\overline{z}_o$, and $\overline{W}(0)$ are the mean values and standard deviations of *S*, S_d (a spacing between depression centers), *D*, z_o, and *W*. *r* is a ratio of crack density (per unit area) on mounds to that in depressions (or shelves).

Table 1: Data used in this work

$\overline{S} \pm \delta\overline{S}$ [a] (m)	$\overline{S}_d \pm \delta\overline{S}_d$ [a] (m)	$\overline{D} \pm \delta\overline{D}$ [b] (m)	H_{max} [c] (m)	$\overline{z}_o \pm \delta\overline{z}_o$ [d] (m)	$\overline{W}(0)$ [e] (m)	r [f]
3.1 ± 0.6	3.4 ± 0.6	1.6 ± 0.6	0.2	0.15 ± 0.10	0.002	≈ 2

[a] Knight [4], Table 1 and bottom of p.249.
[b] Knight [4], Table 1.
[c] Knight [4], bottom of p.249.
[d] Knight [4], Table 2.
[e] Chertkov and Ravina [10], Fig.6.
[f] Knight [4], bottom of p.254.

Estimates of S_{max} and S_{min} flow out of Table 1 as

$$S_{max} \cong \overline{S} + \delta\overline{S} \cong 3.7\,\text{m} \quad , \tag{15}$$

$$S_{min} \cong \overline{S} - \delta\overline{S} \cong 2.5\,\text{m} \quad . \tag{16}$$

To estimate L_{min} and L_{max} we take into account the mean spacing between the deepest cracks (Chertkov and Ravina [9])

$$d(z_m) \cong 2.15 z_o \quad . \tag{17}$$

Then from eqn (17) and Table 1

$$L_{min} \cong d(z_m)\Big|_{z_{omin}} \cong 2.15(\overline{z}_o - \delta\overline{z}_o) \cong 2.15 \cdot 0.05\,\text{m} \cong 0.1\,\text{m} \quad . \tag{18}$$

Accounting for the Poisson distribution of the deepest-vertical-crack spacing (i.e., $F(L) = \exp(-L/d)$ is the probability that a spacing exceeds the *L* value) (Chertkov and Ravina [9]), eqn (17), and Table 1, one can estimate (at $F < 0.01$)

$$L_{max} \cong 4.6 d(z_m)\Big|_{z_{omax}} \cong 4.6 \cdot 2.15(\overline{z}_o + \delta\overline{z}_o) \cong 4.6 \cdot 2.15 \cdot 0.25\,\text{m} \cong 2.5\,\text{m} \quad . \tag{19}$$

An estimate of D_{min} flows out of Table 1

$$D_{min} \cong \overline{D} - \delta\overline{D} \cong 1\,\text{m} \quad . \tag{20}$$

Finally, to estimate W_{max}, we assume the Poisson distribution of the cumulative width, *W* of horizontal shrinkage cracks in dry season (similar to *L* value), i.e., $F(W) = \exp(-W/\overline{W}(0))$ is the probability that the cumulative width exceeds the *W* value. Then at $F < 0.01$ and accounting for $\overline{W}(0)$ from Table 1, one can find

$$W_{max} \cong 4.6 \cdot \overline{W}(0) \cong 0.01\,\text{m} \quad . \tag{21}$$

6 RESULTS AND CONCLUSION

Estimates from eqns (16) and (18) are in agreement with eqn(8). Similarly estimates of eqns (15) and (19) correspond to eqn (9), and estimates of eqns (16) and (19) to eqn (10).

Using eqns (15), (20), and (21) the right side of eqn (14) gives ~0.13m against $H_{\max} \cong 0.2\,\mathrm{m}$ (Table 1). This comparison is satisfactory accounting for an approximate volume conservation of air-filled horizontal cracks (Section 3 and approximate eqn (12)).

Closeness between $\bar{S}_{\mathrm{d}} \pm \delta\bar{S}_{\mathrm{d}}$ and $\bar{S} \pm \delta\bar{S}$ (Table 1) confirms the model prediction relative to an approximate coincidence of the mean spacing between mounds and that between depressions of gilgai relief. Finally, the value of the *r* ratio (Table 1) confirms the model prediction with respect to the density ratio of shallow vertical cracks on the surface of mounds and depressions.

Thus, data from Knight [4] are in agreement with the model predictions and evidence is in favor of the feasibility of the model reflecting a possible mechanism of gilgai relief development. Note, that in real conditions, a natural spatial variability of soil shrinkage properties can influence geometrical characteristics of a gilgai relief. However, the above regularities should be kept on the average.

7 REFERENCES

[1] Edelman C.H. and Brinkman R. Physiography of gilgai soils. Soil Science. 94, 366-370, 1962.

[2] Russell J.S. and Moore A.W. Some parameters of gilgai microrelief. Soil Science. 114, 82-87, 1972

[3] Paton T.R. Origin and terminology for gilgai in Australia. Geoderma. 11, 221-242, 1974.

[4] Knight M.J. Structural analysis and mechanical origins of gilgai at Boorook, Victoria, Australia. Geoderma. 23, 245-283, 1980.

[5] Wilding L.P. and Tessier D. Genesis of vertisols: shrink-swell phenomena, In: Wilding, L.P. and R. Puentes (eds.), Vertisols: their distribution, properties, classification and management. Technical monograph No.18., Soil Management Support Services, College Station, Texas 77843, Texas A&M University Printing Center, pp.55-81. 1988.

[6] Klich I, Wilding L.P., and Pfordresher A.A. Close-interval spatial variability of udertic paleustalfs in East Central Texas. Soil Science Society of America Journal. 54, 489-494, 1990.

[7] Goudie A.S., Sands M.J.S., and Livingstone I. Aligned linear gilgai in the West Kimberly District, Western Australia. Journal of Arid Environments. 23, 157-167, 1992.

[8] White E.M. Formation of gilgai and soil wedges in South Dakota. Soil Survey Horizons. 38, 11-18, 1997.

[9] Chertkov V.Y. and Ravina I. Modeling the crack network of swelling clay soils. Soil Science Society of America Journal. 62, 1162-1171, 1998.

[10] Chertkov V.Y. and Ravina I. Morphology of horizontal cracks in swelling soils. Theoretical and Applied Fracture Mechanics. 31, 19-29, 1999a.

[11] Chertkov V.Y. and Ravina I. Analysis of geometrical characteristics of vertical and horizontal shrinkage cracks. Journal of Agricultural Engineering Research. 74, 13-19, 1999b.

[12] Zein el Abedine A. and Robinson G.H. A study on cracking in some vertisols of the Sudan. Geoderma. 5, 229-241, 1971.

[13] Yaalon D.H. and Kalmar D. Extent and dynamics of cracking in a heavy clay soil with xeric moisture regime. In J. Bouma and P.A.C. Raats (eds.) Proc. ISSS Symp. on water and solute movement in heavy clay soils ILRI. Wageningen. The Netherlands, pp.45-48. 1984.

[14] Dasog G.S., Acton D.F., Mermut A.R., and De Jong E. Shrink-swell potential and cracking in clay soils of Saskatchewan. Canadian Journal of Soil Science. 68, 251-260, 1988.

[15] Bronswijk J.J.B. Drying, cracking, and subsidence of a clay soil in a lysimeter. Soil Science. 152, 92-99, 1991.