Cracking mechanism of soft clay in evaporation and desiccation conditions

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ABSTRACT

The mechanism of soil cracking has long been concerned and discussed from the perspective of macro mechanics. Based on the concept of the contractile skin in the Soil Mechanics for Unsaturated Soils, a mechanical model on which the force equilibrium is established is developed. With the established model, the microcosmic mechanical mechanism for soft soil cracking can be clearly paraphrased. The tensile test of water film and attachments is analogy of soil cracking process. The start, development and end of saturated soil cracking are further studied by different scales and shapes of the model tests.

Keywords: soft clay, desiccation, cracking, mechanism, model test

1 INTRODUCTION

Understanding the mechanism of soft clay cracking in evaporation and desiccation conditions has become urgent because of engineering requirements. For instance, dredger fills in soil reclamation projects in coastal areas is slurry with very high water content. During evaporation and desiccation, the water in soil pores is reduced and thus causes the soil to settle down. After the soil cracks, a crusty layer with a strengthened crust forms, thereby enabling subsequent soil improvement to be performed easily. For some sorts of vacuum preloading technique without surface cover membrane, cracking can cause air leakage and reduce the efficiency of this method (Fig.1). So it is very important that the cracking mechanism of the reclaimed soil under dry conditions and reasonable use of the physical phenomenon.

Several explanations and reasons for cracking have been proposed. Soil cracking is generally explained from the perspective of macroscopic mechanical mechanism. In this paper, a model is established in this study by simulating the stress state of contractile skin based on the latter’s concept in unsaturated soil mechanics. This model can explain the soil cracking mechanism more convincingly compared with previous models. The tensile test of water film and attachments is analogy of soil cracking process. The different scales and shapes of the model are verified by laboratory test results.

Fig. 1 Cracking of soft clay

2 FORMATION AND CHARACTERISTICS OF CONTRACTILE SKIN IN UNSATURATED SOIL

Unsaturated soil is composed of solid particles, pore air, and pore water. The water–air interface of a water film in soil is called contractile skin, which can be regarded as the fourth phase with special properties. Contractile skin is different from the adjacent water phase. The water phase has smaller density and greater thermal conductivity, and its birefringent performance is similar to that of ice (Davies and Rideal, 1963). In the process of soil desiccation, part of water can change into contractile skin with small volume (Derjaguin, 1965). Contractile skin is only several molecules thick. One of its most significant characteristics is that it can bear tensile force. Under the influence of surface
tension, contractile skin interweaves throughout the soil structure like an elastic film and then pulls the soil particles together. Fig. 2 shows an unsaturated soil unit. When the gas phase is continuous, contractile skin and soil particles interact and thus affect the mechanical character of soil (Fredlund and Rahardjo, 1997).

![Fig. 2. Elements of unsaturated soil](image)

### 3 TENSION OF CONTRACTILE SKIN

Surface tension is produced by unbalanced stress in the water molecules in the contractile skin (Fig. 3). The water molecules on the surface of the contractile skin are exposed to an equivalent force. By contrast, the water molecules inside the contractile skin are exposed to unbalanced force. Tension, which is denoted as $T_s$, must be generated in the contractile skin to maintain balance. The direction tangents of tension $T_s$ to the surface of the contractile skin and its size decrease with the increase in temperature (Table 1).

![Fig. 3. Tension and force equilibrium on the contractile skin](image)

| Temperature $T$ /°C | Surface tension $T_s$ /mN/m |
|---------------------|-----------------------------|
| 0                   | 75.7                        |
| 20                  | 72.8                        |
| 40                  | 69.6                        |
| 60                  | 66.2                        |
| 80                  | 62.6                        |
| 100                 | 58.8                        |

Table 1. Surface tension of contractile skin (after Kaye and Laby, 1973)

The pressures on both sides of the film are denoted as $u$ and $u+\Delta u$, respectively. The film radius of the curvature is $R_s$, and the surface tension of the film is $T_s$. Given that the horizontal components in the film balance one another, according to normal balanced conditions, the following can be obtained.

$$2T_s \sin \beta = 2\Delta u R_s \sin \beta \quad (1)$$

In the equation, $2R_s \sin \beta$ is the projection length of the film on the horizontal plane. In the film bidirectional bending, we have

$$\Delta u = \frac{2T_s}{R_s} \quad (2)$$

### 4 UNSATURATED SOIL STRUCTURE MODEL

The analysis above shows that saturated soil develops into unsaturated soil because of desiccation and evaporation; part of liquid water can change into contractile skin with very small volume. For the unsaturated soils, the interaction between soil particles and the contractile skin can be modeled as Fig. 4(a), in which the contractile skins is simulated by elasto-plastic springs as shown in Fig. 4(b). The spring deformation represents the curvature of the contractile skin. The tension of each contractile skin is determined as $T_s$. The stiffness of each spring is different during simulation but the tension of each spring is similar.

![Fig. 4 (a) Interaction (simulated with a tension spring) between contractile skins](image)

![Fig. 4 (b) Contractile skin simulated with a tension spring](image)

### 5 MECHANISM OF SOIL CRACKING

Surface tension $T_s$ can be regarded as a constant because it exhibits minimal change. When the pressure difference acting on the contractile skin (matric suction $(u_a - u_w)$) increases, the contractile skin must be bent to reduce its radius of curvature and balance the vertical stress acting on it. Then, Equation (2) is satisfied. This condition is similar to increasing tensile force on the spring in Fig. 4. For a specific contractile film, its length ($L_s$) is fixed. If the contractile film reaches its
minimum curvature radius \( R_s = \frac{L_c}{2} \) and it still cannot bear the horizontal component of the pressure difference \( \Delta u \), contractile film will break (Fig. 5).

![Diagram of contractile skin failure mechanism](image)

(a) The initial state

(b) The state before cracking

(c) The adjacent contractile skin

Fig. 5 Failure mechanism of contractile skin

It shows that the tension originally withstood inevitably moves downward when the contractile skin on the surface breaks. The soil at the bottom of the crack is initially in a saturated state when the soil surface cracks; this condition is not conducive for the cracking mechanism mentioned above. However, the soil in this area is exposed to air and changes to the unsaturated state because of desiccation. Because of the tension transferred from the upper part, the horizontal contractile skin of this area meets the destruction condition described in Fig. 6. The contractile skin breaks, and the soil cracks deepen. In conclusion, cracks always develop along depths step by step.

The depth of crack is not only associated with the conditions that the soil becomes unsaturated from the saturated one, but also with the equilibrium and deformation compatibility conditions of horizontal tension.

6 SMALL-SCALE MODEL TESTS

Indoor simulation experiments were performed in this study to illustrate further the mechanism of soil cracking. The soil samples consist of clay from Tanggu, Tianjin. The physical characteristics of the soil samples are shown in Table 2, and the grading curve is shown in Fig. 7.

| Plastic limit water content WP (%) | Liquid limit water content WL (%) | Plasticity index IP | Specific gravity GS |
|-----------------------------------|----------------------------------|--------------------|-------------------|
| 25                                | 47                               | 22                 | 2.75              |

![Grading curve of the soil samples](image)

Fig. 7 Grading curve of the soil samples

6.1 Emergence and development of cracks.

Undisturbed soil was stirred to obtain mud from clay with a moisture content of 75%. The obtained mud was then placed in a container (Fig. 8(a)). The temperature was 21 °C, and air humidity was 35%. After 24 h, fine cracks that are approximately 1 mm wide and 4 cm long (Fig. 8(b)) appeared on the soil surface. After 48 h, new cracks developed; the widths of the earliest cracks were extended to approximately 2.8 mm, the lengths to approximately 15 cm, and the...
depths to approximately 2.5 cm (Fig. 8(c)). Cracks with a width of approximately 3.8 mm and depth of 3.2 cm began to run through the soil after 72 h (Fig. 8(d)).

The changes in water content during the test are shown in Table 3.

### 6.2 Relationship between soil water content and matric suction.

The relationship between water content and matric suction was measured through filter paper method (Wang J.). The results are shown in Fig. 9.

![Fig. 8 Cracking process in the soil samples](image1)

![Fig. 9 Relationship between water content and matric suction](image2)

The changes in water content during the test are shown in Table 3.

| Depth (mm) | Initial water content (%) | Water content after 24 hours (%) | Water content after 48 hours (%) |
|-----------|---------------------------|----------------------------------|----------------------------------|
| 1         | 75                        | 55.2                             | 51.5                             |
| 3         | 75                        | 62.5                             | 57.1                             |
| 10        | 75                        | 72.0                             | 71.2                             |
| 20        | 75                        | 74.1                             | 73.5                             |

### 6.3 Research on the cracking mechanism

The grading curve of the soil samples shows that the size of nearly 50% of the soil particles is more than 0.01 mm. The radius of curvature of the skin and the particle size should be of the same size ($R_{c0} = 0.01mm$). Table 2 shows that the temperature is 20 °C, and the surface tension ($T_s$) of the contractile skin is 72.8 mN/m. The maximum suction that the contractile skin can balance can be calculated according to Equation (2).

$$u_a - u_w = 2T_s / R_{c0} = 14.6 \text{kN/m}^2$$

After 24 h, the water contents of superficial soil became approximately 55%. According to Fig. 8, the matric suction of soil at this time should be approximately 15 kPa for the matric suction of soil to exceed the matric suction it can balance. If the soil water content continues to decrease, the matric suction will increase. The individual soil unit with a large size may crack because of the tension originating from the surrounding soil unit. The test results suggest that the soil cracks because the thin layer on the surface (within 1 mm) reached the cracking conditions; the tension of the soil's contractile skin surrounding the cracks then causes the cracks to extend downward (Fig. 6).

### 7 CONCLUSION

The following conclusions were obtained from the theoretical analysis and experiments.

1) Saturated soil becomes unsaturated because of evaporation and desiccation. Part of liquid water can change into contractile skin with a very small volume. Under the influence of surface tension, the contractile skin interweaves throughout the soil structure like an elastic film and holds the soil particles together.

2) When soil becomes unsaturated, the contractile skin of unit soil in the layer satisfies the stress equilibrium condition under matric suction. The water film is straightened because of the tension of the surrounding soil unit. At microscopic level, when the tension on the water film exceeds the maximal surface tension that the water film can withstand, the water film breaks. At macroscopic level, the soil cracks because of the destruction of contractile skins that connect soil particles.

### REFERENCES

1) Davies, J.T. and Rideal, E.K. (1963). Interfacial phenomena, 2nd ed. New York: Academic.
2) Derjaguin, B.V. (1965). Recent research into the properties of water in thin films and in micro-capillaries. Proc. Soc. for Experimental Biology Symp., XIX. The state and movement of water in living organisms. London: Cambridge Univ. Press.
3) Fredlund D.G. and Rahardjo H. (1997). Soil mechanics for unsaturated soils. John Wiley Publishing house.
4) Kaye G.W.C. and Laby T.H. (1973). Tables of physical and chemical constants, 14th ed. Longman.
5) Konrad J M, Ayad R. (1997) A idealized framework for the analysis of cohesive soils undergoing desiccation. Canadian Geotechnical Journal, 34(4): 477-488.
6) Wang J., et al. (2003). Application of filter paper method in field mea surement of matric suction. Chinese Journal of Geotechnical Engineering, 25(4), 405-408.