Study on formation mechanism of ground fissures induced by underground engineering construction in Chongqing area

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Abstract. The geological structure of Chongqing area is complex, many small and medium-sized faults are developed in the axis of anticline fold, and there are many structural fissures in rock strata, and karst landform is developed in some areas. With the development of economy, the construction of underground engineering is increasing, which leads to the rapid decline of groundwater and construction vibration, resulting in a large number of uneven ground settlement, and the formation of ground fissures. This paper introduces the various forms of ground fissures, analyzes the formation process of uneven ground settlement area in the process of underground engineering construction, establishes the stress model of soil surface cracks based on the fracture mechanics theory of cohesive soil cracks, uses the fracture judgment of I-II composite cracks to determine whether the cracks expand or not, and uses the formula of soil cracking angle to calculate its propagation direction, and preliminarily explains the fracture mechanism of soil in the ground fissure area. It provides reference for the further study of corresponding disaster mechanism.

1. Introduction
As an epigenetic geological disaster phenomenon, ground fissures are common in many countries in the world. The frequency and scale of the disaster are increasing year by year, which has become a major regional geological disaster, and the ground fissure disaster in China is also very serious. In Shaanxi, Shanxi, Henan, Shandong, Anhui and other provinces, the damage caused by ground fissures has been reported, and the cumulative economic loss has reached several billion yuan [1]. With the economic development of Chongqing area, engineering activities are increasing, ground subsidence and ground fissure disasters have also appeared, which brings certain losses and disasters. Ground fissures often appear with the occurrence of collapse. Many experts and scholars have carried out extensive research on the ground fissure disaster, but most of them focus on its causes [2,3], and very few have studied the soil fracture of ground fissures. Covarrubias explained the propagation characteristics of cracks in the clay structure of earth dams with three basic types of cracks, and considered that the propagation of cracks was caused by the tensile stress acting vertically on the fracture surface [4]. It is considered that many factors such as tensile stress on the top and bottom of
the dam may be caused by tensile stress in the top of the dam or in the bottom of the dam due to
tensile stress in the top of the dam or in the bottom of the dam [5,6]. Lee et al. Used the method of
linear elastic fracture mechanics (LEFM) to study the crack length of ideal soil cracking. The results
show that the theoretical calculation results are consistent with the experimental results, thus proving
the applicability of linear elastic fracture mechanics in the study of soil cracking [7]. Morris tried to
use linear elastic mechanics, linear elastic fracture mechanics and shear failure methods to study the
 crack length of soil. Its expression is complex and has many parameters, which is difficult to be
applied in practical engineering [8]. Duan et al. considered that in soil mechanics and geotechnical
structures, it is very important to study the failure process of soil based on the concept of fracture
mechanics. Among the three basic types of cracks in fracture mechanics, the cracking problem of type
II crack is the most important [9]. At present, there are few research achievements in this field in
China, In 2000, Yao Hailin gave a preliminary solution to the elastic and linear elastic fracture
mechanics of clay cracking [10]. Taking the underground engineering construction in Chongqing as
the research background, this paper puts forward the conditions for the formation of ground fissures in
the process of underground engineering construction, and describes their development forms. Based
on the fracture mechanics theory of crack propagation in cohesive soil, the propagation of soil fracture
in ground fissure area is studied. The mechanism provides theoretical basis and reference for the
research and prevention of corresponding disaster areas.

2. Formation conditions of ground fissures induced by underground engineering construction in
Chongqing area
In terms of geotectonics, Chongqing not only spans three different secondary tectonic units, but also
six third-order tectonic units. Controlled by the tectonic factors, the geological structure of Chongqing
is relatively complex, and most areas of Chongqing are controlled by fold structures. However, there
are no deep faults developed in the area, and there are not many large faults. In many anticline folds,
small and medium-sized faults are relatively developed, and structural joints and fissures in rock mass
are also relatively developed. In addition, karts landforms are developed in some areas, and karts
collapses often occur. The overlying strata are mostly quaternary artificial fill and residual slope
deposit. After Chongqing municipality directly under the central government, the pace of urbanization
and economic construction has been accelerated, the scale and intensity of engineering economic
activities are increasing day by day, and the underground engineering construction is developing
rapidly. At the initial stage of excavation, improper excavation methods and crossing karts areas,
surface subsidence and ground fissures may occur. On the eve of collapse, ground fissures often
appear on the ground surface, which are called collapse ground fissures [11].

Before the excavation of underground cavern, the rock and soil mass exist in a certain state of
stress balance. The underground engineering construction is carried out in the interior of rock and soil,
which will inevitably disturb the rock and soil and cause surface movement and deformation. Surface
deformation mainly refers to the surface tilt and horizontal deformation caused by uneven settlement
and uneven horizontal displacement. In the process of underground engineering excavation, a large
number of drainage, vibration and other factors will lead to the compression deformation of the soil
layer. When the bedrock fluctuation, uneven soil compressibility and other conditions, there will be
differential settlement distribution on the horizontal plane, making the overlying soil subject to
bending or shear. When the bending or shearing effect exceeds the bearing capacity of the soil, the soil
will be damaged. If the failure develops On the surface or extended to the surface of the ground, it is a
ground fissure.

3. Study on the shape of ground fissures
3.1. Ground fissures before collapse
On the eve of collapse, ground fissures appear on the ground first, which often results from the
connection of ground fissures. Most of the ground fissures are parallel to the long axis of the collapse
pit, and some of them are in the shape of pot teeth, and most of them are tensile. If the cause of the collapse is due to the long-term rain, the rainwater flows into the underground river, the potential erosion is enhanced, and a large amount of underground sediment is washed away, then the ground surface loses its supporting function, and the ground fissures will occur, and then the collapse occurs suddenly along the underground river channel (see Figure 1).

Figure 1. Ground fissures before collapse.

Figure 2. Ground fissures associated with collapse.

3.2. Ground fissures associated with collapse

Collapse usually forms a collapse area on the ground, such as collapse funnel, depression or strip-shaped collapse trough and depression trough. A series of ground fissures are usually associated with the margins of these negative terrains, which are distributed in a circular or centripetal manner around these negative terrains. Close to the collapse centre, the ground fissures are denser and the crack mouth is open; away from the collapse centre, the ground fissures are relatively rare and the crack mouth is small. Sometimes, there are only centripetal ring-shaped ground fissures on the surface without collapse, and the more centripetal the cracks are, the more complete the annular shape is. This phenomenon may indicate the initial stage of collapse. However, the size, length, density and influence range of ground fissures are restricted by the intensity of potential erosion, the scale of collapse, the nature of rock strata and the development of columnar joints. In recent years, there have been many karts collapses in Chongqing area. Here, the karts collapse cracks are taken as an example to introduce their morphological characteristics (see Fig. 2).

Under the dynamic action of groundwater in karts area, the soluble rock stratum and the cracks in the rock layer gradually develop and expand. When the water level rises, the erosion and dissolution of underground water on the roof of the cave are strengthened. The cavity develops to the surface, and the roof of the cave becomes thinner and loses its supporting function. As a result, the roof strata and soil layers at the top fall down due to their own weight and produce micro cracks and ground fissures. The development of ground fissures generally follows the old cracks, but with the expansion of the underlying caves and ground fissures, the collapse or collapse will happen one after another. If we look at the development process of ground fissures, the above phenomena should include three stages: the first stage is the appearance of micro cracks and ground fissures; the second stage is the development and expansion of ground fissures; the third stage is the rapid expansion of ground fissures and collapse. In the depression area, the cracks are distributed in the centre of the depression. Most of the ground fissures are in the same direction as the long axis of these depressions.

4. Fracture mechanics mechanism of ground fissure formation

4.1. Formation process of uneven surface settlement caused by underground engineering construction
According to the research of Yang Junsheng and Liu Baochen[12], the whole excavation of underground engineering is divided into the excavation of infinitely many small units, and the influence of the whole excavation on the surface is equal to the sum of the effects of many infinitesimal excavation on the surface. The unit excavation can be considered to be completed in a very fast moment. When the unit rock and soil is excavated, the surrounding rock and soil are still in the original position, but a small elastic deformation is completed quickly. Then, the surrounding rock and soil began to move towards the excavation space, and the uneven surface settlement gradually formed (see Figure 3).

![Figure 3. Uneven settlement area.](image)

According to Wang Jing Ming’s research on the stress conditions of subsidence basins [13], the above-mentioned uneven subsidence areas can be divided into three small areas (see Figure 4)

(1) Middle zone (settlement line level). The surface subsidence is uniform, the settlement speed and amplitude are the largest, and there is no obvious ground fissure.

(2) Inner marginal zone. The ground surface subsidence is uneven and inclined to the center of settlement, resulting in compression deformation and mechanical conditions of ground fissures.

(3) The outer marginal zone. The surface subsidence is uneven and inclined to the settlement center, but it is convex, resulting in tensile stress and forming tensile ground fissures.

The boundary point between the inner and outer edge is the point with the maximum curvature of the settlement line, which is also the zone where ground fissures are most likely to occur.

![Figure 4. Zoning of uneven settlement area.](image)

1. Marginal zone 2. Middle zone 3. Inner marginal zone 4. Outer marginal zone

![Figure 5. Stress analysis of soil in the outer edge of settlement land.](image)
In the process of the formation of uneven surface settlement, the stress analysis of the whole area in the two edge areas of the settlement area is as follows (see Figure 5), and the outer edge areas of the left and right parts are symmetrical.

In the figure, \( G_h \) is the weight of rock and soil mass, and the tensile stress generated in the outer edge of the subsidence basin is simplified as a concentrated force acting on the soil, which is \( F \). The combined action of the two intensifies the overall mechanical conditions for the development of ground fissures. Under the action of this tension, the surface cracking of soil is expressed in the form of ground fissures.

4.2. Fracture mechanics mechanism of ground fissure formation

The general process of soil cracking in the settlement area can be described as: at the initial time \( t=t_0 \), one-dimensional settlement deformation occurs and the net horizontal stress increases. At \( t_2 \), \( \sigma_h=\sigma_t \), the surface began to crack. When \( K_I>K_{IC} \), the soil will appear unstable cracking, until \( K_I=K_{IC} \), the cracking stops, and the cracking depth is \( D_p \). Where \( K_I \) is the stress intensity factor at the crack tip and \( K_{IC} \) is the fracture toughness of the soil. With the effect of rainfall scouring, the fracture will further crack and expand on the original basis, and so on [14].

Due to water loss and other reasons, some tiny cracks will appear on the soil surface. The direction of the cracks can be horizontal or vertical. These cracks will gradually widen and deepen under the tensile force produced by uneven settlement. It is assumed that the soil is cohesive soil and the initial crack is vertical. Because the tensile force is caused by the uneven settlement of the soil mass, the tension part is provided by the gravity of the settlement difference part, so as the crack extends into the soil, the gravity of the overlying soil increases, and the part of the crack on the surface of the soil bears the effect of the gravity of all the subsidence difference heights under it, so the tension decreases with the crack. The angle between the tension and the horizontal direction is \( \alpha \), and the tension \( F \) is decomposed along the \( x \) and \( y \) directions to obtain the stress analysis model of the crack (see Figure 6). The crack is subjected to a shear force and tension, and the fracture propagation mode of the soil belongs to the I-II composite fracture. I-II composite crack is the combination of type I and type II crack, which is the most common plane crack problem. The ground soil cracking problem studied in this paper belongs to the I-II composite crack problem. A variety of composite fracture criteria have been proposed for composite fracture problems, such as maximum circumferential stress fracture criterion, energy release rate fracture criterion, strain energy density factor Fracture Criterion and empirical criterion.

Based on a large number of calculations and experimental studies in reference [15], it is determined that the law of concrete crack propagation is suitable for clay cracking.

\[
\begin{align*}
\text{Figure 6. Analysis model of crack stress.}
\end{align*}
\]

According to the fracture criterion of I-II composite mode crack of concrete in reference [15], the formula of cracking angle of cohesive soil is modified.
\[ \theta = 2 \arctan \left[ \frac{1}{4} \left( \frac{K_I}{K_{II}} + \lambda \right) - \sqrt{\left( \frac{K_I}{K_{II}} + \lambda \right)^2 + 8} \right] \]  
\[ \lambda = 1.5 - \frac{K_I}{2K_{II}}, \quad 1.5 - \frac{K_I}{2K_{II}} \leq 0 \quad \lambda = 0 \]  

(1)

Where \( K_I \) is the SIF of mode I fracture; \( K_{II} \) is the SIF of mode II fracture; \( \theta \) is the cracking angle; and \( \lambda \) is the correction factor.

The fracture criterion is circular fracture criterion.

\[ \frac{K_I^2}{K_{IC}^2} + \frac{K_{II}^2}{K_{IC}^2} = 1 \]  

(2)

Where \( K_{IC} \) is the fracture toughness of clay.

According to Williams’s displacement expansion formula, the calculation formula of stress intensity factor is deduced.

\[ K_j = \lim_{r \to 0} \left[ \frac{\sqrt{2\pi E}}{4(1-v^2)} \cdot \frac{U_i}{\sqrt{r}} \right] \]  
\[ K_{II} = \lim_{r \to 0} \left[ \frac{\sqrt{2\pi E}}{4(1-v^2)} \cdot \frac{V_i}{\sqrt{r}} \right] \]  

(3)

Where, \( E \) is the elastic modulus of the material; \( v \) is Poisson's ratio; \( U_i \) is the displacement of i node on the crack bank perpendicular to the crack surface; \( V_i \) is the displacement of i node along the crack surface sliding direction on the crack surface; \( r \) is the distance from point i to the crack tip.

The stress intensity factor (SIF) can be obtained from equation (3), which can be substituted into the fracture criterion (1), that is, whether the fracture propagation or not can be determined; then, the direction of crack propagation can be obtained by introducing the stress intensity factor into the modified cracking angle formula (2). Repeated calculation and judgment process can simulate the trajectory of crack propagation.

5. Conclusion
(1) The geological structure in Chongqing area is complex, many small and medium-sized faults are developed in the axis of anticline fold, and there are many structural fissures in rock strata, and karst landform is developed. With the continuous increase of economic development, underground engineering construction causes rapid drop of groundwater, vibration and so on, which makes a large number of uneven ground settlement, and gives birth to the formation of ground fissures.

(2) Ground fissure disaster usually appears with ground subsidence. On the eve of collapse, due to the movement of rainwater or groundwater, the potential erosion is enhanced and a large amount of sediment is washed away from the ground, so the ground surface loses its supporting function and ground fissures are produced. A series of ground fissures are usually associated with the edge of the negative terrain such as collapse funnel, depression or strip-shaped collapse trough and depression trough, and the ground fissures are distributed around these negative terrain in a circular or centripetal manner Under the dynamic action of groundwater in karts area, the soluble rock strata and fissures in rock strata gradually develop and expand, the erosion and dissolution of groundwater on the cave roof are strengthened, and the top strata and soil layers fall down due to their own weight, and micro fractures and ground fissures are produced.

(3) The whole excavation of underground engineering is divided into the excavation of infinitely many small units, and the influence of the whole excavation on the surface is equal to the sum of the influence of much infinitesimal excavation on the surface. The unit excavation can be considered to be completed in a very fast moment. When the unit rock and soil is excavated, the surrounding rock and
soil are still in the original position, but a small elastic deformation is completed quickly. Then, the surrounding rock and soil began to move towards the excavation space, and the uneven surface settlement gradually formed. According to the characteristics of the uneven settlement area, it is divided into the middle area, the inner edge area and the outer edge area.

(4) The crack is subjected to a shear force and tension, and the fracture propagation mode of the soil belongs to the I-II composite fracture. According to the fracture mechanics theory of cohesive soil crack, the stress model of soil surface crack is established. The fracture criterion of I-II composite crack is used to determine whether the crack extends or not, and the expansion direction is determined by the formula of soil crack angle. The fracture mechanism of soil mass in ground fissure area is preliminarily explained.

Acknowledgments
This study in the paper was funded by Science and technology research project of Chongqing Education Commission (No.KJQN202005203).

References
[1] Wu Q., Chen P.P. (2003) Research on State of Art and Prospect of Earth Fissures [J]. The Chinese Journal of Geological Hazard and Control., 14: 22-27.
[2] Nie Z.Y. (2011) Investigation Statistical Analysis and Prevention of Ground Fissure Disaster in Xi'an City [J]. Engineering Technology., 3: 87-88.
[3] Chen Z.X. (2002) Mechanism of Ground Fissures and Its Prevention Countermeasures [J]. Journal of Xi’an Engineering University., 24: 17-20.
[4] Vallejo L. E. (1993) Application of Fracture Mechanics to Soils: an Overview [J]. Fracture Mechanics- Applied to Geotechnical Engineering., 10: 9-13.
[5] Harison J. A. (1993) Fracture Toughness and Tensile Cracking of Soils [D]. PhD Dissertation University of Kentucky.
[6] Harison J. A., Hardin B. O., Mahboub K. (1994) Fracture Toughness of Compacted Cohesive Soils Using Ring Test [J]. Journal of Geotechnical Engineering., 120: 872-891.
[7] Lee F. H., Kei W. W., Seng L. L. (1988) Tension Crack Development in Soils [J]. Journal of Geotechnical Engineering., 14: 915-929.
[8] Morris P. H., Graham J., Williams D. J. (1992) Cracking in Drying Soils [J]. Can. Geotech. J., 29: 263-277.
[9] Duan S. J., Fujii K., Nakagawa K. (1989) Finite Stress Concentrations and Jintegrals From Normal Loads on a Penny-shaped Crack [J]. Engineering Fracture Mechanics., 32: 167-176.
[10] Yao H. L. (2000) Stability Analysis of Expansive Soil Slope Considering Rainfall Infiltration [D]. Doctoral Dissertation of Wuhan Institute of Geotechnical Mechanics, Chinese Academy of Sciences.
[11] Xie G. L. (1988) Ground Fissures [M]. Beijing: Earthquake Press.
[12] Yang J.S., Liu B. S. (2002) Surface Movement and Deformation Caused by Urban Tunnel Construction [M]. Beijing: China Railway Press.
[13] Wang J. M. (2000) Theory and Application of Ground Fissure and Its Disaster [M]. Shaanxi: Shaanxi Science and Technology Press.
[14] Zheng S. H., Yao H. L., Ge X. R. (2007) Mechanical Analysis of Expansive Soil Cracking Under the Influence of Climate [J]. Geology of Shanghai., 2: 29-32.
[15] Hua G. B. (2007) Stability Analysis of Clay Slope Based on Fracture Mechanics [D]. Master’s thesis of Hohai University.