Characteristics and simulation study of ground fissure activities in Gaoliying, Beijing

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Abstract. The ground fissures in Gaoliying, Beijing, has caused panic among local people, and also caused severe damage to buildings and public facilities in its affected area. This paper takes the ground fissures as the research prototype and reveals its development and activities characteristics by field investigation and trenching exploration; The Flac3D finite difference method has also been used to simulate and calculate the deformation and failure characteristics of model strata under different fault dislocations and varying descend amounts of groundwater level. The results show that the ground fissure in Gaoliying are linearly distributed and cause the destruction mainly by vertical dislocation and horizontal tension in the shallow strata; Moreover, the differential settlement of the upper and lower strata of the model near the fault increases with the increase of fault dislocation. Vertical displacement and stress of soils on both sides of the fault are quite different, and the difference increases with the decrease of groundwater level.

1. Introduction

Ground fissure is a geological disaster caused by the geological action inside and outside the earth and has a great impact on urban and rural construction. Its activity can cause damage to buildings, road cracking and deformation, pipeline distortion and dislocation in the affected area. In many countries in the world, such as the United States, China, Saudi Arabia, Kenya and Ethiopia, have appeared a variety of different types of fissure disasters, which causes huge economic losses\cite{1-7}. The geological environment in Beijing, China is very complex and there are many tectonic fault zones. In addition, the exploitation of groundwater resources and various engineering activities in recent years have intensified, which results in many ground fissure disasters in the region. Especially since 1990s, the ground fissure zone in Gaoliying, discovered in Changping District of Beijing (Figure 1), is the most typical one, and its activities are particularly intense, and result in serious damage to the surrounding...
buildings and transportation infrastructure. These have brought great troubles to the safety of local dwellings, traffic construction, land management and planning and development. Many experts and scholars have carried out special investigation and research work, and opinions on the cause of its formation are quite different. Jia Sanman et al[8] believe that the ground fissure in Gaoliying is the result of the superposition of fault structure and over-exploitation groundwater, and is mainly controlled by fault activity; Jiang Yuan et al[9] believe that the uneven settlement occurred in the strata on both sides of the fault is the main cause of the ground fissure in Gaoliying; Lu Quanzhong and Peng Jianbing et al[10] believe that the ground fissure is connected with the underlying faults and has the characteristics of synsedimentary faults. They have found that the exposed location of the ground fissure on the surface coincides with the development position of the Huangzhuang-Gaoliying fault, and it is realized by trenching exploration and drilling that the fault of the deep stratum in the area is larger than that of the shallow stratum.

Figure 1. Geological environment of the study area (Modified according to Haigang Wang,2019).

Over the years, the research on ground fissures in Gaoliying, Beijing, has mainly focused on disaster investigation, distribution characteristics and macro-evaluation, but its activities and destruction characteristics have not been systematically summarized. It is still a blank from the perspective of fault activity and hydrodynamic induction to analyze its causes and expansion mechanisms. In addition, at present, the numerical simulation method is mainly used to study the impact of buried faults on the upper and lower strata, but the simulated working conditions are mostly single. Especially in the simulation of different fault dislocation momentum and groundwater level changes, the characteristics of stratum displacement and internal stress have not been studied. Based on this, this paper chooses the ground fissures in Gaoliying, Beijing as the research object, reveals and summarizes their development and destruction characteristics based on the existing data and field investigation. By means of numerical simulation analysis, it studies the characteristics of formation deformation and internal stress caused by fault activity and groundwater level change respectively. The study can provide a basis for local urban and rural planning, groundwater development and utilization, human-land coordination and prevention and reduction of ground fissures.

2. Research background
The Huangzhuang-Gaoliying fault is one of the important faults in the Beijing Plain. The whole length of the extension is about 132km, the overall strike is NE 20°-50°, the fault surface is inclined to SE, and the inclination angle is 58°-75°. The fault is an active fault since the late Pleistocene until the Holocene. Recent activities are characterized by inheritance of strong north and weak south. Since the late Pleistocene, the vertical displacement rate of Huangzhuang-Gaoliying fault is 0.12-0.2mm/a.
2.1. Development and destruction characteristics of ground fissures
Since the discovery in the early 1970s, the ground fissures of the Gaoliying began to be vigorously active till the 1990s. It is the most severely affected and most developed ground fissure in the Beijing Plain. The research team discovered that through field investigations and visits, the overall strike of the ground fissure is NE45-60°, which is consistent with the strike of the fault. It extends intermittently for 11 km and distributes in zones with a maximum historical activity rate of 13.3 mm/a. The width of ground fissures generally varies from several millimetres to more than ten millimetres, up to 40 cm, which results in a dislocation of 0.5-23 cm and a relatively small horizontal torsion. The influence bandwidth of ground fissures is generally 30-70 m, with a maximum of 300 m; Ground fissures cause cracks and deformations in all the buildings passing through, and the horizontal tension displacement of wall fissures is generally 1-6 cm. Different degrees of crack and destruction occur in the corners of windows and doors where the stress is concentrated (Figure 2). The activity of ground fissures in Gaoliying presents a periodic change in a year. The active period of ground fissures is from April to July every year, accounting for 60% to 70% of the annual activities.

2.2. Sectional structure characteristics of ground fissures
In order to reveal the sectional structure characteristics of ground fissures in Gaoliying, a trench has been excavated by our research group in Tugou Village, Shunyi District, Beijing (Figure 1). The trench trends NE335°, with a length of 52 m, a width of 6 m and a depth of 5 m. The main crack exposed by the trench is NE69°, and the inclination angle is 82°. Along the section, the ground fissure zone is characterized by a single main fissure with approximate straight fault surface, mainly shear. The activity of ground fissures results in a staggered distance of 0.9 m between the upper and lower walls of the red-brown silty clay layer on both sides of the ground fissures. Moreover, the staggered distance increases with the increase of burial depth. This indicates that the vertical dislocations of the formations on both sides of the fault inherit the active characteristics of the fault on the section; Within the 42 m area north of the foot-wall of the main fault, the stratum inclines and deforms obviously, and tends to southeast. It can be seen that the activity of the ground fissures has great influence on the stratum of the upper and lower wall (Figure 3).

3. Numerical simulation
The numerical simulation is a commonly used method to study the causes and activity characteristics of ground fissures. Loukidis et al. (2009) use FLAC software to simulate the fault characteristics of overlying soil layer under the action of concealed ground fissures. It is found that the concealed cracks between the vertical projection of the top surface of the model and the cracks on the surface of the soil layer are the central area of soil deformation [11]; Anastasopoulos et al. (2007) analyze the crack propagation behavior of overlying sand layer under normal fault by elastic-plastic finite element calculation. It is founded that the crack inclination angle appearing in the sand layer gradually increases from bottom to top [12]; Wang Haigang et al. (2013) use FLAC3D software to simulate the development trend of ground fissures in Gaoliying, Beijing. It is considered that under the action of groundwater, the strata near the ground fissures will produce distinct differential settlement [13].
order to further analyze the formation mechanism and propagation characteristics of ground fissures in Gaoliying, numerical simulation method is adopted. On the basis of pre-existence of faults, Flac3D software is used to simulate and study the process of ground fissures and model strata deformation and expansion induced by faults and pumping, and to analyze the variation characteristics of stress and displacement fields in model strata.

3.1. Model building
In this paper, the ground fissures in Gaoliying is taken as the research prototype. The size of the calculation model is set to length×width×height=100×10×50 m, and the fault inclination angle is set as 75°. Combined on-site drilling data, the thickness settings of each stratum are shown in Table 1.

| Model strata | Silty soil | Silty clay | Silty sand | Silty clay | Silty sand | Bedrock |
|--------------|------------|------------|------------|------------|------------|---------|
| Thickness of strata (m) | 6          | 12         | 8          | 8          | 12         | 4       |

3.2. Model parameter
In the numerical calculation, it is assumed that each rock and soil mass is isotropic homogeneous material, without considering the stratification characteristics of rock and soil properties. The ideal elastic-plastic model is adopted and the strength criterion of Mohr-Coulomb is obeyed. The relative displacement between the upper and lower foot-walls of the ground fissures under the action of fault is simulated by the interface contact unit in the finite difference software. The width of the fault zone is not considered at present, and the contact surface is the permeable boundary. The water level is set on the lower bottom of the silty soil (6.5 m), and the rock mass is saturated by default below the water level. In order to simulate the decline of groundwater level, the permeability coefficient and saturation of bedrock are set to 1. The relevant parameters of the model stratum calculation use the physical and mechanical parameters of the actual stratum, which are obtained by conducting an indoor test on the soil sample taken, as shown in Table 2.

| No. | Stratum name | Weight/(kN·m⁻³) | Elastic modulus/MPa | Poisson's ratio | Cohesion/kPa | Internal friction angle/° | Permeability coefficient/(m·s⁻¹) |
|-----|--------------|-----------------|---------------------|----------------|--------------|--------------------------|----------------------------------|
| 1   | Silty soil   | 17.0            | 4.0                 | 0.2            | 15           | 15                       | 5.0×10⁻¹⁰                       |
| 2   | Silty clay   | 17.5            | 8.5                 | 0.35           | 20           | 20                       | 2.0×10⁻¹³                       |
| 3   | Silty sand   | 18.0            | 9.0                 | 0.30           | 0            | 30                       | 1.0×10⁻⁷                        |
| 4   | Silty clay   | 18.5            | 10.5                | 0.33           | 15           | 15                       | 2.0×10⁻¹³                       |
| 5   | Silty sand   | 19.5            | 12                  | 0.30           | 0            | 30                       | 1.0×10⁻⁷                        |
| 6   | Bedrock      | 25.0            | 10000               | 0.25           | 2000         | 40                       | 0                               |

Table 2. Table of calculation parameters for model strata.

Note: Contact surface of fault zone: Normal stiffness = 1.0×10⁸ Pa; Tangential stiffness=1.0×10⁷ Pa; Cohesion = 0; Internal friction angle =10°

3.3. Working condition design and initial conditions
Working condition 1 simulates the crack induced by the fault activity, and the horizontal displacement constraints of the X and Y directions are applied to the left and right sides of the model. At the bottom of the model, displacement constraints in three directions are imposed. The bottom of the lower stratum of the fault is fixed, and the bottom of the upper stratum can move freely. The dislocation of faults is simulated by controlling the bedrock of the upper wall to move down 20, 30, 40, 50 and 60 cm in turn.

Working condition 2 simulates the pumping action to induce cracks, controls the groundwater level to descend 6, 12 and 18 m in turn, and adopts fluid disturbance balance; The vertical displacement of
soil mass is mainly considered in the calculation of groundwater level decline. Therefore, the overlying soil of the model is set to the isotropic seepage model, and the effective stress analysis under stable seepage is adopted. The fluid modulus $K_f=2.0\times10^3$ Pa, and the fluid density $\rho=1.0\times10^3$ kg/m$^3$. In order to avoid negative pore water pressure, the tensile strength of the fluid is set to 0, and the bedrock at the bottom is set as impermeable material[14-16].

4. Results and analysis

4.1. Results and analysis of simulation calculation of fault activity

4.1.1. Vertical displacement change. In this paper, a section of the model is selected for analysis. The vertical displacement nephogram of the model soil mass under different dislocation momentum of fault is shown in Figure 4. It can be seen that the vertical settlement of model soil layer increases with the increase of fault momentum. The settlement response of the upper stratum is prominent, and the vertical displacement of the soil layer at the bottom of the upper stratum is the largest; In the horizontal direction, the settlement of the upper soil layer is significantly larger than the corresponding lower soil layer. In addition, the settlement difference of the soil layer close to the two sides of the fault is obvious. The farther away from the fault, the smaller the settlement amount is.

4.1.2. Vertical stress change. Analyze the vertical stress change of the model soil with the dislocation of the fault. It can be seen that with the fault dislocation, the top soil of the model has different degrees of settlement. The settlement of the top surface is increasing from the bottom to the top. Moreover, the differential settlement on the top of the upper and lower foot-walls of the model increases with the increase of the fault dislocation momentum. However, the farther away from the fault, the gentler the curve becomes, which indicates that the vertical displacement of the top surface tends to be stable.

Figure 4 is a graph showing the variation of the vertical displacement of the top surface of the model with the displacement of the fault. It can be seen that with the fault dislocation, the top soil of the model has different degrees of settlement. The settlement of the top surface is increasing from the bottom to the top. Moreover, the differential settlement on the top of the upper and lower foot-walls of the model increases with the increase of the fault dislocation momentum. However, the farther away from the fault, the gentler the curve becomes, which indicates that the vertical displacement of the top surface tends to be stable.

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Figure 5 is a graph showing the variation of the vertical displacement of the top surface of the model with the displacement of the fault. It can be seen that with the fault dislocation, the top soil of the model has different degrees of settlement. The settlement of the top surface is increasing from the bottom to the top. Moreover, the differential settlement on the top of the upper and lower foot-walls of the model increases with the increase of the fault dislocation momentum. However, the farther away from the fault, the gentler the curve becomes, which indicates that the vertical displacement of the top surface tends to be stable.
is a vulnerable area for ground fissures. The stress change trends of all soil layers are consistent, indicating that the influence of buried depth on the stress distribution of the upper and lower foot-walls is not significant. The redistribution of the stratum stress near the fault leads to a stress concentration zone in the soil. A crack is formed when the concentrated stress exceeds the ultimate stress of the soil.

4.2. Results and analysis of pumping simulation calculation

4.2.1. Vertical displacement change. The research shows that the settlement displacement of the whole soil in the upper part of the model is larger than in the lower part of the model, and the settlement response of the upper soil is larger than in the lower one; The settlement difference between the soil layers near the fault is obvious, and the differential settlement increases with the decline of the groundwater level. The farther the fault is, the smaller the settlement of the soil layer will be, and the more stable it will be.

4.2.2. Vertical stress change. The vertical stress curves of different depths caused by the decline of groundwater level are shown in Figure 6. It can be seen that the stress curve of the upper and lower strata near the fault zone shows approximately "central symmetry". The vertical stress of the model stratum decreases with the decline of the groundwater level, and the stress variation of the deep soil is larger than that of the shallow part; The vertical stress of the same soil layer near the fault is quite different. Moreover, the deeper the stratum is, the greater the stress difference is, which indicates that the continuous decline of groundwater causes the continuous expansion of faults. The farther away from the fault, the gentler the stress curve is, which indicates that the decline of groundwater only causes compression and settlement of strata in a certain range near the fault, while the area far from the fault is rather stable.

![Figure 6. Z-stress curves of different buried strata in the model.](image)

5. Conclusions

(1) Field investigation shows that the overall trend of ground fissures in Gaoliying, Beijing, is NE45°-60°, extending 11 km intermittently. This caused damage to many houses along the route and cracked roads. The dislocation amount generated at the surface is generally 0.5-23 cm, and the horizontal tensile displacement of the wall crack is generally 1-6 cm. The profile of an artificial trench reveals that the fault distance of the upper and lower strata increases with the increase of the buried depth of the stratum.

(2) The simulation results of fault activity show that the settlement of the soil layer on the model is significantly larger than that of the corresponding lower soil layer. The settlement difference of the soil layer close to both sides of the fault is obvious. The differential settlement of the top surface of the upper and lower foot-walls of the model increases with the increase of the fault dislocation momentum. Vertical stresses of soils near the two sides of the fault are quite different, which indicates that the area is a vulnerable area for ground fissures.

(3) The simulation results of groundwater decline show that the settlement difference between the soil layers near the fault is obvious, and the differential settlement increases with the decline of
groundwater level. Vertical stress of the same soil layer near the upper and lower foot-walls of the fault is quite different. Moreover, the deeper the stratum is, the greater the stress difference is.

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