

Research on ground fissure origins and mechanisms in Hebei Plain, P. R. China

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Abstract: Ground fissure hazards frequently emerge in Hebei Plain, which damage roads, dams, buildings and farmland. The paper reviews and analyses current state of knowledge and research into ground fissure and geological environment in Hebei Plain. It is shown that the level of research and investigation is in some aspects insufficient. Knowledge is lacking in the use of corresponding geological concept models for specific ground fissures, three-dimensional numerical simulations of ground fissures caused by pumping through soil with pre-existing fractures, numerical simulations of ground fissures caused by dislocation in intersection faults, and the failure criterion and the constitutive relationship of rock and soil. Furthermore, we put forward geological concept models for ground fissure formation following the dislocation of a buried intersection fault, over-exploitation of groundwater and its compound origin mechanisms in order to provide scientific evidence for the quantitative analysis.

Keywords: Hebei Plain; Ground fissures; Formation mechanisms; Numerical simulation; Problem analysis

Introduction

The Hebei Plain covers a total area about 70 000 km² in the North China Plain, including the cities of Shijiazhuang, Baoding, Cangzhou, Langfang, Hengshui, Xingtai, Handan, Tangshan and Qinhuangdao. Since the first ground fissures were discovered in Handan, Hebei Province in 1960s, many researchers and institutions have carried out extensive investigation and analysis to identify potential ground fissure hazards. Investigation figures show 77 ground fissures were found in the Hebei Plain between 1978 and 1983. Ground fissures developed rapidly in 1980s, increasing to a total of 228 in 1989, affecting 39 cities and counties (WANG Jing-ming and MA Guang-da, 1990). Overall the development of ground fissures in 1990s declined compared to 1980s. However, after 1998 the ground fissures entered a new phase of high activity and by 2013,

the quantity of ground fissures in the Hebei Plain reached 839 (LV Feng-lan *et al.* 2014). The ground fissure distribution area increased over this time, causing ground fissure hazards that damage roads, dams, buildings, pipelines, enclosing walls and cause farmland water leakage. A promulgation of the Beijing-Tianjin-Hebei coordinated development of transportation integration planning (MOT, 2015) is the construction of some higher level highways and railways. Thus, the prevention and prediction of ground fissure hazards has practical significance for future development and safety of infrastructure.

Although previous researchers have conducted a wealth of investigations into the ground fissures in the Hebei Plain and have achieved veritable and worthy results, the level of research in this field remains low. Current research mainly focuses on the analysis and qualitative descriptions of ground fissure distribution, ground fissure origins and formation mechanisms, and prevention and treatment of ground fissures using field geological survey data and information. What is lacking is

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multi-disciplinary systematic research which includes tectonic geology, hydrogeology, and engineering geology and others. Moreover, a shortage exists for quantitative analysis into ground fissure formation. Our paper takes an in-depth look into the formation mechanisms and numerical simulation research for ground fissures, based on recent research progress focusing on the Hebei Plain.

1 Research on the formation mechanisms for ground fissures

Research on the formation mechanisms for ground fissures in the Hebei Plain has recently received increased focus. WANG Jing-ming *et al.* (2000) suggested that the formation of ground fissures was often the comprehensive effect of several factors, including tectonic activity, pumping confined water, rock and soil type, whereby one of these factors dominated. In the Hebei Plain, however, factors influencing ground fissures in different areas are numerous. Especially for the small and the medium-sized ground fissures near the surface, the dominant influence factors are difficult to determine. Thus the formation mechanism for ground fissures in the region is controversial. We will discuss the main theories in the following section.

1.1 Tectonic origins of ground fissures, theory and analysis

According to early research, the greater percentage of ground fissures in the Hebei Plain regions derives from tectonic origins. By analyzing the origin of ground fissures occurring in Handan City, JIANG Wa-li *et al.* (1985) suggested that the development of ground fissures were not caused by declines in groundwater levels. They gave three main reasons: (1) A contradiction exists between the linear features of ground fissures and the elliptical morphology of the groundwater depression funnel; (2) ground fissures caused by groundwater depression should be located in the central region of the funnel, but in the case of Handan ground fissures, they occur only at the edge of the funnel where groundwater declines are only of a few meters; (3) settlement sides of the

ground fissures in Handan City do not point to the groundwater funnel center. In combination with these features of Handan ground fissures, analysis of the Quaternary strata and fault activities in the region add weight to the conclusion that ground fissures in Handan City are caused by the activities of faults. WANG Jing-ming *et al.* (2000) suggested that the primary influence on ground fissures in the Hebei Plain was below-ground tectonic joints, and secondly the action of fault activities in the soil bodies. Closed tectonic joints buried under the ground open with action of the strong stress, which are ideal tectonic conditions for the formation of ground fissures. The occasional occurrence of strong earthquakes strengthens the regional stress field in the Hebei Plain, further releasing energy through aftershocks and consequently causing tectonic joints to open. TIAN Ji-sheng *et al.* (2004) suggested that the tectonic ground fissures in the Hebei Plain were caused by the strong vibration and the dislocation stress of faults, and coincided with the strike direction of the seismogenic faults, but that there was no direct passageway between ground fissures and faults. Data generated by the China Geological Survey projects in the report “The investigation and evaluation of ground fissures in the North China Plain” (2012), provided the platform for LV Feng-lan *et al.* (2014) to propose that although the basement depth in the Hebei Plain was more than 3 000 m and the basement tectonic shape could not affect the occurrence of ground fissures, the accumulation and release of tectonic stress as well as the activity of regional faults inevitably affected the overlying strata and induced the occurrence of corresponding activities such as neotectonic movements, which finally presented themselves as ground fissures on the earth’s surface.

The research we have so far summarized, demonstrates that explanation for the tectonic origin of ground fissures presently relies on field geological survey data and fundamental principles of geology. However, several questions still exist. Firstly, how do we explain that the activity rates of modern ground fissures are higher than the fault creep rates? The horizontal dislocation rates of the faults in Hebei Plain are generally 0.5–2.3 mm/a, while the average horizontal dislocation rates of some ground fissures attain 20 mm/a. Secondly, if the closed tectonic joints buried under the ground

exist, strong stresses that cause the joints to open may not be caused by earthquakes or regional tectonic activities, and the differential settlements caused by the deep groundwater funnel may also enable regional micro-fractures to reopen. Thirdly, there is a lack of the testing, monitoring data and detailed quantitative demonstrations which could help explain the geological background of ground fissure formation, as ground surface ruptures are not only closely related with seismic intensity and the magnitude of fault dislocation, but also with the thickness of the Quaternary overburden. Theoretical research and further testing are still needed to confirm the relationship between influence factors and formation mechanisms for

ground fissures. Fourthly, although research on the distribution and features of the tectonic origin of ground fissures is increasing, there still lacks a geologic conceptual model analysis of tectonic ground fissures, such as the relationship between the tectonic ground fissures and the multiple fault activities for particular tectonic units, especially for ground fissures appearing near the intersection of faults. Through investigation and analysis of the geological profile data, the geological conceptual model of the tectonic ground fissures in the Hebei Plain can be simplified (Fig. 1). Fig. 1 illustrates ground fissure formation at single faults (a) and also at fault intersections (b).

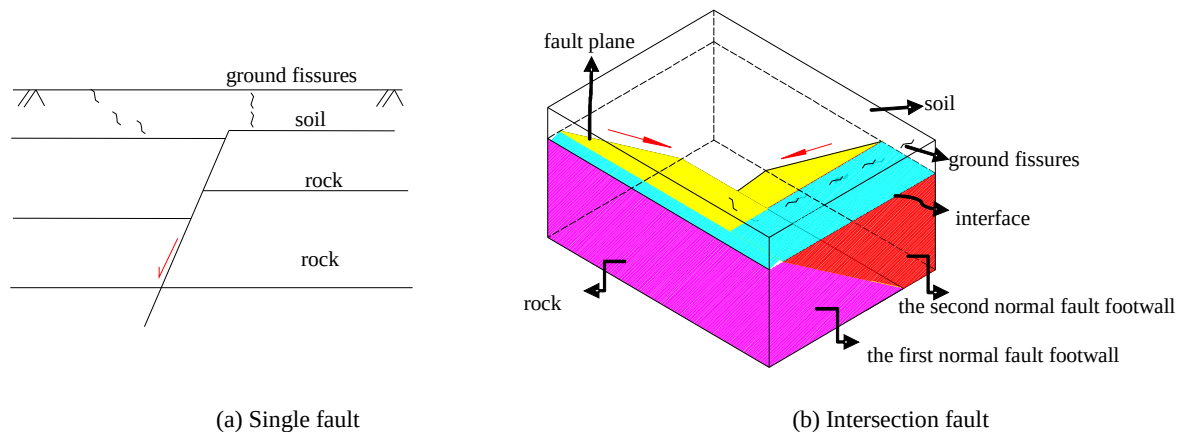


Fig.1 Conceptual model of formation of tectonic ground fissures in the Hebei Plain; (a) is the pattern of ground fissures caused by a single fault dislocation, and the continued creep of normal fault underlying the Quaternary soil bodies accumulates a large displacement, and finally form surface ground fissures; (b) is the pattern of ground fissures appear at the intersection of faults, and the continued creep of two or more active faults result in the ground fissures in the overlying Quaternary soil at the fault intersections

1.2 Origin mechanism and analysis of groundwater over-extraction

The formation of ground fissures due to over extraction of groundwater in the Hebei Plain is thought to be mainly attributed to a differential settlement deformation mechanism, but also partly through dehydration cracks and expansive soil cracks (ZHANG Zhao-ji *et al.* 2009). The main tenets of the differential settlement theory are based on the principles that over extraction of groundwater will lead to compression deformation of loose soil, that when it encounters conditions such as bedrock relief and uneven thickness of the compression layer, a differential settlement will occur that causes the overlying soil bodies to fail

through the action of the bending or shearing, and consequently causing ground fissures to appear on the surface. A discussion of origin and formation mechanisms with reference to groundwater systems theory and Terzaghi consolidation theory, leads authors to determine that the direct cause of ground fissures in Fangjiazhuang, Baodi County, Tianjin was the displacement of the ground surface in the region (LIU Jin-fei and SONG Xue-lin, 2001; LIU Jin-fei *et al.* 2005). The over-extraction of Ordovician limestone water in Fangjiazhuang was the dominant factor leading to ground deformation. Combined with the thickness of the loose layer strata and different kinds of lithology changes in the transverse direction, the over extraction of groundwater provided the ideal conditions for the uneven ground deformation. YANG Wei-min *et al.*

(2014) studied the origin mechanism and evolution process of Caohe ground fissures in Xushui, Hebei Province. Caohe ground fissures develop along the river, and are associated with tension cracks. The results suggested that the ground fissures were mainly caused by excessive local exploitation of groundwater, and that excessive pumping led to a sharp decline in groundwater levels in the Quaternary loose soil layer, thereby increasing the hydraulic gradient and the seepage deformation of the aquifers. Consequently, ground surface settlements on the both sides of Caohe appeared due to a hollowing out of the underlying sand layers, and a small surface subsidence of the river way caused the soil bodies in the center of the river to produce secondary tension stress and generate ground fissures.

In recent years, researchers have found that some ground fissures characteristically form in deep soil layers and gradually develop upward. This phenomenon differs from the differential settlement formation mechanism touched on in the preceding paragraph. Ground fissures generated by differential settlement mechanisms are formed at the surface and descend, the depth of which they develop downwards is finite. Identifying these characteristically upward forming process leads researchers to further propose horizontal permeability stress as a ground fissure formation mechanism, whereby tension stress caused by pumping provides sufficient horizontal strain to induce the deep ground fissures. WANG Qing-liang *et al.* (2002) put forward the theory of

horizontal strain mechanisms to explain ground fissure activity induced by pumping, according to the analytical expressions of horizontal aquifer movement and strains induced by constant volume pumping from a single well in the Thies-Thiem confined system. This theory has been demonstrated through field pumping tests and monitoring data of ground fissures around the Datong Locomotive Factory. In studying the relationships between ground fissures, water levels, and the drainage behavior of ground fissure areas, Holzer *et al.* (1976) considered that horizontal shrinkage caused by the release of water in upper soil bodies following declining water levels was the main factor in ground fissure formation. Through the investigations on deep ground fissures in Hengshui, Hebei Province, WANG Xiu-yan *et al.* (2006) found that ground fissures formed near the ground surface and those formed deep underground exhibited significantly different characteristics. Near the ground surface, the upper sections of ground fissures are wide and the lower sections are narrow, but when ground fissures are formed deep under-ground, the opposite occurs; upper sections are narrow and the lower sections are wide. Characteristics of these ground fissures under deep ground are therefore in accordance with the formation of horizontal permeability tension stress, but this formation mechanism is rarely used in analysis of the ground fissures in the Hebei Plain. A conceptual model of ground fissure formation in the Hebei Plain due to groundwater over extraction is presented in Fig. 2.

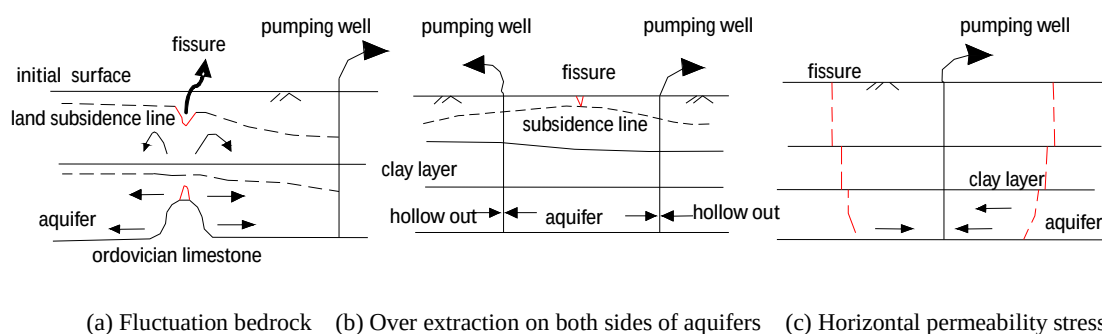


Fig. 2 A conceptual model of ground fissure formation caused by groundwater over-extraction in the Hebei Plain; (a) demonstrates that groundwater pumping leads to a difference in water levels and settlements in the overlying soil layers due to the underlying fluctuation bedrock and causes ground fissures to appear on the surface; (b) illustrates excessive pumping on both sides of the aquifers and how the sand drift layers causes the overlying clay layer to settle unevenly and results in tension ground fissures in overlying soil of the central part of the aquifers; (c) shows that over extraction of groundwater in the radial direction of the horizontal aquifers produces a seepage gradient and if there is differing on soil properties along this gradient, tension stresses reach the tensile strength of soil bodies and the ground fissures will arise from the deep strata.

1.3 Compound origin mechanisms and analysis

Growing research in the field of ground fissure formation mechanisms has led to a strengthening of consensus on the compounding forces of tectonic processes and groundwater over-extraction to ground fissure formation, and a recognition of the overall complexity of ground fissures formation mechanisms. Following an analysis of ground fissure formation factors and relationships between them, LI Jun *et al.* (2003) proposed that tectonic movements and earthquakes are dominant factors in ground fissure formation, that water activities are inducing factors, and that geographical features and lithology are influencing factors. LIU Ke *et al.* (2006) studied ground fissures in Hengshui of Hebei Province and determined that distributions of ground fissures were controlled by the local tectonic base and induced by the artificial over extraction of groundwater. WANG Xiu-yan *et al.* (2006) also investigated the ground fissures in Hengshui of Hebei Province using geophysical methods, and found that the three ground fissures they researched were the product of tectonic activity, and have recently developed due to over extraction of deep groundwater resources. Research of the origin and distribution of ground fissures in Cangzhou of the Hebei Province proposed compound origins for ground fissures, induced by the interaction of various factors including tectonic stress, changes in

groundwater levels, and conditions of the stratum structure (ZHANG Yun *et al.* 2007). Results of a geological survey project analysis concluded that ground fissures are often the comprehensive effect of several factors and dominated by one of these factors (LV Feng-lan *et al.* 2014).

As previously mentioned, although the theories around the compound origin of ground fissures in the Hebei Plain have been proposed, corresponding in-depth and comprehensive research on the formation and mechanism of the ground fissures remain lacking. Further work is required to understand the distribution and characteristics of the ground fissures in the Hebei Plain, and the compound origins of ground fissures. The compound origin of ground fissures requires more investigation, including the consideration of pre-existing ground fissures or the tectonic joints in the soil bodies, and employing theoretical or experimental researches to determine the formation processes of ground fissures caused by pumping of confined water. A conceptual model of this dilemma is shown in Fig. 3(a). Further work is also required to understand the coupling effect of groundwater pumping and the dislocation of faults on ground fissure formation and influencing factors (Fig. 3 (b)). Research is further required to pool all the formation processes of the coupling effect as described above, the ground cracking mechanism and the other aspects of the ground fissures to create a three-dimensional geological model (Fig. 3(c)).

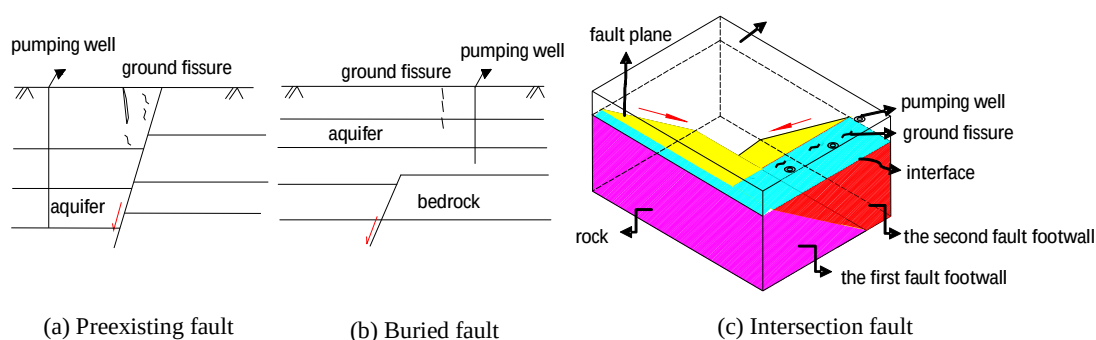


Fig. 3 A Conceptual model of compound origin mechanism in the Hebei Plain; (a) ground fissures caused by pumping in soil bodies contained pre-existing faults; (b) ground fissures caused by coupling of pumping and buried fault dislocation; (c) ground fissures caused by coupling of pumping and intersection fault dislocation.

2 Numerical simulation

Given that ground fissures have regional

characteristics, a large range and sufficient scale model testing is unrealistic. A numerical simulation is needed to impart deep understanding and analysis of origins and formation mechanisms of

ground fissures. Numerical simulation models are seriously restricted due to high nonlinearity in soil bodies, the complexity of fault dislocations and groundwater pumping, and current unconfirmed simulation results. LUO Zhu-jiang *et al.* (2013) established a three-dimensional coupling mathematical model of groundwater exploitation and land subsidence by combining soil nonlinear rheological theory and dynamic change relationships of porosity and permeability coefficients on the basis of Biot consolidation theory. The authors conducted a numerical simulation on the groundwater seepage field, the ground subsidence and the development of ground fissures caused by groundwater exploitation in Cangzhou of Hebei Province. By using a continuum mechanics analysis method to judge the potential occurrence area of the ground fissures, the numerical simulation analyzed the distribution of the displacement magnitude in soil bodies before ground failure. Results implied that ground fissures were mainly distributed at the edge of subsidence funnel, and their horizontal displacements were larger. However, the effect of the discontinuous plane on the seepage and the distribution of stress-strain pressures are required in order to explain actual ground fissures, given the formation of the first ground fissure is likely to change the distribution of the regional stress field and further affect the development of other ground fissures. With reference to this research progress in numerical simulation for Xi'an ground fissures, numerical simulation of the ground fissures in the Hebei Plain are much in need, in order to comprehend influencing geological structures, features and distributions and make predictions for ground fissure behavior alongside long-term over extraction groundwater.

2.1 Numerical simulation of ground fissures caused by pumping in soil bodies with pre-existing fractures

Two-dimensional numerical simulations on ground fissures are more common. YI Xue-fa *et al.* (1999) studied the influence of ground fissures on the distribution of geological stress and strain by assuming the actions of pore water pressure caused by the decline of the water level were equal to an external load on the soil boundary under the

assumption of the known position of the ground fissures. A numerical simulation of the activities of the ground fissure caused by groundwater pumping in uniform soil bodies was undertaken by JIANG Zhen-wei *et al.* (2012) and the authors preliminarily discussed the moving regularity of the ground fissures by using Biot consolidation theory and the two-dimensional finite element method, based on the contact surface element of coulomb sliding and tension. For two-dimensional numerical simulations, research of the formation process of the ground fissures should be conducted for the actual various strata in the Hebei Plain and the issues of contact, the element failure and re-division.

Formation and development of the ground fissures are three-dimensional problems. At present, three-dimensional calculation models of land subsidence have been built, based on a three-dimensional hydrological model and a one-dimensional soil settlement model. These models may be successful in explaining the problem of regional land subsidence. But stress and strain in soil bodies has yet to be explained, and such models are not suitable for ground fissure research. The Biot theory consists of a series of three-dimensional consolidation equations that strictly consider the relationship between pore water pressure dissipation and the deformation of the soil skeleton based on consolidation mechanisms. The pore water pressures and displacements can be solved simultaneously using the balance equation, the constitutive equation, the continuity equation and the geometric equation. The three-dimensional numerical simulation of ground fissures with pre-existing faults can be promoted by applying Biot theory if the seepage field and the stress field are not solved simultaneously under the conditions of complicated boundaries. For the pre-existing fault simulations, the contact surface elements or other discontinuous methods can be used with reference to the two-dimensional numerical simulation.

2.2 Numerical simulation of ground fissures caused by fault dislocation

Currently the continuous medium finite element method is widely used to simulate ground fissures caused by fault dislocation. Elements

known as the weak belt, contact element and the discontinuity grid are used for the simulation of the faults and the locations of the ground fissures are determined by the distribution of the tensile stress or the shear stress in the overlying soil bodies. A comparative analysis of the distribution of shear stress and the cracking zone in the overlying soil bodies through the establishment of a three-dimensional numerical model that included the subsidence quantity of the hanging wall of the faults, found that the numerical simulation results were consistent with the rupture forms in the physical model tests (SHI Yu-ling *et al.* 2009). The numerical simulation was therefore proved effective.

Tectonic units in the Hebei Plain are distributed in a North Northeast direction, including the Jizhong depression, the Cangxian uplift, the Huanghua depression, and the Chengning uplift. Many secondary uplifts and depressions have developed in each tectonic unit. For example, the Jizhong depression is divided into the Shenxian depression, the Shulu depression and the Xinhe salient. The controlled faults in the tectonic units are characteristically active. Numerical simulation of the ground fissures caused by the fault dislocation in the overlying Quaternary strata can be carried out according to dislocation rate or the cumulative settlements. Informative future simulations of the tectonic ground fissures in the Hebei Plain will require comprehensive key research, and suggestions future work are that: (1) The research area for which the numerical simulation is to be made should not be too large, or the role of the controlling buried faults will be weakened; (2) inquiries into the origins and cracking mechanisms of ground fissures induced by the dislocation of buried intersection faults are required as fault intersections often exist at the edge of tectonic units; and (3) studies on the origins and mechanisms of ground fissures caused by the coupling effect of pumping and the dislocation of buried faults are necessary. Research is also needed to introduce knowledge of nonlinear elastic fracture mechanics and damage mechanics to field of ground fissure inquiry.

2.3 Constitutive models and failure criterion of rock and soil

Ground fissures are also problems for the deformation and failure of rocks and soils, and correct applications of the geotechnical constitutive equations affect the accuracy of numerical simulation results. At present, nonlinear elasticity models Mohr-Coulomb and Cambridge clay are commonly used in investigations land subsidence and ground fissures. However, these models do not take into account the effect of time of rock and soil. Consolidation or secondary consolidation will occur in the rock and soil mass due to groundwater pumping. Land subsidence is large in some ground fissure disaster areas, and the creep phenomenon is obvious (ZHANG Shu *et al.* 2007), especially for the constitutive models of the clay layer. Rheological properties need to be taken into account. The simple element models commonly used are the Maxwell model, Kelvin model and three-dimension viscoelastic model in the rheological constitutive models. The yield-surface rheological models mainly study the essential factors of the yield criterion, the flow rule and the hardening law varying with time change in the plasticity theory. The yield-surface rheological theory has developed quickly in geotechnical engineering, and applied to a variety of stress paths. YUAN Jing *et al.* (2004) established the anisotropic tri-yield-surface rheological model of soft soils, based on their three-dimension anisotropic and time-dependent behaviors. The three yield surfaces were respectively one consolidation yield surface and two Drucker-Prager yield surfaces, and the creep rates were determined by the orthogonal principle. Thus, the developments of the theoretical or practical constitutive model of clays are particularly important for numerical simulation studies on ground fissures by incorporating them into the methods of the models built.

The geotechnical failure criteria are key factors for judging the formation of the ground fissures in numerical simulations. At present, there are many shear failure criteria, such as the single shear criterion, the double shear criterion and complex SMP criterion. LUO Ting *et al.* (2004) proposed a new transformation stress method on the base of SMP criterion. The method combined the constitutive relations with the SMP criterion and conducted three-dimension treatments, thus the adopted hardening parameters could consider

the dilatancy under the initial anisotropy and the different consolidation stresses. PENG Jian-bing *et al.* (2008) carried out the studies on the rupture process of the ground fissures through large-scale physical model tests. The F1 and F2 fractures observed from the surface belonged to the tension ground fissures, and the vertical dislocations on the both sides of the fissures were not obvious, thus it was appropriate to establish a judgment criterion based on the tension stresses. The judgment criterion of the tension stresses is that the fissures can appear at points where ratios of the minimum principal stresses to the tensile strength are less than -1 in the soil elements. Although the criterion is easy to understand, the applications of the criterion are limited due to the current tentative theories in soil mechanics and lack of tests of soil tensile strength needed to carry out further studies.

3 Conclusions

Since the 1960s, gradually increasing trends of ground fissure hazards in the Hebei Plain have emerged. People now have realized the danger caused by ground fissures, and are beginning to see growth in studies on the distribution and characteristics of the ground fissures. However, although research into the origins and formation mechanisms of ground fissures are beginning to proliferate, the findings of the field remain controversial. Deep analysis and demonstration are lacking and questions as to how to establish reasonable geologic conceptual models, and how to carry out studies on the dynamic formation process of ground fissures need to be answered. Furthermore, long-term observations are few and far between, and field tests and laboratory tests are even less prevalent. Demonstration tests, field monitoring and the forecast work must be undertaken before deep studies of ground fissures are possible. New technology and new methods may assist us in this task, utilizing the multidisciplinary intersection of engineering geology, hydrogeology, tectonics, fracture mechanics and numerical methods.

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