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ORIGINAL ARTICLE

Overview of ground fissure research in China

Ken W. F. Howard[1] **· Wanfang Zhou**[2]

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Abstract

Ground fissures in China have garnered increasing international attention in recent years due to their areal extensiveness, large scale, and high hazard potential. These fissures, especially those in the Fen-Wei Basin and North China Plain, severely restrict planning and construction in big cities, threaten the operation of underground and above ground railways, and cause serious economic loss. Recent research shows that ground fissures in China occur mainly in sedimentary basins and develop along active faults and at the edges of groundwater cones of depression. Most of these fissures are caused by the combined action of tectonic stress and hydrodynamic force. Effective ground fissure disaster reduction technologies are developed and they include pumping control, reasonable avoidance, adaption to deformation, and local strengthening. This paper provides an overview on ground fissure studies in China and demonstrates how research results can serve economic development and geohazard mitigation.

Keywords Ground fissure · Geological hazard · Distribution pattern · Formation mechanism · Prevention measures

Introduction

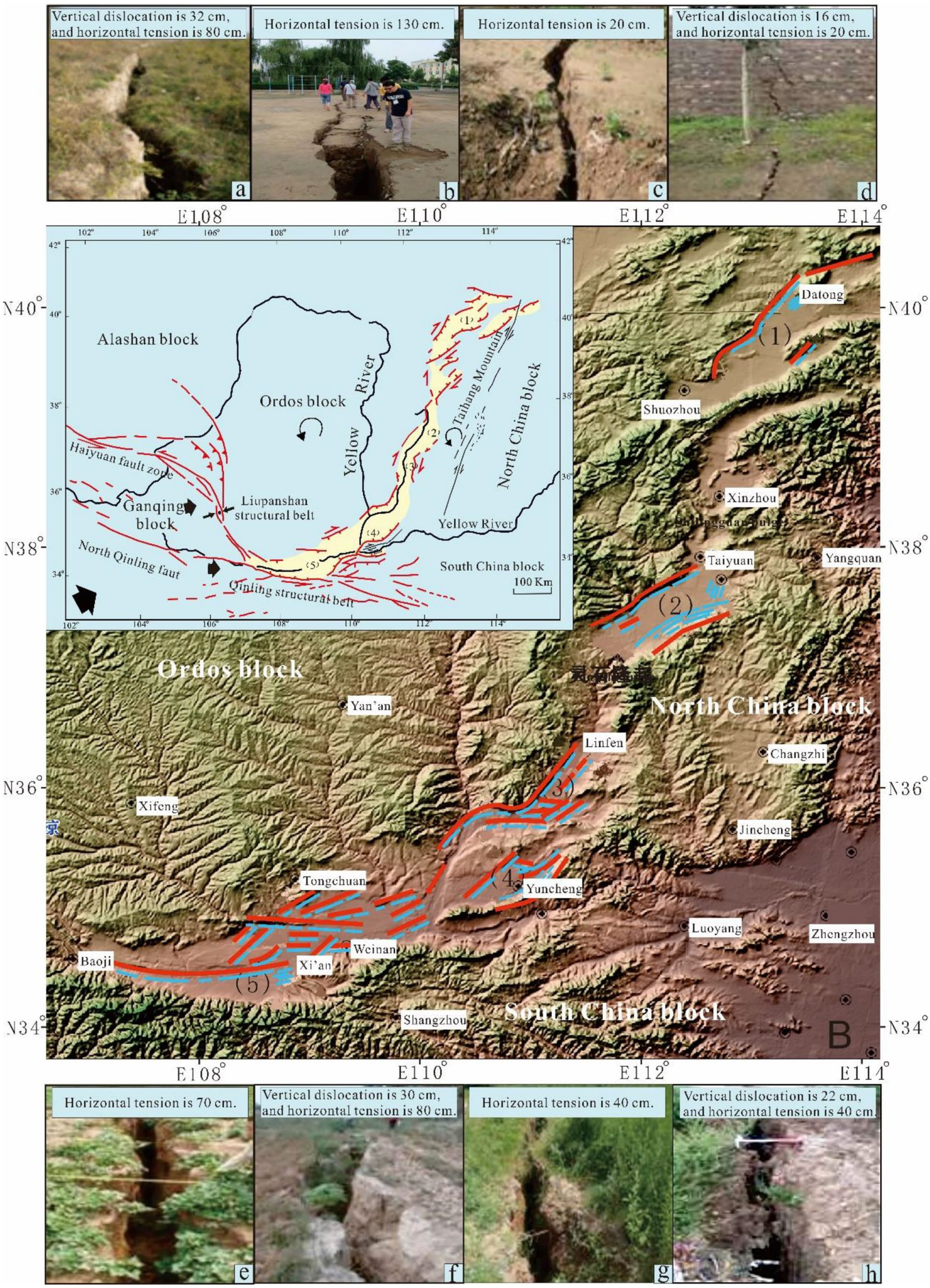
Ground fissures or surface ruptures are almost vertical cracks in the ground with or without vertical offsets. They may be several kilometers long, several meters wide, and tens of meters deep. Formation of these ground fissures, especially the recent ones, is polygenetic and often results from a combination of tectonic faulting and human activities (Lee et al. 1996; Liu et al. 2018). The ground fissures are a geohazard that poses a threat to human life and property. Such ground fissures occur in many countries worldwide, including United States (Leonard 1929; Lofgren 1978; Jachens and Holzer 1982; Holzer 1984; Holzer and Gabrysch 1987), Iceland (Hauksson 1983), Ethiopia (Ayalew et al. 2004; Williams et al. 2004), Saudi Arabia (Bankher and Al-Harthi 1999; Youssef and Norbert 2013), and China (Lee et al. 1996; Meyer et al. 1998; Geng and Li 2000; Li et al. 2000). Increasing international attention has been placed on those in China in recent years due to their areal extensiveness and large scale and the severe damage caused by them (Peng 2012; Xu et al. 2016; Peng et al. 2017a). Field investigation has revealed approximately 4000 ground fissures in 13 provinces, endangering both the means of production and lives of residents of more than 400 counties and cities. This threat is particularly severe in Beijing, the capital of China, and several other big cities, such as Xi'an, one of China's ancient capitals (Peng 2012; Qu et al. 2014). Ground fissure geohazard not only constrains urban planning and construction, effective land use, and industrial and agricultural production, it also poses a significant threat to the safety of high-speed railways, expressways, subways, oil and gas pipelines, water mains, and other infrastructures (Jiang et al. 2012; Peng et al. 2013, 2017b, 2018; Wang et al. 2016, 2018; Yang et al. 2018a). In the past three decades, Chinese geologists have carried out numerous studies and significantly improved our understanding of this major natural hazard (Zhao et al. 2013; Yang et al. 2014; Wang et al. 2010). This paper provides an overview on the damage caused by ground fissures in China and the ground fissure research conducted by Chinese scholars with the intention of providing lessons learnt and practical examples that will be of use to ground fissure research and hazard mitigation worldwide.

✉ Wanfang Zhou
zhou_wanfang@yahoo.com

Ken W. F. Howard
gwater@utsc.utoronto.ca

1 Department of Physical and Environmental Sciences, University of Toronto, Toronto, ON, Canada

2 ZeoEnvironmental, Knoxville, TN, USA


Vertical dislocation is 32 cm, and horizontal tension is 80 cm.
a
Horizontal tension is 130 cm.
b
Horizontal tension is 20 cm.
c
Vertical dislocation is 16 cm, and horizontal tension is 20 cm.
d
Alashan block
Ordos block
Yellow River
Taihang Mountain
North China block
Haiyuan fault zone
Ganqing block
Liupanshan structural belt
North Qinling faut
Qinling structural belt
South China block
100 Km
Datong
Shuozhou
Xinzhou
Taiyuan
Yangquan
North China block
Linfen
Changzhi
Jincheng
Yan'an
Xifeng
Tongchuan
Yuncheng
Luoyang
Zhengzhou
Baoji
Weinan
Xi'an
Shangzhou
South China block
B
Horizontal tension is 70 cm.
e
Vertical dislocation is 30 cm, and horizontal tension is 80 cm.
f
Horizontal tension is 40 cm.
g
Vertical dislocation is 22 cm, and horizontal tension is 40 cm.
h

◂**Fig. 1** Distribution of ground fissures in the Fen-Wei Basin (assembled from Peng et al. 2016c, 2017a). Inset: schematic of the regional structure, showing that the Fen-Wei Basin tectonic belt is located between the structural blocks of Ganqing, Ordos, Qinling, Mt Zhongtiao, and Mt. Taihang. Main image: distribution of ground fissures in the structural belt of the Fen-Wei Basin. Red lines represent active fault, and blue lines indicate ground fissures; the two are closely related. (1) Datong Basin, (2) Taiyuan Basin, (3) Linfen Basin, (4) Yuncheng Basin, and (5) Weihe Basin. Photographs (a–h) show typical examples of surface rupture: (**a**) Luoyun crack in Linfen Basin, (**b**) Beizhang crack in Linfen Basin, (**c**) Qixian crack in Taiyuan Basin, (**d**) Jiaocheng crack in Taiyuan Basin, (**e**) Sanyuan crack in Weihe Basin, (**f**) Kouzhen crack in Weihe Basin, (**g**) Banpo crack in Yuncheng Basin, and (**h**) Xiaxian crack in Yuncheng Basin

Distribution of ground fissures in China

Ground fissures are most common in the Fen-Wei Basin and the North China Plain. The Fen-Wei Basin runs through Shanxi and Shaanxi provinces, whereas the North China Plain encompasses Hebei, Henan, Beijing, and Tianjin (Yang et al. 2018b). Ground fissures are also reported in Suzhou, Wuxi, and Changzhou in Jiangsu province, and locally in Gansu, Liaoning, Jiangxi, Guangdong, and Guangxi provinces (Shi et al. 2007; Wang et al. 2009; Wu et al. 2009). The areas with the highest incidence of ground fissuring, i.e., the Fen-Wei Basin and North China Plain, are in the northern part of China. As shown in Fig. 1, the Fen-Wei Basin consists of five sub-basins, the Datong, Taiyuan, Linfen, Yuncheng, and Weihe. More than 510 ground fissures have been identified in these five sub-basins, influencing more than 60 counties and 400 municipalities. Of these ground fissures, more than 90% exceed 1 km in length, with the longest one extending 46 km (Peng et al. 2016a). Like the Fen-Wei Basin, the North China Plain has undergone strong modern tectonic deformation and frequent earthquake activity. Ground fissures in the North China Plain, as shown in Fig. 2, have been described as "scattered all over like stars in the sky". The fissures in this area are more widely spread and smaller in scale than those in the Fen-Wei Basin but are numerous and diverse. Field investigations have identified 3110 ground fissures in 775 areas encompassing 270 counties.

Damage and risk from ground fissures

The damage caused by ground fissures in China is shocking. Buildings are damaged, roads are cutoff, pipes are broken, and farmland is destroyed all along their paths. Preliminary statistics indicate that they have been the cause of economic losses of more than several hundred billion Yuan in China. A particularly distressing example is the damage in Xi'an, one of China's ancient capitals. Its landscape has been fragmented, triggering a series of disasters that gave rise to the lament that "the gods are angry and the people resentful". Buildings, roads, pipes, and farmland have been damaged in Xi'an, including its internationally famous ancient buildings and city walls (Peng et al. 2006). The Bell Tower subsided approximately 110 mm, and the Dayan Pagoda is now leaning to the northwest by approximately 880 mm. The economic losses caused by ground fissures in Xi'an have exceeded 10 billion Yuan.

Additionally, ground fissures seriously affect and restrict the city planning and development. For example, in Beijing, the capital of China, ground fissures have not only destroyed a large number of buildings; they have also severely limited construction plans and land use in the northern part of the city. Many Chinese cities such as Datong, Linyi, Weinan, Xianyang, and Handan are facing similar crises. It is clear that these massive ground fissure disasters have serious and far-reaching consequences for metropolitan cities (Huang et al. 2007, 2010a, b; Peng et al. 2008).

Ground fissures are also detrimental to infrastructures, also known as "Lifeline Engineering". There is a plan to construct 15 underground railway lines in Xi'an, but these railway lines will intersect the 14 east–west ground fissures present in the central city zone, as shown in Fig. 3. The ground fissures will endanger the safety of the subways. Policy makers and designers, therefore, face the major challenge of devising appropriate engineering measures to avoid or mitigate the negative impacts. Though some measures have been taken to adapt to subway deformation, the cost of disaster reduction for only one line is expected to be 100 million Yuan. Even with these measures in place, many remain concerned about the future security of the Xi'an underground railway system because of lack of knowledge on behavior of the fissures in the next 100 years. Therefore, substantial funds are needed so that long-term monitoring may be carried out.

Many high-speed railways have recently been and are currently being constructed in China. However, a number of these lines cross regions with high densities of ground fissures (Zhang et al. 2012). For example, the Datong–Xi'an high-speed railway passes through the fissured zone of the Fen-Wei Basin; the Beijing–Shenyang high-speed railway passes through the fissured zone of Beijing; the Beijing–Zhengzhou high-speed railway passes through the fissured zone of the North China Plain; and the Beijing–Shanghai high-speed railway passes through the fissured zones of the North China Plain and southern Jiangsu. All these railways are susceptible to ground fissure-related disasters. In particular, the Datong–Xi'an high-speed railway intersects ground fissures at 36 sites. In some areas, the maximum rate of vertical movement at the ground fissures reaches 1.7 cm per year. This poses a deadly threat to the high-speed railway because the subgrade has a maximum residual differential settlement threshold of 15 mm, and the

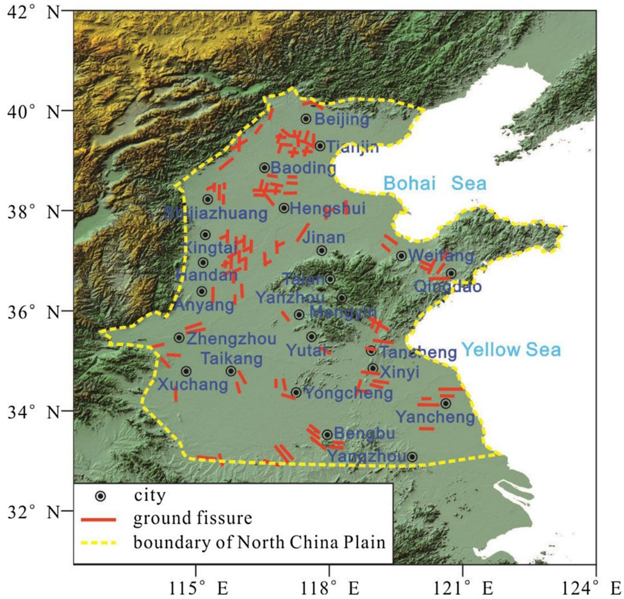


Fig. 2 Distribution of ground fissures in the North China Plain (modified from Peng et al. 2016c)

maximum differential settlement threshold between bridge piers is 5 mm (Peng et al. 2016a). Devising appropriate engineering measures to ensure that the high-speed trains pass through ground fissures safely is a thorny technical problem that has never before been encountered in the history of high-speed railway construction around the world.

Similarly, engineering disasters triggered by ground fissures seriously threaten the safety of expressways and oil and gas pipelines in China. Thus, the ground fissures in northern China pose a major potential safety hazard to the region's urbanization, operation of long-distance lifeline projects, reasonable use of land, industrial and agricultural production, and human security.

Research on ground fissures in China

In China, the ground fissures were first studied in Xi'an in the late 1970s. Chinese scholars have since applied hydrogeology, engineering geology, disaster geology, and civil engineering to their investigation and analysis. This has included geological mapping of ground fissures, prospecting and monitoring of typical regions, research into the mechanisms and causes of ground fissures regionally, and the development of avoidance measures for buildings in fissure-prone areas. This research has provided a range of useful information, but until recently the approaches used were generally limited to field investigation, superficial exploration, and qualitative analysis (Wang 1989; Zhong 1996; Chen et al. 2007; Yi 1981; Wu et al. 1986; Zhang et al. 1990; Xu et al. 1994; Li 1994). With the occurrence of increasingly severe ground fissure disasters in China in recent years, the conflict between the needs of large infrastructure projects and urban development on one hand and the hazard represented by ground fissuring on the other has become increasingly obvious. This has made Chinese scholars carry out numerous research work on the ground fissures of northern China, including regional geological mapping, scientific trenching, remote sensing, precise monitoring, physical simulations, and the development of engineering protection measures. Significantly valuable results are obtained (Peng 1992; Chen et al. 2007; Peng et al. 2007, 2016b, c, 2017b; Ren et al. 2012; Zhang et al. 2018).

Professor Jianbing Peng of Chang'an University and his research team have made a particularly outstanding contribution to ground fissure research in the following two aspects. Firstly, they established a relationship between tectonic dynamics, hydrodynamics, and the disaster mechanism, putting forward a new paradigm in which the formation of ground fissures is controlled by tectonic forces that are driven by crustal stress, but their activity is also intensified and reactivated by hydrodynamic forces. This new theory provides a firm basis for the prevention of ground fissures. Secondly, they pioneered the disaster reduction strategy for subways, high-speed railways, and urban construction. They put forward invaluable guidance and technological innovations, and demonstrated how an understanding of geology can serve both economic development and disaster mitigation. The research methods implemented and achievements made by the team are undoubtedly among the forefronts of global ground fissure research.

To identify the distribution of ground fissures, more than 240 geological maps at different scales have been produced, revealing approximately 3600 ground fissures. These show that the fissures occur mainly in sedimentary basins and develop along active faults and the edge of groundwater cones of depression (Sheng et al. 2003; Wang et al. 2013). The activity and development trends of the fissures have been clarified using an integrated global positional system (GPS) and InSAR monitoring approach. Meanwhile, dating analyses have shown that the ground fissures have undergone three to four episodes of rupture since the late Pleistocene. In the last 50 years, ground fissures have seen four-to-five revivals due to human activity. Ground fissure movement is usually dominated by vertical displacement, and prospecting shows that displacement increases with depth (Deng et al. 2013a, b). These are features of syngenetic faults, indicating that the main ground fissures are outcrops of underlying structural rupture. Indeed, it has been observed that the location and activity of the long and wide ground fissures are usually controlled by underlying faults (Qiao et al. 2018). In a cross section, ground fissures can be divided into a rupture zone and an impact zone. These findings form an important

Fig. 3 Distribution of ground fissures and underground railway lines in Xi'an (modified from Peng et al. 2017b)

foundation for the study of the formation mechanism of ground fissures and for engineering design to mitigate and avoid ground fissure-related disasters.

GPS measurements show that the Fen-Wei Basin is undergoing NW–SE extension at yearly rates of 2–5 mm. In areas where ground fissuring is concentrated, tensile stresses operate perpendicular to the fissuring direction. This is interpreted as implying that the ground fissures are a long-distance effect of eastward squeezing of the Qinghai–Tibet block. This inference is also supported by the results of geophysical prospecting, which show that the synchronous development of ground fissures in a single basin is driven by uplift of the upper mantle and spreading of the middle crust. Scientific trenching and drilling have revealed that the occurrence of ground fissures is usually accompanied by faults that are driven by local tectonic stress at fault zones. Large-scale physical modeling indicates that differential land subsidence and the horizontal movement of aquifers caused by over-pumping of groundwater can reactivate pre-existing ground fissures and that associated land subsidence can also lead to new ground fissures (Liu et al. 2017). These findings have led to a synthesized theory in which ground fissures are caused by the combination of tectonic stress and hydrodynamic force. The above results provide a scientific basis for developing early warning systems and hazard reduction strategies for fissure-prone regions.

There is a potential of shear stress concentration at the intersections between the 15 metro tunnels and 14 ground fissures in Xi'an. Large-scale physical experiments and numerical simulations have been used to model various types of deformation and the process by which ground fissures shear metro tunnels. On the basis of this work, structural measures have been proposed that will allow the metro tunnels to adapt to ground fissure-induced deformation, offering a valuable solution to the unique technical problems faced by underground engineering at sites featuring ground fissures (Peng et al. 2017b). Likewise, experiments using a large-scale model were used to solve potential problems at the 36 intersections between the route of the Datong-Xi'an high-speed railway and ground fissures. These tests elucidated both changes in stress and deformation in the roadbed and the modes of structural failure in the bridge. Structural measures were proposed by which the high-speed railway could adapt to the deformation caused by ground fissures and were successfully applied in the design of the railway. Large-scale physical modeling experiments and numerical simulation have also been applied to understand the mechanisms by which ground fissures damage buildings, roads, bridges, tunnels, and pipes. Meanwhile, disaster reduction technologies have been proposed for ground fissures, such as pumping control, reasonable avoidance, deformation adaptation, and local strengthening, and systematic ground fissure mitigation technologies for urban construction and major engineering projects have been developed.

Conclusions

Significant achievements have been made in China on ground fissure research including (1) identification of the distribution of ground fissures in China and (2) establishment of the relationships among surface rupture disaster dynamic system, deep-earth structural dynamic system, and human activity dynamic system. The academic research results have been applied to engineering works to control the ground fissure-induced geohzards and disasters. These results not only provide a demonstration for international disaster mitigation research, but also highlight the importance and indispensability of engineering geology in sustainable development.

Globally, there are many regions with fragile geological environments similar to that of the North China Plain and Fen-Wei Basin. Although environmental change and disasters are mainly driven by geodynamics, improper engineering can amplify geological threat, worsen the geological environment, trigger geological hazard, and eventually result in disaster. Proactive research is essential in such fragile areas for effective control and management over these geohazard risks. The scientific research on ground fissures in China has provided guidance and practical demonstrations on how geological research can serve economic development and geohazard mitigation.

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