# Chapter 4
# Earth Fissures and Natural Resources Mining

## 4.1 Introduction

Earth fissures are a macroscopic surface phenomenon where surface rock layers and soil formations crack and form fractures of a certain length and width due to natural factors such as tectonic activity and water action, or human factors such as groundwater extraction, irrigation, and excavation. Under external and internal forces, rocks and soil layers undergo deformation. When the applied force exceeds the tensile strength of the rock and internal cohesion of soil layers, they fracture, resulting in the disruption of continuity and the formation of fissures (including joints and faults). Due to the confinement of surrounding rock and soil layers and the pressure from the overlying layers, the fissures become smaller with depth. However, at the surface, the pressure decreases, creating some free space, resulting in wider fissures, which are referred to as earth fissures or ground fissures (Wang 2000).

As a special type of geological hazard, earth fissure disasters directly or indirectly deteriorate the geological environment, posing a serious threat to human life and property safety, and causing significant economic losses (Pacheco-Martínez et al. 2013; Youssef et al. 2014). The frequency and severity of modern earth fissure disasters have been increasing worldwide, occurring in many countries (Burbey 2002; Hjartardóttir et al. 2012; Filippis et al. 2013). Earth fissure disasters are globally distributed, and China is one of the countries that is most severely affected by earth fissures, and the earth fissures are mainly distributed in the North China Plain, Fen-Wei Basin, and the Suzhou-Wuxi-Changzhou region (Li 2003; Wang et al. 2010, 2019; Peng et al. 2017, 2018).

China is one of the countries with the earliest and most extensive records of research on earth fissures. In ancient times, surface cracking phenomena were often considered secondary disasters accompanying earthquakes and did not receive much attention. With the significant increase in demand for resources such as oil and groundwater, uncontrolled exploitation of underground resources has accelerated the process of earth fissures rupturing to the surface. At the same time, the rapid growth



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of the global population and the contradiction between engineering development and earth fissure hazards have become apparent. In the mid-twentieth century, earth fissures gradually attracted the attention of scholars globally. However, by that time, many countries had already experienced large-scale earth fissure disasters, resulting in significant economic losses.

The study of earth fissure disasters in the United States began in the 1920s, starting with the earth fissures in the Goose Creek oil field in Texas between 1918 and 1926 (Minor 1925; Pratt and Johnson 1926). In the following decades until the 1970s, numerous earth fissures appeared in many regions (Jachens and Holzer 1982). During this period, Feth (1951) conducted research on earth fissures in the central and southern regions of Arizona, proposing that the tensile stress caused by uneven subsidence due to localized changes in aquifer thickness was the primary cause of earth fissure formation. The influence of groundwater changes on earth fissure formation was emphasized. After more than half a century of research, three main viewpoints regarding the formation mechanisms of the Doña Ana earth fissures in the southwestern United States have emerged: the tectonic origin theory (Kreitler et al. 1977; Holzer and Gabrysch 2010), the groundwater exploitation theory (Bouwer 1977; Lofgren 1978), and the combined tectonic and groundwater activity theory (Holzer and Pampeyan 1979).

Systematic research on earth fissures in China began in the mid-1970s. After the 1976 Tangshan earthquake, earth fissures appeared successively in various regions, attracting the attention of scholars. Subsequently, starting with the study of the formation mechanisms of earth fissures in Xi'an, Yi (1984) compared the spatiotemporal correlation between changes in groundwater levels, ground subsidence, and earth fissure activity. It was proposed that significant ground subsidence caused by over-exploitation of confined groundwater was the main cause of earth fissure formation and development in the Xi'an area, while being controlled by local geological structural conditions. Xia (1990) further studied the formation mechanisms of earth fissures in the Xi'an area, emphasizing the significant role of modern tectonic activity and human engineering activities in the process of earth fissure formation. With the expansion of the investigation scope and in-depth research, more than 500 earth fissures have been discovered in various areas of the Fenwei Basin. Scholars such as Peng Jianbing have comprehensively summarized the formation mechanisms of typical earth fissures in the region, including the coupling effects of tectonic fissures, pumping-induced fissures, and rainfall-induced fissure expansion (Peng et al. 2016, 2019; Jia et al. 2020).

## 4.2 Classifications of Earth Fissures

Earth fissures are geological phenomena characterized by the release of energy, movement of materials, or deformation and displacement of rock and soil masses. They are a result of the coupling of multiple scales, dynamics, and factors. Earth fissures can be triggered by regional stress fields, fault structures, groundwater exploitation, rainfall, underground mineral resource extraction, collapses, and landslides (Wang et al. 2020). They exhibit different spatial manifestations. Considering the diverse types of earth fissures, this chapter classifies them based on their formation causes, mechanical properties, and spatial forms.

### *4.2.1 Classification Based on Formation Causes*

The Earth's crust and surface are constantly undergoing dynamic changes driven by natural forces, which geologists refer to as geological forces. These forces encompass the natural dynamics (internal and external) that cause movements and changes in the composition of the Earth's crust, internal structure, and surface morphology. Therefore, scholars have classified these forces into internal forces and external forces (Xie 1988). Common types of internal force-induced fissures include earthquake fissures, volcanic fissures, and tectonic creep fissures. Common types of external force-induced fissures include expansive soil fissures, collapse fissures, landslide fissures, subsidence fissures, slump fissures, subsidence fissures, erosion fissures, drought fissures, freeze–thaw fissures, salt dome fissures, and mud volcano fissures. Due to the increasing impact of human activities on the natural environment, many experts and scholars believe that human activities should be separately classified in terms of fissure formation, such as ground subsidence fissures caused by excessive groundwater extraction. The following provides specific descriptions of each type of fissure.

#### **4.2.1.1 Earthquake Fissures**

It is generally believed that the development of earthquake fissures is closely related to the magnitude of the earthquake. Higher magnitude of earthquakes can usually produce wider, longer and deeper earth fissures. The development of earthquake fissures is most concentrated in the seismically active zones, where they tend to be larger in scale. As the distance from the epicenter increases, the number of fissures gradually decreases. However, in some localized areas far from the seismic zone, due to variations and influences of structural conditions, rock and soil properties, landforms, and groundwater, these areas may exhibit a high density of fissures. Overall, earthquake fissures are characterized by their large scale, extensive distribution, and clear directional patterns. They exhibit good continuity in the horizontal plane, with distinct horizontal and vertical displacements. In cross-section, multiple secondary fissures are present, showing overall displacement and multiple stages, and may even exhibit water and sand ejections.

#### 4.2.1.2 Volcanic Fissures

Volcanic fissures triggered by volcanic activity include volcanic inflation cracks and lava extrusion cracks. Volcanic inflation cracks are characterized by their small scale, exhibiting a circular or radial distribution in the horizontal plane, with no significant vertical displacement. In cross-section, the fissure walls are rough, showing clear tensile characteristics and displaying multiple stages and periodicity. On the other hand, lava extrusion cracks are larger in scale, extending over a greater distance, and exhibiting a zigzag pattern in the horizontal plane. They do not show significant vertical displacement but display pronounced horizontal tension.

#### 4.2.1.3 Tectonic Creep Fissures

In addition to the rapid fracturing of structural fissures during earthquakes, tectonic creep fissures can also form due to the slow and steady changes in tectonic stress. In the same tectonic stress field, areas most prone to tectonic creep fissures include zones of strain accumulation, areas with brittle rocks, and regions experiencing intense changes in active structures, such as active fault zones, the axial parts of active folds, and the transitional areas of uplift and subsidence in active structures. Tectonic creep fissures generated during intense crustal movements often have a widespread distribution, ranging from several thousand square kilometers to several hundred thousand square kilometers in size. In extensive regions, tectonic creep fissures do not develop along a single direction but may exhibit multiple sets of fissures with different orientations.

#### 4.2.1.4 Expansive Soil Fissures

Expansive soil, also known as shrink-swell soil or fissured soil, is a special type of cohesive soil. Due to its characteristics of swelling when wet and shrinking when dry, expansive soil often experiences severe shrinkage and generates numerous fissures during dry seasons, especially during years of extreme drought. Although expansive soil rapidly expands after absorbing water during the rainy season, this swelling-shrinking deformation is irreversible. The opening width of the cracks during shrinkage is greater than the closure width during wet expansion, resulting in increasing differences with each cycle of swelling and shrinking. Additionally, local microclimatic influences, such as sun-facing slopes versus shaded slopes or variations in ventilation conditions, can affect the degree of development of expansive soil fissures. Generally, fissures are more developed in the former conditions and less developed in the latter.

#### 4.2.1.5 Collapse and Landslide Fissures

Collapse and landslide fissures often occur together in similar terrain conditions, primarily influenced by gravitational forces. They are initially formed by the development of fissures. Generally, slopes with collapse fissures are steep, with the upper part protruding and the lower part concave. When the fissures extend to a certain extent, rock blocks and soil will fall freely and accumulate at the foot of the slope, forming a talus deposit. Slopes with landslide fissures are relatively gentle, often exhibiting an arc-shaped or straight-line form. The upper part of the slope is concave, while the lower part is convex. Rock blocks and soil slide along the slope surface, maintaining their original structural characteristics. The surface of the landslide body exhibits a stepped morphology, and a series of new fissures are formed during the sliding process.

#### 4.2.1.6 Subsidence and Collapse Fissures

Subsidence and collapse are common phenomena caused by various factors. Prior to subsidence and collapse, the ground often develops fissures, known as subsidence fissures and collapse fissures, respectively. Generally, large-scale caves with a significant height difference between the cave floor and ceiling and shallow burial depth are prone to subsidence and the formation of subsidence fissures. Conversely, collapse and collapse fissures occur in cases where the cave collapses.

#### 4.2.1.7 Swelling, Erosion, and Drought Fissures

The morphological characteristics of swelling fissures are influenced by the landforms formed by loess swelling. Due to the formation of circular depressions during loess swelling, fissures often surround these depressions. The density of fissures around the depressions is influenced by the scale and depth of the swelling and the columnar joints in the loess. Generally, in areas with well-developed columnar joints in loess, the fissures around the edges of the swelling depressions are denser when swelling occurs. The cutting depth of swelling fissures is generally shallow and mostly within the swelling loess layer.

Erosion fissures generally occur in unconsolidated sandy soil and gravel layers. When rainwater falls on the surface of the sandy soil layer, it permeates underground through the pores between the sand particles. During the infiltration, flowing water has two effects: it carries away extremely small particles filling the gaps between coarse particles, increasing the porosity of the sandy soil layer; and under the influence of gravity, loose sandy soil gradually becomes compacted. When these two effects occur simultaneously in the same soil mass after a certain period of accumulation, the surface of the soil layer suddenly collapses in a linear pattern, forming fissures.

Drought fissures mainly occur due to the loss of moisture in the soil layer under arid climatic conditions. These fissures primarily develop on the surface of the soil layer and are not only controlled by dry weather but also closely related to the composition of the soil. In general, silty clay soils are most prone to drought fissures.

#### 4.2.1.8 Thaw-Freeze Earth Fissures

Changes in the moisture content of soil can cause surface cracks in the ground. In cold climates, the water in the soil freezes into ice during the cold season and then thaws back into water after a certain period. The earth fissures that form under these conditions are called thaw-freeze earth fissures. Thaw-freeze fissures are closely associated with cold climate regions and are mostly found in the permafrost zones near glaciers. In these frozen soil areas, the repeated cycles of freezing and thawing can lead to earth fissure formation. Additionally, during the summer, the thawing of the surface layer can induce creep and contribute to earth fissures development. Thaw-freeze earth fissures primarily occur in sloping areas or small valleys.

#### 4.2.1.9 Salt Dome Fissures and Mud Volcano Fissures

Salt dome fissures are mainly caused by the plasticity of rock salt, petroleum, and the overlying rock layers' weight. Sometimes, the compressive forces from crustal movements also play a role. The characteristics of salt dome fissures are influenced by the shape and size of the salt dome. Generally, shallowly buried salt domes exhibit more developed earth fissures, while deeply buried ones have less pronounced earth fissure development and a smaller distribution range. The earth fissures formed prior to mud volcano eruptions have a similar shape to the mud volcano itself, often radiating outward. The scale and density of these earth fissures are controlled by the extent and magnitude of the mud volcano dome's rise. The development of earth fissures is most active when a mud volcano is nearing eruption.

#### 4.2.1.10 Ground Subsidence Fissures

Ground subsidence fissures are typically caused by uneven subsidence resulting from excessive groundwater extraction. The extraction of groundwater causes a loss of water in the aquifer, leading to a decrease in hydraulic head and a reduction in pore water pressure. This increase in effective stress causes a decrease in intergranular pore space, disruption of particle structures, and particle movement and rearrangement, resulting in macroscopic surface subsidence. The formation process of these earth fissures involves the accumulation and dissipation of stress and strain due to differential subsidence. In this process, hidden fractures form in the shallow soil layers at locations of stress concentration, providing a structural basis for the subsequent formation of earth fissures.

### 4.2.2 Classification Based on Mechanical Properties

#### 4.2.2.1 Compressive Earth Fissures

Under the influence of compressive stress, a group of compressive earth fissures can be formed perpendicular to the direction of maximum principal stress. These earth fissures are relatively small, exhibiting a smooth and wave-like linear shape with limited extent. Local bulging or sinking may be observed in the vicinity of these earth fissures. In the natural environment, compressive earth fissures are highly uncommon, making it difficult to locate a representative example of such earth fissures in the field.

#### 4.2.2.2 Tensile Earth Fissures

Tensile earth fissures have a strike parallel or perpendicular to the direction of maximum principal stress or maximum principal tensile stress. These tensile earth fissures are characterized by their wide width and rough, uneven fracture surfaces, often exhibiting a serrated or jagged pattern. They have limited linear extensions, with each segment transitioning into another extension direction. However, the overall extension direction of the entire fracture remains relatively stable. Adjacent to a large-scale tensile earth fissure, there is often a series of smaller fractures parallel to it. Tensile earth fissures are the most commonly observed type of earth fissures.

#### 4.2.2.3 Shear Earth Fissures

Shear earth fissures have a well-defined linear extension, stable orientation, and straight shape, sometimes resembling neatly cut lines. Some shear earth fissures exhibit a series of feather-like small fissures intersecting obliquely with them on one or both sides. Shear earth fissures often appear in zones, with a harmonious relationship between their beginnings and ends. In the plane, some areas have a higher density of shear earth fissures, while others have a lower density. The widths and spacing of dense and sparse zones are approximately similar, resulting in a rhythmic variation in density.

#### 4.2.2.4 Compressive Shear Earth Fissures

When the angle between the strike of a fracture and the direction of maximum principal compressive stress is less than 90° but greater than 45°, it is classified as a compressive shear earth fissure. Compressive shear fractures exhibit a combination of characteristics from both compressive and shear earth fissures. The earth fissure line takes on a gentle “S” or reverse “S” shape and is often composed of several fissures arranged in a staggered pattern. The width of compressive shear fissures varies, and their surfaces are relatively smooth and flat.

#### 4.2.2.5 Tensile Shear Earth Fissures

When the angle between the strike of a fracture and the direction of maximum principal compressive stress is less than 45° but greater than 0°, it is classified as a tensile shear fracture. Tensile shear fractures exhibit a combination of characteristics from both tensile and shear fissures. The fissure line appears relatively straight, but in certain local sections, it often adjusts to accommodate another set of shear fissures, leading to a change in direction.

### *4.2.3 Classification Based on Morphology*

Earth fissures can also be classified based on their morphology. They are classified primarily based on their geometric patterns observed on a plane. In the classification of earth fissures, it is important to consider both the morphology of an individual earth fissure and the combination of multiple earth fissures. The integration of these two aspects is crucial for a logical and comprehensive classification (Table 4.1).

**Table 4.1** Earth fissure classification based on morphology

| Common morphology | Main features |
|---|---|
| Straight-line shape | The earth fissure is flat and straight, with a stable direction of extension, and no turning occurs throughout the crack |
| Arcuate shape | Under certain natural conditions or influences, the fissure bends to form an arc, resembling a curved line |
| "S" and inverted "S" shape | The middle section is straight while both ends curve in opposite directions, giving it a back-and-forth bend |
| Sawtooth shape | Fissure zigzags like the teeth of a saw but extends in a specific direction overall |
| "Z" or "N" shape | The middle and both ends of the fissure are straight, but there's a sudden deviation between them, resembling either a "Z" or "N" |
| Ring shape | The fissure circumscribes a ringed structure, geological entity, or topographical feature, looking almost circular or shaped by several arcuate lines forming a near-circular image |
| Geese-row shape | Several roughly parallel fissures appear in succession, mimicking a line of geese in flight |
| "入" or "人" shape | On one side of the main fissure, a branch meets it at a certain angle but doesn't cut through, resulting in a "入" or "人" shape |
| "X" and grid shape | Two sets of fissures with different orientations intersect in an "X" form. Each set often consists of multiple parallel fissures that frequently weave with the other set, forming a grid-like pattern |

(continued)

**Table 4.1** (continued)

| Common morphology | Main features |
|---|---|
| Broom shape | On one end of the main fissure, a series of smaller fissures develop with varying angles of intersection, looking like the bristles of a broom splaying out |
| Radiating shape | Fissures radiate outwards from the center, akin to the spokes of a bike wheel. The center typically is more elevated than its surroundings, and the fissure width narrows from the center to the edges |
| Centripetal shape | Fissures converge towards the center. Its appearance is similar to the radiating form, but the center manifests as a depression, with the fissure width narrowing from the edges to the center |

## 4.3 Hazards of Earth Fissures

Earth fissures induce deformation and stress fields within a certain range of the surrounding geological body, subsequently impacting buildings through their foundations and bases. The consequences of various earth fissures on human populations primarily manifest as the destruction of surface structures and other artificial facilities, posing a significant threat to human life and property safety. Earth fissure disasters are widespread in China, with the main distribution areas including the Fen-Wei Basin, the North China Plain, and the Suzhou-Wuxi-Changzhou region. These areas are characterized by intense tectonic activity and high population density, which have contributed to the occurrence of large-scale earth fissure disasters. The specific hazards of earth fissures can be summarized as follows.

### *4.3.1 Road Surface Damage*

Earth fissures primarily disrupt road surfaces by causing misalignment, resulting in uneven surfaces or even complete fractures that hinder normal traffic flow. Additionally, the rupture of road surfaces can lead to significant infiltration of surface water during the rainy season. This water infiltration not only erodes the underlying gravel layer but also triggers surface subsidence. When combined with earth fissure activity, these factors exacerbate the extent of road surface damage. The characteristics of earth fissure disasters on road structures are closely related to the development and movement patterns of the fissures. For both flexible road structures, such as asphalt roads and unpaved dirt roads, and rigid road structures, such as concrete roads, their damage characteristics and disaster modes differ due to their distinct mechanical properties when exposed to the same earth fissure environment. These disaster modes can be categorized into four types: slope type (flexible road structures), steep slope type (rigid road structures), tension type, and fragmentation type (Peng et al. 2017).

The slope-type road surface damage is primarily observed when roads with flexible structures, like asphalt gravel, intersect earth fissures. In these cases, there is a significant relative vertical displacement between the upper and lower sections of the fissure, resulting in the damage pattern depicted in Fig. 4.1. It can be observed that the fundamental cause of this type of damage is the relative subsidence of the upper section, which leads to the settling of the road structure above under the influence of gravity. Thanks to the excellent deformation adaptability of flexible road surfaces, a slope that slightly tilts towards the upper section or even a steep slope is formed in the vicinity of the earth fissure. Additionally, small transverse tension cracks may appear in areas with high convex curvature on the slope.

Figure 4.2 illustrates the disaster mode of slope-type road surface damage when roads with rigid structures, such as concrete, intersect earth fissures. In this scenario, if there is a significant relative vertical displacement between the upper and lower sections of the fissure, a steep slope-type road surface damage pattern will occur, as shown in Fig. 4.2a. The fundamental cause of this type of damage is also the relative subsidence of the upper section, resulting in the settlement of the road structure under the influence of gravity. Due to the limited deformation adaptability and low tensile strength of concrete materials, areas with concentrated tensile and shear stresses near the earth fissure can lead to the fracturing of the concrete road surface, forming a steep slope. If the earth fissure is well-developed and has a certain width, it is possible to form a double-section or even multiple-section steep slope damage (Fig. 4.2b).

For nearly vertical tensional earth fissures, regardless of whether the road surface structure is flexible or rigid, tensional cracks generally form parallel to the fissure. As

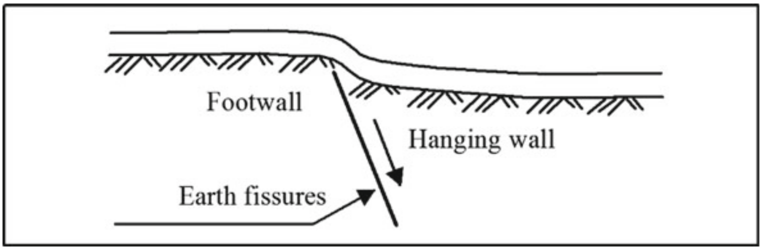


**Fig. 4.1** Illustration of slope-type road surface damage modes (Peng et al. 2017)

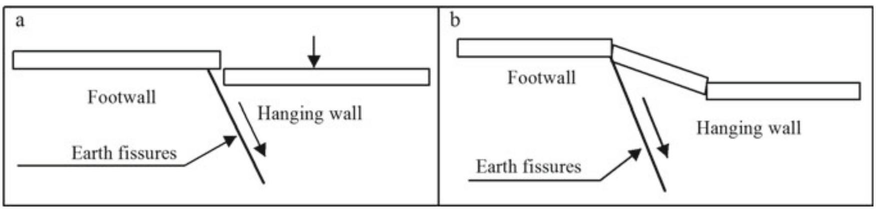


**Fig. 4.2** Illustration of disaster modes for **a** steep slope type road surface damages and **b** double-section steep slope type road surface damages (Peng et al. 2017)

flexible materials have better deformation adaptability, a group of parallel tensional cracks usually forms within a certain range near the earth fissure, although the crack opening width is generally small. In contrast, for rigid road surface structures such as concrete, the opening deformation tends to concentrate on a main crack, resulting in a larger opening width, but fewer cracks compared to flexible road surfaces. The damage mode is shown in Fig. 4.3.

The fragmentation-type road surface damage caused by earth fissures is similar to the mode of rupture observed in the formation of figure-eight-shaped wall cracks. Specifically, when the earth fissures are well-developed, a subsidence trough with a certain width is formed due to the combined effects of fissure creep and surface erosion. This leads to severe damage to the road structure above, especially under repeated vehicular loads, resulting in a fragmented zone on the road surface. The disaster mode is illustrated in Fig. 4.4.

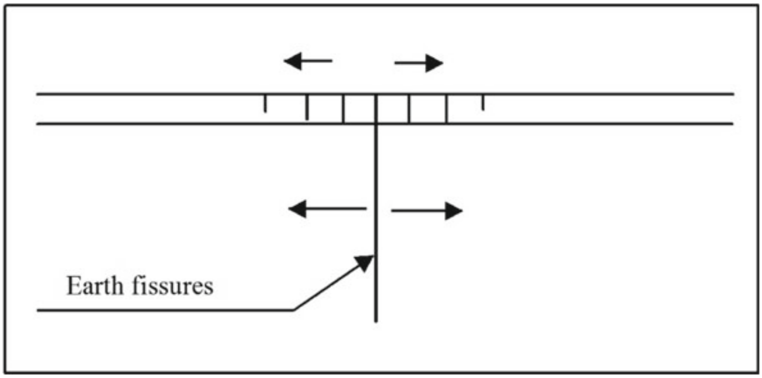


**Fig. 4.3** Illustration of disaster mode for tension type road surface damages (Peng et al. 2017)

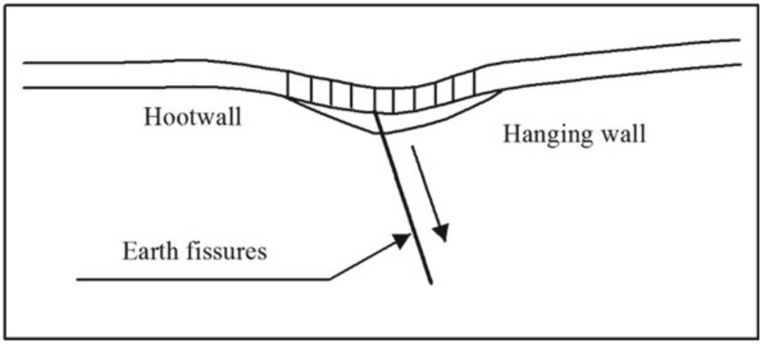


**Fig. 4.4** Illustration of disaster mode for fragmentation-type road surface damages (Peng et al. 2017)

### *4.3.2 Hazards to High-Speed Railway Projects*

The hazards posed by earth fissures can severely constrain local urban planning and utilization. They also pose a significant threat to the safety of local high-speed railways. For example, there are 21 earth fissures or fissure clusters that intersect or covertly intersect with the Datong-Yuncheng high-speed railway. Some of these fissures have branch fissures or secondary fissures, with a total of 36 intersections or covert intersections with the high-speed railway. They are primarily distributed in the Taiyuan Basin, Linfen Basin, and Yuncheng Basin. The causes of these fissures can be categorized into the following types: structural (controlled or influenced by fault creep or hidden faults), subsidence-induced, and paleo-geomorphologically (topographical) controlled.

Peng et al. (2017) studied the earth fissures along the Datong-Yuncheng North high-speed railway. Through physical model testing and numerical simulation of the impacts of fissure activities on the high-speed rail embankment and bridge, they concluded that when the high-speed railway embankment crosses the fissure zone at a small angle, the deformation and failure mode of the concrete base plate of the embankment under the action of the fissures is tension-shear failure caused by torsion and bending deformation. Cracks primarily concentrate in the middle of the plate, with a nearly parallel distribution and intersecting at a small angle with the fissures, with more severe deformation and failure in the lower structure than in the upper structure. However, when the high-speed railway embankment crosses the fissure zone at a large angle, the pressure at the pile end of the cement fly ash gravel piles under the action of the fissures mainly shows a decreasing trend in the upper structure and an increasing trend in the lower structure. When the vertical displacement of the fissure reaches 4 cm, cracks begin to appear near the location of the trackbed board close to the fissure. The failure mode of the cement fly ash gravel piles is bending failure, and the failure surface is approximately horizontal.

### *4.3.3 Impacts on Buildings*

Earth fissures can be a slow deformation geological hazard. The fundamental cause of their occurrence lies in the formation of fissures that reach or approach the surface of the earth, followed by uneven deformation or uneven settlement on the surface due to tectonic creep, groundwater extraction, and surface water erosion. When buildings are situated above or within the uneven deformation zone of the upper and lower plates of an earth fissure, additional internal forces and deformations occur, leading to structural damage or even complete destruction. Therefore, the characteristics of engineering structures and their disaster patterns are closely related to the activity features of earth fissures, meaning that the deformation and destruction patterns of engineering structures are determined by the activity features or patterns of the earth fissures.

Among all forms of structural damages to ground buildings, the most common and typical form is the destruction of the wall. Walls situated above or within the uneven settlement and deformation zone of an active earth fissure will experience varying degrees of damages, characterized primarily by wall cracking. The cracking and destruction of building walls can be classified into four types: inclined type, vertical type, splayed type, and irregular type.

The inclined type is the most common form of wall cracking when the wall crosses over a geological fissure with a significant vertical displacement between the upper and lower plates. The disaster pattern of the inclined type is shown in Fig. 4.5.

The vertical type earth fissure is a horizontal tension crack that typically occurs in the upper wall of shallow earth fissures experiencing horizontal tension. The disaster pattern is shown in Fig. 4.6. The horizontal relative movement is mainly observed on both sides of the fracture surface, with the degree of opening determined by the extent of horizontal relative movement between the upper and lower plates of the earth fissures.

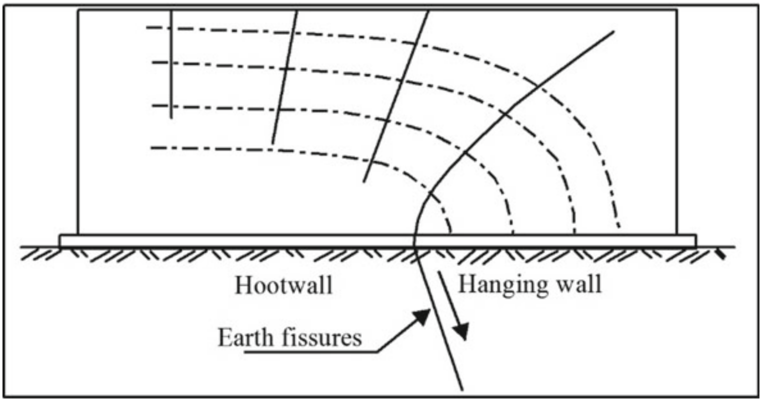


**Fig. 4.5** Illustration of disaster mode for counter-tilting wall fracture (Peng et al. 2017)

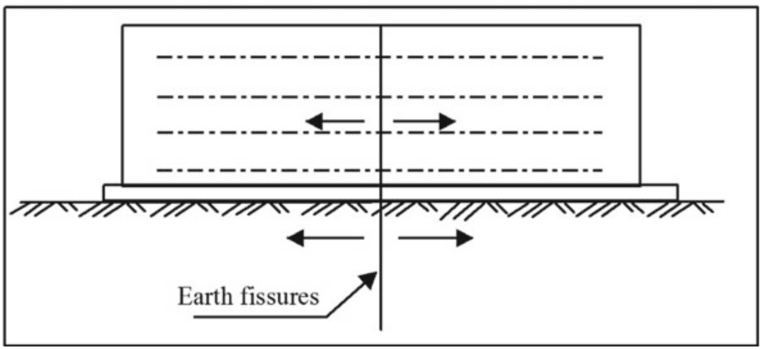


**Fig. 4.6** Illustration of disaster mode for upright wall fracture (Peng et al. 2017)

The splayed type of wall cracking is not commonly observed and only occurs when a wall spans a large-scale and highly active earth fissure. The disaster pattern is shown in Fig. 4.7. From Fig. 4.7, it can be observed that when the earth fissure develops to a large scale, it can create an influence zone several meters to tens of meters wide. Under the combined effects of creep and subsurface water erosion of the earth fissure, the soil in the influence zone forms a funnel-shaped settlement trough. Consequently, two nearly symmetrical sets of principal tensile stress traces, as indicated by the dotted lines in Fig. 4.7, are formed in the upper wall. This results in inclined fractures perpendicular to the principal stress traces at the edges of the settlement trough, forming a splayed type earth fissures.

Irregular earth fissures generally occur when walls are not directly positioned above a earth fissure but are within the influence zone of uneven deformation between the upper and lower plates of the fissure. The disaster pattern is illustrated in Fig. 4.8. Generally, the scale of irregular earth fissures is smaller compared to the aforementioned types of earth fissures, and the relative displacement on both sides of the crack is relatively small.

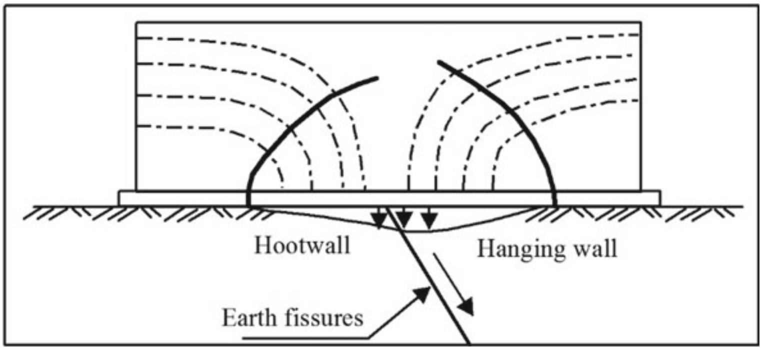


**Fig. 4.7** Illustration of disaster mode for figure-eight wall fracture (Peng et al. 2017)

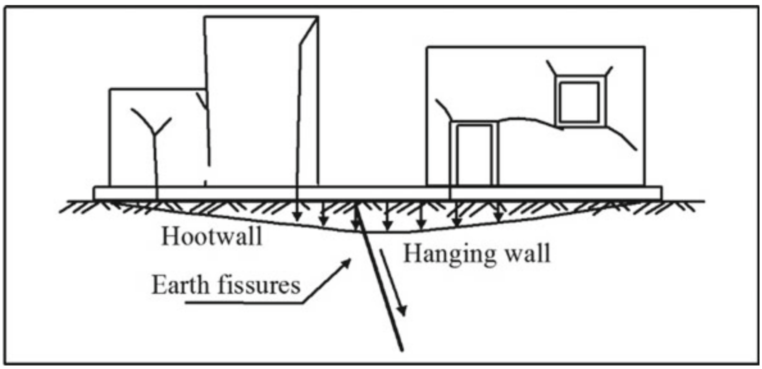


**Fig. 4.8** Illustration of disaster mode for irregular wall fracture (Peng et al. 2017)

These findings contribute to a better understanding of the characteristics and disaster patterns of building structures in relation to the activity features of earth fissures, which are essential for mitigating the risks and improving the resilience of buildings in areas prone to such hazards.

## 4.4 Formation Mechanisms of Earth Fissures

Earth fissures are complex surface geological phenomena formed in specific geological environments. The process of their incubation, formation, and development is a non-equilibrium and nonlinear process. There are various types of earth fissures. The formation mechanisms of some common earth fissures are described below.

### *4.4.1 Formation Mechanisms of Earthquake-Induced Earth Fissures*

The formation of earthquake-induced earth fissures is closely related to the magnitude of earthquakes. The larger the magnitude, the more earth fissures are generated. Based on their causes, earthquake-induced earth fissures can be further classified into tectonic earth fissures and secondary gravity-induced earth fissures.

Tectonic earth fissures are surface destruction phenomena formed in the epicentral region and surrounding areas during seismic activity. They are caused by the rupture of rock layers in the seismic source area, resulting in shallow surface displacement of rock and soil materials (Wang 2000). Tectonic earth fissures mainly extend along fault zones, with large scale and far-reaching distribution. They exhibit obvious directional characteristics. Different seismic fault zones often show regular combinations, reflecting the main structural directions of the seismic region and the regional stress field or local stress field controlling the geological structure. They exhibit significant displacement in both horizontal and vertical directions and can occur in different geomorphic units and lithological positions (Yi and Liang 2010).

Secondary gravity-induced earth fissures are surface cracks formed by the creeping and sliding deformation of shallow rock and soil materials in local zones due to the vibration effects of earthquakes. They can be categorized into three types based on their causes: (1) Intense ground shaking causes inclined surfaces or slopes to become unstable, resulting in rock and soil collapse and tensile earth fissures at the edges of the sliding zone. (2) Various forms of cracks appear in artificial fill structures (such as earth dams, gravel roads, and embankments) due to strong ground motion, with their orientations aligning with the long axis of the fill structures and exhibiting certain distribution patterns. (3) Flat and horizontal overlying layers slide along the underlying inclined layers, leading to the occurrence of tensile earth fissures on the ground. These fissures mostly occur in areas with artificial fill soil.

Overall, the formation mechanisms of earth fissures are complex and involve various geological and geotechnical factors. Understanding these mechanisms is crucial for predicting and mitigating the hazards associated with earth fissures.

### 4.4.2 Mechanism of Formation for Landslide Earth Fissures

Common types of earth fissures caused by landslides can be divided into collapse-type and landslide creep-type. Collapse-type fissures are mainly formed by the development of joint fissures or unloading fissures and are often a precursor to landslide activity. Collapse-type fissures are mainly induced by activities such as excavation at the foot of slopes, open-pit mining, and slope cutting during road construction. The inclination angle of collapse-type fissures is steep, and their spatial distribution density, fissure opening width, and extension length gradually decrease from near the slope surface towards the slope interior. Collapse-type fissures can be formed by tension zones created by stress concentration in local sections of slopes, or by sliding deformation of slope rock and soil materials along unloading fissure zones. For example, in the Yuen Long area of Shenzhen City, Guangdong Province, due to excavation at the foot of slopes, the slope experienced significant unloading deformation, and under the long-term effect of rainfall infiltration, several arc-shaped collapse fissures were formed in the artificial slope zone.

Long-term creep deformation of landslides often leads to the formation of different-shaped landslide fissures. Landslide fissures are the evolution of stress states in slope zones that give rise to landslides, causing changes in the original stress equilibrium state and resulting in the concentration of stresses in local sections that gradually exceed the strength of the rock and soil materials at that site, leading to shear and tensile fractures and the formation of surface cracks. Landslide fissures are both the product of landslide activity and a precursor to landslides, closely related to rainfall infiltration conditions and other triggering factors. Generally, landslide fissures can be divided into the following four categories:

1. Arc-shaped tensile fissures are mainly distributed at the rear of the landslide body, with lengths ranging from a few meters to several hundred meters. They usually take the form of arcs and are roughly parallel to the direction of the landslide rear wall. These fissures are mainly formed by the downward creeping and tearing of the landslide body.
2. Feather-shaped shear fissures are mainly distributed on both sides of the middle part of the landslide body. Due to the sliding deformation of the landslide body, relative displacement occurs between the landslide body and the stationary material in the surrounding area, forming a shear deformation zone at the boundary between the landslide body and the stationary material, which results in shear fissures. Feather-shaped fissures often accompany both sides of the shear fissures.
3. Bulging fissures are mainly distributed at the front of the landslide body. These are tensile fissures formed by the uplift of the landslide body due to being obstructed

during downhill movement, with their directions mostly perpendicular to the direction of landslide movement.

4. Fan-shaped fissures are a common type of fissure in landslide terrain, mainly distributed in the middle and front parts of the sliding body, especially in the area of the landslide tongue. These fissures typically have an open shape, similar to that of a fan. The direction of the fissures is approximately parallel to the sliding direction in the middle part of the landslide body, while in the area of the landslide tongue, they are radially distributed, resembling the radiation lines of a fan. These fissures are primarily formed due to the sliding body sliding to the bottom and spreading to both sides. During the sliding process, the soil in the middle part of the landslide body experiences significant stress and shear forces, leading to the formation of fissures. The direction of these fissures is close to the sliding direction, showing the characteristics of sliding. At the same time, in the area of the landslide tongue, the cracks exhibit a radial distribution, consistent with the trajectory of the outward spreading of the collapse point.

### 4.4.3 Mechanism of Formation for Collapse Earth Fissures

The formation mechanisms of collapse earth fissures can be divided into karst collapse earth fissures and goaf collapse earth fissures.

Karst collapse is a slow process. Prolonged drought and groundwater pumping activities increase the groundwater seepage velocity and hydraulic gradient, resulting in hydraulic erosion on the overlying soil layer caused by the seepage of groundwater. As the dynamic hydraulic environment of karst further evolves, the covering soil layer on the top of the open karst cave is continuously eroded and excavated, and fine particles are gradually carried away by the groundwater flow, causing the soil structure to relax. At the contact between the top of the karst cave and the overlying soil layer, the soil starts to collapse and form initial soil caves. This process is a slow progressive process. During this evolution process, the stress state of the covering soil layer is disrupted, and local tensile stresses concentrate, leading to settlement and tensile deformation of the shallow soil layer, eventually forming a series of earth fissures. Karst collapse earth fissures are common deformation signs before ground subsidence disasters occur and often occur around collapse pits.

Goaf collapse earth fissures mainly occur in the goaf area, and the process of their formation is an extremely complex dynamic process. From the perspective of the mechanical mechanism of formation, before being affected by mining activities, the overlying soil layer in the goaf area is in a state of natural dynamic equilibrium. After the goaf is formed, the stability of the overlying rock and soil mass is supported by mining pillars. In the long-term bearing process, due to the heterogeneity of the rock structure of a few mining pillars with weak structures, progressive damage occurs, leading to deformation, cracking, and collapse of the underlying rock layers, and the bending deformation and further collapse of the overlying soil layer. As the underlying rock mass deforms and collapses, the overlying soil layer undergoes creep. Coupled with the influence of groundwater seepage into the goaf area, earth fissures gradually form on the surface of the goaf.

Overall, both karst collapse earth fissures and goaf collapse earth fissures are complex processes involving the interaction of geological, hydrological, and mining factors. Understanding the formation mechanisms of these earth fissures is crucial for early warning and prevention of ground subsidence disasters.

### *4.4.4 Mechanism of Formation for Expansive Soil Fissures*

The formation of fissures in expansive soils is the result of swell-shrink deformations caused by seasonal wetting and drying of the soil. The primary development depth of these cracks is typically located within the near-surface expansive soil layers or within the non-expansive soil layers situated above the shallow expansive soil strata. Common types of cracks in expansive soils are categorized into plane fracture-type earth fissures of swelling soil and underground fracture traction-type earth fissures of swelling soil induced by tensile forces.

Plane fracture-type earth fissures of swelling soil often evolve from weathering fissures. Densely developed weathering fissures on the surface of expansive soils are, in essence, a type of swell-shrink crack. These fissures represent the cumulative effect of countless seasonal wetting and drying cycles over extensive geological periods, and their opening and closing are entirely controlled by climatic moisture fluctuations. During seasons with ample rainfall, the surface of the expansive soil receives infiltrated rainwater, increasing its moisture content. Consequently, as the soil swells due to water absorption, these swell-shrink cracks gradually close, endowing the soil with a high shrinkage potential. As the environment transitions into the subsequent dry season characterized by scarce rainfall and high evaporation rates, this soil with its high latent shrinkage potential begins to lose its moisture content under the effects of solar heat and atmospheric evaporation. Cracks that had previously closed now gradually reopen in response to the soil's shrinking. With the progression of the dry season and intensifying atmospheric evaporation, the soil continues to lose moisture, leading to the continuous development and expansion of the shrinkage cracks. As the number and size of these cracks increase, a crack expansion cycle system gradually emerges. On one hand, these fissures contribute to the overall structural breakdown of the expansive soil. On the other, their development results in an increased evaporation surface area and depth, leading to more significant soil dehydration, greater soil shrinkage, and thus, rapid enlargement of the cracks. Over time, amidst numerous fissures, one or more dominant cracks may interconnect along their expansion paths to form significant earth fissures.

Underground fracture traction-type earth fissures of swelling soil induced by tensile forces emerge primarily in prolonged dry climatic conditions. Initially triggered by the drying effects of tree root water uptake, these cause "deep" areas of the expansive soil to shrink, resulting in underground concealed cracks. Following this, evaporation from the tree canopy further dries out the soil layers near the tree roots, leading to additional soil shrinkage and further development of the concealed cracks. This process can culminate in the sudden tearing apart of the upper and lower soil layers, giving rise to visible earth fissures. Once these concealed underground fissures appear, if the dry conditions persist, the shrinkage force within the soil can intensify. After an extended dry spell, if a heavy downpour follows, rainwater rapidly infiltrates the surface cracks, penetrating deeper layers. This results in substantial water absorption by the soil within the crack development zone, causing the soil to swell, soften, and decrease in strength. At this juncture, the shrinkage force within the expansive soil's "shrinkage field" greatly surpasses the cohesive force between the soils located above the concealed crack boundary. The intense tensile forces then rapidly pull apart the concealed cracks at the edges of the forested area, severing the tree roots. Consequently, the upper and lower soil strata suddenly tear apart, leading to the formation of pronounced earth fissures.

### *4.4.5 Mechanism of Formation for Collapsible Loess Earth Fissures*

Such types of earth fissures are caused by the collapsibility of loess soil and can form under long-term water saturation conditions, typically being of smaller scale. Due to the development of vertical joints in the loess, its vertical permeability often significantly surpasses its horizontal permeability. When this soil becomes saturated, it primarily undergoes deep vertical infiltration until it encounters the groundwater table or a soil layer with strong water-barrier properties. Only then does lateral saturation become pronounced. Following underground water-induced deformation, annular cracks form around the saturated soil mass, extending to the surface and resulting in earth fissures (Fig. 4.9).

### *4.4.6 Mechanism of Formation for Ground Subsidence Fissures*

A potential cause for the formation of such earth fissures is the excessive extraction of groundwater leading to the creation of subsidence funnels. In the funnel's central region, significant groundwater level decline results in considerable soil compression. This, in turn, leads to a pronounced surface subsidence. The tensile stresses are relatively concentrated, and when the regional tensile stress surpasses the tensile strength of the soil layer, it induces cracking and deformation in the upper soil strata, giving rise to earth fissures (Fig. 4.10). Typically, these kinds of earth fissures do not follow a fixed direction and are generally smaller in scale.

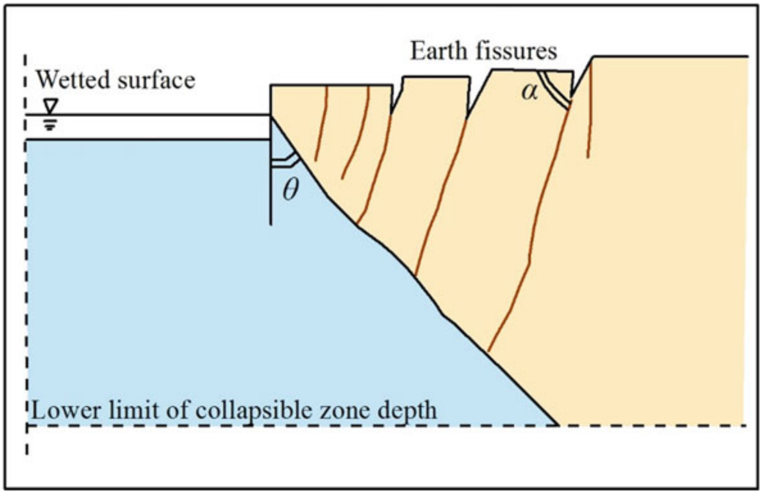


**Fig. 4.9** Patterns of collapsible loess earth fissures (He 2011)

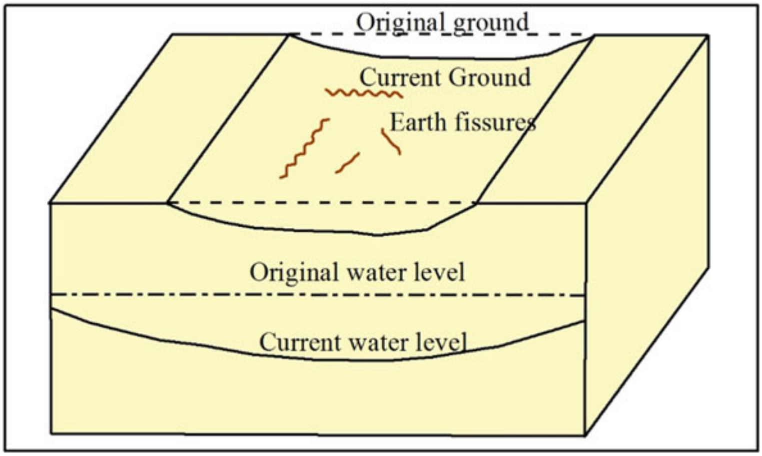


**Fig. 4.10** Patterns of ground subsidence fissures (He 2011)

## 4.5 Groundwater Development and Earth Fissures

With the rapid socio-economic development of cities, the demand for water in agriculture, industry, and daily life has surged dramatically. This has resulted in the over-extraction of groundwater. The extraction of groundwater leads to a decline in the groundwater table, causing compression of the compressible soil layers, which in turn results in land subsidence. As groundwater continues to be extracted, earth fissures may first appear in areas where the land subsidence initially occurs. The exploitation of groundwater is a crucial triggering factor for the formation of earth fissures, a viewpoint accepted by the majority of researchers studying these fissures. However, how groundwater extraction leads to the formation of earth fissures has long been a subject of substantial debate. Numerous scholars have proposed various causative mechanisms over time. In summary, there are primarily five main theories.

1. Permeation Deformation Mechanism. During the groundwater extraction process, earth fissures form due to the permeation deformation mechanism. Once a subsidence pit forms, the groundwater infiltration rate increases, the hydraulic gradient increases, and the dynamic water pressure formed by groundwater seepage produces latent erosion on the soil layer and gradually develops to pipe surge, which relaxes the structure of the soil layer, thus causing the tensile stress of the overlying soil layer to be concentrated and occurring tensile fissure deformation at the surface.
2. Soil Layer Dehydration Shrinkage Deformation Mechanism. Neal (1968) proposed that the shrinkage deformation of soil layers due to dehydration was a cause of earth fissures during groundwater development. As the groundwater level drops, the upper soil layer loses moisture and shrinks in the horizontal direction, leading to surface cracking. Some researchers have validated Neal's causative mechanism through model experiments. The experimental results showed that the aquifer body strain caused by aquifer dewatering is obvious and can cause the contraction deformation of the soil layer in the horizontal direction.
3. Permeation Stress Drag Mechanism (Lofgren 1969). During the seepage of groundwater from the periphery to the center of the landfall funnel, a strong dynamic water pressure is formed along the seepage direction. The kinetic energy generated by the dynamic water pressure on the solid particles will produce an obvious viscous drag effect on the aquifer skeleton, and the accumulation of this viscous drag effect in the whole aquifer will form a tensile strain concentration in the overburden soil layer, thus causing it to crack.
4. Differential Subsidence Deformation Mechanism (Schumann and Poland 1970). Abrupt changes in the bedrock surface morphology or noticeable differences in the thickness of compressible soil layers will result in differential subsidence in loose soil layers, this will lead to a concentration of tensile stresses at the ground surface where compaction subsidence differences are the greatest, resulting in tensile deformation and cracking (Fig. 4.11).

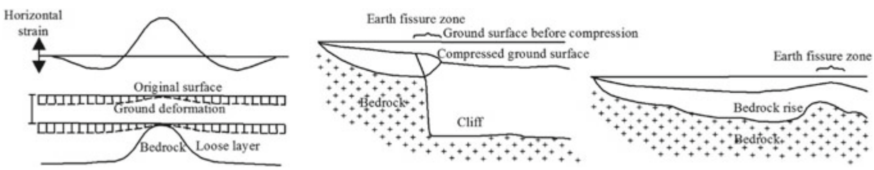


**Fig. 4.11** Differences in pressures (Peng et al. 2012)

5. Rigid Fracture Mechanism. As the groundwater table decreases, the loose soil layer continuously undergoes consolidation deformation. Compared to the consolidation deformation of the underlying soil layer, the surface soil layer's consolidation is almost negligible. Therefore, during the subsidence process, a rigid inversion occurs, leading to fractures forming along the edges of the subsidence basin, as illustrated in Fig. 4.12.

The differential subsidence deformation mechanism has been more widely accepted and is considered the primary factor for the formation of earth fissures. The other mechanisms play dominant roles only in certain specific environments. Earth fissures resulting from differential subsidence due to groundwater extraction are widespread and have significant impacts. For instance, the bedrock undulation-induced earth fissures in the Suzhou-Wuxi-Changzhou region and the ancient river channel earth fissures in the North China Plain both fall under this category. Both have been caused by uneven subsidence due to over-extraction of groundwater. The extraction of groundwater causes the aquifer to lose water, leading to a decrease in hydraulic head, a reduction in pore water pressure, and an increase in effective stress. This, in turn, leads to a reduction in inter-particle voids. The granular structure gets disrupted, particles move and rearrange, which macroscopically manifests as ground subsidence. This process precisely serves as the driving force and the fundamental reason for earth fissures caused by differential subsidence. The formation process of such earth fissures is the evolution of stress and strain from accumulation to dissipation. In this process, the superficial soil undergoes concealed fractures at stress concentration points, laying the structural foundation for the eventual formation of fissures.

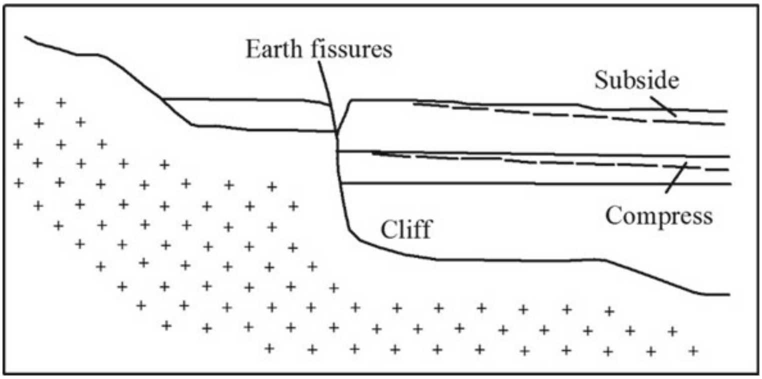


**Fig. 4.12** Brittle fracture mechanisms (Peng et al. 2012)

## 4.6 Coal Development and Earth Fissures

Many regions are endowed with rich coal reserves, primarily extracted through underground mining. As a result of prolonged and extensive coal extraction, numerous voids or "mined-out" areas are created, often leading to the formation of earth fissures. After the coal is extracted, an underground cavity emerges. In an attempt to reestablish a geological equilibrium, the subterranean strata undergo repositioning and redistribution. This realignment process induces various physical and chemical alterations. When the coal beneath the surface is depleted and these voids form, the overlying rock layers, influenced by gravitational forces, descend and move. This movement compresses and bends the rock strata, causing surface deformations, subsequently resulting in earth fissures. Fissures arising from coal extraction are categorized as non-tectonic origin fissures. Their occurrence has posed severe threats to the safety of mining operations. Underground coal seam mining, the formation of the air-mining zone is the main reason for the formation of earth fissures in coal mines, and the geometric characteristics of the earth fissures, such as the scale, width and depth of the cracks, depend on the depth and area of the air-mining zone, topography and geomorphology, stratigraphy, lithology, and other geologic and mine mining conditions.

Following coal extraction, the structural integrity of the mined-out voids primarily relies on their inherent strength and the support provided by safety pillars (often referred to as barrier pillars). When the void spans a substantial area and these safety pillars are subsequently mined, the overlying rock strata, under the influence of their own weight, will descend as a whole. This results in a progression from bottom to top characterized by a caving zone, a fissure zone, and a subsidence zone. Due to variances in subsidence speed and magnitude, surface depression basins are formed. Based on the stress conditions within these depression basins, they can be categorized into three zones: the central zone, the inner edge zone, and the outer edge zone (Fig. 4.13).

1. Central Zone (Intermediate zone in Fig. 4.13). The surface sinks uniformly, with the maximum rate and amplitude of subsidence, and there are no obvious earth fissures.
2. Inner Edge Zone. The surface sinks unevenly, tilts to the center of the basin, is concave, produces compressive deformation, the surface is squeezed, and there are no mechanical conditions for the generation of earth fissures.
3. Outer Edge Zone (Outer marginal zone in Fig. 4.13). The surface subsidence is uneven, tilted toward the center of the basin, but convex, producing tensile stress and forming tensile earth fissures.

Mining-induced collapse cracks are another form of earth fissure in the coal mine area, which are developed immediately above the mining area and are in the form of wide below and narrow above. Its development conditions are shallow burial of coal seams, small thickness of overlying rock body in the mining area, and the formation

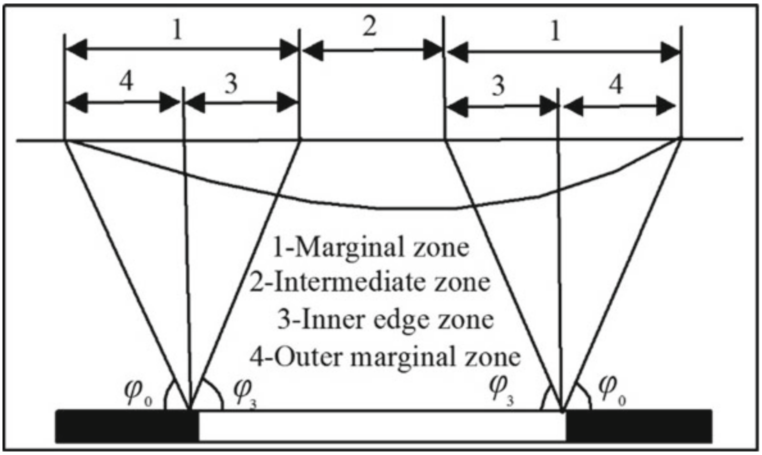


**Fig. 4.13** Diagram of sedimentary basin zoning (China Institute of Hydrogeology and Engineering Geology 1996)

of rift zones reaching the surface, and the spatial relationship with the earth fissures in the subsidence basin is shown in Fig. 4.14.

A common feature of both types of earth fissures is that they are tensile cracks formed under the influence of self-weight stress in the rock mass. Their distinctions lie in their morphological characteristics and the damages they cause. The latter's harm is primarily manifested in the changes to the geological environment, while the

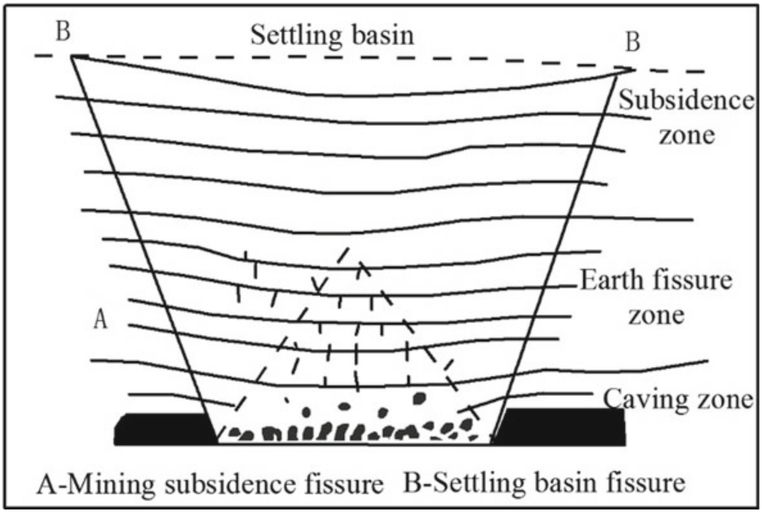


**Fig. 4.14** Diagram of overlying rock failure in goaf area (China Institute of Hydrogeology and Engineering Geology 1996)

former primarily affects and damages surface structures. These two types of earth fissures coexist and are often found together within coal mining areas.

## 4.7 Prevention and Control of Earth Fissures

### *4.7.1 Preventive Measures*

Earth fissure disasters predominantly occur within zones comprised of major fissures. All engineering projects and buildings that span these main fissures are at risk of damage. Investigations and research should be strengthened for naturally occurring earth fissures. Regional evaluations of areas prone to fissure occurrences should be conducted, prioritizing avoidance to either prevent or mitigate disaster losses. For earth fissures caused by human activities, the key lies in prevention, rational planning, and strict prohibition of unreasonable engineering activities near the fissures. The preventive measures that can be adopted are.

#### 4.7.1.1 Avoidance Measures

When carrying out development and construction in areas where tectonic earth fissures are prevalent, a detailed engineering geological survey should be the first step. This entails investigating the regional tectonics and the history of fault activities. It's essential to ascertain the fissure development zones and potential hazard areas in the proposed construction site. Urban development plans and rational layout of buildings should be crafted to ensure that engineering facilities avoid the earth fissure hazard zones as much as possible. It is especially crucial to strictly limit the construction of permanent facilities across these fissures.

For engineering facilities already constructed within the earth fissure hazard zones, reinforcement measures should be adopted based on the specific circumstances. For example, underground pipeline projects that span earth fissures can adopt measures such as external corridor isolation, internally suspended pipeline supports combined with active flexible joint connections to prevent damage from fissures. Facilities that have already suffered significant damage from earth fissures might require partial or complete demolition to prevent further extensive damage to the entire structure or neighboring buildings.

#### 4.7.1.2 Controlling the Inducing Effects of Human Factors

For non-tectonic earth fissures, measures can be taken to prevent or reduce their occurrence based on the reasons for their formation. For instance, engineering measures can be adopted to prevent collapses and landslides. The extraction of groundwater can be controlled to prevent and mitigate ground subsidence; for loess wet-collapse fissures, it's essential to prevent the infiltration and erosion caused by precipitation and the use of industrial and domestic water. During underground mining in mining areas, depending on the actual conditions, one should control the scope of mining, increase the number and size of reserved protective pillars to prevent mine collapses that may induce earth fissures.

#### 4.7.1.3 Monitoring and Forecasting Measures

Earth fissure activities can be monitored using methods such as surface exploration, ground deformation measurement, fault position measurement, audio-frequency magnetotelluric measurements, and high-resolution P-wave reflection measurements. This aids in predicting and forecasting the direction of fissure development, its rate, and the potential range of its impact.

### *4.7.2 Remedial Measures*

When designing specific remedial measures, different treatments should be applied to different types of earth fissures. With the current level of technology, it is impossible to completely prevent the occurrence of tectonic earth fissures. Therefore, the remediation of tectonic earth fissures mainly includes the fissure displacement method, partial demolition method, foundation reinforcement measures, and structural strengthening of the upper sections. Non-tectonic earth fissures, on the other hand, have various causes. Different remedial measures need to be adopted for non-tectonic earth fissures with different causes to achieve better disaster mitigation effects. The leading factors in the formation of non-tectonic earth fissures are surface soil conditions and the water environment, which are subject to local condition changes. Thus, the preventive and control strategies for non-tectonic earth fissures also have commonalities, primarily focused on eliminating the impacts of these local conditions. Measures that can be adopted for non-tectonic earth fissures include removing the weak foundation, localized inundation method, and compaction filling method. Detailed introductions are as follows.

#### 4.7.2.1 Fissure Displacement Method

The displacement method, as a special treatment for foundational soil, adopts the approach of using fissures to remedy fissures. The theoretical basis for this method lies in the principle that the extension of earth fissures also follows the path of least energy. By this approach, a trench can be excavated at the location where the earth fissure passes through or is predicted to pass, avoiding structures. This trench connects with the earth fissure, forming an "artificial fissure." This induces the tectonic fissure to develop along the "artificial fissure," severing the connection between the damaged building foundation and the tectonic earth fissure, thereby preventing further damage to the building.

#### 4.7.2.2 Partial Demolition Method

Zhang (1990) proposed the principle of "demolish part, retain the whole." For buildings situated directly across a tectonic earth fissure, the damaged parts can be demolished, effectively dividing one structure into two, thereby safeguarding the entire building from the influences or damages caused by the earth fissure. If it's a multistory building and only the ground floor is damaged, the affected ground floor can be demolished, disconnecting its foundation from the earth fissure. Reinforcement and support measures can then be applied to the upper levels, achieving a satisfactory disaster mitigation effect.

#### 4.7.2.3 Foundation Reinforcement and Structural Strengthening Measures

These measures are primarily designed for buildings that, due to site constraints, are situated within protective zones or cannot be relocated. For instance, for frame structures within the protective belts, their foundations can be designed with crossed foundational beams. If considering treatment for collapsible soil and using loess as the foundation, it's prudent to design it as a ribbed raft slab foundation. For standard residential buildings, a shallow embedded reinforced concrete ring beam foundation can be adopted. Along the direction parallel to the earth fissure, settlement (or contraction) joints can be installed to divide larger structures into simpler independent units.

#### 4.7.2.4 Removal of Unsuitable Foundations

This measure is a fundamental solution for mitigating non-tectonic earth fissures. Techniques such as excavation and soil replacement can be employed to completely remove problematic components from the building foundation, like expansive clays, soft soils, and backfilled soils. For broader and thicker layers of soft soil (like marine silt layers), other treatments such as dynamic compaction slurry displacement, sand well consolidation, and vacuum preloading drainage consolidation can be adopted.

#### 4.7.2.5 Localized Water Immersion Method

This method is suitable for collapsible loess foundations. By controlling localized water immersion, structures tilted due to earth fissures or surface subsidence can be realigned.

#### 4.7.2.6 Tamping Fill Method

This approach is applicable in areas where the development of earth fissures has stabilized. Backfilling and compaction are done along the direction of the earth fissure's propagation, followed by waterproofing treatments.

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