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Earth Fissures in Jiangsu Province, China and Geological Investigation of Hetang Earth Fissure

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Abstract

Earth fissures are a geohazard in Jiangsu Province, China. They can be caused by earthquakes and active faults, underground mining, groundwater extraction and landslides. In order to establish a provincial rehabilitation plan in Jiangsu, a range of monitoring programs, surveys, geological investigations and modeling have been implemented or planned. One of the focuses of the project is the land subsidence and earth fissures caused by excessive groundwater withdrawal in Suzhou, Wuxi and Changzhou (Su-Xi-Chang) area, southern Jiangsu province. Hetang earth fissure within the Su-Xi-Chang area was first reported in 1995 and a series of investigation has been conducted since then. The site investigations and geophysical survey in 1997 has recognized the causative factor as the excessive groundwater drawdown coupled by the underlying bedrock ridge. An open trench excavation in 2007 and a plane strain analysis suggest that Hetang earth fissures may have cracked from the bedrock ridge to ground surface. Geological drilling in 2007 has further confirmed the existence and configuration of the ridge and extracted soil samples for laboratory tests to obtain soil parameters for numerical analyses and modelling of land subsidence and earth fissures in the Su-Xi-Chang area, Jiangsu, China. The laboratory tests are currently in progress and the result of numerical analyses and modelling is expected to be presented in the near future.

Key words： Earthquake, Earth fissure, Landslide, Land subsidence, Groundwater withdrawal, Underground mining

1. Introduction

Earth fissures, or ground cracks, are a widespread geohazard in Jiangsu Province, China. They can be developed due to earthquakes, active faults, groundwater withdrawal, landslides, underground mining and change of physiochemical properties of soils/rocks. At present, the literature on earth fissures in Jiangsu Province is predominantly on those caused by groundwater withdrawal in southern Jiangsu Province (Zhu et al. 1993; Gao et al. 1997; Hu and Wu 1998; Chen et al. 2003; Yu et al. 2004; Zhang et al. 2007; Wang et al. 2008a). Earth fissures caused by other factors are less investigated. Recently, earth fissures in Xuzhou karst area (Wang et al. 2008a) and earth fissures in a gypsum mine in Nanjing after a mine flooding accident (Wang et al. 2008b) have been reported. This paper presents several types of earth fissures observed in Jiangsu Province, China and a case study of geological investigations of Hetang earth fissure in Jiangyin County, which is part of the Geological Investigation and Monitoring of Jiangsu Province Environmental Ecosystem project. The purpose of the project is to develop a provincial geohazard remediation plan in Jiangsu, China.

2. Geological and Environmental Background

Jiangsu Province is located in the coastal area of eastern China on the Great Yangtze Delta Region. Geologically, Jiangsu can be structurally divided into three plates, namely Yangtze Plate, Huabei Plate and Su-Lu Plate as shown in Fig. 1. Each of the plates has different geological settings. Pre-Quaternary strata, from Archaean Group to Neogene of Cenozoic Group, are distributed with spatial variations of different rock types. Quaternary strata, from Pleistocene to Holocene, are extensively presented as different clays and sandy soils with a varying degree of consolidation (Wang et al. 2008a). Mineralogically, there are many mineral resources, such as metalliferous and non-metalliferous deposits, coal, petroleum and natural gas, with varying degrees of exploitation that are highly associated with the market demand and the industrial scale. Jiangsu is densely populated and groundwater is an important resource for human consumption, agriculture and industry. In southern and central Jiangsu Province, there are four aquifers in the Quaternary: one unconfined aquifer and three confined aquifers that are denoted as CA1, 2 and 3, respectively (Wang et al. 2009), and groundwater extraction is mainly from CA2. In northern Jiangsu Province, groundwater may be extracted from the shallowly buried and fractured karst stratum (Wang et al. 2008a).

3. Earth Fissures in Jiangsu Province

There were 119 earth fissure zones with more than 600 fissures of a total length more than 80 km, involved in 36 counties in Jiangsu province (Gao et al. 1997). The occurrence has come to a climax since 1989 in the Su-Xi-Chang area, with an addition of 25 earth fissure zones between 1989 and 2005.

Earth fissures are commonly associated with other geogazards, such as earthquakes, land subsidence and landslides. There are many factors affecting the development of earth fissures, such as stratagraphical and hydrogeological heterogeneities of Quaternary sediments, geological anomalies of bedrock that include buried faults, scarps, ridges soluble rocks, the extent and intensity of human activities and weather conditions (Ayalew et al. 2004). In Jiangsu province, hydrogeological conditions are often related to groundwater decline and the subsequent subsidence (Chen et al. 2003; Zhang et al. 2007; Wang et al. 2009). Moreover, the immediate triggering factors are usually rainfall (Gao et al. 1997), earthquakes (Hu et al. 1997) and mining operations/accidents (Wang et al. 2008b).

A universal classification of earth fissures is yet to come in academia, however, the earth fissures impending a geohazard in Jiangsu Province can be broadly classified as earth fissures caused by earthquakes and active faults, earth fissures associated with land subsidence due to underground mining and groundwater withdrawal and earth fissures induced from landslides.

3.1 Earth Fissures caused by earthquakes and active faults in Jiangsu Province

The fissures caused by earthquakes and faults in Jiangsu Province are well recorded as tabulated in Table 1 and Table 2 for ancient and recent earthquake/fault earth fissures, respectively. This type of earth fissure may also be termed as tectonic earth fissure.

Table 1, Ancient earthquake related earth fissures in Jiangsu, China (Wang 2000)

Date	Location	General descriptions	Remarks
127 B.C.	Pei County	Land subsidence for several meters in depth	
4 August 1605	Huashan Mountains	Ground cracks with opens of 0.5 to 0.7 m.	
1633	Zhenjiang City	An earth fracture of more than 10 m long	
Autumn of 1638	Yizheng County	A ground crack of 10 m long and 1.0 m aperture	Many houses tilted and damaged.
1646	Dafeng County	Earth fissures	
1650	Suzhou, Zhenjiang, Zhenze and Qingpu	Earth fissures	
August 1689	Jinshan Bridge	Land subsidence with cracking sound and a 0.7 m sinkhole in diameter	
1850	Xixiao Mountains	A rock crack of several meters long and deep	Sound was heard as thunderclap.

Table 2, Recent earthquake related earth fissures in Jiangsu, China

Date	Location	General descriptions	Remarks
27 August	Suqian	Ground fractures of about 40 m	A villager's house was

1976	County	long and 20 mm aperture, in NNE direction.	damaged, and the groundwater level raised 2 m in a 46-meter-deep well. On 5 September 1976, the water table retreated (Wang 2000).
Early September 1976	Lishui County	An earth fissure of 200 m long	In May 1977, the Ms = 4.1 Baima Earthquake occurred 15 kilometers away (Gao et al. 1997).
9 July 1979	Liyang County	Two sets of earth fissures in the soil strata after the Ms = 6.0 Liyang Earthquake. The direction of one set of fissures was NE10°-20°, the other was NE35°, the aperture of fissures was 5 to 25 mm, the length was 20 to 130 m, the visible depth was about 2 m.	The earth fissures across a farmland and villages resulted in damages to the farmland and houses (Hu et al. 1997).
1982 and 1986, respectively	Xinyi County	Earth fissures	Damaged houses and endangered the living and working of the local community. They were

			caused by the activation of Tanlu Fault Zone (Li et al. 1988).

3.2 Earth Fissures due to Extractive Activities in Jiangsu Province

Land subsidence is a common phenomenon in extractive industries, such as groundwater, petroleum, natural gas and mining. In addition, earth fissures are also observed. In Jiangsu province, this type of earth fissures is widely spread in the areas of underground mining and groundwater pumping.

3.2.1 Earth Fissures caused by underground mining

The earth fissures caused by underground mining are distributed in Lianyungang, Xuzhou, Zhenjiang and Nanjing cities, where old mining workings are left unsupported. When the abandoned workings collapse, ground failure extends upward progressively to the ground surface, causing land subsidence and earth fissures. Depending on the overburden of the orebody, there are two types of mining related earth fissures in Jiangsu Province, namely exposed bedrock earth fissures and soil covered earth fissures.

The exposed bedrock earth fissures are associated with shallow underground mining, where the overburden rock is exposed at the ground surface. In this category are Jinping Phosphorite Mine, Meishan, Yeshan and Weigang Iron Ore Mines. Taking Jinping

Phosphorite Mine as an example, there are two groups of earth fissures in the mine area. Fig. 2 is a photograph of the exposed rock fissure at a cliff. At present, the closed old workings are at –50 m, -110 m, -170 m, -230 m, -290 m, -350 m and –470 m levels. The area of land subsidence is about 600 000 m^2 and appears like an ellipse on the ground surface. The subsidence trough is 1,650 to 2,100 m long and 30 to 600 m wide. Earth fissures are developed surrounding and crossing the trough. The length of earth fissures is from several to hundreds of meters, the opening is from several to 1,800 mm and the depth is from several to hundreds of meters. The interval of fissures varies greatly. The surfaces of fissures are typically smooth and straight, with a dip angle of 69°-87°. Clustered fissures are parallel to the longitudinal axis of the subsidence depression. The earth fissure zone is controlled by underground mining activities. The peak occurrence of earth fissures was between 2000 and 2001, during which a national heritage in the vicinity was affected in addition to destruction of houses, landslides and inflows of surface water into tunnels.

The soil covered earth fissures are associated with the land subsidence of underground coal mining, mainly distributed in Xuzhou region and scattered in Yixing and Jintan Counties. Land subsidence and earth fissures in Xuzhou are distributed in Jiuli, Jiawang and Tongshan districts and Pei County. The fissures are 10 to tens of meters in length and several to tens of millimeters in aperture. The directions of earth fissures are generally parallel to the long wall panel face, which is along the dip direction of the coal seam. The land subsidence and earth fissures have not only damaged farmlands, buildings and roads, but also jeopardized the environmental ecosystem as well as the urban development of

Xuzhou City. Based on a field investigation in 2001, earth fissures have occurred in 30 administrative villages, affecting 9,252 families and 3,3750 persons. During the rainy season, many houses collapsed and there was a casualty in 2000. Consequently, many villagers were forced to migrate. As the small coal mines were enforced to shut down in Jiawang district, local residents with some financial difficulty for migration may have to face some long-term challenges, such as geohazard and unemployment.

3.2.2 Earth Fissures due to Groundwater Withdrawal

Excessive groundwater withdrawing can lead to land subsidence and earth fissures. Not all land subsidence leads to earth fissures. Earth fissures under a regional land subsidence background are generally developed with differential subsidence. This may be contributed by heterogeneities of Quaternary sediments and anomalies of bedrock such as ridges, faults and scarps that are covered by Quaternary deposits. The compaction of the heterogeneous Quaternary over such bedrock structures may be uneven and result in fissuring.

In Jiangsu Province, the Su-Xi-Chang area is of the most serious land subsidence due to excessive groundwater extraction from the Quaternary aquifers (Chen et al. 2003; Zhang et al. 2007; Wang et al. 2009) as shown in Table 3. Furthermore, earth fissures are widely spread and scattered mainly in the west of Wuxi City, Jiangyin County and Wujin County. The first earth fissure was reported in 1989 at Henglin town, 18 km southeast of Changzhou City (Zhang et al. 2007). Earth fissures and house damages in Dongting

County, Wuxi City, have forced the terrified villagers to leave their houses since 1990 (Zhu et al. 1993). Between1994 and 1998, earth fissures occurred five times in the western area of Wuxi City (Hu and Wu 1998). The causative mechanisms of earth fissures in the Su-Xi-Chang area due to excessive groundwater extraction were summarized as bedrock ridges and cliffs, karst of shallow limestone and alteration of the Quaternary strata (Yu et al. 2004). Wang et al. (2008a) reported earth fissures triggered by excessive groundwater withdrawal and coupled by geological structures in Jiangsu Province. Specifically, the development of earth fissures due to groundwater extraction in Xuzhou City is highly associated with the development of karstic cavities and sinkholes and their distribution is controlled by an Ancient Yellow River fault with all the 17 sinkholes on the fault. On the other hand, in the rapidly developing Su-Xi-Chang area, groundwater is mainly pumped from CA2, which is distributed neither homogeneously nor isotropically. Coupled with the dramatic anomaly of the bedrock topography, such as an ancient Yangtze River course and bedrock hills, geological-structure-controlled differential settlement and earth fissures are prominent.

Table 3, Maximum land subsidence in Suzhou, Wuxi and Changzhou

Location	Maximum land subsidence
Suzhou City	1664 mm by 2001
Wuxi City	1924 mm by 2000
Changzhou City	1800 mm by 2002

3.3 Earth Fissures due to Landslides

Earth fissures are a key component of a landslide field survey. Tensile and shear earth fissures can be developed from landslides. Tensile fissures are mainly distributed in the rear of a sliding body, composing of several arch fissures, and shear fissures are on two lateral sides. Landslides are mainly distributed in Lianyungang, Xuyi, Zhenjiang and Nanjing in Jiangsu Province, where landslides occur about 100 times during the rainy season every year. Fig. 3 is a photograph of tensile fissures on the back of a sliding body in Yuntai Mountains. Important triggering factors for landslides may include unloading at slope toe, loading on slope, blasting and rainfall, which may either decrease the resisting force or increase the driving force or a combination of both, and which may reduce the shear strength of discontinuities as well, jeopardizing the slope stability.

4. Geological investigation of Hetang Earth Fissure

Hetang town is in southern Jiangyin County, Jiangsu Province, it is about 20 km north of Wuxi City and about 50 km east of Changzhou City. Hetang earth fissure was first observed in 1995 at a kindergarten (Wang et al. 2008a). Since then, a series of geological investigations, namely site investigation, geophysical survey, trench excavation and geological drilling, has been conducted to understand the causative mechanism and to develop an effective regional geohazard remediation plan.

To investigate the causative mechanism of Hetang earth fissure, site investigations were immediately organized right after the occurrence and a shallow seismic survey was conducted in 1997 along three lines as depicted in Fig. 4. The results of the site investigations and the shallow seismic survey (Wang et al. 2008a) are briefly summarized as following: The earth fissure trended at NE20°, gradually extended to the north and south and the development peaked in 1998. The earth fissure zone, comprising three fissures, was 500 m long and 60 m wide (Fig. 4). The northwest side of the fissure was offset downwards 50 to 150 mm with a maximum of 300 mm. The aperture of the fissure was 30 to 60 mm and the visible depth was 60 to 90 mm. Since it is located at an area of high density of buildings, the earth fissure has caused a severe damage to buildings and houses in the fissure zone. The direct economic loss is estimated at 1.5 million dollars. The bedrock topography revealed by the seismic survey indicates that there is a bedrock ridge underneath with a slope angle of 12 to 15° (Wang et al. 2008a).

To develop a geohazard rehabilitation plan in the fissure affected area in a provincial government sponsored campaign to tackle geohazards, further geological investigations were conducted at Hetang earth fissure in 2007. An open trench excavation was conducted on 11 September 2007. The trench is located at the southern part of the fissure zone, perpendicular to the fissure, e.g. striking at 110°. The trench is 2.0 m × 1.0 m × 1.8 m. The soil profile on the northern wall of the trench, from top downwards, is 0-10 mm concrete pavement, 10-70 mm mixed fill, 70-90 mm soil fill, 900-1200 mm grey silty clay and 1200-1800 mm grey-yellow clay.

The earth fissure was not apparent in the loose fill on the cross section in Fig.5. In the grey silty clay, the fissure of 1.0 mm aperture was visible. Further downwards, the interface between the silty clay and clay was clearly faulted by 100 mm with NW side downwards, and there was a shear zone of 20-50 mm wide where the soil was disturbed. Outside of the shear zone, there was no visible soil disturbance. The fissure within the trench was trended NE35°, dipping to the west of a dip angle 80° or steeper.

The groundwater level in the unconfined aquifer is very shallow; it was 1.0 m below the ground surface on 12 September 2007 in a well 20 m away from the excavation. Though the ground surface at the site is 500 mm higher than that at the well, the excavation was expected to encounter an inflow of groundwater. So during the excavation, there was a pause at the 1.5 m depth, then accelerated the excavation till 1.8 m deep. A small inflow from the fissure was observed at this level. As the excavation was within the clay layer, not reaching the water-bearing sand layer, it can be inferred that the clay layer is ruptured and the fissure becomes a channel to the aquifer.

Between 20 August 2007 and 10 September 2007, three geologic drill holes, denoted as ZK1, ZK2 and ZK3 in Fig. 6, were completed along No.1 Line of the shallow seismic survey in 1997 (see Fig. 4). The total drilling was 267.2 m, and the thickness of the Quaternary was 64.0 m, 111.9 m and 79.9 m at ZK1, ZK2 and ZK3, respectively. Soil samples were extracted at different levels from the drill holes for laboratory tests. The soil stratagraphy along the line is shown in Fig. 6. The geological cross section confirms the bedrock abnormality found in the shallow seismic survey (Wang et al. 2008a).

5. Discussion and analysis of Hetang earth fissure

Earth fissures due to groundwater withdrawal have been intensively studied. Two mechanisms have been predominantly employed to explain the earth fissuring under this circumstance, namely, differential subsidence (Bouwer 1977; Holzer and Pampeyan 1981; Wang et al. 2008a) and differential horizontal movement driven by hydraulic force (Lofgren 1978; Helm 1994), resulting from the consolidation of sediments in an aquifer system due to groundwater drawdown. Recently, to predict and simulate earth fissures, the consolidation and ground loss theories were employed to calculate the horizontal and vertical displacements of sediments over a sinusoidal basement to compute the land subsidence and location of earth fissuring (Rojas et al. 2002), and four conceptual models were presented to simulate the earth fissuring under groundwater deletion involving in multi-factors of differential horizontal and vertical displacements, in-situ stresses and preexisting structures (Sheng et al. 2003).

At Hetang earth fissure, there is a spatial correlation between the development of earth fissures and the ridge and slope of the underlying bedrock hill. The bedrock hill affects the stratum structure of the Quaternary aquifer system (Fig. 6). In this area, groundwater has been excessively extracted for a long period, so large differential settlement has been formed due to the consolidation of the sediments under the increased effective stresses from the groundwater drawdown. Tensile deformation can be developed in sediments overlying the bedrock ridge due to bending. Once the tension exceeds the limit of the tensile strain of soils, a fissure occurs. As the fissure is developed longitudinally along the bedrock ridge, the elastic deformation of the Quaternary sediments can be analysed under plane strain conditions governed by following equations.

$$\varepsilon_x = \frac{\partial u}{\partial x}; \varepsilon_y = \frac{\partial v}{\partial y}; \gamma_{xy} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \qquad (1)$$

where,

u = horizontal displacement, m;

v = vertical displacement, m;

ε_x = normal strain in horizontal direction;

ε_y = normal strain in vertical direction;

γ_{xy} = shear strain.

There is a well-established land subsidence station with multi-layered extensometers to monitor the strata compaction in Quaternary in Changzhou City, Jiangsu Province, China (Wang et al. 2009), which is about 50 km away from Hetang town. As there are similar geological and hydrogeological settings, the land subsidence at the site of Hetang earth fissure is estimated at 106 mm (Table 4) based on the strata compaction data from the Changzhou land subsidence station. Fig. 7 illustrates the dimension of the bedrock hill with reference to the bedrock level at the trough centre. Using equation 1 and data in Table 4 and Fig. 7, the plane strains at Hetang earth fissure are ε_x = 0.1%, ε_y = 0.2% and γ_{xy} = 0.4%. The calculated horizontal strain is in line with the observation that the tension strain required for the development of a crack generally ranges from 0.1% to 0.4% (Jachens and Holtzer 1980). This may suggests that the fissure is fully developed from the top of the ridge to the ground surface.

Table 4, Comparison of land subsidence at Hetang

	Site of Hetang earth fissure	Centre of local subsidence trough
Thickness of Quaternary deposits (m)	64	141
Land subsidence (mm)	106 (estimated)	1310 (measured)
Differential subsidence (mm)	1204	

6. Conclusion

Earth fissures as a geohazard observed in Jiangsu Province, China can be caused by earthquakes and active faults, industrial activities in particular underground mining and groundwater pumping, and landslides in mountains. Currently, a great effort is made to understand the mechanism in order to establish a provincial geohazard rehabilitation plan. This includes a range of monitoring programs, surveys, geological investigations and modeling funded by both provincial and national governments. One of the focuses is the land subsidence and earth fissures caused by excessive groundwater extraction in the

Su-Xi-Chang area, southern Jiangsu Province.

The geological investigations of Hetang earth fissure in the Su-Xi-Chang area have been conducted under this context. Early site investigations and geophysical survey were conducted in 1997 and identified that the causative factor is the excessive groundwater drawdown coupled by the underlying bedrock ridge (Wang et al. 2008a). From the geological investigations in 2007, the open trench excavation and the plane strain analysis suggest that Hetang earth fissures may have cracked from the ridge to the ground surface; the geological drilling has confirmed the existence of the bedrock ridge and provided soil samples for laboratory tests to obtain soil parameters for numerical analyses and modelling.

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Figure Captions

Fig. 1 Geological sketch map of Jiangsu Province, China (after Wang et al. 2008a)

Fig.2 Exposed rock fissure at Jinping Phosphate Mine

Fig. 3 Yuntai landslide rear fissure

(Colour in web publication and black and white in printed publication)

Fig. 4 Distribution of earth fissures at Hetang (after Wang et al. 2008a)

(Colour in web publication and black and white in printed publication)

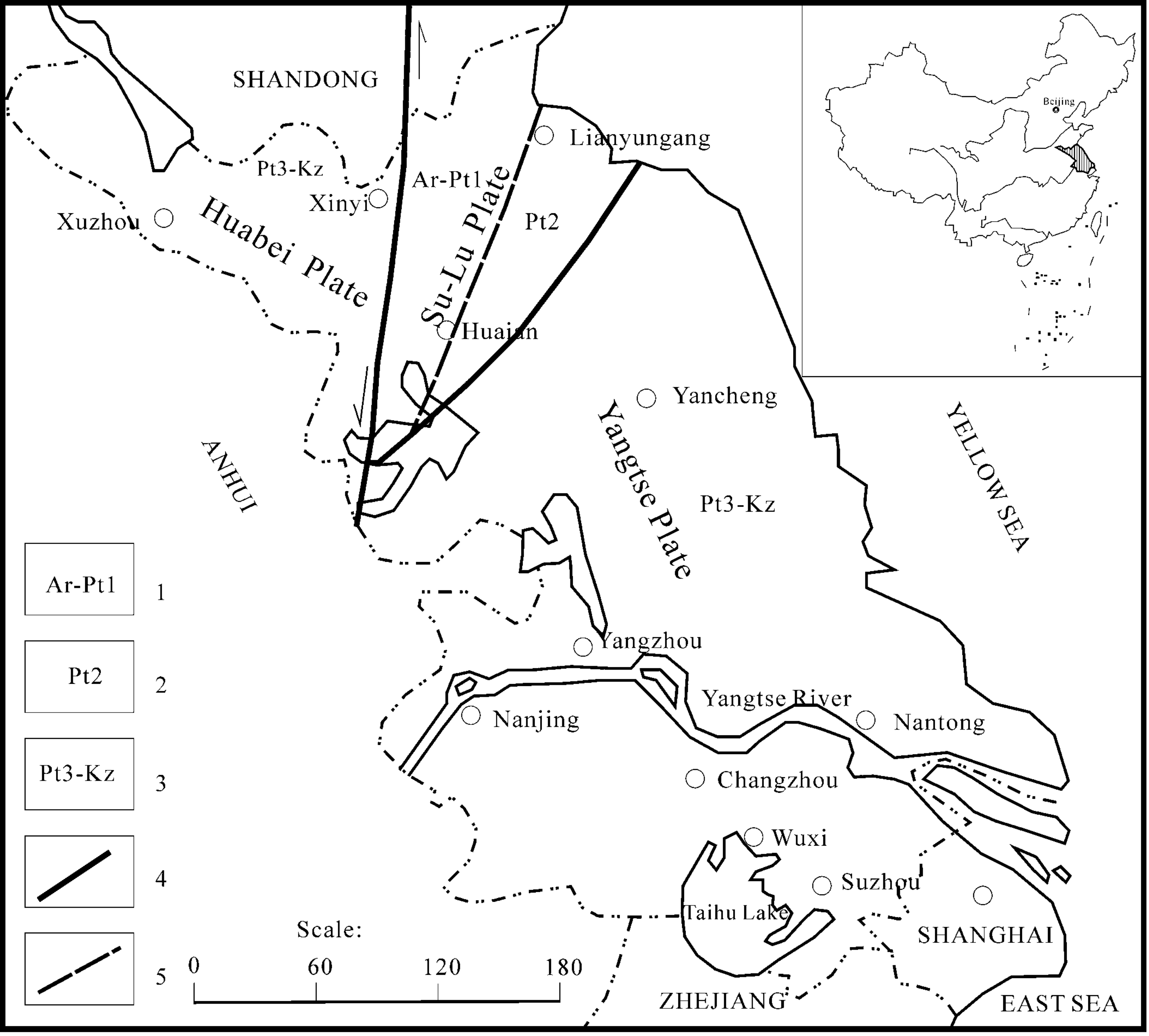
Fig. 5 Cross section of the open trench excavation of Hetang Earth Fissure

Fig.6 Geological cross section of Hetang Earth Fissure

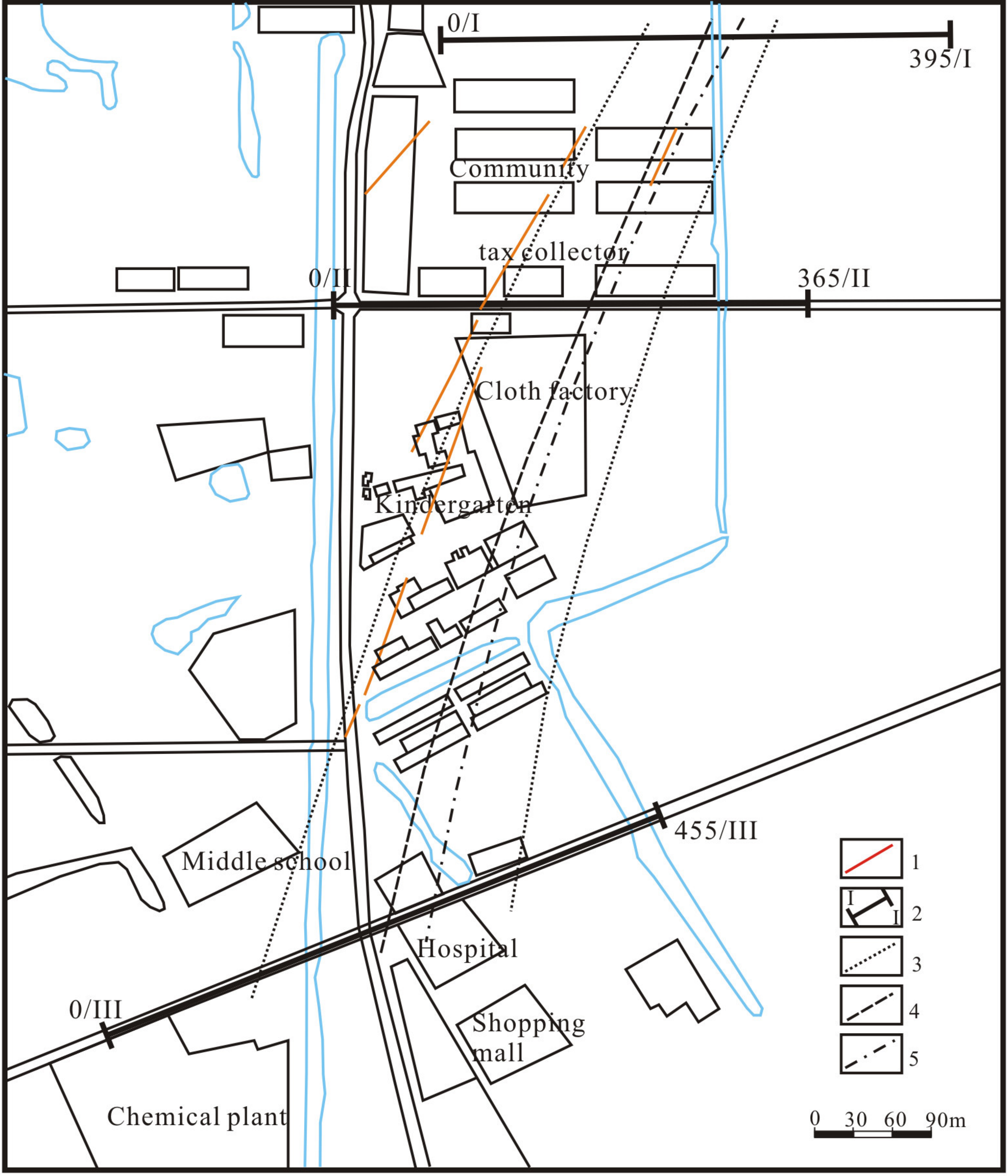
(1) Silty clay with ferro-manganese concretion, grayish yellow, tawny, wet
(2) Silty clay with silt seam containing mica, grayish yellow, wet, soft
(3) silty sand containing mica and shell fragments, gray, medium dense
(4) Silty clay with ferro-manganese concretion, gray, grayish yellow, tawny, wet, stiff
(5) Silty sand containing mica and calcium lump, grayish yellow, wet, medium dense
(6) Silty clay with ferro-manganese concretion, yellowish gray, tawny, wet
(7) silty clay with silt and silty sand seams, yellowish gray, gray, wet, soft
(8) clay with ferro-manganese concretion and lump, tawny, grayish yellow, wet, stiff
(9) Silty clay with silt seam, yellowish gray, wet
(10) Silty clay containing calcareous concretion and lump, tawny, wet
(11) Silt with silty clay seam, medium dense
(12) Silty clay with calcareous concretion, gray, wet, soft
(13) Silty sand and silt, grayish yellow, gray, medium dense
(14) Silty clay with ferro-manganese and calcareous concretion, brown, yellowish gray, wet, stiff
(15) Clay and silty clay containing slime and calcareous concretion, yellowish gray, gray, wet, stiff
(16) Silt with silty clay, gray, wet, dense and stiff

(17) Fine and medium sand, gray, saturated, dense
(18) Silty clay interbedded with silt and silty sand, gray, soft
(19) Silty and fine sand, grayish yellow, wet, medium dense
(20) Medium to coarse sand and gravel, wet, medium dense

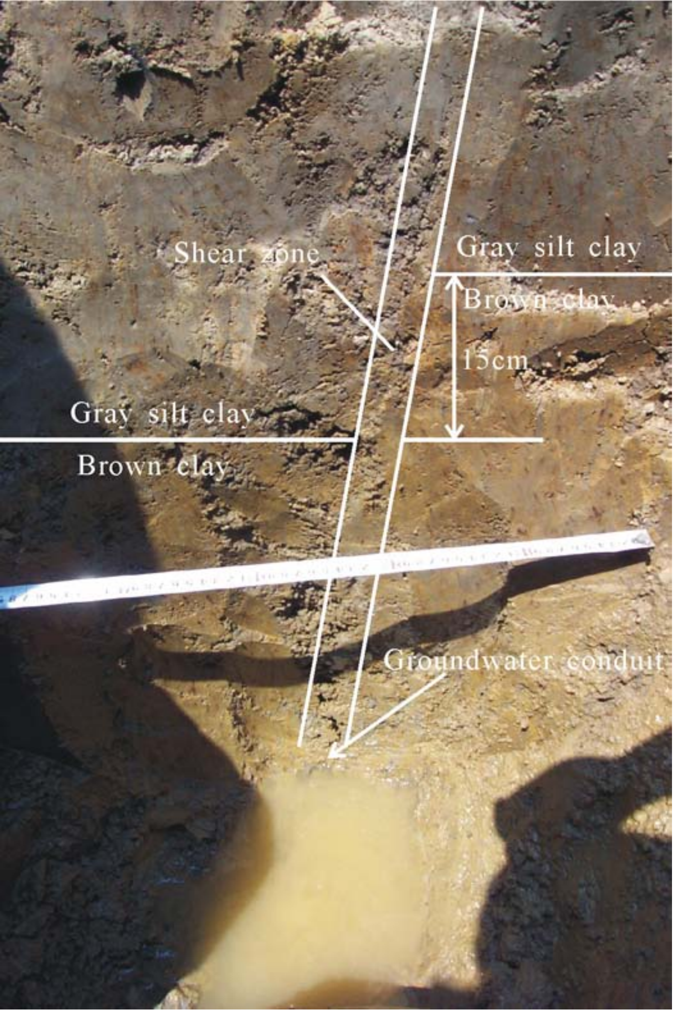
Fig. 7 Deformation analysis of the Quaternary sediments over a bedrock slope

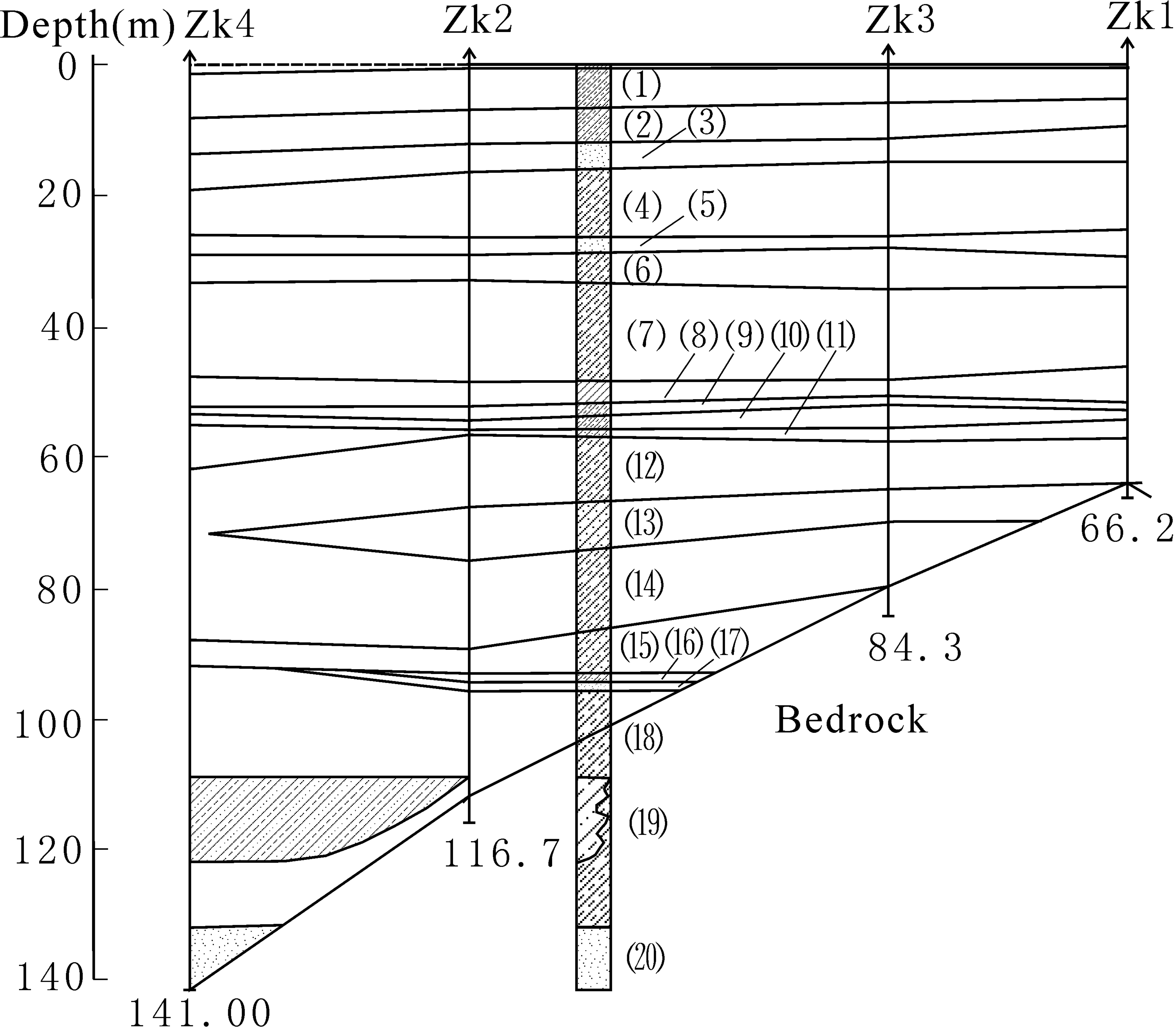


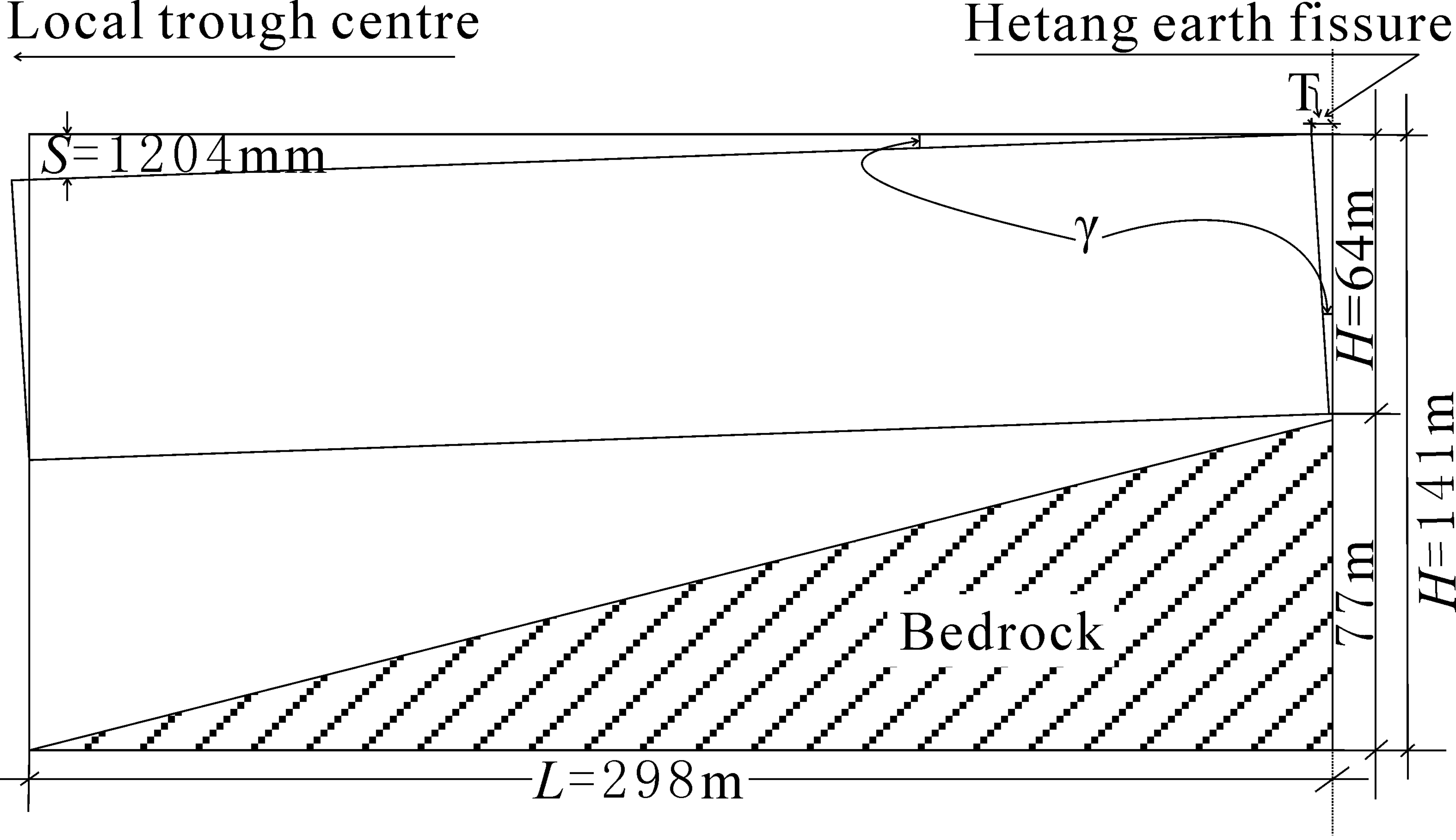
1, Archaean-Old Proterozoic; 2, Middle Proterozoic;
3, New Proterozoic -Cenozoic; 4, Plate Boundary Fault; 5, Fault.



1, earth fissures; 2, seismic reflection line; 3, steep edge of bedrock hill; 4, center line of the bedrock hill; 5,top line of the bedrock hill


Shear zone
Gray silt clay
Brown clay
15cm
Gray silt clay
Brown clay
Groundwater conduit


Depth(m)
Zk4
Zk2
Zk3
Zk1
0
20
40
60
80
100
120
140
(1)
(2) (3)
(4) (5)
(6)
(7) (8) (9) (10) (11)
(12)
(13)
(14)
(15) (16) (17)
(18)
(19)
(20)
66.2
84.3
116.7
141.00
Bedrock



Local trough centre
Hetang earth fissure
T
S=1204mm
γ
H=64m
H=141m
77m
Bedrock
L=298m