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ORIGINAL ARTICLE

Characteristics of land subsidence, earth fissures and related disaster chain effects with respect to urban hazards in Xi'an, China

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Abstract The ancient capital of Xi'an is a typical city in China with a shortage of water resources. With an urban population of 7 million, its domestic and industrial use of water depends almost entirely on groundwater. Large-scale long-term extraction of groundwater has caused severe land subsidence and triggered the reactivation of active normal faults in the Quaternary under-consolidated sediments underlying the city. This has further led to ground ruptures that have gradually evolved into earth fissure zones. During this process, there has been a close spatiotemporal relationship between land subsidence and the formation of earth fissures. From field monitoring data, the subsidence bowls are typically located in loess depressions between earth fissure zones within structural blocks of sediment cut by active Quaternary faults and preexisting fault planes. The subsidence bowls are generally elliptical in shape, with the long axes consistent with the preferred orientation of the earth fissures. The underlying Quaternary active faults and preexisting fault planes predispose the intervening sediment blocks to formation of earth fissures, and intense groundwater extraction has led to accelerated subsidence and earth fissuring during the past 50 years. Mining groundwater, land subsidence and earth fissures occur in a sequence and constitute a disaster chain with respect to urban hazards in Xi'an. Thus, it is important to understand the relationships between these events. This paper summarizes the characteristics of land subsidence and earth fissures in Xi'an and discusses the chain of relationships that connects them.

Keywords Land subsidence · Earth fissure · Groundwater extraction · Disaster chain · Xi'an City

Introduction

The Wei River Basin is one of the most water resource-deficient areas in northwest China. Xi'an, located in the middle of the Wei River basin, is bounded by the Chan and Ba Rivers to the east and the Jv River to the west, and to the north and south by the Wei River and the Qinling Mountains, respectively. Owing to its rapid economic development, Xi'an's requirements for water resources have increased significantly, but there are insufficient surface water resources to satisfy domestic and industrial requirements. Consequently, the city's water sources have depended heavily on groundwater for a long time, such that the groundwater has been over-exploited for more than 50 years. Long-term intense groundwater extraction has caused severe land subsidence and triggered the formation of earth fissures in Xi'an. The maximum subsidence has reached approximately 3 m, with 14 earth fissures having been discovered. Land subsidence and earth fissures have caused substantial damage to buildings, metro railways, municipal pipelines, roads, bridges and other infrastructure (inset, Fig. 1), with huge attendant economic losses

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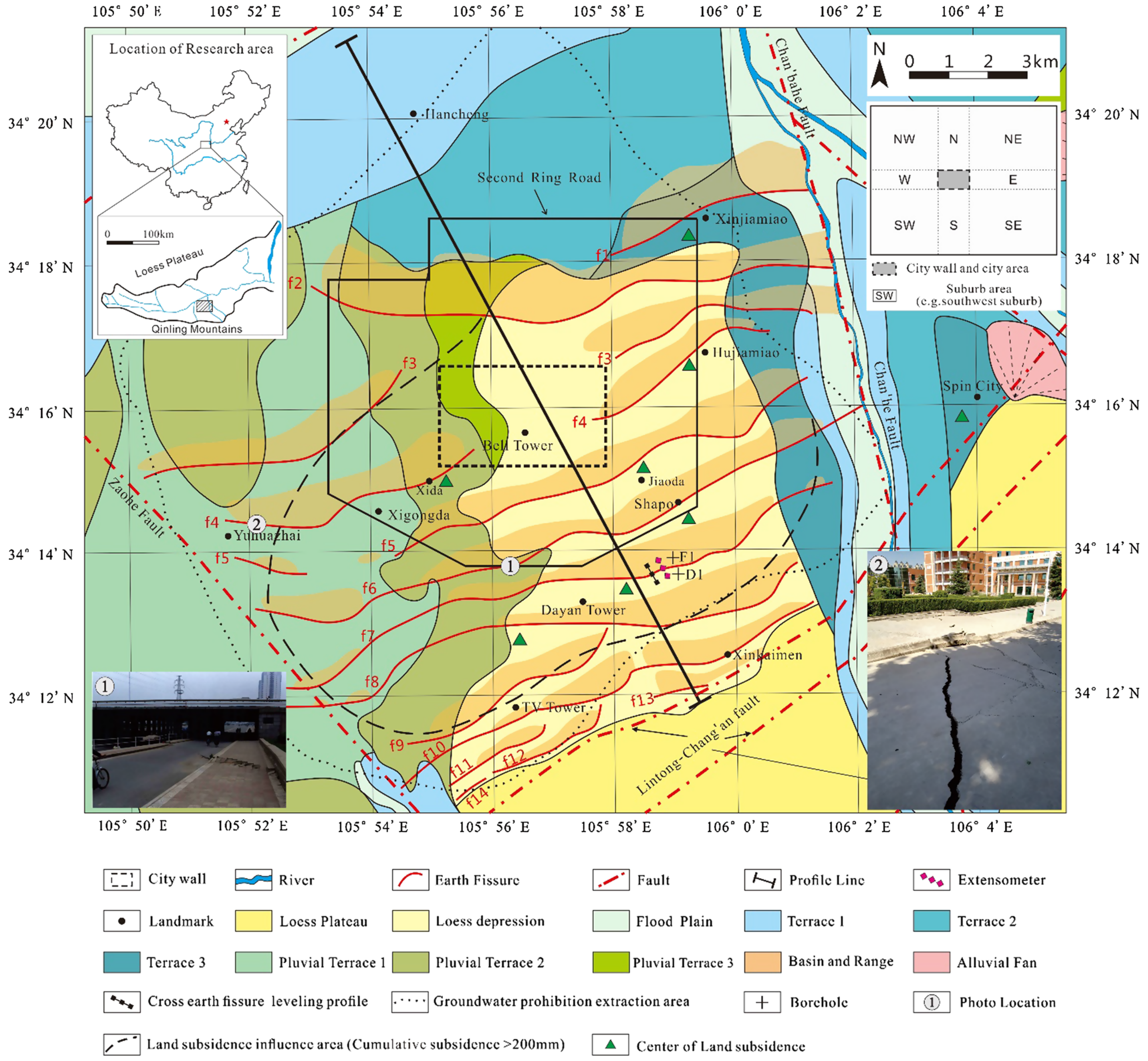


Fig. 1 Map of the Quaternary geology of Xi'an. The map shows the locations of earth fissures, land subsidence areas and extensometer groups. The profile in this map is shown in Fig. 2. *Inset on the left top* shows the location of the study area relative to China and the Wei River Basin. The *inset at the top right* shows the limit of city and suburbs. The *inset at the bottom right* is a photograph of a playground at Xi'an International University near Yuhuazhai, which has been damaged by the f4 earth fissure. The *inset at the bottom left* is the Second Ring Road, which has been damaged by the f6 earth fissure in the south suburb

(Hyndman and Hyndman 2014; Peng et al. 2013; Wu and Chen 2002).

Land subsidence and earth fissures have occurred in other cities in China, as well as in other countries. Many areas, such as the southwest USA, Mexico, Libya, Saudi Arabia, Greece, and the Fenwei basin, North Plain and the Southern Yangtze Delta of China have all experienced these two geohazards (Bankher and Al-Harthi 1999; China Geological Survey 2015; El Baruni 1994; Holzer 1976; Holzer et al. 1979; Kontogianni et al. 2007; Li et al. 2000; Pacheco-Martínez et al. 2013; Raspini et al. 2013; Xue and Zhang 2016). The significant damages caused by earth fissures and land subsidence are major geological engineering concerns for geoscientists.

Earth fissuring is a geological process with a multiplicity of possible origins and has been studied by many scholars. In the 1920s, many earth fissures were found in tectonic valleys in the southwest USA such as in Arizona, California and Nevada (Galloway et al. 1999). Based on the evidence that those valleys were experiencing strong

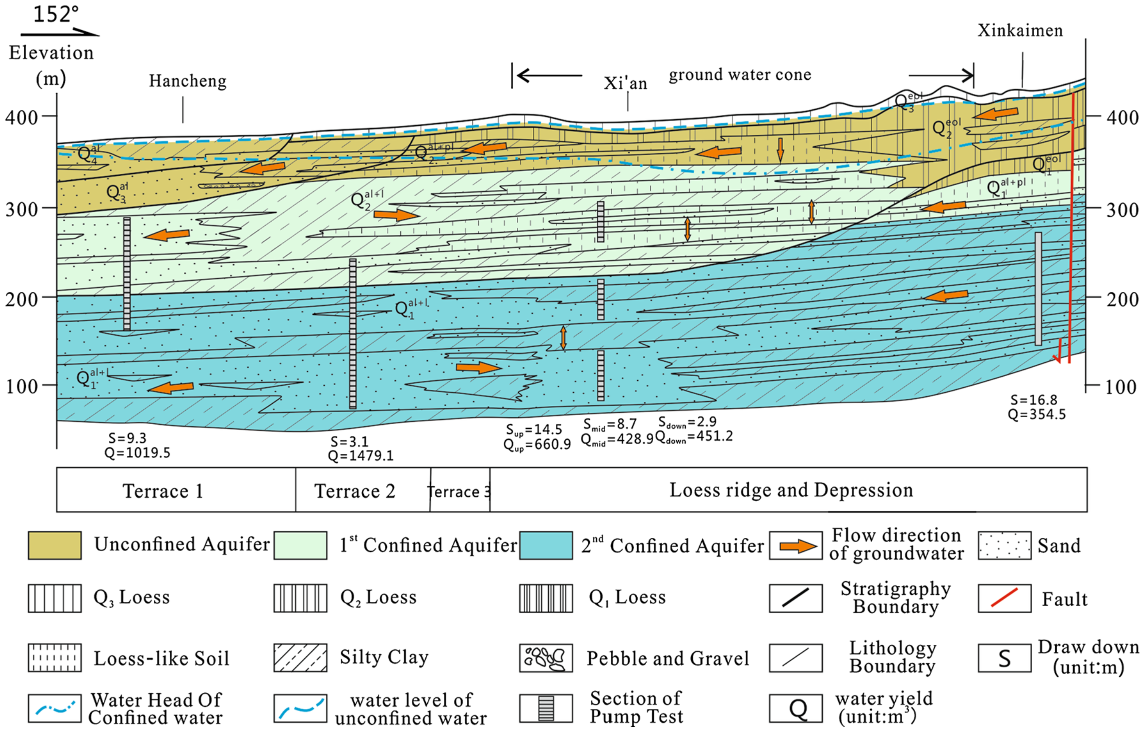


Fig. 2 Hydrostratigraphy along a profile (marked in Fig. 1) through Xi'an. The aquifer structure of Xi'an can be divided into three parts: an unconfined aquifer and two confined aquifers above 300 m depth. The confining layer varies in thickness and has a discontinuous distribution and is therefore not shown in this figure

neotectonic movement, some scholars proposed a tectonic origin mechanism for earth fissure formation (Leonard 1929). Later, it was noticed that earth fissures usually occur in arid or semi-arid areas. The long-term exploitation of groundwater in these areas leads to a widespread decline in the groundwater level and accompanying land subsidence. Some scholars have thus proposed a groundwater withdrawal mechanism for earth fissure formation (Adiyaman 2012; Sheng 1996). To this day, there remain various mechanisms and hypotheses for different aspects of earth fissure formation, but it is mostly accepted that earth fissures are influenced by extraction of groundwater to some degree (Budhu and Shelke 2008; Burbey 2010; Carpenter 1993; Helm 1994; Hernandez-Marin 2009; Holzer and Pampeyan 1981; Jachens and Holzer 1982; Rothenburg et al. 1995). Fletcher et al. (1954) proposed a seepage deformation mechanism. According to this mechanism, seepage forces in the groundwater drawdown cone increase with rising in hydraulic gradient, resulting in potential seepage erosion that loosens the soil structure and concentrates tensile stress in the soil, finally resulting in a fracture. Schumann and Poland (1969) proposed a localized difference compaction mechanism to explain how earth fissures occur in alluvium over bedrock scarps. Finally, Bouwer (1977) proposed a hypothesis of rotation of a rigid slab of alluvium around the edge of a buried fault.

Study of the earth fissures at Xi'an in China began in the mid-1970s. Because of the lack of long-term observation data, studies have mainly been qualitative for most of this long period. Thus, various hypotheses for earth fissure formation were developed during this period. These originating mechanisms can be grouped into three classes: tectonic, land subsidence, and composite. Each of these three classes can be further subdivided. For example, tectonic mechanisms include block oblique lift (Zhang 1990), gravity tectonic extension (Wang 2004), concealed fault creep (Liu, 1986; Wang 2000), and main faults stretching (Peng et al. 1992). Despite each study supporting different summarization modes, most researchers believe that earth fissures in Xi'an are directly controlled by the activity of the Lintong–Chang'an fault. Tectonic origin mechanisms can well explain the sub-parallel distribution and equal spacing of the Xi'an earth fissures, but have difficulty in explaining the high rate of earth fissure activity and associated relationship with land subsidence. The land subsidence mechanisms are similar to the groundwater mechanism in southwest USA. This type of mechanism hypothesizes that excessive extraction of groundwater is the controlling factor behind the origin and development of earth fissures. Land subsidence mechanisms explain the high activity of the earth fissures in Xi'an very well, but do not provide any support for the sub-parallel distribution and equal spacing of its earth fissures (Peng 2012).

Since the early 1990s and the widespread use of GPS, InSAR technology and further accumulation of hydrogeological and geological monitoring data, researchers have achieved a more profound understanding of earth fissures and have proposed the composite origin mechanism. This type of mechanism assumes that, although land subsidence and earth fissures do show a clear relationship, the largest earth fissures are significantly controlled by the underlying geological structure. Thus, earth fissures result from a combination of groundwater withdrawal and tectonics (Peng 2012). This combined mechanism has been verified by a significant amount of monitoring data and can well explain the earth fissure formation process and is supported by most researchers. However, there are still some critical problems that have not yet been solved for the composite origin mechanism (Peng et al. 2007), such as the specific roles played by tectonics and groundwater and the sequence of earth fissure development. The aim of this study is to summarize the characteristics of land subsidence and earth fissures and discuss the chain relationship between these events based on field data. This work will provide a reference for people seeking to prevent and control these two geohazards in the coming years.

Geological background

The city of Xi'an is located in the middle part of the Wei River depression basin, which is to the north of the Qinling Mountains and south of the Loess Plateau (Fig. 1). The complex geological setting profoundly controls the characteristics of land subsidence and subsequent earth fissures in the area.

Landforms

Xi'an has an undulating ground surface, with the overall terrain gradually inclined from the southeast to the northwest, and the landforms gradually shifting from loess tableland terraces to a flood plain. The tableland is in the southeast of Xi'an, with thick Quaternary eolian loess accumulation. Terrace 1 (Fig. 1) is in the north of Xi'an and has a thick deposit of Holocene alluvial sediments, which are mainly composed of medium-fine sand or medium-coarse sand and thin clay interbeds. Terrace 2 (Fig. 1) and higher terraces are mainly composed of Pleistocene sandy-clay and pebbly sediments covered by loess. Xi'an has a developed basin and range landform, which has caused the engineering geological conditions to exhibit banded inhomogeneity.

Tectonics

The Wei River Basin, which is part of the Fenwei Basin, was under a tensional stress field with a NNW–SSE orientation during the Himalaya period. The basin and its edge have developed a series of normal faults. There are several active faults around the Xi'an land subsidence area, including the Lintong–Chang'an fault, the Chan River fault, the Ba River fault and the Wei River fault, as well as their secondary faults. The primary faults—the Lintong–Chang'an fault and the Wei River fault—mainly trend ENE. The former dip NNW and the latter dip SSE, forming a graben structure. Xi'an is located in the common hanging wall of the two normal faults. Thus, the activity of these faults directly results in overall slow subsidence of the region around Xi'an. On the basis of the Quaternary sediment accumulation rates and precision leveling results, the movement rate for the normal faults is about 3–4 mm/a, although subsidence reached 100 mm/a in the Yuhuazhai area in the southwest suburb in the 1990s. There is, therefore, a large discrepancy between the tectonic subsidence rate and the total subsidence rate experienced in the region. This difference indicates that the natural tectonic subsidence caused by neotectonic movement is not the primary cause of subsidence in the area and can be ignored for the research period.

Lithology

Quaternary deposits occur widely, with a maximum thickness of more than 700 m. The thickness of these deposits increases from southeast to northwest. The stratums related to groundwater exploitation and land subsidence are mainly located above a depth of 300 m and consist of three layers from top to bottom (Fig. 2). The engineering geological properties of each layer are significantly different. The superficial layer (15–30 m) is Upper Pleistocene loess. The loess is loose, and vertical joints are developed. The normally consolidated soils have a void ratio of more than 0.7 and a coefficient of compressibility of 0.2–0.45 MPa^{-1}, and hence they are regarded as medium–high compressibility soils. The middle layer in the deposit (30–130 m) is Middle-Pleistocene fluvial and lacustrine strata, which are mainly composed of thin silt clay and silt, have a void ratio of 0.7–0.9 and a coefficient of compressibility of 0.1–0.32 MPa^{-1}. The lowest layer (below 130 m) is thick Lower Pleistocene fluvial strata composed of gravel and cohesive soil interbeds possessing a void ratio ranging from 0.5 to 0.8 and coefficient of compressibility ranging from 0.1 to 0.13 MPa^{-1}. The above test data from borehole samples indicate that the compressibility of the upper strata is highest, the compressibility of the lowest strata is lowest, and the compressibility of the middle layer is intermediate between the values of the top and bottom layers. The compaction of each soil layer is caused, not only to its compressibility, but also the thickness and pore pressure within the layer.

Hydrogeology

The thick, saturated Quaternary sediments in the Xi'an area constitute a rich groundwater system that can be divided into three aquifers: an upper unconfined aquifer (depth range of less than about 100 m); a middle confined aquifer (depth range approximately 100–300 m); and a lower confined aquifer (deeper than about 300, also called deep confined aquifer).

The unconfined aquifer in the subsidence area is mainly composed of loess, loess-like soil and sand. Because of the thinness of the aquifer and its heavy contamination, the unconfined aquifer is used only for irrigation and afforestation in Xi'an.

The middle confined aquifers can be subdivided into the first and second confined aquifers from top to bottom of the profile shown in Fig. 2. The first and second confined aquifers are widely distributed and are mainly composed of fluvial and alluvial deposits. The sediments of the first and second confined aquifers are mainly medium-grain sand and sandy gravel. The first and second confined aquifers are separated by the first confining layer, which is composed of clay and silty clay deposits. Compared with the unconfined aquifer, the middle confined aquifers are thick and less contaminated, so they are the primary exploited aquifers. To increase groundwater yield and reduce cost, most pumping wells in Xi'an are multi-aquifer wells which penetrated first and second confined aquifers. The numerous multi-aquifer wells established direct hydraulic link between two confined aquifers and result in the head in each aquifer almost the same. Before groundwater exploitation was restricted or prohibited in 1996, 75–82 % of the total amount of water pumped from the groundwater system was produced from the middle confined aquifers.

The deep confined aquifer is separated from the middle confined aquifer by the second confining layer. The deep confined aquifer is scarcely exploited because of the poor water quality and high cost of pumping, thus the exploitation in deep confined aquifer has little effect on land subsidence.

Characteristics of land subsidence

Groundwater extraction and development of land subsidence

The history of groundwater extraction in Xi'an can be generalized into three stages on the basis of the pumpage (Fig. 3): the origin stage (before 1970); the increasing stage (1971–1997); and the decreasing stage (after 1997). The origin stage was the early period of groundwater extraction in the region. Because of the small amount of pumpage, extensive groundwater drawdown cones did not exist until 1968 (Fig. 4a). After 1970, groundwater pumpage gradually increased from year to year, resulting in a sharp drop in confined groundwater levels and expansion of drawdown cones. Historical maps of the confined groundwater-level contours (Fig. 4b–d)indicate that the extent of the 350-m contours continued to expand with the increasing pumpage. In 1978, the 350-m drawdown cones were in three isolated sites (Fig. 4b). However, the cones continued to extend

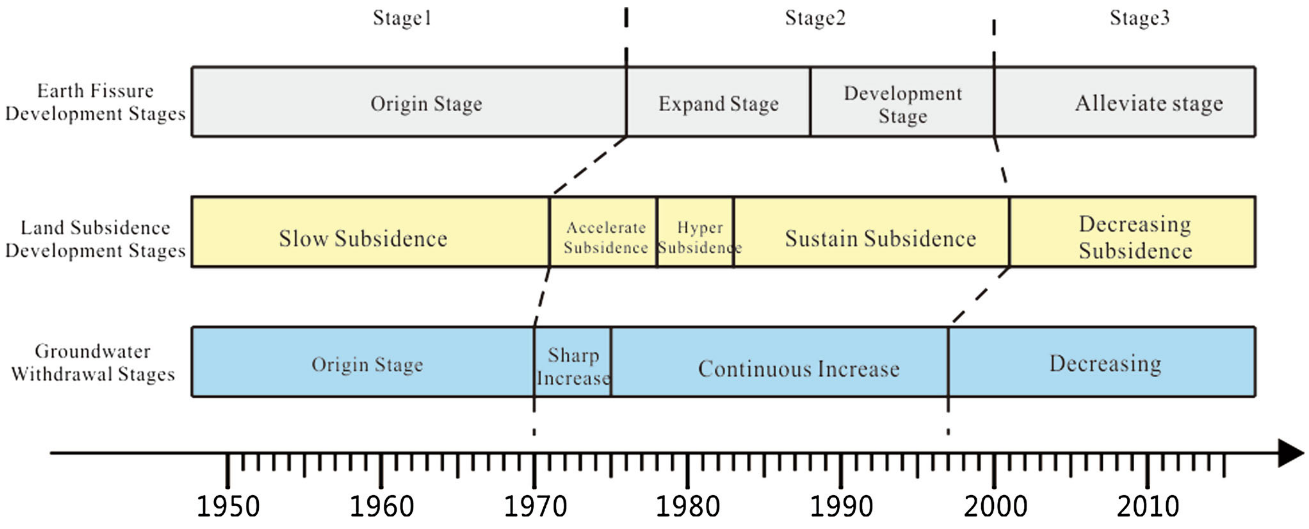


Fig. 3 History of groundwater extraction, land subsidence and earth fissures in the Xi'an region

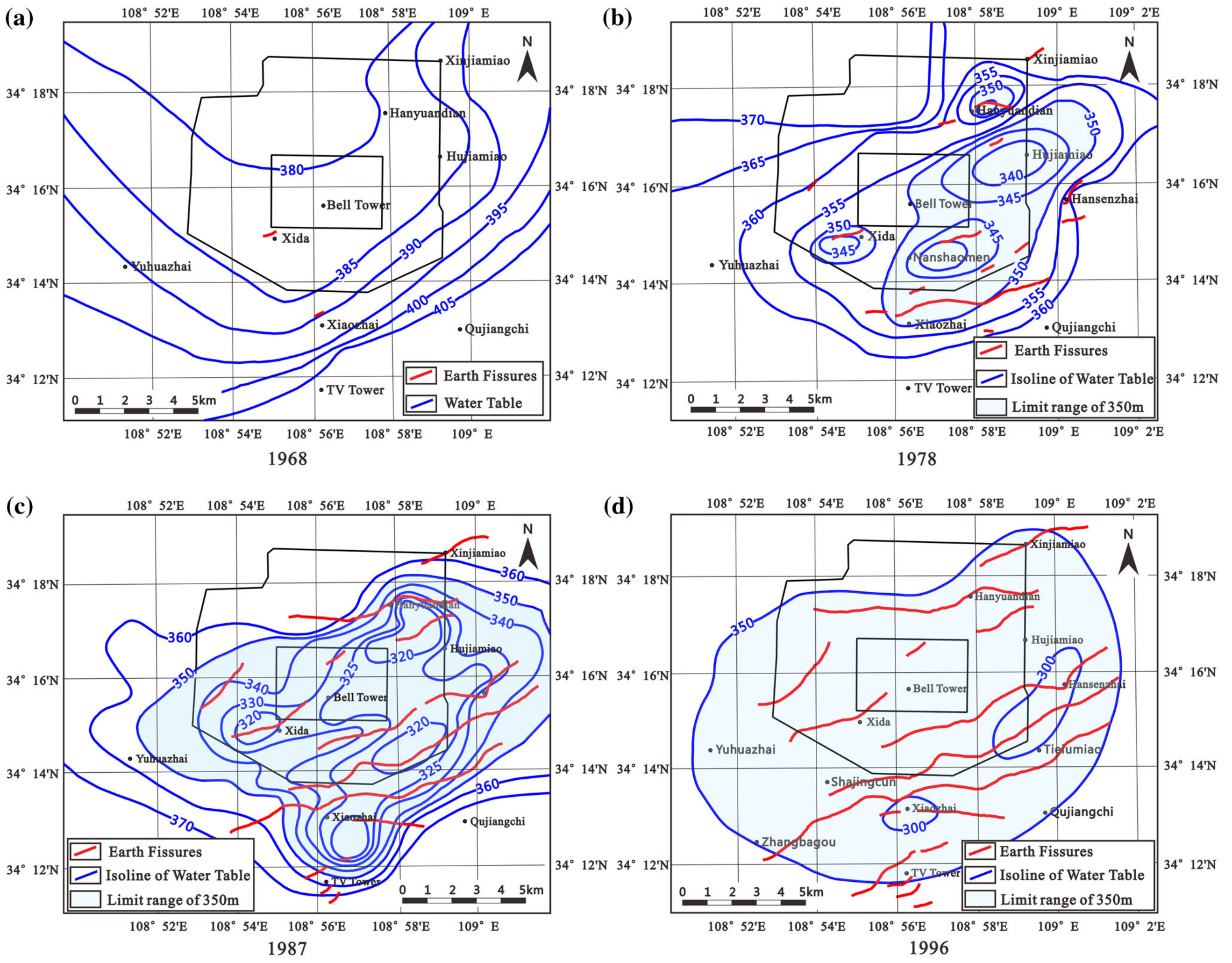


Fig. 4 Distribution of earth fissures and contours of confined groundwater level (altitude in meters, the reference datum used is WGS-84) between 1968 and 1996: **a** 1968, **b** 1978, **c** 1987 and **d** 1996

(Fig. 4c), with all of them joining together and forming a single drawdown cone by 1987 (Lee et al. 1996).

To prevent continuous decreases of groundwater levels and to mitigate land subsidence, the Hei River Reservoir was put into production in 1997 to deliver water to the urban area. The Xi'an government also issued a series of resolutions in 1998 to prohibit or restrict groundwater extraction in urban and suburban areas in the region. The availability of the additional surface water and the new restrictions on groundwater extraction led to a substantial reduction in groundwater pumpage. Compared with previous years, the amount of water withdrawal from the confined aquifers dropped to approximately 68 % in 2000 and 59 % in 2005. Figure 5 shows groundwater-level hydrographs of some typical monitoring wells in Xi'an. It is obvious that the groundwater level in most areas of Xi'an rose rapidly after 1997 with implementation of the new measures.

Areal and temporal characteristics of land subsidence

Land subsidence in Xi'an was first discovered in the 1960s by a citywide level survey. During its development, land subsidence generally followed the stages of groundwater extraction in the region. Based on field data, the land subsidence can also be divided into three stages on the basis of the subsidence rate (Fig. 3): a slow subsidence stage (before 1970); a strong (accelerated, hyper and sustained) subsidence stage (1971–2001); and a decreasing subsidence stage (after 2001). The land subsidence trends are consistent with the trends in groundwater extraction, with the changes in groundwater pumpage and fluctuations in groundwater levels resulting in different characteristics of subsidence in each stage. The distribution of the subsidence bowls coincides with the locations of the cones of depression (Figs. 4, 6), further emphasizing the close

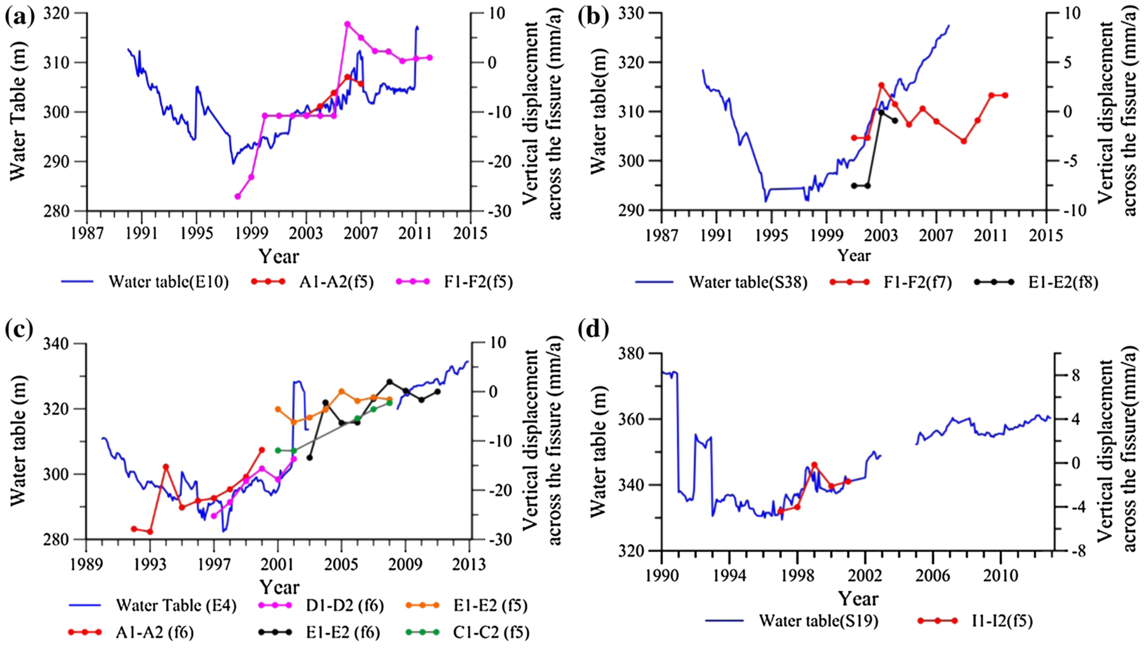


Fig. 5 Hydrographs of groundwater levels in confined aquifers and the vertical displacement rate across the earth fissure at four selected sites in Xi'an: **a** the Fuli district of Xiguangchang in the east suburb; **b** the finance and economics college in Xiaozhai in the south suburb; **c** Jiaodaercun in the southeast suburb and **d** the site known as Mailbox 90 in the southwest suburb. *Each curve* shows a sudden rise in groundwater level after 1997 and a generally good relationship between earth fissure movement and groundwater level fluctuations in Xi'an. The location of each earth fissure and groundwater monitoring point is indicated in Fig. 7

relationship between land subsidence and groundwater extraction in both time and space.

In the slow subsidence stage, the average rate of land subsidence was only 2 mm/a, with a maximum cumulative subsidence of less than 100 mm. During this period, four land subsidence bowls were formed. In the strong subsidence stage, both the area and the rate of subsidence increased significantly compared with the previous stage, with the rate of subsidence staying at a high level during the entire period. The maximum rate of subsidence observed during this stage was more than 190 mm/a. The number of subsidence centers also increased from four in the previous stage to seven in 1996 (Fig. 7). With increasing groundwater pumpage, those previously isolated subsidence bowls coalesced and formed larger bowls. Although excessive groundwater exploitation was limited in 1998, the rate of subsidence that year was still 80–100 mm/a. These high rates of subsidence lasted until 2001, indicating a several-year lag between groundwater extraction and land subsidence, when land subsidence gradually shifted into the current decreasing subsidence stage. Because of the continuing decrease in groundwater extraction, the annual subsidence has decreased from tens of millimeters per year to subsidence on the order of 10 mm/a. In fact, a modest subsidence recovery (i.e., a rise) has taken place in the northern suburb.

In addition to the relationship with groundwater extraction, the land subsidence in Xi'an has two other important and unique characteristics. First, the land subsidence affected a large area and was controlled by its geological setting. Figure 7 shows the cumulative land subsidence in Xi'an based on the 1960–1996 leveling survey. The whole urban and near-suburb area was affected by an accumulative subsidence of more than 200 mm. By the end of the last century, the area in which the cumulative subsidence exceeded 200 mm was approximately 150 km^2, and the area in which the cumulative subsidence exceeded 1000 mm reached 42.5 km^2. The land subsidence in Xi'an does not have a uniform distribution; in fact, the subsidence is controlled by the geological setting. The landform, tectonics, and lithological and hydrogeological characteristics of the region all influence the distribution of land subsidence.

From the history map of land subsidence evolution for the region (Figs. 6, 7), all of the subsidence bowls are located in loess depressions. Because of the land subsidence map of 1960–2008 (Fig. 6d) mapped by contouring of sparse monitor data, the abrupt change belts are not obvious. Through time, the elongation of mapped subsidence bowls gradually becomes evident, as does the elongate elliptical shape of the bowls. For instance, the Xinjiamiao land subsidence bowl is located in the Xinjiamiao depression and the Hujiamiao and Xigongda land subsidence bowls are located in the Xigongda depression (Lee et al. 1996; Peng 2012). From these figures, it is apparent that land subsidence in the region is constrained by landforms. As the landforms are a direct result of long-

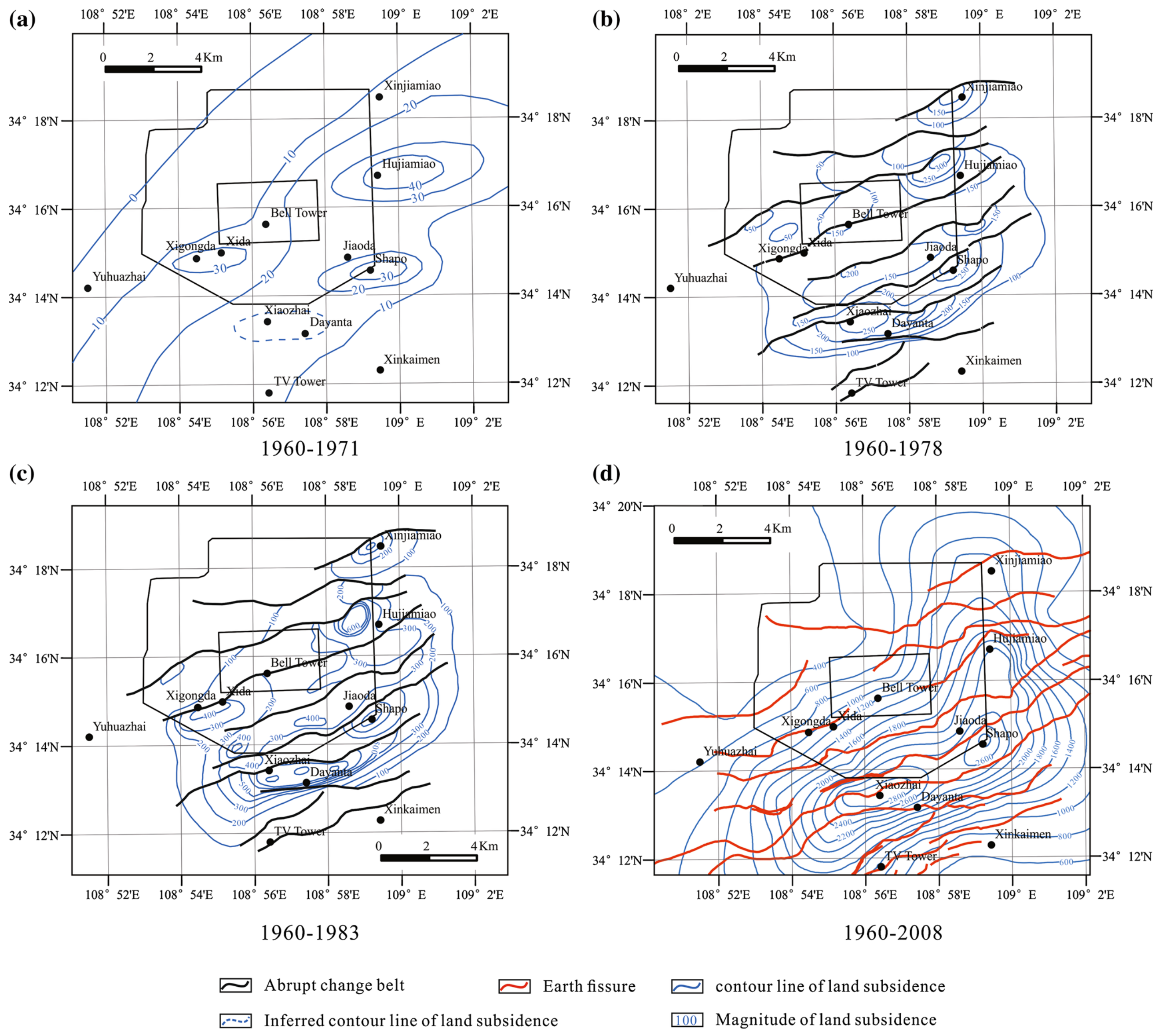


Fig. 6 Contour map of cumulative land subsidence measured in different years by leveling surveys (**a**–**c**) or by leveling surveys and InSAR (**d**): **a** 1960–1971, **b** 1960–1978, **c** 1960–1973 and **d** 1960–2008. The distribution maps of earth fissures are for the end of each stage

term fault activities, it can be inferred that the geological structure, which is controlled by tectonic activity, fundamentally governs the characteristics of land subsidence in Xi'an.

Another characteristic of the land subsidence in the region is that the compaction of each layer at different depths has a significant effect on subsidence. Extensometers and water level monitor wells installed at the Geotechnical School in the southeast suburb have been used to monitor the compaction of each soil layer and groundwater level changes since 1992 (Fig. 8). From the extensometer monitor data, it is clear that there are considerable differences in the compaction of individual hydrogeological units at different depths. The cumulative subsidence values of the first and second confined aquifers are 503.06 and 248.51 mm, respectively. In contrast, the cumulative subsidence values of the unconfined aquifer and the deep confined aquifer are only 186.09 and 106.28 mm, respectively. Similarly, the unit thickness subsidence of the first and second confined aquifers are 6.11 and 3.42 mm/m, respectively. The unit thickness subsidence of the unconfined aquifer and deep confined aquifer are only 1.77 and 0.99 mm/m, respectively. This contrasting monitoring data from the extensometer group show that a large proportion of the subsidence is attributable to the compaction of the first and second confined aquifer systems (Fig. 9).

Based on the above characteristics of land subsidence, we can conclude that excessive groundwater withdrawal is the

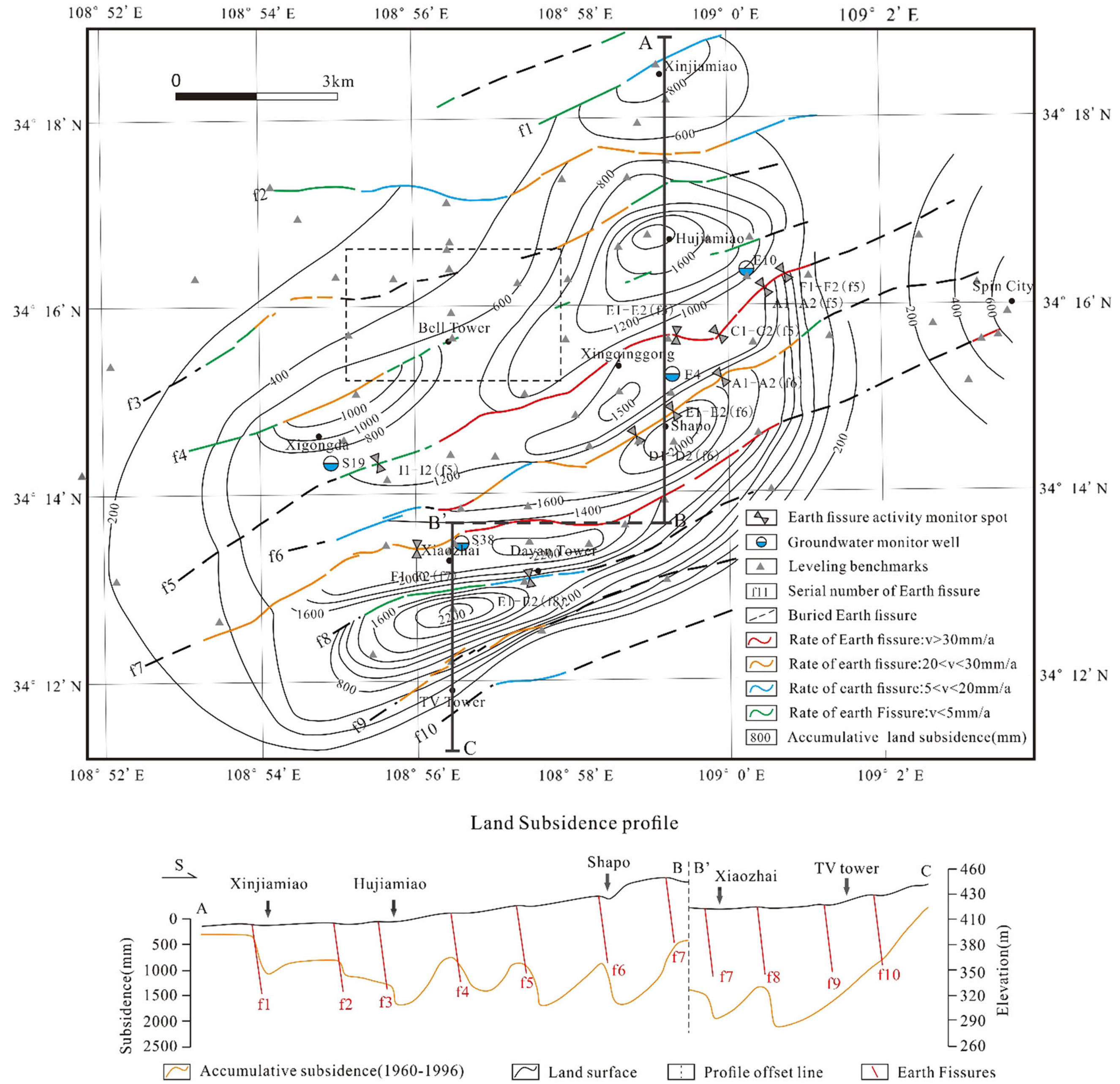


Fig. 7 Land subsidence and earth fissures in Xi'an in 1996. The *upper part* displays the contour of land subsidence; the *lower part* displays subsidence profiles across Xi'an, 1960–1996

main reason for land subsidence in Xi'an. Thus, excessive groundwater exploitation and land subsidence constitute one of the links in the aforementioned geohazards chain.

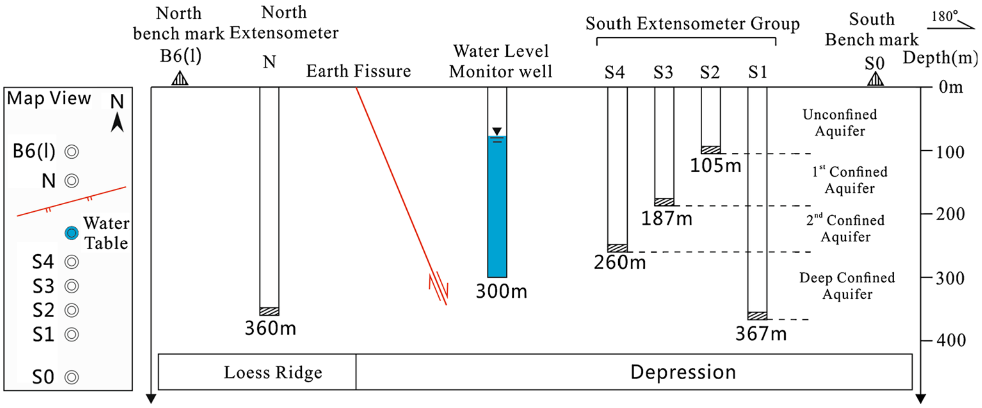
Characteristics of earth fissures

Areal and temporal characteristics of typical earth fissures

In the modern era, the first earth fissure in Xi'an was found in 1960. Since then, 14 earth fissures have been documented. The earth fissures in this region are characterized by a banded, sub-parallel and equally spaced distribution (Fig. 1). Almost all of the fissures extend in the ENE direction and dip toward the SSE with the averaged dip angle of 76°–86° and are coincidently located with the major normal fault zone in the Quaternary deposits and the basin and ridge landform.

The basin and ridge landform in the region is caused by long-term activity of the Lintong–Chang'an fault and a series of secondary faults. Boreholes F1 and D1 are located in the footwall and hanging wall, respectively, of the f7

Fig. 8 Plan layout and installation details of the borehole extensometers at Xi'an Geotechnical School



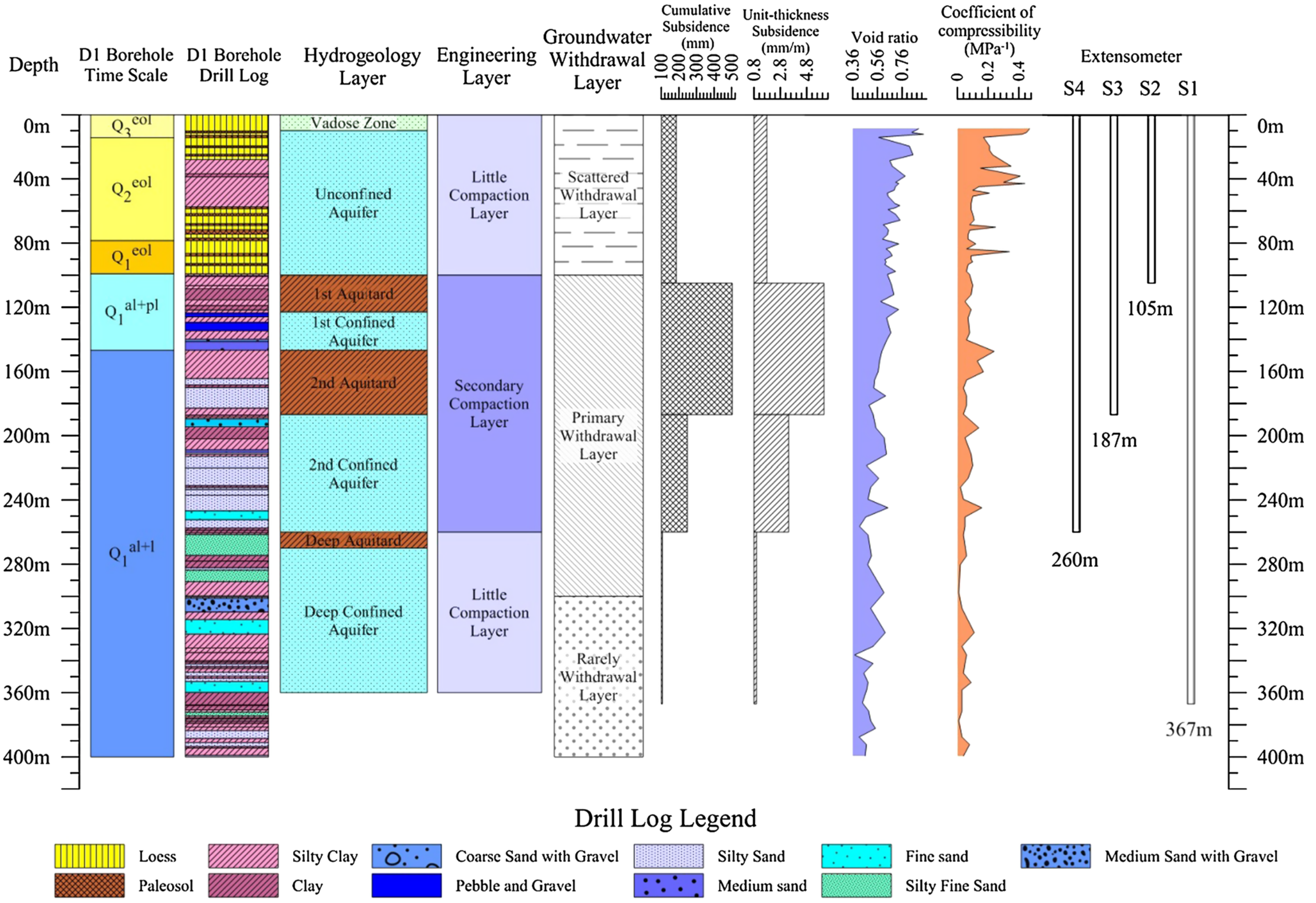


Fig. 9 Soil stratigraphy and properties at the borehole extensometer site at Xi'an Geotechnical School. The hydrogeology layer, engineering layer and groundwater withdrawal layer are divided on a regional scale. The coefficient of compressibility is calculated for a stress increment of 0.1 MPa^{-1} in excess of the in situ vertical effective stress of the soil sample at the sampling depth. The cumulative subsidence is subsidence from 1960 to 1996, and the unit thickness subsidence defined as the accumulated subsidence per unit of stratum thickness. The location of the borehole is indicated in Fig. 1

earth fissure (Fig. 1), at Xi'an Geotechnical School. Borehole logs reveal that the fault throw at the bottom of the Upper Pleistocene layer (1st paleosol layer bottom) is 2.4 m, while the fault throw of the Middle-Pleistocene layer bottom (8th paleosol layer bottom) is 19 m (Fig. 10). This suggests that the underlying fault was growing during sedimentation and continued to move until the Quaternary period. The long-term sustained creep of the fault caused a large difference in the strata between the loess ridge region and the depression region. Specifically, the sand layers have approximately the same thickness in the two landforms, but the cohesive soil layer in the depression is much thicker than the soil layer in the loess ridge landform. This phenomenon is caused by each sand layer being deposited over a short time. During this short period of time, the displacement of the underlying fault creep was small, so the difference in sand layer thicknesses is low. In contrast, the cohesive soil sediment was deposited much more slowly than the sand layers. During this longer period of time, the displacement of the underlying fault creep was large and the differences in thickness of the cohesive soil layer are remarkable.

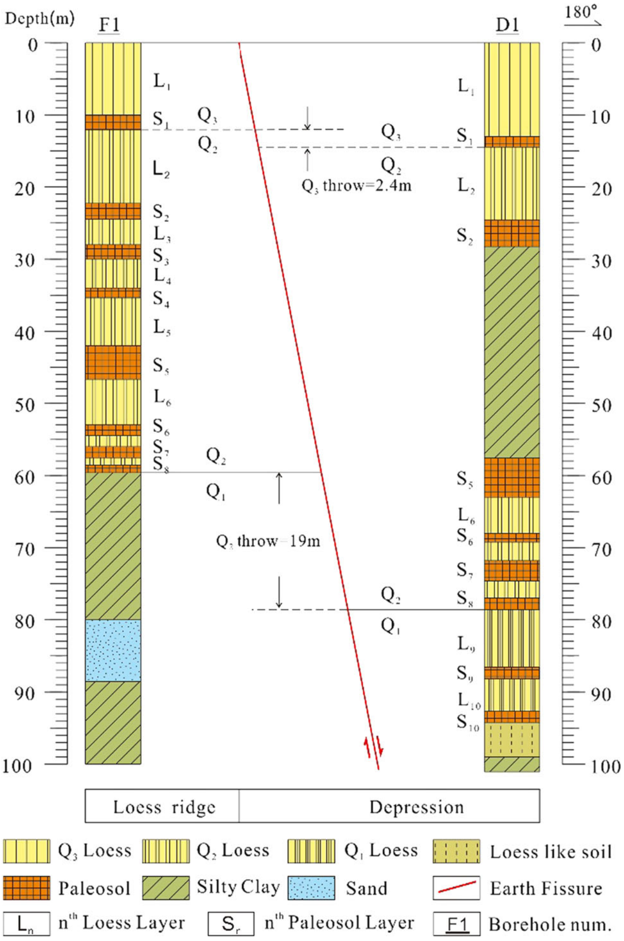
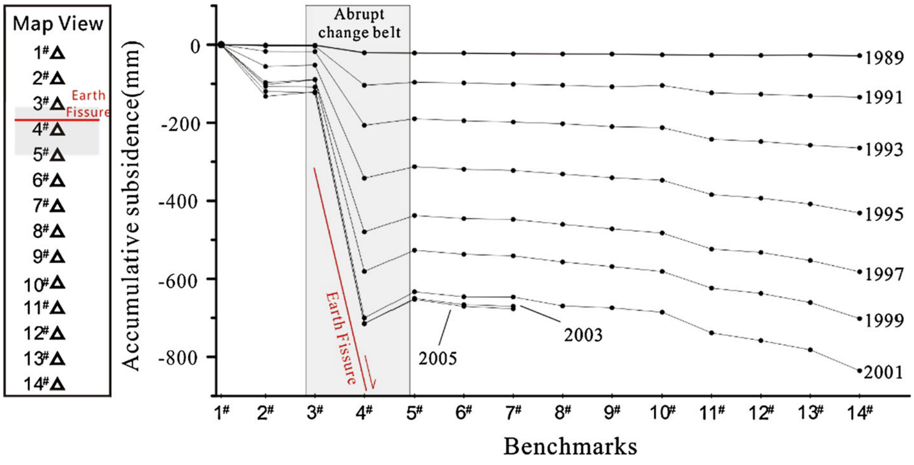


Fig. 10 Comparison diagram of borehole logs at the loess ridge (F1) and in the depression (D1)

Land subsidence in Xi'an is largely caused by compaction of cohesive soils (including interbeds). Therefore, land subsidence is controlled by changes in groundwater level and the thickness and compressibility of the cohesive soil layer. From borehole logs, the cumulative thickness of the cohesive soil layer in the hanging wall of the preexisting fault (depression) is 148.46 m within a 200 m depth, but in the footwall (loess ridge) is only 128.3 m. The soil layer on the loess ridge is relatively older than the soil layer in the depression landform at the same depth. In general, the older soil has a smaller void ratio and compressibility. Because the preexisting fault acts as a partial groundwater barrier, it is difficult to recharge the confined aquifers in the depression landform by lateral groundwater flow. After large-scale over-pumping, the drawdown in the depression landform is relatively larger than in the loess ridge. In addition to the influence of compressibility, the compression of the confined aquifer systems in the depression landform is greater than in the loess ridge. There is remarkable differential compression concentrated in the vicinity of the fault plane, forming an abrupt change belt. Because the preexisting fault plane is a weak interface within the soil body, differential land subsidence is most likely to be concentrated on the fault plane, reactivating any preexisting earth fissures and accelerating the earth fissure's high-speed creep along the preexisting fault plane. The differential subsidence decreases drastically as the distance to the fault plane increases (Fig. 11). The ground surface becomes gentle, and the ground surface gradient is not large enough to trigger cracks without a preexisting fault. All known earth fissures occur to the south of the

Fig. 11 Profiles of elevation changes on a level line perpendicular to earth fissure f7 at Xi'an Geotechnical School. This cross section of the earth fissure zone shows that land-surface elevations on both sides of the fissure are decreasing, with most of the subsidence occurring on the downthrown side of the earth fissure. The location of the profile is indicated in Fig. 1



loess ridge where preexisting faults are located (Fig. 1). The synsedimentary faults are essential to earth fissure formation.

Movement characteristics of a typical earth fissure

Closely spaced benchmarks were set in a line perpendicular to the trend of the f7 Earth fissure in Xi'an Geotechnical School. From monitoring data of the levels across the earth fissure (Fig. 11), the activity of the earth fissures and the differential subsidence are highly consistent. The vertical deformation gradient near the earth fissure is largest in the closest leveling section. As the distance from the earth fissure increases on both sides, the vertical deformation and gradient become smaller.

Discussion

From the perspective of spatial distribution, the Xi'an earth fissures have obvious structural properties; however, from the viewpoint of their activity and evolution, the earth fissures are profoundly influenced by groundwater extraction and land subsidence.

(1) Earth fissure development has followed groundwater extraction and land subsidence.

The development of earth fissures in the region has generally followed the stages of groundwater extraction and land subsidence and has demonstrated three stages (Fig. 3). The first stage was the earth fissure origin stage (before 1976). During this period, the subsidence rate was small, with an average subsidence rate of <7 mm/a. Earth fissure activity was weak and only discovered in scattered sites. In 1960, earth fissures were reported only in Xiaozhai and Xida (Fig. 4a). Because of their small scale and weak activity, earth fissures during this period only caused minor economic losses on a scale that was not sufficient to attract enough attention.

The second stage was the earth fissure development stage (1977–2000). Large-scale mining of groundwater started in 1976, and the drop in water levels in the confined aquifers began to accelerate at this time. Meanwhile, the number and length of earth fissures obviously increased. Despite the fact that the distribution area of the earth fissures increased significantly, the earth fissures still were within the 350-m groundwater-level contour (Fig. 4b). Until 1987, the expansion of the 350-m groundwater level remained within a fairly prescribed area, and the earth fissures extended accordingly. The main earth fissure distribution pattern was formed in this stage (Fig. 4c). Between 1987 and 1996, water levels in the confined aquifers receded still further. Eleven earth fissures formed during these years, which have been connected to the drop in groundwater levels and increased subsidence (Figs. 4d, 7). The main characteristics of this second stage are that ground deformation was obvious and earth fissure activity increased significantly. During this stage, the number of earth fissures increases year by year, the horizontal opening and vertical displacement of earth fissure enlarge significantly, and many buildings were damaged.

The third stage was the earth fissure alleviation stage (after 2001). The main characteristics of this stage are that the rates of earth fissure creation and differential subsidence both decreased and more recently have essentially stabilized. Earth fissure f7 is used as an example (Fig. 7). The annual average rate of differential subsidence for f7 slowed significantly from 52.7 mm/a in 2000 to 0.97 mm/a in 2005. From 2005 to 2011, the stable state of the earth fissure was even more obvious, with the horizontal opening and the vertical displacement along the strike of the earth fissure no longer increasing.

In fact, high fissure activity now only appears in certain zones. Most of the earth fissure activity rate in the region has significantly decreased or remains stable. According to monitoring data in 2011, the vertical displacement rate of earth fissures f2, f5, f7 and f9 were all within 2 mm/a, and only the vertical displacement rate of earth fissures f11 and f12 exceeded 20 mm/a; these latter are near the boundary of the groundwater prohibition extraction area.

(2) Areal distributions of earth fissures and land subsidence are closely related.

Overall, the earth fissures in the early years of fissure development in the region were distributed through the abruptly changing belt of land subsidence (Fig. 6a–c). Later, although the influence area of land subsidence expanded widely, the earth fissures primarily remained in the affected subsidence area at the abruptly changing belt of subsidence, with the strikes of the fissures coincident with the long axes of the subsidence bowls. At the same time, earth fissure development in response to land subsidence and land subsidence has been limited to the area between two earth fissure belts, resulting in a subsidence shape of an elongated oval or half-oval. The inset in Fig. 7 shows a profile of subsidence from the north through several land subsidence bowls to the south of Xi'an. From the figure, most of the area in subsidence profile A–B (B′)–C subsided more than 500 mm from 1960 to 1996, and all earth fissures are located in the area with prominent land subsidence. The profile also indicates that the earth fissures were coincident with zones of localized differential subsidence and near points of maximum differential subsidence. The earth fissures are more related to differential displacement than to the magnitude of subsidence.

In general, in the south and east suburbs of Xi'an, earth fissures exhibit high activity. In those areas, there is also a significant rate of subsidence (Fig. 6d). For each strip of earth fissures, segments with strong or moderately strong activity always occur near the center of the subsidence bowl. That is to say, the activity rate of earth fissures in the center of a subsidence bowl is greater than that at the subsidence bowl edge. This phenomenon shows that the activity of an earth fissure has a close relationship with the fissure's location in a land subsidence bowl.

(3) Earth fissure activity is significantly correlated with land subsidence rate or groundwater level.

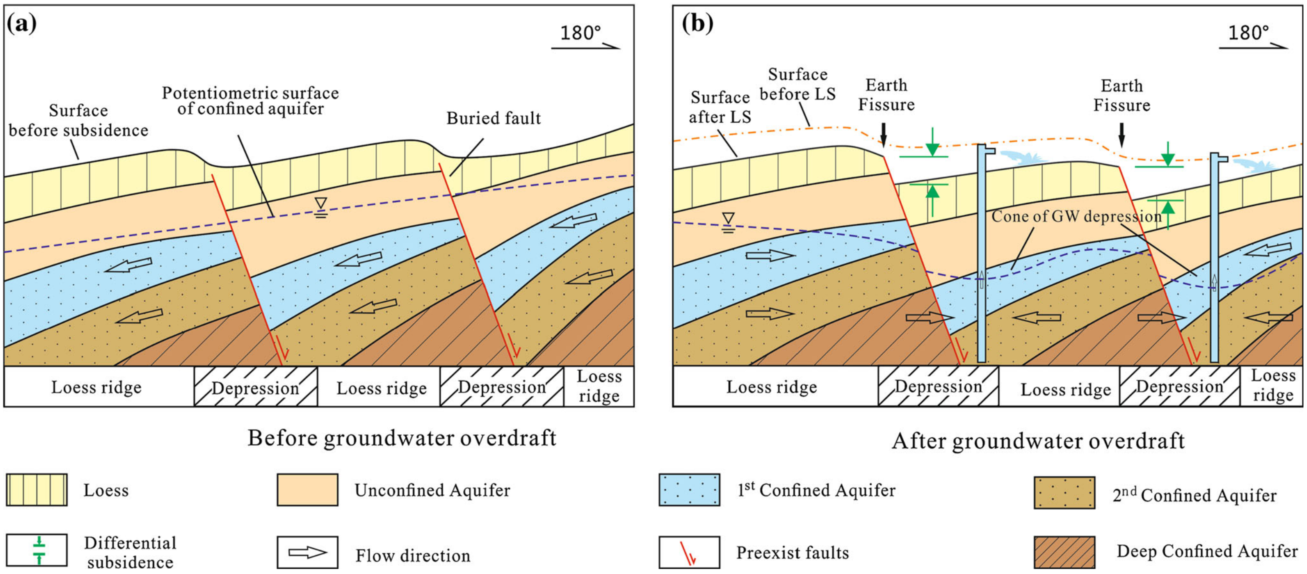
The activity rate of the earth fissures, as measured by peer monitoring stations, is highly correlated to the nearby confined water level (Fig. 5). Earth fissures move faster when the groundwater level falls and become slower when groundwater level rises.

Although the activity of each earth fissure or each section is not exactly the same, the overall trend of earth fissure activity and groundwater level or land subsidence is consistent within the region. All of the activity progresses from weak to strong before gradually returning to a weak level of activity. After 1998, the Xi'an local government limited the extraction area for groundwater. At the same time, the south suburb waterworks began to operate which use surface water as their water source. High efficient utilization of surface water reduced groundwater pumpage significantly. These various and effective artificial measures significantly lowered earth fissure activity. The activity gradually decreased to a rate similar to what the region experienced prior to over-pumping, which is on the same order as the activity to be expected because of activity on the Lintong–Chang'an fault.

A disaster chain refers to the phenomenon of a series of geohazards, all of which possess a successive origin in time and are all linked to each other in space and have interconnected origins. From the above three points, it is apparent that groundwater exploitation, land subsidence and earth fissures appear either synchronously or with a slight time lag (Fig. 3). These activities create a time disaster chain, while the resulting drawdown cone expansion, land subsidence area extension and lead fracture development constitute a space disaster chain.

As described above, groundwater exploitation, land subsidence and earth fissures have similar development times, development space and movement characteristics. This relationship is caused by the closely linked formation mechanism. Figure 12 provides a clear and concise explanation of the correlation between groundwater withdrawal, land subsidence and earth fissures.

Before groundwater overdraft, groundwater was under natural conditions, natural recharge was dynamically balanced by natural discharge and the water levels were relatively stable. Groundwater flowed from the southeast toward the northwest of Xi'an (Fig. 12a). With increasing demand for groundwater, the water budget of Xi'an has been drastically altered by intensive exploitation. More groundwater has been discharged than has recharged the aquifer system, causing a substantial drop in confined-aquifer water levels. After long-term overdraft, confined groundwater generally flows toward pumping centers and water levels drop consistently. Because of differences in groundwater level declines and the different thicknesses of compressible sediments deposited in adjacent blocks either side of the synsedimentary faults, remarkable differential subsidence has occurred between the footwall and hanging



Before groundwater overdraft

After groundwater overdraft

Fig. 12 Schematic diagram of proposed earth fissure development: **a** before groundwater overdraft, groundwater was sustained by natural recharge and no land subsidence or earth fissures occurred; **b** after groundwater overdraft, excessive pumping caused the water level to drop and induced differential land subsidence and earth fissures wall of the fault. As the differential land subsidence increases, stress is concentrated on the preexisting fault plane buried by the Quaternary deposits. When the stress concentration is sufficiently large, preexisting faults can be reactivated and begin to slip, forming earth fissures at the ground surface (Fig. 12b).

Conclusions

Tectonic action is the controlling factor behind the earth fissures in Xi'an, and thick Quaternary loose sediment is the material basis for land subsidence and earth fissure development. Excessive exploitation of confined aquifers caused a drastic drop in groundwater levels, loose sediment consolidation and serious land subsidence disasters. Groundwater, land subsidence and earth fissures appeared successively in time, with the increased activities of each event linked to each other in space and forming a complete geohazards chain. Over-extraction of the confined aquifers is the main factor causing land subsidence in Xi'an and is the primary reason that the earth fissures in the region have exhibited such strong activity. Groundwater exploitation, land subsidence and high activity of earth fissures have all been consistent in time and space. Land subsidence accelerated the motion of the earth fissures and increased their vertical movement. By restricting or prohibiting groundwater exploitation and sustainably increasing the conjunctive usage of surface water, the groundwater level in the region has recovered and earth fissure activity has also gradually slowed to a lower level. These resource management activities will help minimize land subsidence and earth fissure hazards in the near future.

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