Exploration of Laoyachen fault in Zhengzhou and its activity investigation^{*}

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Abstract

In the paper, an exploration is made by the techniques of shallow seismic prospecting, borehole composite profile analysis, field morphological investigation, and new geological dating for the Laoyachen fault in Zhengzhou that was originally recognized as an active one. The result from shallow seismic prospecting indicates this fault only existed in the stratum prior to the Neogene, dislocations and activity traces of this fault could not be found in the Neogene stratum. At the same time, the surface morphological investigation reveals that the location of the so-called “fault scarp” is not consistent with that of Laoyachen fault. Moreover, seismic drilling and borehole composite profile analysis also indicate that the scarp only developed in Malan Loess. The stratum beneath it is gentle and no dislocation traces can be seen. Therefore, we propose that this scarp is not relevant to the Laoyachen fault, which might be resulted from the diverted course of Yellow River. Laoyachen fault is not an active one.

Key words: Laoyachen fault; fault activity; shallow seismic prospecting; drilling; morphological investigation

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Introduction

With the occurrences of North Range earthquake of Los Angeles in America and Hyogo-ken Nanbu earthquake in Japan in the late 1990s (Miyata and Maeda, 1998), the governments of foreign countries have realized more and more clearly the significance and urgency for the exploration and study of urban active faults. Projects of hazard mitigation have been conducted one after another in large cities for the purpose of making more reasonable urban planning and anti-earthquake prevention and to reduce possible urban earthquake losses by means of exploring active faults with potential seismic risks in cities and the surrounding regions. At present, the methods used to investigate urban active faults in the world are mainly detailed active fault mapping, drilling and trench-prospecting, deformation monitoring as well as integrated geophysical exploration, *etc* (Yeats *et al*, 1997; Fuis, 1998; Fuis *et al*, 2001). In China, some urban earthquakes, such as the *M*7.8 Tangshan earthquake in 1976 and the *M*7.6 Taiwan Chi-Chi earthquake in 1999, have caused serious personnel casualties and economic losses. To draw a lesson from Tangshan

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earthquake and some other large earthquakes occurred in China and abroad, the Chinese government has paid great attentions to the active geological structures represented by active faults and their seismic risk problems. In the late 1990s, the Chinese government began to work out an overall scheme for exploring active faults and evaluating their seismic risks in large cities. Moreover, tests were carried out in certain cities as Fuzhou, *etc.* by integrating multi-methods of geological morphology, geochemistry, geophysics and so on. On the basis of the obtained results, active fault exploration has been conducted successively in more than 20 large cities in China (DENG *et al*, 2003), including the exploration of active fault in Zhengzhou city.

Laoyachen is a major fault zone in Zhengzhou city, which extends from the south bank of the Yellow River in the north, passes through the urban area of Zhengzhou along the east side of Mangshan to the southeast, and goes towards Shibalihe (LIU, 2001). Therefore, studying the behavior characteristics and activity of Laoyachen fault is of great significance for the production and construction of Zhengzhou city, which is also an important basis for evaluating seismic risk and hazard of this city. In view of the major significance of Laoyachen fault and the concrete condition of Zhengzhou city, a special study is arranged in the project of active fault exploration in Zhengzhou city, which is to explore the Laoyachen fault and investigate its activity.

Laoyachen fault was first discovered in 1988 in the seismic risk zoning of Zhengzhou city. Then by an integrated study on the Laoyachen hidden fault situated in the urban area of Zhengzhou city, it is proposed that the fault was active in the Recent^① (YAO, 1992; HOU and WU, 2000; ZHAO *et al*, 2007). The major basis then were the interpretation for the shallow seismic S-wave prospecting profile arranged on Dongfeng and Jinshui roads and the morphologic scarp on the east side of Mangshan. However, a number of specialists queried the validity of this fault's activity, for Laoyachen is a hidden fault. Therefore, for a matter-to-fact attitude to this problem, we attempt to interpret the activity of Laoyachen fault by a convincing demonstrative method. However, the Neozoic stratum is rather thick in this area, and the location, property and faulting activity of the object fault are uncertain. Finally, we decide to use the integrated techniques of shallow seismic prospecting, borehole composite profile analysis, field morphological investigation, and new geological dating and make every effort to reveal the relationship between the activity of Laoyachen fault and the morphologic scarp.

1 Shallow seismic prospecting

In the project of shallow seismic prospecting, 11 lines are arranged in the measuring area for P-wave seismic prospecting, which are divided into two groups according to the designed exploration depth. One contains four middle-shallow seismic prospecting lines with a depth of 1~2 km (ZP_1 ~ ZP_4) and the other includes seven shallow seismic prospecting lines with a depth of 30~100 m (QP_1 ~ QP_7) (Figure 1). Among them, ZP_1 , ZP_2 , QP_1 , QP_2 and QP_4 lines span the morphologic scarp at the north end of the fault and they are measured in this seismic prospecting (Figure 1). For a convenient stratum deviation of profile reflection waves and a reliable geological explanation, the buried depth of reflection interface of corresponding stratum is calculated on the basis of seismic wave velocity obtained in data processing and the two-way arrival time of reflection wave on

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different interfaces of time section. In the geological stratification for the profile reflection waves, the data of seismic risk zoning of Zhengzhou city and the geological drilling data of the region near the measuring area are used as reference. The stratum reflection waves are shown as T_Q , T_N , T_E , T_P , T_C , $T_0 \sim T_5$ and $T_{01} \sim T_{05}$. On the profile, T_Q , T_N , T_E , T_P and T_C represent respectively the bottom boundaries of the Quaternary, Neogene, Paleogene, Pamian, and Permo-Devonian systems; $T_1 \sim T_4$ indicate the internal-stratum interface reflection of the Neogene and T_5 denotes the internal stratum reflection of the Paleogene (YAO, 1992; LIU *et al.*, 2007). The following is a comparative introduction for the ZP_2 and QP_2 measuring lines spanning the morphologic scarp near Guying.

Figure 1 Faults distribution in Zhengzhou region

QP : No. of shallow seismic prospecting lines; ZP : No. of middle-shallow seismic prospecting lines; L_1 : Location of bore-hole composite profile on Dahe road in Guying town; L_2 : borehole composite profile besides the 107 highway

Figure 2 Profile of superimposed reflection waves of shallow earthquakes on ZP_2 line

The fault didn't cut through the Neogene stratum upwards and the stratum tended to be gentle since the Neogene system

The fault characteristics revealed by the profile of ZP_2 line in Guying are very clear (Figure 2). Near the pile of 4 700 m, all the reflection waves with a profile two-way arrival time less than 1.0 s have shown a distinct waveform distortion and an evident offset of co-phase axis, accompanied by the phenomena of abrupt change of reflection energy and lateral offset of co-phase axis. Moreover, the attitudes of strata on both sides differ greatly with an approximately horizontal attitude on the west of pile 4 700 m and eastward tilting of all stratum interfaces on the east of pile 4 700 m, indicating that fault should exist here. Taking into account the location and property of the fault appearing on the profile, it should be the reflection of Laoyachen fault, which is a normal fault with an apparent dip of $60^\circ \sim 70^\circ$ tilting to the northeast on the profile. It has dislocated the strata of Pamian, Carbonic or Ordovician systems, or it perhaps has extended to the crystalline basement. Considering from the T_N reflection wave and the lateral continuity of co-phase axis of each reflection wave in shallow, no stratum offset phenomenon caused by faulting can be seen within the Q+N stratum. The continuity of strong-energy standard reflection wave

T_N on the profile is especially well, which indicates that Laoyachen is a fault formed before the Neogene.

The relief variation of the Quaternary stratum interface within the segment of QP_2 line is not large and only small uplift can be seen in the middle of the profile (Figure 3). While in the Neogene system with the two-way arrival time less than 200 ms, all the stratum reflections have a monoclinical shape of high in the west and low in the east. And the dips of these reflection interfaces enlarge gradually with the increasing depth. Considering from the lateral continuity of co-phase axis of profile reflection wave, the co-phase axes of reflection waves are relatively continuous in the lateral direction, especially the standard reflection waves T_Q and T_2 , which can be traced continuously and reliably on the whole profile and there is no dislocation phenomenon in the co-phase axis of reflection wave. We can therefore propose that Quaternary active fault does not exist in the range of this measuring line, indicating that Laoyachen fault has not extended into the Quaternary system.

Figure 3 Profile of superimposed reflection waves of shallow earthquakes on QP_2 line

Multico-phase axes of reflection waves with strong energy, good lateral continuity, and distinct step relief variation can be recognized on all explored shallow lines, except the 107 highway where not very clear disturbing co-phase axis phenomenon has been found in the depth less than 70 m. The results all indicate that the co-phase axes of profile reflection waves are continuous laterally, especially the standard reflection waves T_Q and T_2 . They can be traced successively and reliably on the whole profile and they have no offset phenomenon. By comprehensive analysis on the characteristics of time section and depth section of superimposed reflection waves of seismic measuring lines with different exploring depths arranged on Laoyachen fault, we have known that Laoyachen fault appears from the north to the south only on the middle-shallow seismic lines with an exploring depth of 1~2 km, and its upper breaking points are all located near the T_N reflection surface at the bottom of Neogene. It is apparent that Laoyachen fault has dislocated the Paleogene (E) stratum and the strata beneath it, while the above Q+N stratum has not been dislocated (Figure 4). Moreover, active fault dislocating into the Quaternary coverage has been discovered neither on the shallow P-wave measuring line with a depth of 30~100 m nor on the shallow S-wave line with a depth of 10~50 m. Therefore, Laoyachen fault should be a NNW-striking normal fault with a dip of $60^\circ\sim70^\circ$ tilting to the NE. It has dislocated the strata formed prior to the Neogene and it is not active any more since then.

Figure 4 Profile of reflection depth of middle-shallow earthquakes

P: Pamian; E: Paleogene; N: Neogene; Q: Quaternary. (a), (b), (c), (d) indicate that Laoyachen fault have not dislocated the Neogene and the stratum has been gentle since the Neogene

2 Borehole composite profile analysis

On the basis of the results from shallow seismic prospecting, we arrange two borehole composite profiles in order to study further the activity of Laoyachen fault. One is L_2 located at the convergence of 107 highway and Beijing-Guangzhou railway in the south of Zhengzhou city, the other is L_1 located at Dahe road of Guying town in the north of Zhengzhou city (Figure 1). The borehole composite profile at Dahe road of Guying town is basically coincident with Dahe road measuring line (QP_2), including three boreholes of ZZ_{01} located below the slope of fault scarp, ZZ_{02} above the slope of fault scarp, and ZZ_{03} in the middle of the slope. The lithologic characters of these three boreholes are mainly loose silt and clay containing consolidated and hard calcareous cement: calcareous slate stratum. By comparative analysis of these three boreholes, we have determined three marker beds. The first marker bed is the loess-type loess, the second marker

Figure 5 L_1 borehole composite profile at Dahe road of Guying town

No dislocation is found in the two marker beds of calcareous slate, indicating that the fault has not cut through these strata

bed is the first calcareous slate stratum with a buried depth of 55 m, and the third marker bed is the second calcareous slate stratum with a buried depth of 63 m. The top-and-bottom heights of these two thick calcareous slate strata are consistent in the three boreholes, indicating that these two strata are successively horizontal (Figure 5), which is in an agreement with the explanation for QP_2 shallow seismic prospecting.

Figure 6 L_2 borehole composite profile beside the 107 highway

The borehole shows that there is no dislocation in the third marker bed that belongs to the late stage of early Pleistocene by dating analysis, indicating that the fault has not cut through the Quaternary stratum

In this project, a shallow prospecting line (QP_7) is arranged beside the 107 highway (across the Beijing-Guangzhou railway). It has been discovered from the result of shallow seismic prospecting that there is a not very distinct co-phase phenomenon of disturbance in the depth below 70 m. On the neighboring middle-shallow prospecting line (ZP_4) (see Figure 4d), the fault is also found in the deep depth and its upper breaking point is about at the depth of 800 m. Therefore, four boreholes with a depth of 117 m are arranged along this line from the west to the east. The lithologic characters of these 4 boreholes are approximately consistent, which can be divided into two parts from the top to the bottom. The color is light in the upper part and the consolidation is bad and loose with low calcareous content, while the color is dark in the lower part and the consolidation is good with a high calcareous content. In the upper part, three distinct marker beds can also be seen. They are the black peat layer, red clay layer, and the layer with high calcareous content. It is evident from these three marker beds that there is no stratum offset above the depth of 68 m (Figure 6).

In the 107 highway profile, we have totally collected and analyzed one ^{14}C sample, six light stimulating samples, and 10 ESR samples (five sedimentary samples and five carbonate samples) (Table 1). It is apparent from Table 1 that the third marker bed belongs to the late stage of early Pleistocene. The stratum beneath it belongs to the Quaternary with an age larger than 2 000 ka. According to the results from real dating and spore-pollen analysis, the location of 70 m of the profile serves as a distinct boundary for dividing geological epochs: the stratum above 70 m is the Quaternary sediment, while the stratum below 70 m belongs to the Neogene. We can therefore conclude that Laoyachen fault is not active any more since the Neogene.

Table 1 Age table of borehole chronologic samples at the convergence of 107 highway and Beijing-Guangzhou railway on the south of Zhengzhou city

No. of sample	Depth/m	Lithology	Type of sample	Age/ka
ZZ06-D1	2.2	Greyish-black clay with more carbon	^{14}C	9.095±0.09
ZZ06-D3	6.6	Grey silt, fine sand	OSL	48.5±2.8
ZZ06-D4	13.3	Greyish-yellow silt	OSL	77.0±18
ZZ06-D5	19.5	Greyish-yellow clayey silt	OSL	135.5±10.4
ZZ06-D7	28.2	Greyish-yellow clayey silt	OSL	185.6±12.0
ZZ06-D8	29.8	Bronzy clay	OSL	190.8±2.7
ZZ06-D11	41.7	Greyish-yellow coarse sand	OSL	167.1±13.1
ZZ06-D14	49.9	Calcareous sandstone	ESR carbonas	1267±125
ZZ06-D15	55.9	Yellow clayey silt	ESR sediment	670±65
ZZ06-D17	64.2	calcareous slate stratum with calcite crystal	ESR carbonas	1491±150
ZZ06-D19	66.9	Greyish-yellow clay	ESR sediment	803±80
ZZ06-D20	67.3	calcareous slate stratum	ESR carbonas	1596±160
ZZ06-D21	68.9	Bronzy aleurite	ESR sediment	888±90
ZZ06-D25	76.8	Bronzy fine sand	ESR sediment	1125±110
ZZ04-D2	85.3	Brownish-red silty clay	ESR carbonas	>2000
ZZ04-D1	83.1	Brownish-red silty clay	ESR carbonas	>2000
ZZ06-D31	89.8	Brownish-red coarse sand	ESR sediment	>2000

Note: The age of geological samples are determined by the Institute of Geology, China Earthquake Administration.

3 Investigation of fault scarp

The fault scarp on the east side of Mangshan extends in the strike of NW and its location is shown in Figure 1. Some geoscientific researchers proposed that the formation of scarp landform was controlled by Laoyachen fault (YAO, 1992; HOU *et al*, 2000; ZHAO *et al*, 2007). To determine the relation between them, we have obtained the geometric shape of the scarp by many measuring means. Our investigation results indicate that the scarp can be divided into three segments from the NW to the SE. The first segment extends from the east side of Mangshan to the north of Guying and the height difference of the scarp is about 15 m. Its west side is characterized by the loess terrace cut deeply through the trench valley and its east side is river plain; The second segment starts from the south of Guying to the north of Zhengzhou and the height difference of the scarp is about 8~10 m. However, its trace is not clear in local sections due to some artificial transformations; The third segment extends from the south of Zhengzhou and is buried gradually into the lower part of the river alluvial layer southwards after the height difference of the scarp reduces to about 3~5 m.

The relation between the scarp and Laoyachen fault is discussed by integrating the results from the researches in both geophysical prospecting and drilling. We can see from the borehole composite data in the section 2 of this paper that there is no stratum dislocation on the Guying borehole composite profile spanning the scarp for a distance of 500 m (Figure 5).

It is apparent from the explanation of geophysical prospecting that the location of fault is not consistent with that of scarp (see the locations of fault and scarp in Figure 1). We can see from the figure that the location of surface projection of the breaking point obtained from geophysical prospecting in the first segment in the northern part is basically the same as the location of scarp; The location of surface projection of the breaking point in the second segment in the middle part is not consistent with the location of scarp; The location of surface projection for the breaking point in the third segment in the southern part has a relatively large difference to the location of scarp.

The data from geophysical prospecting and drilling indicate that the scarp and Laoyachen

fault have no inevitable dislocation relationship between them. By referring to the relevant literatures we have known that multiple channel migrations of Yellow River occurred in Zhengzhou area in history (XIA *et al.*, 1993). We propose that the morphologic scarp relates closely to the channel migration of Yellow River. The drilling data indicate that the morphologic scarp developed in the Malan loess. The stratum beneath the Malan loess was relatively gentle without any clear dislocation and the thicknesses of the rock strata on the upper and lower sides of the scarp were correspondent. We therefore conclude that the scarp should be generated after the formation of Malan loess due to aggressive action. And the main reason should be the multiple channel migrations of Yellow River, which is not relevant to Laoyachen fault.

4 Conclusion

The shallow seismic prospecting, borehole composite profile analysis and field morphological scarp investigation for Laoyachen fault have been conducted in the paper. The results have revealed that Laoyachen fault is a NW-striking normal fault tilting to the northeast. The fault dislocated the strata prior to the Neogene (N), but fault offset was not discovered within the Neogene and Quaternary strata. Meanwhile, the morphologic scarp on the east side of Mangshan is not consistent with the real location of fault. The drilling data indicate that the scarp only developed in the Malan loess. The stratum below the Malan loess is gentle and no offset and discordant phenomena can be found. Therefore, it is considered that the formation of scarp is not relevant to the fault, but the multiple channel migrations of Yellow River in this area should be considered as a reason for the development of morphologic scarp on the east side of Mangshan. Although the reason for the formation of scarp needs further exploration, we can still conclude that Laoyachen fault is not an active one and the morphologic scarp developed on the east side of Mangshan has no direct relation with Laoyachen fault.

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