Geomorphic analysis of Xiadian buried fault zone in Eastern Beijing plain based on SPOT image and unmanned aerial vehicle (UAV) data

Yanping Wang, Pinliang Dong, Yueqin Zhu, Jun Shen and Shunbao Liao

Department of Ecology and Environment, Institute of Disaster Prevention, Hebei, China; Department of Geography and the Environment, University of North Texas, Denton, TX, USA; Development and Research Center, China Geological Survey, Beijing, China

ABSTRACT
This study presents geomorphic analysis of Xiadian buried fault in eastern Beijing plain (China), based on the analysis of a Satellite Pour l'Observation de la Terre (SPOT-5) image, a high-resolution digital elevation model (DEM) derived from an unmanned aerial vehicle (UAV) system, SRTM DEM and field investigation. Interpretations of the SPOT-5 image show that the pits always distribute between fault scarp segments or shallow grooves. The geomorphic features near the fault show echelon arrangements caused by dextral strike-slip activities of the fault. Based on this, the characteristics of stress field in this area have been clearly inferred. At centimeter-level accuracy, UAV-derived DEM profiles can clearly show micro tectonic landforms such as fault scarps, shallow grooves, steep slopes, and pits. Combined with previous research and field measurements, the evolution rates in length and height of the fault scarps are analysed. Furthermore, the deflection analysis of the drainage system also shows the characteristics of the continuous strike slip activity of the Xiadian fault. The study can provide valuable insight into geomorphic analysis of buried and semi-buried active faults in plain areas with increasingly frequent human activities.

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1. Introduction
Buried active faults pose a significant seismic hazard, especially around megacities like Beijing, Tokyo, and Mexico City. At present, faults in plain areas can be identified by LiDAR-derived high-resolution digital elevation models (DEM) (Kondo et al. 2008; Bhosle et al. 2009; Ahmad et al. 2015; Deffontaines et al. 2017; Goto et al. 2017; Chang et al. 2018; Dong and Chen 2018). Various geomorphological indexes have been proposed to quantify fault activity (Troiani and Seta 2008; Arrowsmith and Zielke 2009; Parul et al. 2013; Troiani et al. 2014; Gao et al. 2015; Liu et al. 2015; Liu and Du 2016;
Kaushal et al. 2017; Wang et al. 2017; He et al. 2018; Pavano et al. 2018; Sharma et al. 2018; Wang et al. 2019). Terrain analysis of seismogenic faults has been well documented in studies around the world (Cello et al. 2000; Lin et al. 2003; Pucci et al. 2003; Maschio et al. 2005; Irikura 2012; Mahmood and Gloaguen 2012; Robinson and Davies 2013; Koukouvelas et al. 2018), and has become a major method for studying neotectonics, seismogeology, and paleoseismology (Papanikolaou et al. 2015). In addition, Noriega et al. (2006) and Chen et al. (2013) demonstrated that deflected streams can be used to compute fault slip rate in history by sediment dating on the offset stream channels. Furthermore, analysis of the current stress field based on 3D Mohr diagrams and slip tendency factors was proved by Taghipour et al. (2019) to have many advantages in estimation of the fault reactivation potential.

In terms of the topography and deformation characteristics of the Xidian fault in the eastern Beijing plain, several studies have been carried out using different measurement methods. Wang (1981) used level measurement or real-time kinematic (RTK) measurement, to show that the Xidian fault is a dividing line between different strain states, that is to say, the strain situation on both sides of the East and the west is different in the eastern Beijing plain. Meng et al. (1983) studied the scale, occurrence, combination, and mode of activity of the Xidian fault through seismic archaeology, deformation archaeology and field measurement. Xiang et al. (1988) studied the earthquake mechanism, the tectonic stress field, the ground displacement field, and the location of the epicentre based on 14 slope angle profiles with the simple levelling instrument. The results of Xiang et al. (1988) suggest that the dislocation number of the free surface of each section of the Xidian fault is roughly the same as the result measured from drilling and trench, or slightly smaller. The strike slip displacement and the mechanical properties of the fault were determined by Jiang (2000). Mao et al. (2010) accurately measured the coseismic dislocation volume of more than 10 measured lines by RTK measurement technology, and identified the mechanical properties reflected by the fault scarps along the Xidian fault by analysing the geomorphic features of fault scarp and river twisting. Wang et al. (2014) analyzed and processed a variety of images to identify the Xidian fault scarps.

However, geomorphic features, as a very economical and practical method, have not been fully excavated in this study area to analyse tectonic activity. By fully mining and analyzing the geomorphic signs transformed by human activities, we are going to reveal the fault activity reflected by the hidden structural geomorphic features. Based on a SPOT image and DEMs from the Shuttle Radar Topography Mission (SRTM) and unmanned aerial vehicle (UAV) data, this study focuses on two aspects of the Xidian fault: (1) The relationship between micro-geomorphic features (such as scarps, pits, shallow grooves, steep slopes) and mechanical properties of the Xidian faults. (2) Evolution law of the Xidian fault landform reflected by fault scarps and drainage deflection.

2. Study area and data

The Xidian fault is located in the eastern Beijing plain, on the boundary between Tongxian uplift and Dachang sag in northern China (Xu et al. 2000), as shown in Figure 1. This Holocene active fault, with a right lateral slip, a NE-SW trend and a
south dipping of $50^\circ-70^\circ$, is about 100 km long (Mao et al. 2010). It is the largest fault in the region characterized by dextral activity and normal slide faulting, and the seismogenic fault of the 1679 Sanhe-Pinggu M8 earthquake. In order to research conveniently, the rectangular area of fracture distribution was taken as the study area. The landform is generally a wide range of gently sloping terrain, with slightly higher in the northwest and lower in the southeast. The area is affected by two groups of faults: (1) NE trending faults, such as Xiadian, Gaoliying, Shunyi, Tongxian-Nanyua, Hexiwu and Baodi, etc, and (2) NW trending faults, including Nankou-Sunhe and Twenty Li Changshan faults.

Figure 1. Location of the study area in Eastern Beijing plain. The background is a digital Terrain Model comes from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) data. The Xiadian fault zone is adapted from Deng (2007).
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Data used in the study area include UAV DEM, SRTM DEM, SPOT 5 and historical documents. UAV DEM is generated by unmanned aerial vehicles photogrammetry and corrected by ground control point survey. In this study, it's used to compute the slope, aspect and topographic profile survey of fault scarps. SRTM DEM is the global digital elevation model data released by NASA in 2003, which is generated from Interferometric SAR images by Interferometric Synthetic Aperture Radar (InSAR) technology. There are four versions in total and the version 4.1 is employed to extract drainage system in this study. SPOT-5 is the fifth satellite in the SPOT series of CNES (Space Agency of France), placed into orbit by an Ariane launcher. It has two high resolution geometrical (HRG) instruments that were deduced from the HRVIR of SPOT 4. In this study, HRG2 image, with a 1 A produced level and a 10 m pixel size, is used to identify spatial distribution characteristics of fault scarps and pits. The image was taken on 16 April 2012 and its centre coordinates are N39.738130, E116.894152.

3. Methodology

Main methods employed in this study include remote sensing image analysis, field survey, micro-geomorphic feature analysis, historical documents analysis, evolution law analysis of fault scarp and stress field analysis of fault zone, as shown in Figure 2.

3.1. Micro-landform analysis based on remote sensing images and field survey

Although in plains there are few large geomorphic units, micro-topography, such as scarps, steep slope, shallow ditch, pit, depression, low-lying land, drum, ridge,
irrigation drainage lines, etc., still contains abundant information of tectonic movement. Different fault activity time and activity intensity related to different geomorphic features (Bhosle et al. 2009). Some fault scarps, steep slopes, shallow grooves and irrigation drainage lines can be recognized through visual interpretation of high-resolution remote sensing images, and also can be confirmed by field survey. Meanwhile, human activity influence and irrelevant geomorphic erosion can be excluded through field survey.

3.2. Geomorphic indexes analysis based on UAV DEM and SRTM DEM

Topographic analysis is an important method for understanding the characteristics of underlying geological activities. Three geomorphic indexes, including terrain profile analysis, slope, aspect analysis and drainage system, are applied in this study. UAV DEM has relatively high resolution and is especially suitable for analysis of little fault scarps, fine cross-fault topographic profiles survey, terrain slope and aspect analysis. However, based on cost consideration, drainage system extraction and analysis should better be done on SRTM DEM.

Drainage system is extracted from SRTM DEM through hydrological analysis model provided by ArcGIS10.0. The analysis model determines the direction of water flow in each grid cell by combining the eight neighbourhood grid codes of the central grid cell with the eight directions of the actual flow direction. This method can extract the low-lying Valley as drainage. Even dry riverbed can also be extracted. In order to effectively eliminate smaller drainage networks and retain large drainage networks, the flow rate greater than 800 m$^3$ is set as the extraction threshold. Finally, the four grades drainage network was extracted successfully.

3.3. The evolution rule of fault scarp

Based on abundant research data and a long research history, evolution rule analysis of fault scarp can reveal the relationship between time and geomorphic evolution rate. Tsimi and Ganas (2015) has already derived empirical relationships among triangular facet slope, facet height and slip rates along active normal faults with time going on in mountain area. In this study, the change of length, height and slope of Xiadian fault scarp are adopted to analyze the evolution law in plain area.

3.4. Stress field analysis of fault zone

Based on a theory of Pollard et al. (1982), Tang (1992) and Dai et al. (2006), mother faults in deep crust always diffuse into echelon fractures in shallow sedimentary layer due to the effect of tension and torsional stress, when local stress field changes. Each single fracture is arranged in parallel, but not in the same straight line. If the next one output on the left side, it is called the left column, and the same token, when outputting on the right is called the right column.

Mechanical analysis of rock mass suggests that normal stress $\sigma$ and shear stress $\tau$ can be produced when maximum principal stress and fracture propagation direction
at a certain angle $\alpha$. A possibility of whether a fault can be diffused as an echelon fracture is related to two parameters and to a pore-water pressure inside the rock mass. Use the following formula:

$$\zeta = \tau / (\sigma - p)$$  \hfill (1)

where $p$ is the pore water pressure inside the rock mass before fracture. When $\sigma$ increases to a certain extent, and then $\zeta$ correspondingly increases to a certain threshold, it will produce echelon fractures. Studies show that under normal conditions, a diffusion of several new faults into echelon arrangements from mother ruptures requires less energy to enter a new stress zones than a parent ruptures change alone (Pollard et al. 1982).

Stress field analysis can be used to identify the relationship between geomorphic distribution characteristics and fault activity under the control of stress field.

4. Results

4.1. Micro-landform analysis of the Xiadian fault zone based on remote sensing images and field survey

Up to now, a total of 14 linear structures have been discovered through image interpretation and field investigations, as shown in Figure 3. However, only two sections of the scarp are left, with a total length of about 1000 m, section 6 and 7, corresponding to Pangezhuang southern section scarp, which is described in previous literature (Meng et al. 1983; Xiang et al. 1988; Jiang 2000; Mao et al. 2010; Wang et al. 2014). At present, the maximum height of the two scarps is 1.1 m and 0.85 m respectively, and the maximum gradient is 40° and 30° respectively. The other 12 sections of the linear structure have been degraded to steep slopes or grooves. Obviously, the fault scarp is fading away with time going on.

4.2. Topographic feature analysis of the Xiadian fault zone based on UAV DEM

In order to identify the scarp landform more clearly, DEM data was produced by UAV technology in the local fault scarps area (Section 6 and 7 in Figure 3) in August 2016. The data was generated with PhotoScan software, through rapid stitching of aerial photography, orthophotos and 3D surface model (DSM), and then highly corrected by artificial removal of tall buildings, finally outputting a DEM with a precision of 0.3 m, as shown in Figure 4(c). Compared with the ZY-3 DEM (Filmed in December 2016, as shown in Figure 4(b)) and SRTM DEM (shown in Figure 4(a)) in the same area, the geomorphic features of the scarp can be identified more clearly.

In order to reveal more micro-geomorphic features of the fault scarp, slope gradient and slope aspect are analyzed by ArcGIS 3D analysis model on UAV DEM, as shown in Figure 4(e,f). There is a clear SSE direction of the slope aspect (represented by cyan strip) on the scarp of the fault in Figure 4(e), indicating that the slope aspect is consistent with the fault scarps’ geomorphic features. Furthermore, the most NEE and SWW slope aspect direction (represented by purple stripes and yellow stripes respectively) is
mainly consistent with the irrigation line, as shown in Figures 4(e) and 5. The maximum slope here is 87°, the minimum 0°, and the average 8° (the slope map is dominated by the purple tone, Figure 4(f)). The SE slope direction is mainly related to the gently tilted terrain formed by long-term activities of NE faults in Beijing plain.

In order to further analyze the spatial distribution of the fault scarp, nine parallel survey lines are designed in UAV DEM (Figure 6), perpendicular to the fault scarp, and then topographic profile is also generated (Figures 7 and 8). Scarps and trenches can be seen clearly when the 6th and 7th lines cross Xiadian fault. The drop of the scarp is about 1.5 m. Obviously, it's larger than the actual measurement (1.1 m) by field survey. This is mainly due to narrow span in field measurement of the scarp, without considering the drop that the scarp on both sides evolved into a steep hill. Whereas on UAV DEM, these degraded drops can be calculated intuitively. However, on the 4th and 5th lines across the fault, when the fault passes, the scarp has degenerated into a steep slope.

4.3. Analysis of the evolution rule of the Xiadian fault scarp

The evolution trend over the past 300 years can be described as the length, height and gradient changes of the scarp, as shown in Table 1 and Figure 9. In addition, the maximum scarp height and slope information of each period are all at the same location (Pangezhaung).
Figure 4. Comparative analysis of UAV DEM, SRTM DEM and zy-3 DEM. (a) SRTM DEM. (b) ZY-3 DEM. (c) UAV DEM. (d) Fault scarps overlay on the UAV DEM. (e) Aspect analysis based on UAV DEM. (f) Slope analysis based on UAV DEM.
According to Ren Shu’s investigation in Qing Dynasty and ‘Sanhe County Earthquake’ records, on the day after the earthquake, fault scarp is about 30 km long, and the maximum drop of the fault scarp, located at Pangezhuang village, is about 3.3 m. The scarp slope at that time is an obviously vertical drop. However, according to Wang (1981), the Xiadian surface fault is degraded to 10 km long, and the maximum vertical displacement of the fault scarp is 2.8 m high in Pangezhuang, with a slope of 60° approximately. A field survey conducted by Meng in 1983 also indicates that the Xiadian earthquake rupture is 10 km long, but the maximum vertical displacement in Pangezhuang is degraded to 2.75 m, with a slope of 58°. A study from Xiang et al. (1988) indicates the same surface fault length, but the maximum vertical displacement in Pangezhuang is degraded to 2.72 m, with a slope of 55°. Then Jiang (2000) also report a 10 km long surface fault, a maximum 2.5 m high drop and a 50° slope in Pangezhuang. Afterwards Mao et al. (2010) measured a 10 km total length of Xiadian surface fault by RTK, and record a maximum 2 m height drop and 45° slope in Pangezhuang. However, image analysis by Wang et al. (2014) shows the total length has been degraded to 1.7 km, with a maximum 2 m height drop and 42° slope in Pangezhuang. Until now, our field survey and remote sensing analysis indicates a 0.8 km total length, and a maximum 1.1 m height drop and 40° in Pangezhuang.

According to Meng et al. (1983), Xiang et al. (1988), Jiang (2000), Mao et al. (2010), and Wang et al. (2014), surface scarps in Dongliuhedun, Erliban, Jianglicun and Dongxingzhaung have all disappeared. As shown in Figure 3, on the first, second, third, fourth, fifth, eighth, ninth, tenth, eleventh and twelfth section, there are only shallow grooves.

4.4. Analysis of the characteristics of the drainage system on the Xiadian fault zone

Figure 10 shows that the flow direction of the drainage system in the study area is from northwest to southeast. From west to east, there are mainly Beiyun River, New
Chaobai River, Chaobai River, Baoqiu River, Ju River and Ju River’s tributaries. Interestingly, younger tributaries with lower grade have more obvious deflections when crossing the Xiadian fault. For example, on the middle segment of the Xiadian fault, there is a very obvious dextral deflection on the first and second grade drainage at B1, B2, A5 and A6 in Figure 10, a smaller dextral deflection on the third grade drainage at C1 and C2, and no obvious deflection on the fourth grade drainage when crossing the Xiadian fault at D1 and D2. Meanwhile, there are similar laws at D3, B3, A7, A8 and A9 on the northeast segment of the Xiadian fault. However, on the southwest segment of the Xiadian fault, there are consistent sinistral deflectons near
the Xiadain fault, furthermore, no significant difference in deflection cumulative quantity between different grades of drainage, as shown at D4, D5, B4, A1, A2, A3 and A4 in Figure 10.
5. Discussion about the mechanics mechanism

5.1. The relationship between micro-geomorphic features and the mechanical analysis of Xiadian echelon fault

Pits always appear between every two scarps or shallow grooves, as shown in Figure 3, is probably due to gradually excavating and exploiting sands based on the

| Measuring time (a) | The total length of scarp (km) | Maximum height of scarp (m) | Maximum slope of Scarp (°) | Source of data |
|-------------------|-------------------------------|----------------------------|---------------------------|----------------|
| 1679              | 30                            | 3.3                        | 90                        | Ren (1760)     |
| 1981              | 10                            | 2.8                        | 60                        | Wang (1981)    |
| 1983              | 10                            | 2.75                       | 58                        | Meng et al. (1983) |
| 1988              | 10                            | 2.72                       | 55                        | Xiang et al. (1988) |
| 2000              | 10                            | 2.5                        | 50                        | Jiang (2000)   |
| 2010              | 10                            | 2.5                        | 45                        | Mao et al. (2010) |
| 2014              | 1.7                           | 2.0                        | 42                        | Wang et al. (2014) |
| 2017              | 0.8                           | 1.1                        | 40                        | Field survey and remote sensing measurement |

Note: Data in the table are mainly summarized based on previous studies and field surveys.

Figure 9. Evolution law of the length, height and slope of the fault scarp with time going on (a) visual interpretation of the water system network, (b) automatic water system network.

5. Discussion about the mechanics mechanism

5.1. The relationship between micro-geomorphic features and the mechanical analysis of Xiadian echelon fault

Pits always appear between every two scarps or shallow grooves, as shown in Figure 3, is probably due to gradually excavating and exploiting sands based on the
original sand boil terrain. Furthermore, field survey discovered all pits extending to the northwest of the fault is mainly because the sand layer in the northwest side is high, which is related to rise of northwest plate and decrease of southeast plate of the Xiadian fault activity.

Figure 10. Visual interpretation and automated extraction of the water system network.
However, what does the combination of pits, fault scarps and shallow grooves tell us?

The combination of pits, fault scarps and shallow grooves probably reflects the change of regional stress field in Beijing plain. The main compressive stress field changed from NW direction to NEE direction since neo-tectonic period based on Wang (1979) and Li et al. (1982)’s survey. The change produced a rotation angle $\alpha$ between the NNE direction compressive stress field and NE trending fault distribution, and then put an increase in the $\zeta$ ratio, and eventually led to the formation of the Xiadian echelon fault, as shown in Figure 11.

5.2. Evolution law of the Xiadian fault activity with time going on

The historical analysis of fault scarps can help us understand the evolution law of fault landforms, and then infer the latest stick slip time of the Xiadian fault. The total length of the scarps, the maximum height of the scarps and the maximum gradient of the same place (Pangezhuang) all have a trend of accelerated disappearance with time going on, which reflects that human activities have accelerated the weathering and erosion of the surface. In accordance with this trend, all the scarps of the

Figure 11. Stress analysis diagram of Xiadian fault.
Xiadian fault will disappear in a few years. According to statistics, the seismic fault scarp or fault cliff roughly became a slope of about 27° after a thousand years (Wallace 1977). However, it can be predicted that the landform of the Xiadian fault can only exist for up to 340 years.

On the other hand, how many information can be excavated from the deflection analysis of drainage system? Based on Ouchi (2005)’s theory, younger and lower grade tributaries have steeper deflection than older and higher ones, probably because the younger and lower grade tributaries have less time and less traffic to adjust from deflection. By the same token, Cumulative quantity (1.6 km width) of the deflections is larger at B1 and B2 than at A5, A6, A7, A8 and A9 (0.8 km width), probably because the bigger and older drainage has longer time to accumulate the continuous offset. No obvious deflection at D1 and D2 is probably because the Nankou-sunhe fault passed through at D1 and D2 diluted the activity of Xiadian fault here. The same thing happened at D3 where the activity diluted by Twenty Li Changshan fault, and C1 and C2 also diluted by some unknown fault. The consistent sinistral deflectons on the southwest segment of the Xiadian fault indicate a left lateral strike slip movement, probably because the activity of Nankou-Sunhe fault changed the mechanical properties in southwestern segment of the Xiadian fault, and made it relatively independent, based on Che (1994) and Wang (1979)’s theory. If the age of drainage evolution can be determined through cosmogenic nuclide dating in the future, the slip rate of faults in different periods can be calculated by the deflection accumulation on different grade drainage.

6. Conclusion

Based on High precision topographic profile analysis, drainage system deflection analysis, combined with remote sensing interpretation, field investigation, previous research summary, geomorphic characteristics and their relations with fault activities are analyzed in detail. Meanwhile, stress field and landform evolution law of the Xiadian fault zone are also discussed. The distribution of micro-tectonic landform near the fault shows echelon arrangement, probably caused by the change of regional stress field in Beijing plain. There is a trend of acceleration in micro geomorphic evolution under the participation of human activities. Evolution trend analysis is very suitable for understanding the evolution of fault topography in areas with large amount of research results and a high precision current UAV DEM. The results of drainage system deflection analysis in Middle and Northeast segments of the Xiadian fault all reflect a general dextral deflection, which is related to the dextral strike slip activity of the Xiadian fault. However, in the Southwest segment of the Xiadian fault, consistent sinistral deflectons indicate a left lateral strike slip movement. These are consistent with previous research conclusions. Furthermore, younger and lower grade tributary has less accumulation and steeper deflection than older one, probably because younger and lower grade tributary has less time and less traffic to adjust, which is an important clue to analyze the intensity of strike slip activity in different periods.
Disclosure statement

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