Study on Intensity Anomaly of Great Earthquake in China

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SUMMARY
Earthquake intensity is an important measure for the extent of earthquake hazard. It is closely related to site condition, ground motion intensity and seismic wave propagation approach. Study on intensity anomaly has great theoretical significance and engineering value for earthquake resistant engineering. There are two intensity anomalies worth studying in great earthquake occurred in China. One is Yutian Ⅵ degree low intensity anomaly in Tangshan earthquake, the other is Hanyuan Ⅷ degree high intensity anomaly in Wenchuan earthquake. This paper reviews the study progress of intensity anomaly, makes a detailed summary of the geological structure background and damage characteristics about the two anomalous regions, and contrasts the anomalous generation mechanism. It also proposes further research on the generation mechanism and distribution law of intensity anomaly，which offers reference value for carrying out comprehensive research on intensity anomaly in the future.

Keywords: Tangshan earthquake Wenchuan earthquake Intensity anomaly Site condition Relative analysis

1. INTRODUCTION

Earthquake intensity is an important measure for the extent of earthquake hazard. It is closely related to site conditions, intensity of ground motion and the approach of earthquake wave propagation. Study on intensity anomaly has great theoretical significance and engineering value for earthquake engineering. There are two intensity anomalies worth studying in great earthquake occurred in China. The first one appeared in Tangshan earthquake, 1976, in Yutian, which is almost 50 km northwest from the epicenter. A low-intensity anomaly region with the intensity of Ⅵ degree was observed. This phenomenon was also observed in Sanhe-Pinggu great earthquake in 1679. The second appeared in Wenchuan great earthquake, 2008, in Hanyuan, which is almost 200 km from the epicenter. A high-intensity anomaly region with the intensity of Ⅷ degree was observed. It not only made severe damage to the old town in Hanyuan, but also caused huge life and economic loss. Studies on the anomaly generation mechanism, distribution law and earthquake damage features not only bear great theoretical significance and engineering value, but also provide guidance for the further study of intensity anomaly. It is emphasized that reasons for intensity anomaly are very complicated. Currently, site condition is generally believed to be the main reason to produce intensity anomaly. On the basis of summarizing the status quo of intensity anomaly research, this paper analyses and generalizes the tectonic setting, earthquake damage features and generation mechanism of intensity anomaly in Yutian and Hanyuan, and compares the generation mechanism of these two intensity anomalies from various aspects. This offers crucial reference value for carrying out comprehensive researches on earthquake intensity anomaly.

2. STATUS QUO OF EARTHQUAKE INTENSITY ANOMALY RESEARCH

China began its research work on intensity anomaly after Xingtai earthquake in 1966, and found that the seismic intensity contour map was not regular elliptical images after macro-inspection, but the irregular shapes that usually occurred in intensity anomaly areas (Diao and Li, 2006). The research on Xingtai intensity anomaly opened up a new area for site conditions influence on earthquake disasters and drew significant conclusions that site conditions do affect the intensity distribution. In other countries, the researchers did not realize that earthquake waves could reflect multiple times in weak foundations like lagoons and basins, and could increase the earthquake damage until the Mexico earthquake in 1985 and the Kobe earthquake in 1995. Currently, the methods to research intensity anomaly research mainly include macro-inspection and site testing after earthquake, analysis of earthquake records and numerical simulation.

2.1. Macro-Inspection and Site Testing

Macro-inspection after earthquake is the most important method for earthquake damage investigation. It could access the earthquake damage data timely and accurately, and provide first-hand information and materials to the research on intensity anomaly and earthquake damage distribution. Another important method for research is site testing, which applies ways like drilling holes, microtremor test and artificial blasting, so as to analyze and study regional geological structure, soil characteristics and earthquake wave propagation characteristics of intensity anomaly area. These two methods complement each other and are widely used in the previous research of intensity anomaly. For example, Yao *et al*. (1974) used the two methods to analyze how different soil, terrain conditions and broken fault impact the high-intensity anomaly area in Jingjing-Huolu (Yao *et al*., 1974). They thought that the intensity anomaly area was mainly caused by the total reflection of the crust interface shear wave, and the thick layer (about 20m), sand pebbles and aquifer had great impact on the intensity values, which was generally 1 to 2 degree higher than the intensity value in bedrock region. Since then, many other scholars have also adopted these methods to research intensity anomaly, such as Yutian intensity anomaly region in Tangshan earthquake, Ninghe intensity anomaly region in Tangshan earthquake and Hanyuan intensity anomaly region in Wenchuan earthquake (Tian *et al*., 1981; Yang and Liu, 1994; Gao *et al*., 2008; Bo *et al*., 2009; Qi *et al*., 2010). All in all, macro inspection and site testing after earthquake are good methods that can explain the intensity anomaly in a better way.

2.2. Analysis of Earthquake Records

Analysis of earthquake records is an empirical method to estimate site response, which is used actual earthquake data or microtremor data to analyze site response. It has crucial engineering application value, because of this method requires no detailed mastery of the nature of site soil, operates quite easily and bears definite physical meaning. This method can be categorized as traditional spectral ratio method (Borcherdt, 1970), generalized linear inversion method (Andrews, 1986) and horizontal-to-vertical spectral ratio method (H/V method, Nakamura, 1989). For instance, Bonilla *et al*. (1997) applied traditional spectral ratio method, generalized linear inversion method and H/V method respectively to analyze the site amplification effect of intensity anomaly region in San Fernando Valley basing on the acceleration time history records of aftershock in North Fields earthquake in 1994 (Bonilla *et al*., 1997). He found that the quality factor has significant impact on site response, especially at high frequencies, which finally theoretically explains the reason for abnormal site response in the valley. According to the data of principal earthquake acceleration records, Wang (2011) used traditional spectral ratio method which considering the impact of geometric attenuation to study the soil amplification effect near 25 strong motion stations in Weihe basin(Wang, 2011). He found that the Ⅶ intensity anomaly along the edge of Weihe basin from Baoji to Meixian in Wenchuan earthquake was mutually caused by basin edge effect and soil amplification effect. Thus, the analysis of earthquake records can explain the intensity anomaly well and could be truly reflect site response. However, due to the restriction of the layout of strong motion station, there are inadequate strong motion's records can be used for scientific research, which fact limits the application of this method in studying intensity anomaly.

2.3. Numerical Simulation

Although numerical simulation is widely applied in earthquake response analysis, it is less used to comprehensive analyze generalization mechanism of intensity anomaly. It mainly simulates and analyzes part of the factors that related to topography in anomaly region, soil conditions and other complicated characteristics. At present, there are many numerical analysis methods can be used to study factors affects ground motion like topography, soil condition and others, these include finite element method (FEM), finite difference method (FDM), frequency domain equivalent linearization wave method (WM), spectral element method (SEM) and boundary element method (BEM) (Liao and Li, 1989; Zhang and Chen, 2007; Hu *et al*., 2011). They are often used in combination because every one of them focuses on different aspects. For example, Olsen used finite difference method and finite-fault model to simulate directly at the phenomena that the earthquake damage are worse in Los Angeles Basin than other regions in nine different earthquakes, and adopted the peak velocity as indicator to assess the amplification effect, and simulated the three-dimension earthquake response of basin soil in different earthquakes, thus explained why earthquake damage was worse (Olsen, 2000). Li *et al*. (2003) used explicit finite element to simulate earthquake response of fault site under the input of pulse seismic wave (Li *et al*., 2003). He studied intensity anomaly in Tuanshu fault site and found that the amplification effect of soil site near bedrock foot of mountain is 2 to 4 times on average stronger than the site far away from bedrock foot of mountain or in the area of mountain bedrock. In general, numerical simulation method can offer better quantitative explanation of intensity anomaly according to earthquake response theory.

In addition, analytical method could also be used in intensity anomaly research because it is more reliable than numerical simulation when study the nature of such problems. It can not only verify the accuracy of the numerical method, but also provide evidence for calculation results of strong motion records analysis. But analytical method requires higher level of mathematical physics calculation, such as boundary conditions, constitutive relations, and calculates parameters. There are some restrictions on the calculation as well. Moreover, analytical method ignores how some factors, such as topography, soil characteristics and geological structure impact the intensity anomaly. Therefore, it seldom used in the study of intensity anomaly.

3. YUTIAN LOW INTENSITY ANOMALY REGION

Yutian low intensity anomaly region is located in the centre and north part of Yutian county, and an area of a low intensity of Ⅵ degree, while the intensity of most areas in Tangshan was Ⅶ degree (Tian *et al*., 1981; Yang and Chen, 1981). The region is an oval-shaped with a length of 30km from east to west, a width about 13km from south to north, covering an area of 300 km^2. Most of the houses in the anomaly region remained intact, only a few individual cracks or minor damage were observed. There was no obvious damage on the surface of the house.

3.1. Geological Structure of Yutian Anomaly Region

Judging from the geological structure, Yutian anomaly region is located at the south edge of Yinshan zonal structural belt and above Jixian broken concave of Yanshan fold belt, the west edge is Baodi uplift (Tian *et al*., 1981; Zhang and Zhu, 1981; Shou *et al*., 1983), and the south is Wuqing depression bounded by Baodi fracture. This region is a relatively stable geological unit where there is no deep fault and active fault going through. It is on relatively good alluvial foundation soils in this region. The Moho interface and Conrad interface depth of this region are 34km and 18km respectively. Depth contours of the two interfaces show a nearly east-west trending and the depth is increasing from south to north. There is no deep fracture that cuts Moho's or Conrad's interface. As far as the regional landform is concerted, this region crosses the ancient alluvial-pluvial fan of Huanxiang River, Yanshankou and Jiyun River (Zhang and Zhu, 1981; Shou *et al*., 1983). Areas that surround the region are alluvium mainly contain sand and clay. The terrain here is relatively flat. The north part of this region is the hilly part of southern Yanshan mountain foot and the south part are plains and depressions of broad retreat sea. The bedrock landform of the region is slope of transition zone from the north part of the bedrock hill to the south part of Yahongqiao depression. The overburden thickness is uneven and gradually increases from northeast to southwest. The thickness of the quaternary is 140m to 300 m in the northern, and increases to more than 700 m in the southern depression areas. The soil layer 50m below ground surface is mainly composed of gravel, sand soil and clay, which structure is formed in ancient times and is dense and solid.

3.2. Main Features of Yutian Low Intensity Anomaly Region

After the Tangshan earthquake, the investigation showed that most of the houses were moderately damaged in the centre and northern parts of Yutian county. The intensity of this region is Ⅵ degree, but the damage of houses in the surrounding areas was more serious and the intensity is Ⅶ degree, which indicated there were many geological phenomena like sand blasting, water inflow and ground deformation. The finding of task force's of Tangshan earthquake macro expedition also showed that the majority of the houses were in good condition with only individual old house's wall coating or roof falling, very few of the old houses roof collapsed. There was no obvious surface damage and sand blasting or water inflow. In addition, the earthquake damage investigation by Zhang *et al*. (1981) showed that the ratio of second-class houses that were severely damaged and collapse in the region was less than 2% (Zhang and Zhu, 1981). There was no brick chimney collapse, the damage of the surrounding houses was much worse. Ratio of the severely damaged and collapse was about 40% to 50%. Especially in the northern piedmont areas where there were all stone masonry structures, the ration was about 70%. Tian *et al*. (1981) did an earthquake damage investigation among in 740 villages in Yutian county and 25 villages in Fengrun county in 1980 (Tian *et al*., 1981). They calculated the damage index values based on data of investigation and drew the earthquake damage map of Yutian county. They used the damage index of 0.2 as the boundary of low-intensity anomaly region and concluded that region was an oval shape with a length of 30 km from east to west and 13 km from north to south in witch. The area is about 300 km^2. There is a good correlation between the region and aerial housing collapse envelope of Tangshan earthquake in 1976.

4. HANYUAN HIGH INTENSITY ANOMALY REGION

Hanyuan old town and surrounding areas were severely damaged in Wenchuan great earthquake, 2008. The intensity of this region was Ⅸ degree. The earthquake damage in Hanyuan new town was slightly insignificant and the intensity was Ⅶ degree. The comprehensive assessment showed that the earthquake intensity of Hanyuan county was Ⅷ, and was the only Ⅷ degree high intensity anomaly region in the Ⅵ degree regions. The intensity anomaly region was approximate in oval shape, with long axis of about 30 km is along northwest to southeast direction, and the short axis is about 17 km. The total area of this region was about 400 km^2 (Gao *et al*., 2008; Bo *et al*., 2009).

4.1. Geological Structure of Hanyuan Anomaly Region

Hanyuan anomaly region is located in the east edge of the north Hengduan Mountains part and is the transition zone between the Western Sichuan plateau and Sichuan basin. It belongs of part of the second-level unit of geotectonic in Daliangshan middle uplift region which is part of China west strong uplift region. This region has been experiences a significant uplift process since Quaternary, with the topography mainly characteristic of tectonic denudation mountain and valley or basin formatted by erosion and accumulation (Gao *et al*., 2008; Gu *et al*., 2009). As far as the regional geological tectonics are concerned, the region is located at the interchange of Central Sichuan block, Sichuan-Qinghai block and Sichuan-Yunnan block (Gao *et al*., 2008; Bo *et al*., 2009). The directions of faulted structure are NE, NW and NS. Most of the faults in this region are the general active faults of the Quaternary, distributing among the They are located in the southeast part of Xianshuihe fault and Haitang-Yuexi part of Daliangshan fault. They manifest obvious activity of the Holocene. Hanyuan old town is located at the interchange of Liusha River and Dadu River. It is the central part of Hanyuan syncline, where are all kinds of formations belonged to Paleozoic, Cambrian, Mesozoic, Jurassic, Cenozoic, Tertiary and Quaternary. The main buildings and residential area nearby in this region are located in the first-level terraces of Liusha River, first-level terraces of Dadu River and northern piedmont of Hanyuan valley basin. The soil in this region is loose and thick, similar to the weak basin site condition. Hanyuan new town is however located in Luobogang between Dadu River and Liusha River. The soil layer in this area is modern alluvial sediments and relatively denser, and contains lots of gravels, it belongs to second-class site (Gao *et al*., 2008; Gu *et al*., 2009).

4.2. Main Features of Hanyuan High Intensity Anomaly Region

According to the findings of China National earthquake disaster assessment team in Wenchuan Great earthquake, there are many housing types in Hanyuan county. In the Hanyuan old town two main housing types include old fashioned wooden frame structure, brick fracture and a small amount of frame structure. While in the Hanyuan new town the main housing type is brick and frame structure. The damage index of the old fashioned wooden frame structure in the old town is 0.75 and the damage index of brick and frame structure in the same region is 0.66. While in the new town the damage index brick and frame structure is 0.30, and the damage index of different housing types in other towns or rural sampling points varies. According to the Hanyuan earthquake investigation on 86 houses in the old town, the masonry buildings in the old town are damaged most seriously. The ratio of severely disrupted building is 44.93%. The bottom frame structure and multi-story reinforced concrete structure remain basically intact or moderately damaged. The ratio of severely disrupted building in this category is less than 15%. In addition, landslide and rolling stone can be found in Anle town and observed the wilderness of Liyuan town. Ground fissures and liquefaction of sand soil are observed in the field of Baiyan town. In short, the range of Hanyuan anomaly region is enormous (Gao *et al*., 2008; Boo *et al*., 2009; Lu *et al*., 2009) and severely damaged. The earthquake damage of housing in Hanyuan old town can be divided into several partitions. The damage index of the old town is 0.5 with an intensity of Ⅸ. The average damage index of other areas is 0.2, and the intensity is Ⅶ.

5. ANALYSIS OF EARTHQUAKE INTENSITY ANOMALY MECHANISM

Viewing from the aspect of engineering seismology, the reasons for intensity anomaly relate to many site conditions. Such as topography, soil characteristics, soil structure and fault structure. They also relate to the interference of earthquake wave. Study on anomaly mechanism and distribution pattern has significance and great value in engineering for urban planning, site selection and seismic design.

5.1. Analysis of Yutian Low Intensity Anomaly Mechanism

After Tangshan earthquake, the Yutian low-intensity anomaly drew much attention of scholars and researchers home and abroad. Tian *et al*. (1981) did some investigation of earthquake damage and geological structure in Yutian intensity anomaly region and collected a large amount of drilling holes data (Tian *et al*., 1981). They analyzed the mechanism of anomaly in direction of geological structure and soil structure, and then concluded that the two main reasons for the intensity anomaly. The first one is the tectonic setting stability in the region, because it bore the feature of simple structure and ancient exposed strata. The second reason was that the soil layer contained coarse particulate matter and clay. Liu *et al*. (1982) did drilling exploration in 26 villages in or nearby the Yutian intensity anomaly region (Liu *et al*., 1982). He acquired the soil histogram and seismic wave velocity data within 30m underground in these 26 sites, and adopted the average soil shear modulus as the index to analyze the differences in different areas inside or outside the abnormal region. The result showed that there were two reasons for the low intensity anomaly. First, the soil layer within 20m underground had relatively high average shear modulus. And second, the soil layer contained more coarse grained soil. Between 1987 and 1988 China and Japan did a joint research on deep geological structure and shallow soil characteristics in Yutian. Researchers arranged 6 artificial blasting points and 83 vibration observation points in Yutian abnormal region and areas nearby, and completed lots of tests, such as artificial seismic wave measurements in large areas, shear wave velocity test and ground pulse test. The results showed that the good basement structure, soil structure and soil condition of the abnormal region were the main reasons for less earthquake damage. According to the data of the shallow and deep geological structure, the wave velocity and artificial seismic wave measurements, Yang *et al*. (1995) adopted the methods of seismic microzonation to study Yutian low intensity anomaly (Yang and Liu, 1995). They found that greater thickness of overlying soil and special soil wave velocity structure were the main reasons for intensity anomaly. In summary, good regional tectonic setting, the special soil structure and good soil characteristics are the main factors contributing to the low intensity anomaly phenomenon in Yutian.

5.2. Analysis of Hanyuan High Intensity Anomaly Mechanism

After Wenchuan great earthquake, the Hanyuan high-intensity anomaly drew much attention to scholars and researchers home and abroad. At present, we believe that site conditions, like as resurrection of Beihou mountain landslide and special soil structure what amplifies the seismic ground motion are the main reasons (Bo *et al*., 2009). Beihou mountain landslide is located in the north of Hanyuan county, it is formed in late Tertiary or early Quaternary, and is an ancient landslide which in large scale and slide repeatedly. The landslide looks like a round-backed armchair with the posterior wall repeatedly collapses and slides. The leading edge is ancient accumulation and extends to the underground of Hanyuan old town. After the earthquake, strong ground motion reenergized the resurrection of Beihou mountain landslide and cracking phenomena like trailing edge crack, surface water flow, sand liquefaction and retaining wall cracking were also observed. Based on the field investigation data, we adopted finite element method to estimate the natural period of landslide and compared it with the predominant period of strong motion near seismic monitoring station in Hanyuan county. The result showed that the value of the two periods was close to each other, thus the landslide could resonate by earthquake, and made the earthquake damage more serious in Hanyuan old town. In addition, the Quaternary sediment in Hanyuan old town was thick and contained fluvial gravel, sand and clay sediment, it also had special soil structure in which silt and silty clay deposited directly on the great angular gravel and drift pebbles. According to the drilling hole data on the site, we used one dimension soil layer seismic response analysis method to study the seismic response of special soil layers when the thickness of gravel layer changed within a certain range. The result shows that the gravel layer in which middle coarse sand and silty clay deposited significantly amplified the ground motion. Especially when the thickness of gravel layer reached 16m, the amplification factor of the surface peak acceleration would reach 3. Which fact caused the high intensity anomaly in Hanyuan old town. Moreover Gao *et al*. (2008) preliminarily studied the possible reasons for high-intensity anomaly by analyzing the main factors of Hanyuan high-intensity anomaly region (Gao *et al*., 2008). They thought that site condition, earthquake source process and spatial distribution of energy release were the main reasons for high-intensity anomaly. They also thought that seismic wave propagation and vibration isolation effect or excitation effect of fault fracture belt might also be the reasons for the anomaly. In summary, Hanyuan high-intensity anomaly was the result of multiple factors, among which the resurrection of Beihou mountain landslide, site conditions and effect of special soil structure on seismic ground motion were the main factors.

5.3. Mechanism Comparison between Yutian and Hanyuan Intensity Anomaly

Yutian and Hanyuan drew much attention of scholars and researchers because they both had great influence among all earthquakes in China and were characteristics of obvious ground motion. The mechanism comparison between them not only has an important theoretical significance and great value in engineering, but also provides a reference for further study of intensity anomaly.

First of all, judging from the regional geological tectonic back ground, Yutian is located in the relatively stable geological unite which bear no deep fault and active fault through. Yutian also has relatively good diluvium soil. Meanwhile, Hanyuan is located at the interchange of Central Sichuan block, Sichuan-Qinghai block and Sichuan-Yunnan block, the faults developed greatly in the region and had distinctive Holocene activities. Secondly, judging from the soil characteristics of the abnormal region, the soil layers within 20m underground in Yutian are dense and contain more coarse grained soil, while Hanyuan old town is located at the interchange of Liusha River and Dadu River, the soil in the region is loose and thick, similar to the weak basin site condition. Thirdly, considering soil structure, Yutian has special soil layer in which the hard soil layer covers the relatively soft soil layer, but in Hanyuan the relativ ly hard soil layer cover the soft layer. Finally, the topography of Yutian county is generaliy flat and changes very little. While the topography of Hanyuan is mainly tectonic denudation mountain and valley or basin formatted by erosion and accumulation and also is influenced by the resurrection of Beihou mountain landslide. Therefore, whichever point of view, the seismic conditions of low intensity anomaly region are better than the ones of high intensity anomaly region. This not only provides references for site collection, but also promotes further research of intensity anomaly conditions.

6. CONCLUSIONS

The appearance of intensity anomaly region is very common in destructive earthquake damage investigation. Study on the generation mechanism and distribution law of typical intensity anomaly region not only has important theoretical significance and great value in engineering, but also plays a guiding role in intensity anomaly research. In general, the research of intensity anomaly is not comprehensive at present. Most of them are based on macro-earthquake damage data, regional tectonic and local site condition. The research findings cannot fully explain the reasons for intensity anomaly, and most of them are qualitative analysis, only a few are quantitative analysis, especially they lacks quantitative analysis based on strong motion records. Therefore, further research should be based on the summaries of macro-damage characteristics in typical intensity anomaly region. Comprehensive consideration of should be taken many factors, such as focal mechanisms, regional geological structures, buried bedrock topography, bedrock ground motion inputs, local site conditions, seismic wave propagation characteristics and soil nonlinearity. We can establish the seismic response analysis model, which can take into account the nature of soil, soil structure, bedrock topography and regional tectonic setting respectively, so as to carry out seismic response analysis in intensity anomaly region. Then we summarize all possible reasons for intensity anomaly based on all the factors above, and according to the results of strong motion records analysis, qualitative analysis and quantitative analysis, we amend the results and find the prediction method of intensity anomaly which can be used in engineering. This can not only promote the research of intensity anomaly mechanism, but also provide basic information for disaster assessment of intensity anomaly region, urban planning, site collection and seismic design.

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