Simultaneous Inversion of Earthquake Relocation and Velocity Structure in the Shanxi–reservoir\textsuperscript{1} Wenzhou

Zhong Yuyun\textsuperscript{2}, Zhang Zhenfeng\textsuperscript{2} and Kan Baoxiang

Earthquake Administration of Zhejiang Province\textsuperscript{3} Hangzhou 310013 China

Using the data of P-wave travel time recorded at the Shanxi-reservoir seismological network and Zhejiang and Fujian local networks\textsuperscript{4} we implemented a simultaneous inversion of earthquake relocation and velocity structure and determined the new locations of earthquakes in the Shanxi-reservoir. The results show that: (1) the overall epicenter distribution is NW directed\textsuperscript{5} and the Shanxi reservoir induced seismicity has a close relationship to the Shuangxi–Jiaoxiyang fault; (2) the focal depth of the Shanxi reservoir induced seismicity is 5.4 km in average\textsuperscript{6} less than the average focal depth in the South China earthquake zone; (3) the focal depth is shallower on the reservoir shore and deeper in the reservoir inundation area. At the beginning of the reservoir induced seismicity\textsuperscript{7} the focal depth increased gradually. This may be due to the gradual penetration of water into a larger depth that induced deeper earthquakes; and (4) there is a low P-wave velocity anomaly in the study area\textsuperscript{8} located at the intersection of multiple faults in the reservoir inundation area. The Shanxi reservoir induced seismicity mostly occurred in this low-velocity anomaly zone. This may be related to water penetration.

Key words: Shanxi reservoir; Velocity structure; Simultaneous inversion; Earthquake location

INTRODUCTION

The Shanxi reservoir is located at the upper reaches of Feiyun River in Wenzhou city\textsuperscript{9} southern Zhejiang Province\textsuperscript{10} and the dam is situated 1 km from Shanxi town in the valley of the upper reaches\textsuperscript{11} 35 km from Wencheng county and 115 km from Wenzhou city. The absolute height

\textsuperscript{1} Received on May 10\textsuperscript{12} 2010. This project was supported by the National Key Technology R&D Program (2008BAC38B03-01-05) and the Earthquake Scientific Research Project (200708020) \textsuperscript{13} China.
of the dam is 156.8 m, length is 308 m and maximum storage is \(18.24 \times 10^8 \text{m}^3\). The highest water level reaches 154.75 m. The rock strata in the dam site is rhyolite porphyry which is a paleo-volcanic neck phase product. The dam is steel reinforced concrete face rockfill. The project was commenced in 1966 and was completed in December 2001. The reservoir began storing water in May 2000 and since the \(M_{1.3.5}\) earthquake occurring in the reservoir area on July 28 2002 there has been seismic activity there every year. As of December 31 2009 300 earthquakes with \(M_\text{L} \geq 2.0\) had been recorded including 241 earthquakes with magnitude between 2.0 ~ 2.9, 46 earthquakes with magnitude between 3.0 ~ 3.9 and 13 earthquakes with \(M_\text{L} \geq 4.0\) the strongest of which was a \(M_{4.6}\) earthquake occurring on February 9 2006. According to the measurements taken by the digital seismologic network of Zhejiang Province all earthquakes took place in the reservoir area around the border between Baoyang village of Taishun county and Shanxi Wencheng county in the upper reaches of the dam with epicenters concentrated in a small diamond-shaped block (about 7 × 11 km) surrounded by a NW-NE trending fault and its surroundings. Research on the relocation and velocity structure of Shanxi reservoir earthquakes is of great significance to the cognition of seismogenic structure crust media seismogenic background and earthquake mechanisms and to the trace analysis and forecasting of seismic sequence.

Accuracy of hypocenter location is mainly affected by factors such as the layout of seismologic networks, seismic phases available to the location, accurate reading of arrival time of seismic waves and crustal velocity structure models taken. Under the conditions of existing earthquake location methods and seismic surveillance at present using high-precision crustal velocity structure models is critical to the improvement of accuracy of earthquake location. With the development of seismic tomography technology the establishment of numerous 3D crustal velocity structure models will provide a good basis for earthquake location.

Inversion of location of the Shanxi reservoir earthquake sequence and crustal velocity structure is performed in this paper by using simultaneous inversion of hypocentral location and velocity structure. By studying the distribution characteristics of seismic sequence and velocity structure features of the hypocentral region the seismogenic structure and seismogenic environment of Shanxi reservoir earthquakes are investigated.

1 EARTHQUAKE LOCATION

1.1 Data

When the \(M_{1.3.5}\) earthquake took place in July 2000 there was no seismologic station within the range of 50 km from the epicenter only the Wenzhou station and Qingyuan station within a 100 km range so the location accuracy was low. Location accuracy of almost half of the earthquakes was of class II namely the epicenter error was between 5 km ~ 15 km. In 2003 2 digital telemetry seismic networks the Shanxi network and the Huangtan network were established and put into operation in April 2003. An earthquake occurred on February 4 2006 after which 4 mobile stations were set up in the epicentral area namely Xinpu Lianyun Baoyang and Yunhu stations. Including the three existing stations i.e. Shanxi Huangtan and Taishun station there are 7 stations within a range of 30 km to the epicenter. The instruments installed in the stations are all FSS-3 type three-component short-period seismographs which form a small-scale reservoir seismologic network. Monitoring ability and location accuracy of the network were greatly improved. In 2007 some reconstruction work was done to mobile stations and the location of some stations changed. By using regional network data of Zhejiang and Fujian
provinces and the P-wave arrival time data obtained before the reconstruction of Shanxi reservoir mobile stations simultaneously inversion of hypocentral location and velocity structure of earthquakes occurring in July 2002 ~ June 2007 is performed in the paper.

In order to make sure that there are enough rays for coverage in 3D velocity structure inversion, earthquakes with clear records at more than 3 stations are chosen. 313 earthquakes with 2267 Pg waves arrival time data are selected in this paper and seismic phase identification of records with travel time residuals greater than 1.0s is re-conducted. Travel time distribution with epicenter distances is shown in Fig. 1.

Fig. 1
P-wave travel time for inversion

1.2 Location Method

Aki (1976) proposed the method of using travel time data of regional earthquakes to determine 3D velocity structures of crust below the network. And according to Liu Futian et al. (1989) the tomography method for velocity image reconstruction can boil down to solving a matrix equation

\[ \delta t = A \delta v + B \delta X \]  

In this formula, \( \delta t \) denotes vector of travel time residuals, \( \delta v \) the disturbance vector of velocity at model’s grid nodes and \( \delta X \) the hypocenter parameter disturbance vector. \( A \) denotes the partial derivatives matrix of travel time to velocity and \( B \) denotes partial derivatives matrix of travel time to hypocenter parameters.

In the process of simultaneous inversion of hypocentral location and velocity structure, travel time residuals are caused by the disturbances of hypocenter parameters and velocity. According to fundamental formulae (1) of simultaneous inversion, velocity parameters and hypocenter parameters are inter-coupled with each other. Inversion of two kinds of parameters with different dimensions simultaneously in the same equation not only results in a numerical instability algorithm increase but need large quantities of computer memory and machine-hours. Therefore parameter separation must be performed. The orthogonal projection operator proposed by Liu Futian (1989) decouples velocity parameters and hypocenter parameters, that is, de-composing equation (1) into two equations to solve the velocity parameters and hypocenter parameters respectively.

\[ (I - P_B) A \delta v = (I - P_B) \delta t \]  
\[ B \delta x = P_B (\delta t - A \delta v) \]

In these formulae, \( I \) denotes identity matrix, \( P_B \) orthogonal projection operator on space image \( R \).
from \( R_m \) to \( B \) which relates to hypocenter parameters. The analysis after decoupling of velocity parameters and hypocenter parameters shows that determination of velocity disturbance quantity is not directly related to disturbance quantity of hypocenter location but only to its initial value while the disturbance quantity of hypocenter location is significantly related to velocity disturbance quantity. Despite the influence of the seismologic network layout seismic phases available to location and accurate readings of arrival time of seismic waves earthquake location accuracy is also affected by velocity structures. According to formula (2) and (3) velocity structure parameters in the research area are firstly determined in the process of inversion and then hypocenter parameters thus eliminating the uncertainty of velocity structure and its effects on location accuracy. Therefore earthquake location quality can be effectively improved by simultaneous inversion of hypocenter location and velocity.

### 1.3 Initial Velocity Model

Tectonically Shanxi reservoir is situated at the southeast coastal fold zone of the South China fold system. The crustal structure of the South China fold system is divided by the Zhenghe-Haifeng fault. On the west of the fault (Wuyi uplift) the crust is similar to the lower Yangtze sag being 2-layer structured; and on the east of the fault (southeast coastal fold zone) the crust consists of 3 layers of media with a depth of 29.5 km (Wang Chunyong et al. 1995; Wang Chunyong et al. 1998). There is more research on the crustal velocity structure of the southeast coastal fold zone. Liao Qilin et al. (1990) obtained the two-dimensional velocity structure of the Ningde-Yongchun section. Wu Jiansheng et al. (1995) collected deep seismic sounding data from 28 survey points in the eastern Yangtzi-South China structure and obtained a velocity structure histogram of this area. Zheng Xinsen et al. (2003) obtained the crustal structure of each tectonic unit in South China by using more than 30 pieces of deep seismic sounding data in South China and statistically merging data on the basis of tectonic units. Crustal velocity hierarchical models developed by different researchers vary. Considering the multiplicity of inversion of deep seismic sounding data and the inhomogeneity of crustal structures and after a comprehensive analysis a one-dimensional reference velocity model is selected for use in this paper as shown in Table 1.

<table>
<thead>
<tr>
<th>Depth from the surface (km)</th>
<th>0</th>
<th>3</th>
<th>17</th>
<th>29.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (km/s)</td>
<td>5.5</td>
<td>5.57</td>
<td>6.2</td>
<td>6.81</td>
</tr>
</tbody>
</table>

This study adopts the method developed by Zhou Longquan et al. (2006). The research area selected in the inversion calculation is a rectangular region with a range of (27.0° ~ 28.0°N, 118.8° ~ 120.8°E). Due to the distribution of earthquakes and networks earthquakes near the research area borders are fewer thus grid spacing is relatively larger while earthquakes are rather concentrated near the center of the research area and thus grid spacing is relatively small. In the plane direction the research area is divided into a total of 20 grids of 5 × 4 each.

## 2 LOCATION RESULTS AND ANALYSIS

Of the 313 earthquakes 306 earthquakes occurred in the Shanxi reservoir area and after re-location hypocenter parameters of 297 earthquakes were obtained. In simultaneous iterative inversion of velocity structure and hypocenter parameters the initial travel time RMS residual is 0.42s and after iteration the RMS residual reduces to 0.3s. On average location deviation is 0.37 km in the latitudinal direction, 0.34 km in the longitudinal direction and 0.42 km in the
vertical direction.

Fig. 2 is the epicenter distribution map of the same number of earthquakes before and after re-location. It is clear that the epicenter distribution becomes more concentrated after re-location and shows a NW-trending distribution on the whole. The major axis of epicenter distribution is about 11 km, the minor axis about 3 km. For earthquakes occurring before 2005, the epicenter location after re-location changed greatly with a difference of 1.4 km on average before and after the relocation. After February 2006, especially after the installation of the mobile stations in the epicentral area on February 8, the difference in distance of epicenter location from the relocations significantly reduced with an average of 0.7 km, which indicates that location accuracy and network layout are closely related to each other.

Faults exposed in the reservoir area are mainly of 2 sets of structure, the NW-trending and the NE-trending structure, and a small number of SN-trending and EW-trending faults (Fig. 2). There are 14 faults within the reservoir area, most of which are superficial faults and developed in the upper Jurassic volcanic rocks and lower Cretaceous volcanic sedimentary formation. The NE-trending faults mostly reverse strike slip faults, strike N40° ~ 60°E and dip NW with dip angles of 60° ~ 80°. The fault zone is about 20 km ~ 30 m in width in which compressional lenticles and cleavage are developed. The faults were formed in the Pre-Mesozoic and with shallow erosion in the crush zone cut by NW-trending faults. The NW-trending faults which are reverse faults and reverse strike-slip faults, strike N40° ~ 50° W and dip NE with dip angles of 60° ~ 70°. Compressional lenticles, gouge and schistosity are developed in the fault zone. The faults were formed in the late Yanshanian period. After re-location, the dominant direction of epicenter distribution is consistent with the strike of NW-trending Shuangxi-Jiaoxiyang fault which passes through the reservoir area and all earthquakes are distributed in the WS side of the fault. According to the “Work Report on the Study of Reservoir-induced Earthquake Prediction for the Shanxi Reservoir Project, Feiyun River, Zhejiang Province,” the Shuangxi-Jiaoxiyang fault strikes N60°W and dips SW with a dip angle of 80°. The fault plane is smooth and undulated. The fault extends 20 km long including a segment of 7.5 km inundated by the reservoir water.

Focal depths of 297 earthquakes after re-location are all less than 10 km, with a maximum of 9.5 km, and an average depth of 5.4 km among which focal depths of 11 earthquakes are less than 3 km amounting to 4% of the total and focal depths of 254 earthquakes are between the range of 3.0 km ~ 6.9 km, amounting to 86% of the total. Zhang Guomin et al. (2002) have examined the focal depth distribution patterns in the Chinese Mainland and in each seismic zone. Their study results show that the focal depth of the South China seismic area is 10 km on average deeper than that of the Shanxi reservoir earthquakes, which may be due to the reason that the seismicity in the Shanxi reservoir area is reservoir-induced thus its earthquake mechanism is different from that of tectonic ones. Especially earthquakes with $M_L \leq 3.0$ mostly took place in 2002 the beginning of reservoir-induced earthquakes. The focal depths underwent a process of gradually deepening in the early years which may have been caused by the penetration of reservoir water into the deeper part that induced earthquakes at a greater depth.

Fig. 3 displays the focal depths distribution along AB section and CD section in Fig. 2b. AB is parallel to the strike of the Shuangxi-Jiaoxiyang fault and CD is generally vertical to the strike of the Shuangxi-Jiaoxiyang fault. The results show that earthquakes are asymmetrically V-shaped distributed along AB section. There are relatively fewer earthquakes at the point A (the NW end) on the northern shore of the reservoir with focal depths less than 5 km. At the entrance to the reservoir area, the focal depths of earthquakes are 5 km, which is consistent with the actual situation.
Fig. 2
Epicenter distribution of Shanxi reservoir-induced earthquakes before and after re-location
(Black lines denote faults, blue lines rivers and reservoir, blue triangles station locations, and AB CD denote respectively profile location made along dominant direction of epicenters and its vertical direction)

Fig. 3
Focal depth distribution along section AB and section CD and velocity structure
(Numerical values on the right of color codes denote P-wave velocity values, unit: km/s)

Fig. 4
Test result of P-wave detecting plate at different depths
(Blue lines denote faults, circles test results of detecting plate, solid rims positive velocity disturbance quantity, and hollow rims denote negative velocity disturbance quantity)
reservoir area, earthquakes become very dense and focal depths increase rapidly with the deepest focal depth located at the intersection of the Shuangxi-Jiaoxiyang fault and a near SN-trending fault and its neighboring segments. This area is also where the first earthquake took place in 2002. Then focal depths gradually become smaller to the direction of southeast, and at the vicinity of point B in the south coast of reservoir focal depths are all less than 5 km. In order to analyze earthquake distribution in the plane vertical to the Shuangxi-Jiaoxiyang fault section CD is made near point A and only earthquakes within 1 km from both sides of section CD are projected on the section plane. Fig. 3 shows that earthquakes at the WS end (point C) are relatively deep and earthquakes at the EN end (point D) are relatively shallow. According to the distribution of focal depths it can be speculated that the NW-trending Shuangxi-Jiaoxiyang fault may be the seismogenic fault of the Shanxi earthquake sequence.

3 ANALYSIS OF CRUSTAL VELOCITY STRUCTURE AND SEISMOGENIC BACKGROUND

Resolutions of solutions of different depths are estimated by using detecting plate in this paper. The fundamental principle is that on the basis of given velocity model parameters, disturbance of grids alternated with positive and negative is processed and then according to actual ray coverage theoretical travel time data is obtained by forward calculation. Certain random error is then added to theoretical travel time data which as observation data is to be inverted. Then inversion method is required to be consistent with the method in the process of actual imaging. Lastly similitude between inversion results and the detecting plate is compared as estimation of solution reliability. Disturbed values taken in this paper are ± 3% of the normal values. Fig. 4 provides resolutions of solutions at depths of 3 km and 17 km respectively. The figure shows that on the detecting plate at depth of 3 km (especially within an oval frame) both amplitudes and positive and negative phases are well restored therefore resolutions of solutions at this depth are satisfactory. Disturbance scheme of positive and negative phases at the depth of 17 km are not well restored which may be due to the fact that less rays pass through this depth. For focal depths of the Shanxi reservoir induced earthquakes are all less than 10 km and most epicenter distances from stations are less than 20 km.

Fig. 5 provides P wave velocity distribution at the depth of 2 km, 5 km and 8 km and epicenter distribution within 2.0 km upper and lower of the corresponding depths. In the inversion model the initial velocity given at a depth of 2 km is 5.57 km/s and inversion results show that there is an abnormal low P-wave velocity zone at depth 2 km with abnormal rate of 4%. The low-velocity zone is located roughly in a triangular area and its vicinity which is surrounded by the near SN-trending fault the near EW-trending fault and the NW-trending Shuangxi-Jiaoxiyang fault. This low-velocity zone is in the reservoir inundated area. Earthquakes at this horizon (focal depths are less than 4 km) are mostly within the P-wave low-velocity zone only a small number of earthquakes are in the reservoir shore area where the transition of low velocity to high velocity occurs. As the depth increases the range and abnormal values of P wave low velocity zone both gradually decrease and at the depth of 5 km the abnormal rate decreases to 2% or so. The dominant direction of epicenter (within the range of 3.0 km ~ 7.0 km) distribution at this horizon is also NW which is consistent with the strike of the Shuangxi-Jiaoxiyang fault. Despite most earthquakes being outside the low P-wave velocity abnormal zone flooded by the reservoir there are still a small number of earthquakes that are in the P-wave velocity variation gradient belt on the reservoir bank. At the depth of 8 km the P-wave abnormal zone disappears and at this horizon (focal depths are greater than 7 km) earthquakes are all in the reservoir inundated zone where the first earthquake took place in 2002.

Earlier studies show that earthquakes mostly take place in the high-low velocity transition
P-wave velocity at different depths and earthquake distribution after re-location
(Values on the right side of color codes denote P-wave velocity values\[\text{unit: km/s}\]; others are the same with that in Fig. 2)

zone\[\text{there are many moderate and minor earthquakes distributed in area with relatively high velocity in particular. However, the results of this study show that the Shanxi reservoir induced earthquakes mostly take place in the low velocity abnormal zone in the reservoir inundated area. According to the studies by Guo Gui’an et al. (1992), the Xinfengjiang reservoir induced earthquakes occurred mostly in low velocity areas and few earthquakes in high velocity zones which may be due to the close relationship between reservoir-induced earthquakes and water penetration.}

4 CONCLUSION

Adopting the simultaneous inversion method of hypocenter location and velocity structures and using P wave travel time data provided by regional seismological networks of Zhejiang, Fujian Province and Shanxi reservoir network, hypocenter parameters of Shanxi reservoir induced earthquakes and velocity structure of reservoir area are re-determined. The results show that:

(1) Epicenter distribution becomes more concentrated after re-location and it shows a NW-trending dominant distribution as a whole. The dominant distribution direction of epicenters is consistent with the strike of the Shuangxi-Jiaoxiyang fault which passes though the reservoir area and all earthquakes are distributed at the SW side of this fault. According to hypocenter distribution traces along the dominant distribution direction and its vertical direction it can be speculated that the NW-trending Shuangxi-Jiaoxiyang fault is possibly the seismogenic fault of the Shanxi reservoir earthquake sequence.

(2) Focal depths of Shanxi reservoir induced earthquakes are all less than 10km with an
average of 5.4 km smaller than that of earthquakes in South China where the average focal depth is 10 km. This may be because Shanxi reservoir earthquakes are reservoir-induced earthquakes and the seismogenic mechanism is different from that of tectonic earthquakes.

(3) Earthquakes are asymmetrically V-shape distributed along the section of the NW-trending seismic band and earthquakes on north south coast of reservoir are relatively superficial with focal depths of less than 5 km. Focal depths of earthquakes in reservoir inundated zone are relatively deeper. In particular earthquakes with $M_c \leq 3.0$ mostly took place in 2002 the beginning of reservoir-induced earthquakes. Also focal depths underwent a process of gradually deepening in the early years which perhaps resulted from the gradual penetration of reservoir water into a deeper depth that further induced deeper earthquakes.

(4) There is a low P-wave velocity abnormal zone in the research area located roughly in a triangular zone with its vicinity surrounded by the near SN-trending fault the near EW-trending fault and the NW-trending Shuangxi-Jiaoxiyang fault. The Shanxi reservoir induced earthquakes mostly took place in this low velocity abnormal zone. This area is not only where the first earthquake took place in 2002 but also the area with greater focal depths of earthquakes occurring after 2006. This may be related to the penetration of reservoir water after impoundment.

ACKNOWLEDGEMENTS

The authors would like to extend heart-felt thanks to Dr. Zhou Longquan China Earthquake Networks Center who provided the computation program for this study.

REFERENCES


About the Author

Zhong Yuyun born in 1966 a research professor of Earthquake Administration of Zhejiang Province is engaged mainly in the research of earthquake forecasting. E-mail: Hzyuyun@163.com