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Research Article

Influence of the Three Gorges Reservoir Impoundment on Xiannvshan Fault Activity

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Since the initial impoundment and commissioning of the Three Gorges Reservoir in June 2003, seismic activity surrounding the reservoir region has undergone substantial changes. Leveraging geological and hydrogeological data from the Three Gorges Reservoir area, this study statistically analyzes the historical water level and earthquake catalog within the reservoir. By examining the correlation between reservoir water levels and earthquake frequency, the relationship between seismicity along the Xiannvshan fault and water level is analyzed. Additionally, the ArcGIS software is employed to evaluate the spatial pattern of earthquake epicenters during the filling of the Three Gorges Reservoir, with the goal of elucidating the impact of water impoundment at the Three Gorges on the activity along the Xiannvshan fault. The results demonstrate the following. (1) There is a complex process of "continuous loading, permeation and saturation, rebound and rebalancing" in the crust of the reservoir head area during the impoundment of the Three Gorges Reservoir area, and the activity of the Xiannvshan fault is closely related to the reservoir water level. (2) At the 135 m impoundment stage, Xiannvshan fault activity is mainly affected by reservoir water level and is positively correlated with reservoir water level. At the 156 m impoundment stage, reservoir water load is still the main influencing factor of Xiannvshan fault activity, but the permeability of reservoir water is enhanced in this stage. (3) The earthquake epicenters near the northern section of the Xiannvshan fault are clustered during the 175 m experimental impoundment stage. During the continuous loading stage, the reservoir water load is still the main control factor of the Xiannvshan fault, and the seismic activity is significantly enhanced. From November 2010 to November 2013, during the permeation and saturation stage, the dominant factor of Xiannvshan fault activity changed from reservoir water load to reservoir water infiltration along the Xiannvshan fault. The period from 2013.11 to 2014.5 was a vertical rebound stage, and the infiltration effect of reservoir water had a more significant impact on Xiannvshan fault activities.

1. Introduction

The Three Gorges Project of the Yangtze River is the largest water hydraulic engineering in China at present and is one of the largest reservoirs in the world. It plays an important role in water storage, power generation, flood control, and other fields, and its impact on the surrounding environment has been widely concerned by scholars at home and abroad [1]. The Three Gorges Reservoir officially began to store water in 2003, and the water level elevation was raised from 135 m to 175 m by using the method of graded storage. As one of the main faults in the Three Gorges reservoir area, the Xiannvshan fault occurred many small-to-moderate earthquakes near its northern section after impoundment. The research shows that the activity degree of the Xiannvshan fault has a strong correlation with the water storage capacity of the Three Gorges Reservoir. Therefore, it is necessary to study the impact of reservoir water storage on the activity of the Xiannvshan fault.

In existing studies, most researchers observed the trends and patterns of reservoir-induced seismicity through graphical statistics of water level and earthquake data. Extensive research has been done by international scholars on the interaction between fault activities and reservoir impoundment. Gahalaut [2, 3] calculated that the sustained seismicity at India's Koyna reservoir may relate to the geometry of fault distributions and stress transfer. Their work revealed the mutual influence between reservoir loading and regional tectonic fractures by considering their combined effects. In 2017, Yadav et al. [4] constructed a 3D seepage model in the Koyna–Warna region of India to observe the relationship between pore pressure diffusion and reservoir-triggered earthquakes. They considered factors like pore pressure diffusion and fault reactivation and found that the pore pressure diffusion velocity along faults in earthquake-prone layers was 2-6 m/day. The time for the triggering water head to diffuse along faults to the earthquake-concentrated layers lagged behind the maximum water level time by two months. D. Gough and W. Gough [5] studied the RIS at Lake Kariba and stated that either the release of preexisting stress due to water loading or the increase in pore pressure resulted in the earthquakes, but they thought that the former mechanism was more likely the cause of the earthquakes. Silva et al. [6] combined geophysical observations and hydrogeological data to evaluate local structural effects on reservoir-triggered earthquake magnitudes; however, they only considered qualitative structural impacts without quantitative geometric modeling. K. Gahalaut and V. K. Gahalaut [7] used satellite imaging to detect fault activity changes before and after impoundment, but their understanding of underlying mechanisms was still inadequate. Catherine et al. [8] utilized high-precision GPS measurements to confirm the low strain rates in the Koyna–Warna region, but they failed to capture subtle postimpoundment deformations.

In addition, scholars have also expounded and studied other reasons. Carder [9] proposed that the reservoir water load of Lake Mead in the United States caused new activities in the reservoir area with stable faults. Kanamori and Rivera [10] proposed that the reservoir load can promote and inhibit the occurrence of earthquakes of normal fault type and reverse fault type, respectively. Hainzl and Ogata [11] used the ETAS model to quantitatively analyze the fluid-induced effect and believed that the internal stress triggering and external stress change are the fundamental causes of underground fluid-induced seismic activity. Gupta et al. [12] systematically analyzed the seismic sequence characteristics of some typical reservoir-induced earthquakes and believed that the reservoir-induced earthquake foreshock b value > aftershock b value > local natural earthquake b value. Zoback and Hickman [13] studied the induced earthquakes at Monticello Reservoir, South Carolina, and suggested that failures of preexisting fractures and the instability of a reverse fault due to an increase in pore pressure triggered the earthquakes.

In recent years, domestic scholars have made a lot of achievements in the study of the Three Gorges. Wu et al. [14] believed that the main impact of fault activity on the reservoir area is reservoir-induced earthquake through the survey, statistics, and theoretical analysis of active faults in the west route of the South-to-North Water Transfer Project. Li et al. [15] carried out statistical analysis and analogical analysis on the distribution law, mutual relationship, and activity of faults in the Xiaolangdi Reservoir area of the Yellow River. Ma et al. [16] took fault activity as an earthquake-inducing factor and used the grey clustering method to predict and evaluate the reservoir earthquakes in the Three Gorges region of the Yangtze River. Cheng et al. [17] studied the relationship between the Zipingpu reservoir and the Wenchuan earthquake by calculating the relevant characteristics of the fault under the reservoir impoundment. Shi and Cao [18] calculated the fault Coulomb stress state in the Longmen Mountain area by using the improved Coulomb stress calculation method and pointed out the shortcomings of the traditional calculation method. Wu et al. [19] based on the finite element method of linear elastic theory, established the three-dimensional finite element model of the head area of the Three Gorges Reservoir, simulated the changes of the total displacement field and the tectonic stress field of the northern section of the Xiannvshan fault after the impoundment, and believed that when the Three Gorges Reservoir was at the high-level impoundment (175 m), the three groups of main stress values in the deep part of the northern section of the Xiannvshan fault and Jiuwanxi fault increased sharply compared with those before the impoundment, the three groups of main stress values increased, and the shear stress and shear strain energy were easy to concentrate; it is easy to accelerate the instability of the northern segment of the Xiannvshan fault and induce the reservoir earthquake. Yao et al. [20] and Zhang et al. [21] believed that the earthquakes here are typical reservoir-induced earthquakes, which are closely related to water infiltration, pore pressure, and water level fluctuations. The majority of the micro and small earthquakes are caused by karst collapse, mine collapse, bank reformation, superficial unloading, and so on. The larger earthquakes are related to the fault structures to some extent. Zhang et al. [22] relocated the earthquakes in the TGR region with a double difference method, and they proved the important role of pore pressure diffusion in RIS with time.

Based on the research background of the influence of the impoundment of the Three Gorges Reservoir on fault activity, the geological and hydrogeological data of the Three Gorges Reservoir area, and the historical water level data of the Three Gorges Reservoir area and the historical earthquake data in the reservoir area, this paper discusses the influence of the impoundment of the Three Gorges Reservoir on fault activity, mainly from the historical water level of the Three Gorges Reservoir area and the historical earthquake in the Three Gorges Reservoir area.

2. Research Area

Located in the hinterland of the Chinese Mainland, the Three Gorges of the Yangtze River is the general name of Qutang Gorge, Wu Gorge, and Xiling Gorge. The Three Gorges Reservoir Area is located in the middle of the Yangtze River basin and belongs to the upper reaches of the Yangtze River. The reservoir area starts from the Hanjiang Plain in the east, connects the Sichuan-Hubei Plateau in the south, borders the Daba Mountains in the north, and ends in the Sichuan Basin in the west. The length of the reservoir area is about 600 km, the maximum width is up to 2000 m, and the total area is about 10000 km^2. The whole reservoir area extends from Chongqing to Yichang City, Hubei Province. The coordinate range of the reservoir area is 109.4°-110.4° E, 30.6°-31.4° N. The Three Gorges reservoir area has a subtropical monsoon climate. It is hot and rainy in summer and cold and dry in winter. Controlled by the climate, the Three Gorges Reservoir often forms floods in the rainy season, and the Three Gorges Reservoir can play the role of flood blocking and peak cutting and significantly intercept the upstream flood. The dam site of the Three Gorges Reservoir Area is located in Sanduping, Yichang City. There are many fault zones around the reservoir area. These fault zones extend each other and cut each other on the surface, forming a series of block geological structure combinations of positive and negative. The Xiannvshan fault is located in the NW direction of the Three Gorges reservoir area and the southwest of the Huangling anticline. It is the key observation area of seismic activity in this area and the main research object of this paper. The fault has been active since the neotectonic movement and is one of the important faults in the Three Gorges reservoir area. The Xiannvshan fault is about 19 km away from the nearest point of the Three Gorges dam site. The complex structural characteristics of the northern segment of the Xiannvshan fault are derived from multiple stages of deformation. The basic evolution process can be summarized as the Yanshanian Huangling anticline uplift, forming a large dip dextral extensional fault. The nature of regional stress in the Himalayan period changed, forming a dextral reverse fault [23, 24], pushing the Triassic and early strata over the Tertiary strata [25]. According to data, the Xiannvshan fault is still active. According to data and published documents, since the impoundment of the Three Gorges Reservoir, a large number of small earthquakes have occurred around the Xiannvshan fault, which can be roughly divided into tectonic earthquakes, mining earthquakes, and collapse earthquakes. Effective identification of these minor earthquake types is of great significance to the study of seismic activity characteristics and trend near the Xiannvshan fault [26]. The Xiannvshan fault shows a clear linear structure. The geographical location map of The Gorge Reservoir Area—Xiannvshan—is shown in Figure 1.

3. Seismic Activity and Xiannvshan Fault

The Three Gorges Project has played a huge role in water storage, flood control, power generation, navigation, and other aspects. However, because the Three Gorges Reservoir is located in Hubei and Chongqing, with complex terrain conditions and frequent extreme weather such as rainstorm, it has been a natural geological disaster-prone area in history and has induced many natural disasters of different degrees during the operation of the Three Gorges Reservoir. Among them, the surrounding earthquakes caused by the impoundment of the Three Gorges Reservoir are the focus of many scholars and the main research direction of this paper.

Existing research results show that reservoir-induced seismicity is the result of the combined effects of natural environmental factors and human factors. The natural environment factors are mainly the degree of geological tectonic activity and the development of faults where the reservoir is located. The human factors are mainly reservoirs of different scales in terms of storage capacity constructed by damming rivers, as well as the amount of water stored. The majority of earthquakes in the study area were the reverse faulting and strike-slip faulting types, associated with the heavily fractured, deep-crustal northwest-trending Fairy Mount fault. The maximum principal stress is in a subhorizontal orientation of 290°, which is in good accordance with the hydraulic fracturing experiments [27]. This indicates that the seismicity in the study area is under the control of the regional stress field. A great number of earthquakes in the study area occurred on the reverse and strike-slip Fairy Mount faults, although it is commonly believed that reservoir-induced earthquakes mainly occur along normal faults and only rarely on strike-slip faults [28, 29]. Roeloffs [30] and Segall and Fitzgerald [31] suggest that water impoundment can trigger reverse faulting in a compressive environment. For regions where reverse faulting dominates, the weakening effect of water on the fault plays a key role in triggering earthquakes [32]. The weakening effect will extend to a wider area if the water is applied periodically over a long period.

Reservoir water storage increases the pore pressure in the reservoir area and surrounding aquifers, causing changes in local stress states, and rapid rises and falls in water levels disrupt rock stress equilibrium, inducing microearthquakes and fault activity. In studies of reservoir-induced seismicity and storage capacity, it is believed that the probability of seismicity for reservoirs with less than 1 billion m^3 capacity is less than 5%, while for those above 1 billion m^3 capacity, it is about 14%, indicating a direct relationship between reservoir seismicity and capacity.

Since the 1950s, many seismic monitoring systems and seismic observation points have been set up around the Three Gorges reservoir area. The monitoring shows that from 1959 to 2003, the number of earthquakes in the Three Gorges reservoir area was very small. Before the impoundment, the Three Gorges Reservoir area was mainly dominated by small- and medium-sized earthquakes, with epicenters spread throughout the whole study area. The seismicity of the whole study area was not high, the frequency of earthquakes was low, and the intensity was small. The distribution of earthquakes in the reservoir area was the typical point. During this period, the seismicity in the reservoir area basically represented the background value of natural earthquakes in the region. However, since the impoundment began in 2003, tens of thousands of earthquakes have occurred in and around the Three Gorges Reservoir area. In addition, seismic activities in the study area have different performances in three different impoundment stages. In general, during the whole impoundment process, the frequency of earthquakes in the Three Gorges Reservoir has increased with the rising of the impoundment water level, and there have been many earthquakes of magnitude 3.0 or more. And the focal depth gradually deepened, and the epicenter continued to approach the northern segment of the Xiannvshan fault. A huge amount of reservoir water load leads to the instability of karst caves, mine caves, shallow rock strata,

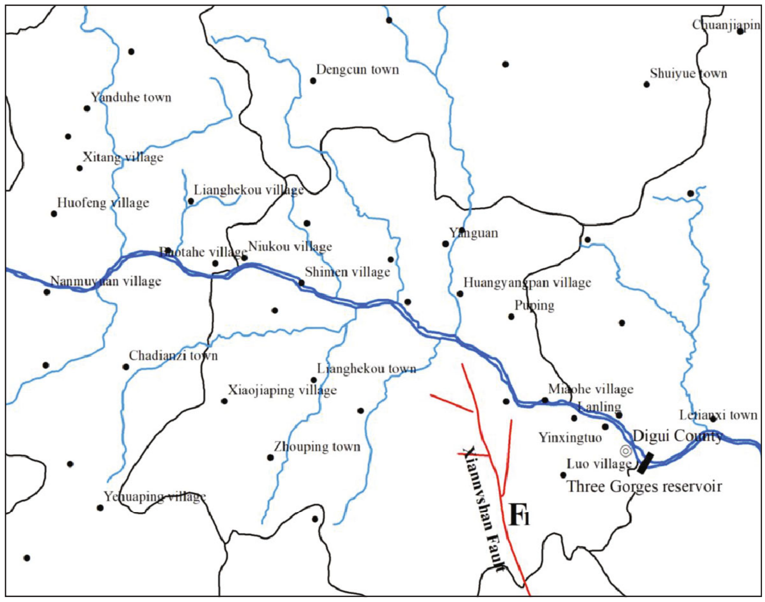


Figure 1: Geographic location of the Three Gorges Reservoir area—Xiannvshan fault.

and fault zones along the Yangtze River near the reservoir, leading to earthquakes.

According to the published documents, the crust of the Three Gorges Reservoir Area is stable, and the seismic level in the whole reservoir area is not high. It belongs to the moderate earthquake background of relatively typical type 6. Most of the earthquakes occurred are natural tectonic or subsidence earthquakes formed by the activities of the surrounding faults.

After the reservoir began impounding, the number of earthquakes in the reservoir area increased significantly. As the water level in the reservoir rose, the frequency of earthquakes also increased, manifesting as reservoir-induced seismicity. Near the Xiannvshan fault, seismic activity was centered around the fault, showing an expanding trend outward, with epicenters gradually approaching the reservoir area. During impoundment, as reservoir water infiltrated the surrounding geological environment, faults around the reservoir would be affected as follows: On the one hand, the reservoir water penetrating into the deep cracks of bedrock can offset part of the positive pressure acting on the fracture surface, and at the same time, the friction coefficient of the fracture surface can be reduced due to the physical and chemical effects caused by the reservoir water infiltration, thus greatly reducing the antisliding strength of the fracture surface. Under a certain initial stress, the rock mass is unstable, and an earthquake occurs [33]. Huang et al. [34] found that water infiltration and diffusion reduces the rock strength when the rock is immersed in water for a long time. The rocks in the vicinity of the Fairy Mount fault are permeable limestone and sandstone. The dissolution of limestone leads to heterogeneity of water infiltration and local stress concentration in the rock mass. This stress difference may induce some micro to small earthquakes [35]. As the pore pressure increases, the strength decreases. When the change in strength becomes negative, rupture occurs [36]. The protracted seismicity has a close relationship with the continuous water-level changes [36]. The chemical effect of water is another reason for induced earthquakes [37]. The clay minerals in the fault zone will be saturated under continuous water action. The softening and weakening effect of the water results in the reduction of the friction coefficient and the shear strength on the fault plane. The friction coefficient for pure clays may be lower than 0.2 under water action if the fractures were initially dry [38, 39]. On the other hand, the swelling of clay minerals also produces additional stress that contributes to the deformation development and the instability of the rock mass.

4. Relationship between Reservoir Water Level and Seismic Activity

Since 1959, the Three Gorges Reservoir has possessed certain seismic monitoring capability. This study is based on the frequency of earthquakes before and after impoundment (2000-2003) in the reservoir area and divides the period after impoundment (2003-2021) into 135 m impoundment stage (2003.06.01-2006.09.20), 156 m impoundment stage (2006.09.20-2008.09.27), and 175 m experimental impoundment stage (2008.09.27-2021.12.31). The influence of the Three Gorges Reservoir impoundment on the activity of the Xiannvshan fault was studied.

In this study, the period from January 1, 2000, to May 1, 2003, is selected as the study period before the reservoir impoundment. The change of earthquake frequency during the impoundment period is shown in Table 1.

It can be seen from the analysis in Table 1 that before the impoundment, the earthquake frequency in the Three Gorges Reservoir area is mainly microearthquakes, with large randomness and low frequency, indicating that the occurrence of earthquakes in the region is not affected by the outside world.

Table 1: Changes of earthquake frequency during impoundment period.

Impoundment period	Earthquake frequency 0-0.9	1.0-1.9	2.0-2.9	>3
Before impoundment (2000.01.01-2003.05.01)	83	51	6	1
During 135 m impoundment (2003.06.01-2006.09.20)	915	144	16	1
During 156 m impoundment (2006.09.20-2008.09.27)	1868	280	20	1
175 m experimental impoundment stage (2008.09.27-2009.12.31)	1446	232	33	1

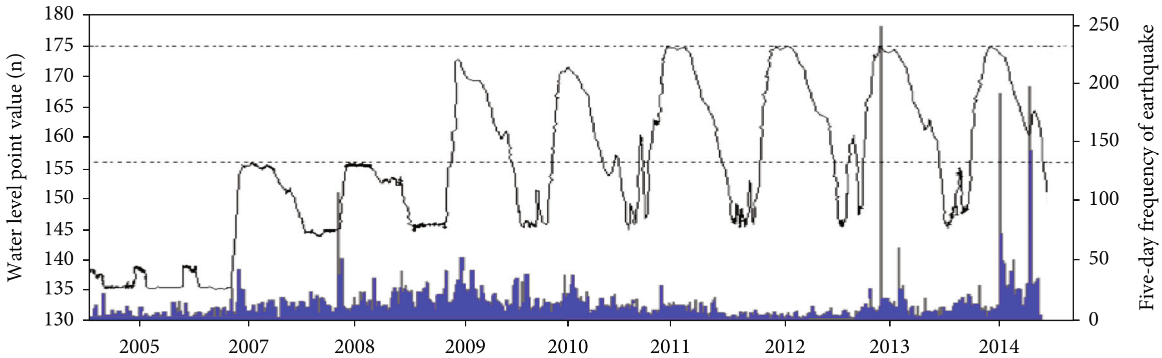


Figure 2: Relation between the water level in the Three Gorges Reservoir and the 5-day frequency of the earthquake.

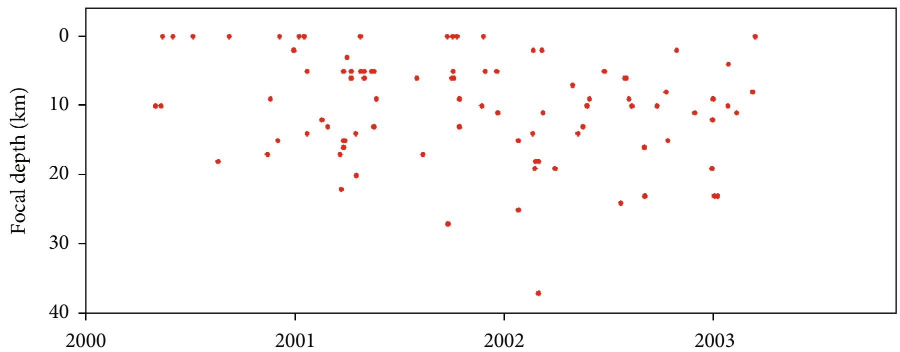
From June 1, 2003, to September 20, 2006, the 135 m impoundment stage of the Three Gorges Reservoir lasted for 39 months. This impoundment is the experimental impoundment stage of the Three Gorges Reservoir and the first impoundment of the Three Gorges Reservoir. During the impoundment period, the network monitored 1076 earthquakes, 8 times the number before the impoundment, of which 915 earthquakes with magnitude 0-0.9 occurred, accounting for more than half of the total number of earthquakes. However, the distribution law of this earthquake is still not strong, only showing that the load effect of the reservoir area at this stage is relatively limited.

From September 20, 2006, to September 27, 2008, the 156 m impoundment stage of the Three Gorges Reservoir lasted for 24 months. The first impoundment of the Three Gorges Reservoir was from 135 m to 156 m. The number of earthquakes near the Xiannvshan fault increased rapidly. A total of 2169 earthquakes were monitored, and during this time period, an outbreak period of reservoir earthquake was formed, and the earthquake was distributed in strips near the Xiannvshan fault, with a trend of continuous expansion. It can be seen from the data that when the water level elevation reaches 156 m, the earthquake frequency shows a high-frequency increase, and most of them are concentrated in the rising and falling periods of the water level, which indicates that the change of the load in the reservoir is the main reason for the occurrence of earthquakes in this area, which belongs to the reservoir-induced earthquake.

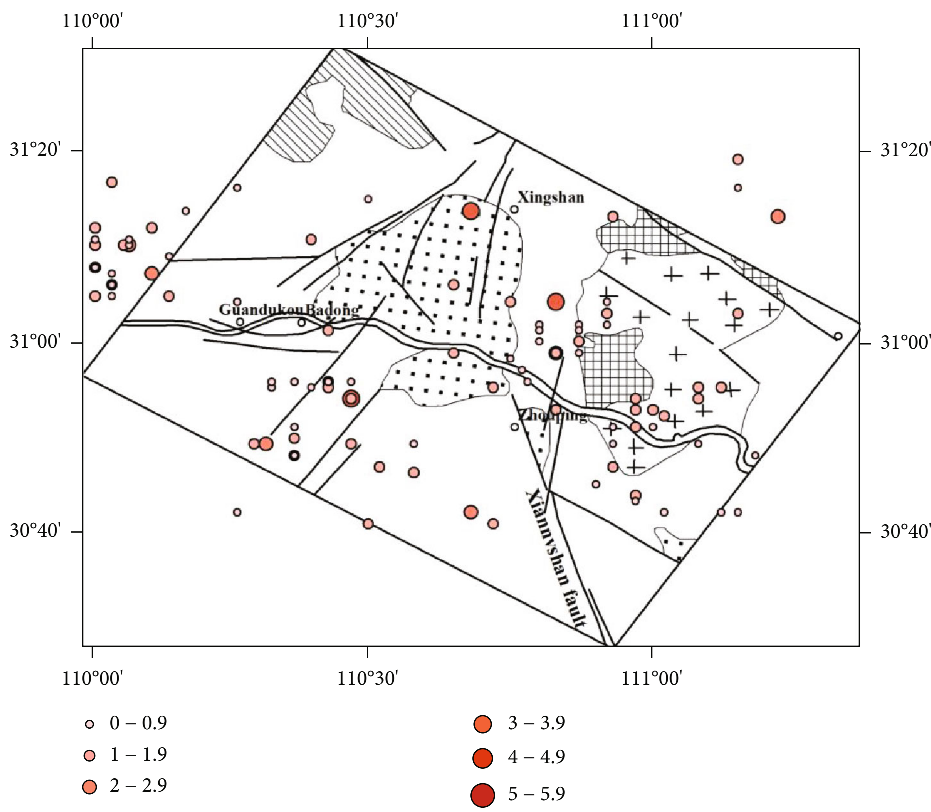
From September 27, 2008, to December 31, 2009, the 175 m experimental impoundment stage of the Three Gorges Reservoir lasted for 15 months, after which the water level fluctuated back and forth between 156 and 175 m. The location of the earthquakes also moved northward. Although the elevation of the water level in the reservoir area rose during this period, the frequency of earthquakes decreased all the time, indicating that the load in the reservoir decreased, and the effect of the earthquake caused by the load gradually decreased.

4.1. Relationship between Seismic Activity and Structure. From the data and seismic frequency, it can be concluded that the seismic activity is closely related to the structure of the Three Gorges Reservoir and its surrounding areas in the time period before and after the impoundment. According to the published documents, the crust of the Three Gorges Reservoir Area is stable, and the seismic level in the whole reservoir area is not high, belonging to a relatively typical medium earthquake background. Most of the earthquakes occurred are natural tectonic or subsidence earthquakes formed by the activities of the surrounding faults.

Since the impoundment of the Three Gorges Reservoir, the number of earthquakes in the reservoir area has increased significantly, and with the increase of the elevation of the water level in the reservoir, the frequency of earthquakes has increased, which is manifested by the earthquake caused by the reservoir load. The area where the earthquake occurred is centered on the Xiannvshan fault, showing a trend of continuous outward expansion, and the epicenter of the earthquake is constantly close to the reservoir area. During the impoundment process, along with the continuous infiltration of the reservoir water into the geological environment outside the reservoir, the fault zone around the reservoir area is also constantly changing, and the softening of the fault medium will further lead to the gradual emergence of geological problems around the reservoir area, which may lead to earthquakes caused by fault activity.



(a) Source depth of reservoir area before impoundment

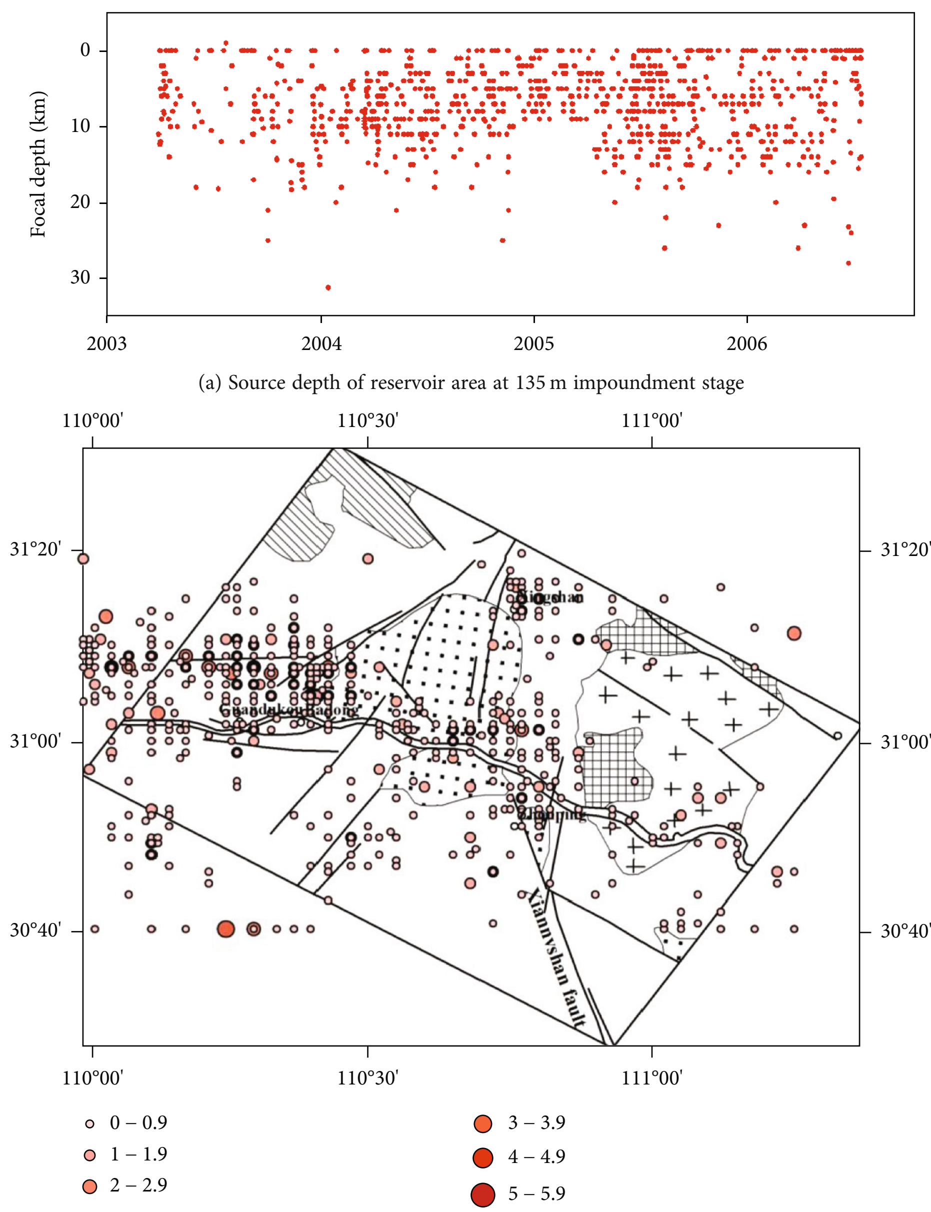


(b) Epicenter distribution in reservoir area before impoundment

Figure 3: Source depth and epicenter distribution in reservoir area before impoundment.

4.2. Impact of Impoundment on Xiannvshan Fault Activity. Due to the lack of ultramicroseismic data after May 2014, the data density is low and has no statistical significance, so the data from January 18, 2000, to May 1, 2014, were selected to draw the 5-day frequency relationship between the water level in the Three Gorges Reservoir area and the earthquake to analyze the response of the northern segment of the Xiannvshan fault to the impoundment of the Three Gorges Reservoir. Before June 2003, the seismic activity in the area was relatively small, basically representing the background value of the natural earthquake in the area. See Figure 2 for details.

From June 1, 2003, to September 20, 2006, it was within the 135 m impoundment period of the reservoir area. With the rise of the water level in the reservoir area and the increase of the water load in the reservoir area, the frequency of earthquakes in the region increased on the 5th day, and a 1.3 magnitude earthquake occurred at 15:36 p.m. on June 7, 2003, with a focal depth of 11.0 km. Within about a week after the earthquake, the earthquakes in the region were mainly microearthquakes of magnitude 0.0-0.9, while earthquakes of other magnitudes were not significantly enhanced. These microearthquakes occurred in a week after the water level in the reservoir area rose to 135 m, and with the water level stabilizing, the frequency of the subsequent earthquakes on the 5th day decreased significantly, but the overall frequency of the earthquakes on the 5th day was still higher than that before the impoundment on June 1, 2003. According to Simpson and Leith [40], it may be classified as "fast response" earthquake. The maximum magnitude of 3.2 occurred at 11:14 on



(a) Source depth of reservoir area at 135 m impoundment stage

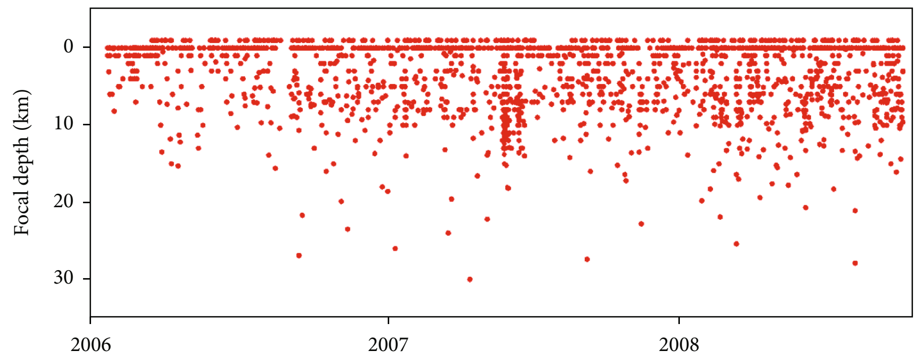
(b) Epicenter distribution in the reservoir area during the 135 m impoundment stage

Figure 4: Source depth and epicenter distribution in reservoir area during 135 m impoundment stage.

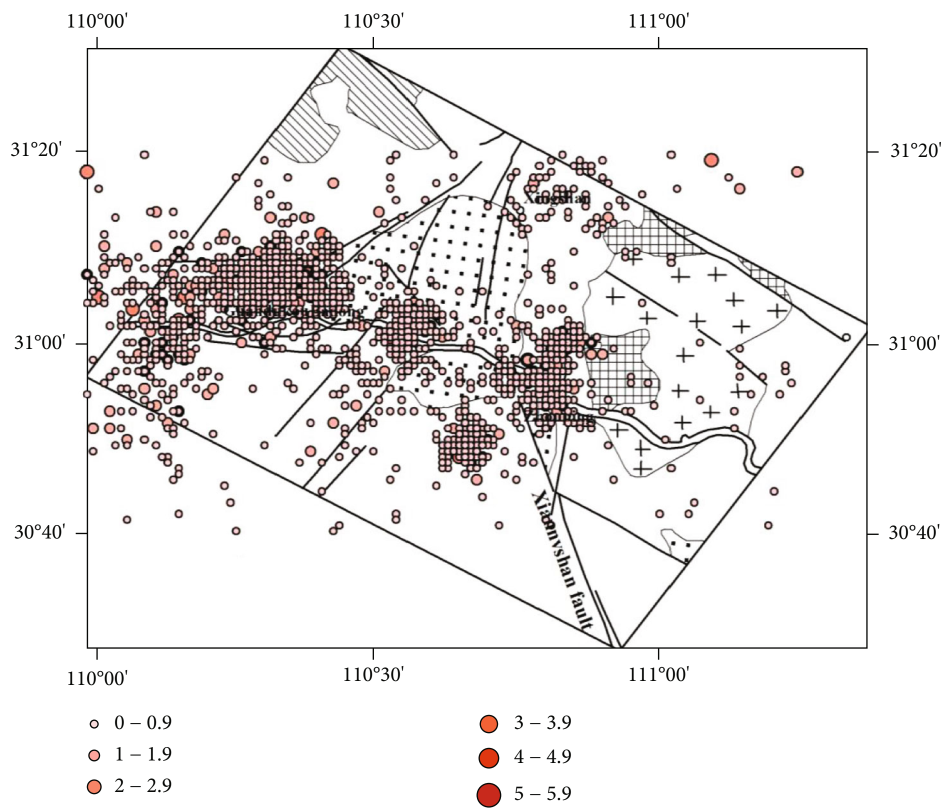
September 13, 2004, and the focal depth was 0 km. In general, during the 135 m water storage period from June 1, 2003, to September 20, 2006, the 5-day frequency of earthquakes was significantly higher than before.

From September 20, 2006, to September 27, 2008, it was a 156 m impoundment period in the reservoir area. Along with the rise of water level, the reservoir water load increased, and the seepage effect increased. At 15:30 p.m. on September 22, 2006, a 1.8 magnitude earthquake occurred, with a focal depth of 0 km, and accompanied by multiple microseisms. After the water level rose to 156 m, the 5-day frequency of earthquakes in the region increased significantly, continuing the characteristics of rapid response. The maximum value of the 5-day frequency of earthquakes was 108. At this stage, the impact of reservoir water storage on seismic activity was still dominated by reservoir water load, and the permeability of reservoir water was also enhanced at this stage.

During the 175 m experimental impoundment period of the reservoir area from September 28, 2008, to now, the annual variation of the water level in the reservoir area can reach 30-40 m, which further deepens the impact of the reservoir water load on the seismic activity. The seismic activity in the region shows the characteristics of overall magnitude increase and frequency increase. On the whole, the 5-day frequency of the earthquake is still higher than the previous stage. Yao et al. [20] believe that during the 175 m experimental impoundment stage of the Three Gorges, there is a complex process of "continuous loading-seepage saturation-rebound and rebalance" in the crust of the region. The water level in the reservoir area



(a) Source depth of reservoir area in 156 m impoundment stage



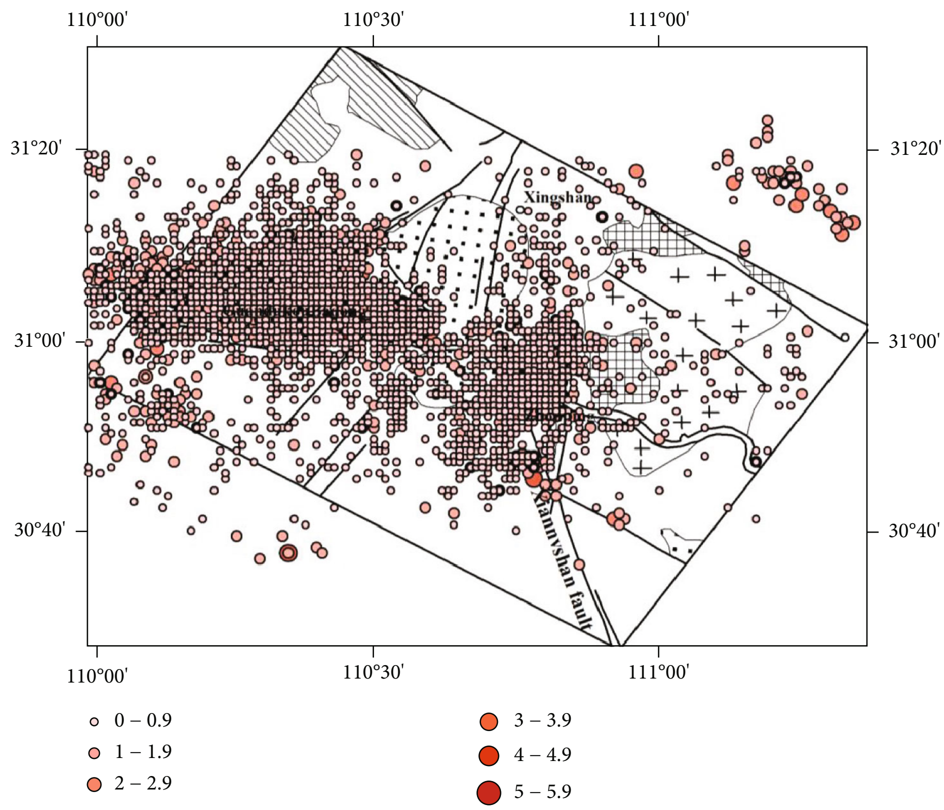
(b) Epicenter distribution in reservoir area during 156 m impoundment stage

FIGURE 5: Source depth and epicenter distribution in reservoir area during 156 m impoundment stage.

has risen continuously since September 28, 2008, and reached 175 m for the first time in October 2010, which is in the stage of continuous loading. The seismic activity in this stage is positively correlated with the water level in the reservoir area. It can be seen that with the rise of the impoundment water level in different stages of the reservoir area, earthquakes in the reservoir area also became strong, the magnitude of the earthquake increased, and the frequency of the earthquake on the 5th day increased. During the period from November 2010 to November 2013, the shallow crust of the reservoir area has been nearly saturated with water under the continuous infiltration of reservoir water, which is the stage of infiltration and saturation. At this time, the relationship between reservoir impoundment and seismic activity changes, and the overall level of seismic activity in this stage is lower than that in the 156 m impoundment stage. At this stage, the magnitude of the earthquake increased significantly, and the 5-day frequency of the earthquake increased significantly, with the maximum value of 249.

4.3. Relationship between Reservoir Impoundment and Focal Depth and Epicenter Spatial Distribution. In order to better judge the relationship between the change of epicenter and focal depth of the earthquake and the Xiannvshan fault, the spatial distribution map of the epicenter and focal depth distribution map of the earthquake during the impoundment process of the Three Gorges Reservoir are analyzed at different stages. When calculating the distribution of earthquakes, map processing software ArcGIS was used,

(a) Source depth of reservoir area in 175 m impoundment stage



(b) Epicenter distribution in the reservoir area during the 175 m impoundment stage

Figure 6: Source depth and epicenter distribution in reservoir area during 175 m impoundment stage.

which can effectively display the spatial distribution of earthquakes.

4.3.1. Before Impoundment. From 2000 to the time of impoundment, the level of seismic activity in the Three Gorges Reservoir area was low, and most of the earthquakes were small- and medium-sized earthquakes with typical point-like distribution, as shown in Figure 3. Although the level of seismic activity is low, it can still be found that the epicenter of the earthquake is relatively concentrated in the northern section of the Xiannvshan fault, indicating that the seismic activity in the reservoir area during this period may be less affected by the reservoir water level, or it is controlled by the regional tectonic stress and Xiannvshan fault, which is the same as the previous conclusions.

4.3.2. 135 m Impoundment Stage. In the 135 m impoundment stage, with the rise of the water level in the reservoir area, the seismic activity has increased. Although the number of earthquakes is small, it is distributed throughout the reservoir area, as shown in Figure 4. After the 135 m impoundment, the seismic activity is distributed along both sides of the Yangtze River. At the same time, it can be found that compared with before the impoundment, the number of microseisms near the northern section of the Xiannvshan fault is significantly increased, and the epicenter of the microseisms is concentrated towards the northern section of the Xiannvshan fault, the focal depth is basically consistent with that before the impoundment, which indicates that the seismic activity in this impoundment stage has a clear relationship with the impoundment. It may be that the water level in the reservoir area rises, the load of the reservoir water changes the local stress field, and the reservoir water begins to seep along the Xiannvshan fault. The activity of the Xiannvshan fault has increased, but the impact on the focal depth is not significant.

4.3.3. 156 m Impoundment Stage. In the 156 m impoundment stage, it can be seen from Figure 5 that with the rise of water level, the reservoir water load increases, the seepage effect increases, the epicenter of the earthquake spreads around the reservoir area, the microseismic activity increases significantly, the focal depth also increases, and the epicenter of the earthquake near the northern section of the Xiannvshan fault is clustered. It may be that the reservoir water seeps into the deep part of the Xiannvshan fault zone, which changes the physical and chemical properties of the deep rocks and deepens the focal depth. At this stage, the focal depth is shallow compared with that before impoundment, and the focal depth is increased on the whole. At the same time, the epicenter distribution is more dense and clustered near the Xiannvshan fault.

4.3.4. 175 m Experimental Impoundment Stage. The previous part of this paper has explained that there is a complex process of "continuous loading——seepage saturation——rebound and rebalance" in the 175 m experimental impoundment stage, which is consistent with the research conclusions made by Yao et al. [20] here. During the continuous loading stage from September 2008 to October 2010, the reservoir water load is still the main control factor of seismic activity. The depth of the earthquake source in this stage is mainly within 10 km, which is basically consistent with the 135 m and 156 m impoundment stages, and still has a positive correlation with the reservoir water level, The seismic activity has increased significantly. From November 2010 to November 2013, it was the stage of infiltration and saturation. At this time, the shallow crust was in the state of saturation, and the focal depth of this stage gradually deepened. It is speculated that at this stage, the dominant factor of the activity of the Xiannvshan fault changed from the reservoir water load to the downward seepage of the reservoir water along the Xiannvshan fault. During the period from November 2013 to May 2014, it belongs to the vertical rebound stage. According to the analysis in Figure 5, the focal depth of this stage is further deepened, and the effect of reservoir water infiltration on the activity of the Xiannvshan fault is more significant. At the 175 m experimental impoundment stage, the epicenter of the earthquake near the northern section of the Xiannvshan fault was clustered. With the 175 m experimental impoundment stage tending to be stable, reservoir water infiltration and fault softening have become the main influencing factors of the active change of the Xiannvshan fault.

Figure 6 shows the focal depth and epicenter distribution during the 175 m impoundment stage. At this stage, the focal depth increased significantly compared with that before impoundment. At the same time, the epicenter distribution is obviously more dense, and it is clustered near the Xiannvshan fault.

5. Conclusion

Through the analysis of the correlation between the seismic activity of the Xiannvshan fault and the reservoir water level during the impoundment of the Three Gorges Reservoir and the spatial location of the earthquake epicenter, the influence of the impoundment of the Three Gorges Reservoir on the Xiannvshan fault activity is discussed, and the following conclusions are drawn:

(1) During the impoundment process of the Three Gorges Reservoir, there is a complex process of "continuous loading - seepage saturation - rebound and rebalance" in the crust of the head area of the reservoir. The activity of the Xiannvshan fault is closely related to the reservoir water level. From the beginning of impoundment to the 175 m experimental impoundment stage, the seismic activity in the reservoir area is obviously related to the reservoir water load caused by the rapid rise of the reservoir water level, which is a rapid response to the rise of the reservoir water level, and the focal depth has a law of changing from shallow to deep

(2) At the 135 m impoundment stage, the activity of the Xiannvshan fault is mainly affected by the reservoir water level, which is positively correlated with the reservoir water level, and has the characteristics of rapid response. With the rise of the reservoir water level, the earthquake frequency near the Xiannvshan fault increases significantly, and the epicenter is concentrated towards the Xiannvshan. At the 156 m impoundment stage, the epicenter of the earthquake near the northern section of the Xiannvshan was clustered. The main factor affecting the activity of the Xiannvshan fault was still the reservoir water load, but the permeability of the reservoir water was also enhanced at this stage

(3) During the 175 m experimental impoundment stage, the epicenter of the earthquake near the northern section of Xiannvshan was clustered. During the continuous loading stage from September 28, 2008, to October 2010, the reservoir water load may be the main control factor of the Xiannvshan fault. The focal depth of this stage is mainly concentrated in the range of 10 km, which is basically consistent with the 135 m and 156 m impoundment stages, and still has a positive correlation with the reservoir water level. The seismic activity is significantly enhanced. From November 2010 to November 2013, it was the stage of infiltration and water saturation. At this time, the shallow crust was in the state of water saturation, the focal depth of this stage gradually deepened, and the dominant factor of the activity of the Xiannvshan fault changed from the reservoir water load to the downward seepage of the reservoir water along the Xiannvshan fault. During the period from November 2013 to May 2014, it belongs to the vertical rebound stage, in which the

focal depth is further deepened, and the effect of reservoir water infiltration on the activity of Xiannvshan is more significant. With the 175 m experimental impoundment stage tending to be stable, reservoir water infiltration and fault softening may become the main influencing factors of the active change of the Xiannvshan fault

6. Prospects

This study has comprehensively elaborated on the mechanisms, influencing factors and prediction of reservoir-induced seismicity, and further verified the research results through case analysis. However, reservoir-induced seismicity is a complex issue with some aspects that are worth further in-depth research. Firstly, studies should be strengthened on the physical mechanisms and quantitative correlations of reservoir-induced seismicity. Currently, understanding of mechanisms like microseisms and fault reactivation is still insufficient. In addition, quantitative models corresponding to reservoir water level changes and earthquake occurrences need further establishment and validation. Secondly, more diversified monitoring case studies of reservoir-induced seismicity should be conducted. Reservoirs of different types in regions with varying geological structures may demonstrate distinct induced seismicity patterns. Increasing the number of monitoring examples can better summarize the unified laws of reservoir-induced seismicity. Finally, big data approaches should be fully employed to establish an integrated analysis platform for multisource heterogeneous data encompassing hydrology, pore pressure, seismic activities, etc., to realize intelligent monitoring and early warning for reservoir-induced seismicity. Looking ahead, with advances in observation means and cross-disciplinary integration, the prediction and early warning capabilities for reservoir-induced seismicity will be remarkably enhanced. This will mitigate the impacts of reservoir construction and operation on seismic hazards, enabling safer exploitation and utilization of hydropower resources.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

Zhang Jiayu managed the conceptualization, methodology, software, and investigation and wrote and revised the original draft. Lili Zhang conducted the supervision and review. The review was done by Yaowen Zhang. The review was done by Yunsheng Yao. Software and review were done by Li Haoran. Review and revision were done by Dai Yiming. Wang Renlong managed the methodology. The revision was done by Hu Caixiong.

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