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Analysis of the relationship between water level fluctuation and seismicity in the Three Gorges Reservoir (China)

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ABSTRACT

The Three Gorges Reservoir is a good site for the further researches on reservoir induced seismicity due to decades' seismic monitoring. After the first water impounding in 2003, seismic activity becomes more frequent than that before water impoundment. In order to quantitatively study, the relationship between the water level fluctuation and earthquakes in TGR, we introduced statistical methods to attain the goal. First of all, we relocated the earthquakes in TGR region with double difference method and divided the earthquakes into 5 clusters with clustering analysis method. Secondly, to examine the impacts of water level fluctuation in different water filling stages on the seismic activity in the 5 clusters, a series of statistical analyses are applied. Pearson correlation results show that only the 175 m water level fluctuation has significantly positive impacts on the seismic activity in clusters I, II, III and V with correlation coefficients of 0.44, 0.38, 0.66 and 0.63. Cross-correlation analysis demonstrates that 0, 1, 0 and 0 month time delay separately for the clusters I, II, III and V exists. It illustrated the influences of the water loading and pore pressure diffusion on induced earthquakes. Cointegration tests and impulse response analysis denoted that the 175 m water level only had long term and significant effects just on the seismic events in the intersection region of the Fairy Mount Fault and Nine-brook Fault. One standard deviation shock to 175 m water level increased the seismic activity in cluster V for the first 3 months, and then the negative influence was shown. After 7 months, the negative impulse response becomes stable. The long-term effect of the 175 m water impoundment also proved the important role of pore pressure diffusion in RIS with time.

1. Introduction

Human-induced earthquakes have become an important topic of political and scientific discussion, owing to the concern that these events may be responsible for widespread damage and an overall increase in seismicity. It has long been known that impoundment of reservoirs, surface and underground mining, withdrawal of fluids and gas from the subsurface, and injection of fluids into underground formations [1,2] are capable of inducing earthquakes.

In general, reservoir induced seismicity (RIS) is known to have a close relationship with water impoundment. The first RIS example originated in the Lake Mead Reservoir, which was created by the Hoover Dam in the United States during the 1930s [3]. Although RIS events have been continuously reported since then, most with small magnitudes were of little concern. Until the 1960s, four $M \geq 6.0$ reservoir-induced earthquakes separately occurring at Koyna, India ($M6.5$); Cremasta, Greece ($M6.3$); Hsingfengjiang, China ($M6.1$); and Kariba, Zimbabwe ($M6.1$), caused the scientific community to seriously regard RIS [4] due to human casualties and

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severe damages to the dams and attachments resulting from these events. In China, approximately 20 RIS events have been determined, which account for 11% of the total RIS cases.

The occurrence of RIS is controlled by many factors, such as regional stress field state, areal geology, permeability of rocks and fractures, water level fluctuations and dimensions of the reservoir [5,6]. Continuous seismic surveillance and accurate hypocentral location are of great importance for RIS research because they can offer precise spatial–temporal migration information of seismicity and other important materials. From the perspective of continuous monitoring, the Three Gorges Reservoir (short as TGR) on the Yangtze River in China is a very well-documented case of RIS. TGR is one of the world's largest artificial reservoirs, which is tectonically located in a relatively stable Yangtze para-platform [7]. However, the regional geological setting is very complex. The arc-shaped structural belts collided and promoted the formation of a series of fold belts. The tectonic framework of the study area is controlled by Huangling anticline and Zigui basin, and NW\NE\NWW-trend faults are developed in this region. Before water impounding in 2003, there are few earthquakes in this region. Since water filling, the amount and frequency of the earthquakes sharply increased.

Many researchers have studied the RIS activities in this region. Yi et al. [8] presented a preliminary correlation between seismicity and the geological setting, particularly faults in the reservoir area. Shi et al. [9] examined the relationship between the co-seismic changes in water level and the changes in aquifer parameters. Zhang et al. [10] discussed the RIS types in TGR, and qualitatively analyzed the so-called rapid response and delayed effect separately caused by water loading and pore diffusion. And they think that different RIS types have different mechanisms and controlling factors. Although the common knowledge is that RIS must have a correlation with water level changes, the quantitative estimation of the relationship is absent in TGR. Therefore, the purpose of the paper is to investigate the correlation from the respective of statistical seismology and try to dig out more detailed information to provide efficient interpretation for the RIS mechanism.

The structure of the paper is as follows. The earthquakes relocation and spatial–temporal distribution are presented and preliminarily analyzed in Section 2. Section 3 describes the correlation between the water level fluctuation and seismicity with statistical methods, including Pearson correlation, cross correlation, impulse response analysis, etc. The discussion and conclusions are depicted in Section 4.

2. Spatial–temporal distribution of RIS in TGR

The TGR dam started in December 1994 and the water level reached the spillway for the first time in May 2003. The water impoundment is divided into 3 stages. The first stage started on 26 May 2003 with water level rising from 60 m to 135 m; the second stage began on 7 September 2006 with water level at an elevation of 156 m; the third stage started on 28 September 2008 with the water level annually fluctuating from 145 m to 175 m. The TGR monitoring system is a special-purpose RIS surveillance network with the world's most advanced and complete means. The analysis of more than decades' seismic data accumulation could reveal a detailed picture of the spatial–temporal evolution of seismic activity over several annual cycles of water level fluctuation. In the paper, the seismic data between 2003 and 2009 recorded by the TGR seismic network and the water level data in the reservoir measured by TGR authority are utilized.

To clearly study the relationship between the two variables, we firstly relocated the earthquakes in the TGR with the double difference method put forward by Waldhauser [11]. For further analyzing the earthquake characteristics, we adopted the nearest neighboring method to do the cluster analysis [12]. In this method, the similarities are determined by the squared Euclidean distance. The best results are retrieved when the threshold value of the squared Euclidean distance is taken to be 1.1 km. After clustering, the earthquakes are divided into 5 clusters and the earthquakes are inhomogeneously distributed with time. The spatial–temporal distribution of the 5 clusters is shown in Fig. 1.

The earthquakes in cluster I are distributed in a mass in Huofeng area, where the limestone and karst are developed. The number of the earthquakes during the 135 m water impoundment is much bigger than that after 156 m and 175 m water impoundment.

The earthquakes in clusters II and III linearly are distributed along the NE-trend Gaoqiao Fault and most occur during 156 m and 135 m water impounding. The earthquakes in cluster IV are distributed into clumps in Xietan area where the mine coals are developed and mostly are related with 156 m water impoundment. The earthquakes in cluster V are distributed in the intersection region of the NW-trend Fairy Mount Fault and the nearly NS-trend Nine-Brook Fault, which seemed to have close relationship with 175 m water impoundment.

Referring to Yi et al. [8], the seismic background of the TGR is very weak, and the maximum monthly earthquake frequency

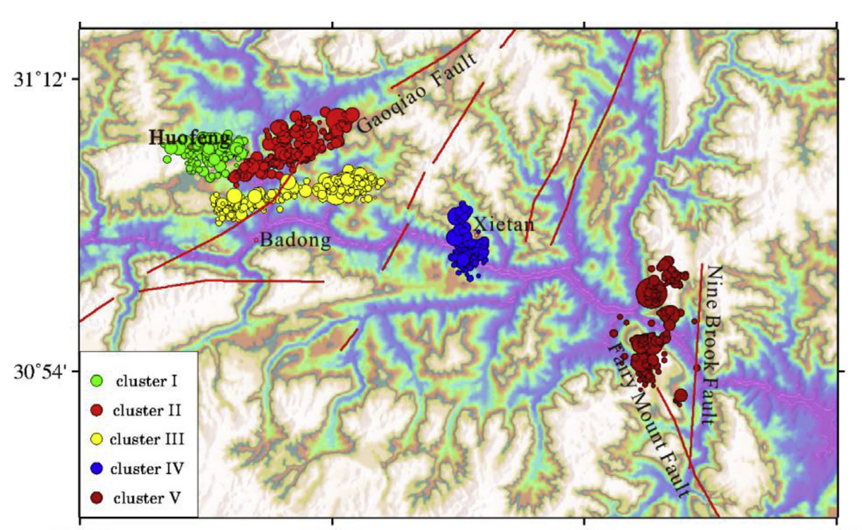

Fig. 1. Earthquake spatial distribution in TGR region from 2003 to 2009.

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