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Analysis of the return period and correlation between the reservoir-induced seismic frequency and the water level based on a copula: A case study of the Three Gorges reservoir in China

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ABSTRACT

Studies have considered the many factors involved in the mechanism of reservoir seismicity. Focusing on the correlation between reservoir-induced seismicity and the water level, this study proposes to utilize copula theory to build a correlation model to analyze their relationships and perform the risk analysis. The sequences of reservoir induced seismicity events from 2003 to 2011 in the Three Gorges reservoir in China are used as a case study to test this new methodology. Next, we construct four correlation models based on the Gumbel, Clayton, Frank copula and M-copula functions and employ four methods to test the goodness of fit: Q-Q plots, the Kolmogorov-Smirnov (K-S) test, the minimum distance (MD) test and the Akaike Information Criterion (AIC) test. Through a comparison of the four models, the M-copula model fits the sample better than the other three models. Based on the M-copula model, we find that, for the case of a sudden drawdown of the water level, the possibility of seismic frequency decreasing obviously increases, whereas for the case of a sudden rising of the water level, the possibility of seismic frequency increasing obviously increases, with the former being greater than the latter. The seismic frequency is mainly distributed in the low-frequency region ($Y \leqslant 20$) for the low water level and in the middle-frequency region ($20 < Y \leq 80$) for both the medium and high water levels; the seismic frequency in the high-frequency region ($Y > 80$) is the least likely. For the conditional return period, it can be seen that the period of the high-frequency seismicity is much longer than those of the normal and medium frequency seismicity, and the high water level shortens the periods.

1. Introduction

As important artificial water conservancy facilities, reservoirs play an irreplaceable role in impoundment and power generation, flood control and irrigation, domestic water supply, inland water navigation and other aspects (Gupta, 2002); thus, reservoirs have become a key factor to the improvement of the national economy and people's livelihoods. However, one cannot ignore the series of disasters that have been induced during the construction and operation of reservoirs; in particular, the reservoir-induced seismicity is more severe with the characteristics of great harmfulness, weak controllability, complicated causes, less predictability, etc. Furthermore, compared with a natural earthquake, reservoir-induced seismicity has unique laws regarding the temporal and spatial activities as well as certain correlations with the filling of the reservoir.

Many studies have been devoted to the correlation analysis between the fillings of a reservoir and the induced seismicity, most of which are conducted using statistical analysis to obtain the variation trend and rule. From the water load-unload investigations at the Koyna reservoir in India, Gupta et al. found that the water loading rate exceeding 12 m per week provided the essential occurrence condition for the earthquakes greater than magnitude of 5 (Gupta et al., 2015). Awad et al. indicated a correlation between the time distribution of shallow seismicity and the water level change at a high rate at the Aswan region in Egypt (Awad and Mizoue, 1995). In addition, an association of the seismicity rate with seasonal variations of the water level was noted by Mekkawi et al. for the Aswan reservoir seismicity induced in the period of 1982–2001 (Mekkawi et al., 2004).

In the current studies, cross-correlation analysis has been widely used to measure the matching degree between the values of reservoir water level and induced seismic activity at any point in time. Ibenbrahim et al. found that there is a time lag of 160 days between the reservoir water level and frequency of induced seis-

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micity with the correlation parameter of 0.86, and the frequency of the micro-earthquakes decreases when the reservoir remains at a high level in the Tarbela reservoir, Pakistan (Ibenbrahim et al., 1989). In a study of the Koyna reservoir, Pandey et al. analyzed the cross-correlation between the water level and the strain factor for the seismicity greater than magnitude 3 and proposed that the periods of the seismic energy release are caused by the annual reservoir water level fluctuations (Pandey and Chadha, 2003); in addition, Telesca calculated the cross-correlation between the daily water level and the number of seismic events per day and noted a 223 days lag, revealing that, with the decrease of the water level, the seismic activity is enhanced (Telesca, 2010). More studies based on cross-correlation analysis can be found in the literature (Selim et al., 2002; Telesca et al., 2012). In addition to cross-correlation analysis, some workers have made use of linear correlation analysis, hypothesis testing, Singular spectrum analysis, etc. to study the correlation (Ohtake, 1986; Kafri and Shapira, 1990; Telesca et al., 2012; Kumar et al., 2012).

The following characteristics of the approaches presented above are notable: the observation method is demonstrated to be more intuitive and convenient to use but lacks a suitable quantitative description of the correlation; linear correlation analysis cannot capture the non-linear relationship (Dietrich, 1991); cross-correlation analysis can assess the association between the fillings of reservoir and induced seismicity globally, but cannot reflect their related patterns accurately. In this paper, a methodology is proposed in which we build a joint probability distribution model based on a copula function to fit the correlation between fillings of reservoir and induced seismicity. Copula functions are used because they not only can describe the nonlinear, asymmetric and tail dependence structure but also can construct the joint distribution of the variables without the limit to the types of their marginal distributions (Zhang and Singh, 2007).

2. Methodology

2.1. Data sources and description

The Three Gorges reservoir in China is a world famous water conservancy project, with a capacity of approximately 393 bn cubic meters. The reservoir region stretches along the Yangtze River from Chongqing to Yichang, with the dam located at Sandouping. According to the geological tectonics shown in Fig. 1, the head region of the Three Gorges reservoir belongs to the cores and two wings of the Huangling Vault and mainly includes the Huangling Anticline and the Zigui Basin. Six regional great faults, i.e., the NNW Xiannushan fault, the NNE Jiuwanxi fault, the NE Xingshan-Shuitian fault, the NNE Niukou fault, the NE Gaoqiao fault, and the EW Mutianwan fault, are distributed in the reservoir region. Clastic rock with sand-shale as its main component is distributed in the Zigui Basin, and the Huangling Anticline corresponds to crystalline rock dominated by granite. Moreover, limestone surrounds the Zigui Basin and the Huangling Anticline (Ma et al., 2010).

The Three Gorges reservoir has played important roles in impoundment and power generation, flood control and irrigation and other aspects; however, the induced seismicity has raised much concern. To monitor the induced seismicity of the Three Gorges reservoir and its surrounding areas, especially in real time, in 2000, the Digital Telemetry Seismic Network of the Yangtze River Three Gorges Reservoir, which was established jointly by the China Earthquake Administration, the China Three Gorges Corporation, the Changjiang Water Resources Commission and the Sichuan Earthquake Administration, consists of 24 telemetered substations, 3 relay stations, 2 strong earthquake stations and 1 network center. As shown in Fig. 1, the Digital Telemetry Seismic Network is primarily distributed at the head region of the Three Gorges reservoir between the dam site and Nanmuyuan of Badong County, with the effective detection range of 270 square kilometers. Moreover, in the monitoring capability, the network can continuously monitor the earthquake greater than magnitude 0.5, of which the location accuracy of the epicenter reaches 1–2 km (Liu and Zhang, 2002).

According to the literature, before the impoundment of the Three Gorges reservoir, the seismic activity is weak, with approximately 6 earthquakes per month on average, and the maximum magnitude is 4.3 (Guo et al., 2012). Based on the earthquake catalogue provided by the Digital Telemetry Seismic Network of the Yangtze River Three Gorges Reservoir and the Three Gorges Project Operational Records published by the China Three Gorges Corporation, the data sets of monthly average water level and the corresponding monthly induced seismic frequency from 2003 to 2011 are obtained (China Three Gorges Corporation, 2013). It can be seen that from the data sets, after the impoundment of the Three Gorges reservoir since June of 2003, the seismic activity has significantly increased, with most of the activity being shallow earthquakes with the concentrated focal depth in the range of 10 km to <20 km (Li et al., 2003). From 2003 to 2011, the Digital Telemetry Seismic Network of the Yangtze River Three Gorges Reservoir has already recorded approximately 3174 seismic events: 2710 earthquakes of M0-M0.9, 417 earthquakes of M1-M1.9, 45 earthquakes of M2-M2.9, 1 earthquake of M3-M3.9, and 1 earthquake of M4-M4.9; the maximum magnitude is 4.1 (China Three Gorges Corporation, 2013).

For this study, we performed preliminary statistical analysis on the original data set and necessary data conversion, as shown in Fig. 2, to build the correlation model of water level and seismic frequency based on copula function.

2.2. Theory and classification of the copula function

For the analysis of the correlations among the variables, the marginal distribution of each variable and the joint distribution of each variable are indispensable. However, because there are many different types of variables, their marginal distributions are often difficult to obtain, and even if the marginal distributions are known to us, the determination of their joint distribution as well as the relationships among them are quite difficult to achieve.

Copula theory was proposed by Sklar; he thought that one joint distribution can be resolved into several marginal distributions of the random variables and one copula function, which can describe the correlation between variables (Sklar, 1959). Nelsen proposed the following rigid definition of the copula function: the joint cumulative distribution $F(x_1, x_2, \cdots, x_N)$ of any continuous random variables $X_1, X_2, \ldots, X_3$ and the respective marginal distribution function $F_{x_1}(x_1), F_{x_2}(x_2), \ldots, F_{x_N}(x_N)$ are joined together by the copula function $C(u_1, u_2, \ldots, u_N)$, which can be written in the form of formula (1) (Nelsen, 1983):

$$F(x_1, x_2, \ldots, x_N) = C[F_{x_1}(x_1), F_{x_2}(x_2), \ldots, F_{x_N}(x_N)] \quad (1)$$

Of the different types of generators to classify copula function, which mainly include normal copula (Arbenz, 2013), t-copula (Cherbini et al., 2004), and Archimedean copulas (Genest and Mackay, 1986), Archimedean copulas exhibit excellent performance (such as extensibility, associativity and symmetry) and have been applied in many different fields (Frees and Valdez, 1998). Hu proved that the linear combination of the three individual Archimedean copulas, such as Gumbel, Clayton and Frank cop-