Comprehensive Study on Reservoir-induced Seismicity in the Xiaowan Reservoir, Yunnan Province, China

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Introduction

The Xiaowan reservoir is located in the middle section of the Lancang River in the west of Yunnan province, China, and the Xiaowan Reservoir Digital Seismic Station Network (XRDSSN) had been in operation since 21 May 2005. Its filling operations took place in five phases, starting on December 16, 2008. The seismicity in the Xiaowan reservoir area after the impoundment has changed obviously with respect to the pre-impoundment. A notable increase in seismicity was only observed during the third filling phase, starting on July 15, 2010. Seismicity increase was mostly localized within two clusters, located to the northwest and west of the dam. Seismicity rates in these clusters showed a significant correlation with the water level increase, with the seismicity starting to increase when the water level reached the area covered by the two clusters, which additionally support they were induced by the reservoir impoundment. 3-D shear wave velocity images, measured by the local earthquake tomography method SIMUL2000, show that low-Vs anomalies after the impoundment can be found beneath and around the Lancang River and the Heihui River in the reservoir area, where the two clusters are located. It may be related to the water loading and unloading and water permeation. We further investigate source parameters for 44 pre-impoundment earthquakes and 164 post-impoundment earthquakes with $M_L \geq 2.0$. Corner frequencies, seismic moments, and stress drops are obtained based on the spectral analysis of regional data, upon corrections for geometrical spreading, frequency-dependent *Q*, and site effects. Our results show that during the post-impoundment phase reservoir-induced seismicity (RIS) inside the two clusters have systematically lower stress drops with respect to those occurring at further distance, and surrounding natural tectonic earthquakes, by a factor of about two to three times, suggesting a possible source characteristic that differentiate reservoir-induced seismicity from natural tectonic earthquakes.

Results

1.Relationship Between RIS and Reservoir Filling

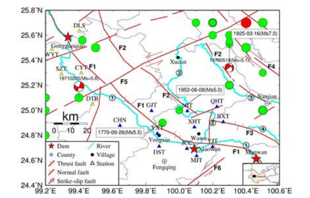

Figure 1. The distribution of rivers, faults and stations in the Xiaowan reservoir area. The main six faults are showing by the *red thick curves*. Their names are as follows: *F1* Lancang river fault, *F2* Weixi-Qiaohou fault, *F3* Wuliangshan fault, *F4* Honghe fault, *F5* Ruili-Longling fault, *F6* Nandinghe fault. The main four rivers' names are as follows: (1) Lancang river, (2) Heihui river, (3) Lishe river, (4) Moshui river. The *green solid circles* are historical earthquakes (*M*s≥5). The biggest earthquake with *M*s7.0 occurred on 16 March 1925 is shown by *red circle*. Most of these earthquakes mainly concentrated in the periphery of the reservoir, and only two earthquakes occurred around the Xiaowan dam. The *blue* and *yellow solid triangles* denote the stations finished in the first and second stage, respectively. The small map in the *lower right corner* is an index map to show the location of our study area.

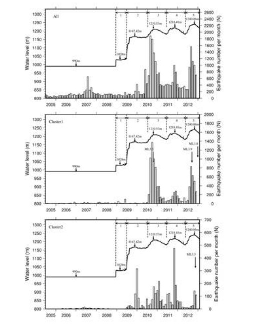

Figure 3 Relation between water level (meters above sea level) and seismicity in the Xiaowan reservoir. There are five water filling periods shown by *vertical broken lines* in the Xiaowan reservoir since the first filling began on 16 December 2008. The increase in seismicity in the Xiaowan reservoir was not obvious after the first filling until the third filling began on 15 July 2010. $M_L \geq 3.5$ in cluster 1 and $M_L \geq 3.0$ in cluster 2 are shown by *vertical arrows*.

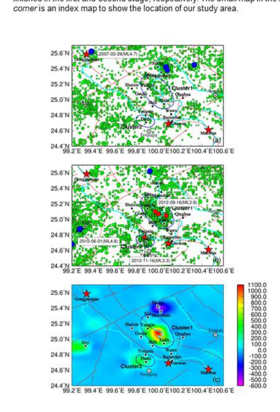

Figure 2. Map showing the distribution of earthquakes with $M_L \geq 1.0$ before and after the first filling began on 16 December 2008 in the Xiaowan reservoir area. A pronounced increase in seismicity is observed in two clusters (labeled by *blue curves*) after the impoundment. The earthquakes with $M_L \geq 4$ are shown by the *blue solid circles*. The rivers and main faults are shown by the *cyan* and *red curves*, respectively. The *red stars* are dams. (a) Seismicity before the impoundment (from 21 May 2005 to 15 December 2008). There are four earthquakes with $M_L \geq 4$ and the biggest earthquake with $M_L 4.7$ occurred on 28 March 2007 in Gongguoqiao. (b) Seismicity after the impoundment (from 16 December 2008 to 31 December 2012). There are six earthquakes with $M_L \geq 4$ and the biggest earthquake with $M_L 4.8$ occurred on 1 June 2010 in Xiyi. Four earthquakes with $M_L \geq 3.5$ occurred in the first cluster and only one earthquake with $M_L \geq 3.0$ occurred in the second cluster. All of them are shown by the *red solid circles*. (c) The change of the number of events per each grid (0.1*0.1 degree) after and before the impoundment (the number of post-impoundment events minus that of pre-impoundment ones)

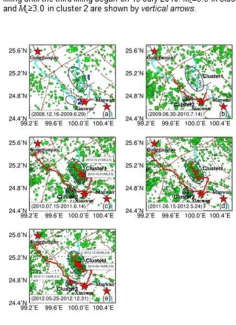

Figure 4 The distribution of elevated water levels and earthquakes occurred after the impoundment in different water filling period in the Xiaowan reservoir. *Red thin curves* denote the main faults and the *red stars* are dams. The *cyan curves* are rivers and the *red thick curves* denote the elevated water levels in different fill period. The time when the seismicity begins increasing has coherence with the position flooded by the elevated water.

2. 3-D shear wave velocity images in the Xiaowan reservoir area

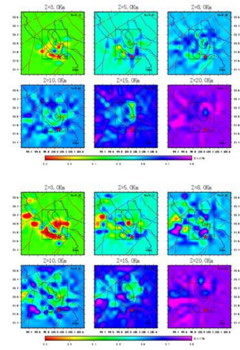

Figure 5. 3-D shear wave velocity images before (*up*) and after (*down*) the impoundment, measured by the local earthquake tomography method SIMUL2000. Low-Vs anomalies after the impoundment can be found beneath and around the Lancang River and the Heihui River in the reservoir area, where the two clusters are located.

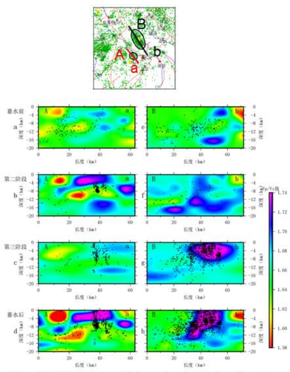

Figure 6. 3-D Vp/Vs tomographic images in vertical depth sections along defined profiles (up) in the Xiaowan reservoir area in different water filling period. a Before the filling. b and c denote the second and third filling phase, respectively. d After the filling. Hypocentres near the profiles within 0.1° are projected as dots. The epicentres are shown as *black circles* in horizontal planes.

3.Source parameters for events in the Xiaowan reservoir area

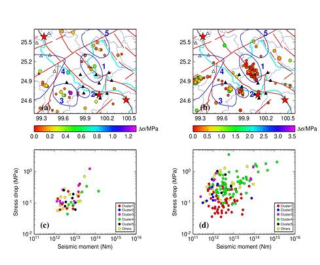

Figure 7 The distribution of the stress drops and scaling relations of source parameters for pre- and post- impoundment earthquakes in the Xiaowan reservoir. These *left charts* are results for earthquakes occurred before the first filling and these *right charts* are results for those after the third filling. Despite the two clusters mentioned previously, three clusters are added to discuss the distribution of stress drops in Xiaowan reservoir area.

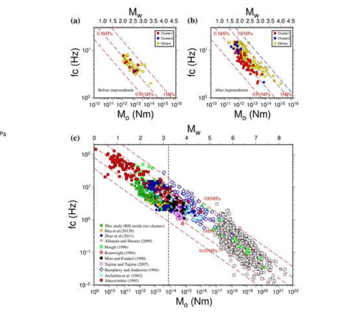

Figure 8 Corner frequency versus seismic moment (*lower scale*) and moment magnitude (*upper scale*). The *dashed lines* show constant stress drops of 0.01, 0.1, 1, 10, and 100 MPa. (a) and (b) are results for earthquakes occurred before the first filling and after the third filling, respectively. The stress drops for the earthquakes inside and outside two clusters are flat before the impoundment, but the stress drops for RIS inside two clusters are obviously lower than those outside two clusters. (c) is the comparison between our results for RIS inside two clusters and others. The *vertical dashed line* marks the higher magnitude cutoff of our data. The results of this paper are plotted as *solid green circles*. All other *differently shaped symbols* show data from various other studies collected by Allmann and Shearer (2009), Zhao et al. (2011) and Hua et al. (2013). To identify reservoir induced seismicity cases from others, we use *circles* only to denote the RIS. For the results obtained from Zhao et al. (2011), we also use *circles* to denote them because their results include some RIS.

Conclusions

- The increase in seismicity in the Xiaowan reservoir was not obvious after the first filling until the third filling on 15 July 2010 and this evidently increased seismicity mainly concentrated in two clusters to the northwest and west of the dam. For these earthquakes in the west cluster after the second filling and those in the northwest cluster after the third filling, their seismicities showed strong visual correlation with water level and the seismicity increased time is consistent with the time when the elevated water reached the area covered by these two clusters respectively, indicating that they were induced by reservoir impoundment.
- 3-D shear wave velocity images, measured by the local earthquake tomography method SIMUL2000, show that low-Vs anomalies after the impoundment can be found beneath and around the Lancang River and the Heihui River in the reservoir area, where the two clusters are located. It may be related to the water loading and unloading and water permeation.
- Stress drops for the events inside cluster one and two before water filling are almost the same of those outside two clusters with the same magnitude range. However, RIS inside these two clusters after the third filling appear to have systematically lower stress drops with respect to these surrounding natural tectonic earthquakes, by about a factor of 2-3 times. The phenomena of lower stress drop for RIS are observed both in low and high seismicity region, indicating lower stress drop for RIS does not just result from lower background stress level and it may be considered as the pronounced characteristics that differentiate it from normal tectonic earthquake.

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