Influence of the Impoundment of the Three Gorges Reservoir on the micro-seismicity and the 2013 M5.1 Badong earthquake (Yangtze, China)

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Abstract On December 16, 2013, right after the Three Gorges Reservoir (TGR) reached its highest annual water level, a powerful M5.1 earthquake occurred in Badong County, China's Hubei Province. The epicenter is 5.5km away from the upstream boundary and 100km from the dam. Was this earthquake triggered by the impoundment of the TGR, and what are its subsequences? To answer these questions, we constructed a coupled three-dimensional poroelastic finite element model to examine the ground surface deformation, the Coulomb Failure Stress change (ΔCFS) due to the variation of elastic stress and pore pressure, and the elastic strain energy potential accumulation in the TGR region upon the occurrence of this event. Our calculated maximum surface deformation values beneath the TGR compare well with GPS observations, which validates our numerical model. At the hypocenter of the earthquake, ΔCFS is around 8.0~11.0kPa, revealing that it may be eventually triggered by the impoundment. We also discovered that the total elastic strain energy potential accumulation due to the impounded water load is around $1.7 \times 10^{12} \text{J}$, merely equivalent to 0.01% of the total energy released by this event, indicating that the this earthquake is predominately controlled by the typical regional

25 tectonic settings as well as the weak fault zones, and the reservoir impoundment might only
26 facilitate its procedure or occurrence. Furthermore, the stress level in this region remains high
27 after this earthquake and the subsequent reservoir-triggered micro-seismicity or even bigger
28 event are highly possible.

29 **Keywords:** Micro-seismicity; Three Gorges Reservoir (TGR); Reservoir-Triggered-Earthquake
30 (RTE); Coulomb Failure Stress (CFS); Badong earthquake;

32 **Introduction**

33 Active debates were raised in recent years whether the Three Gorges Reservoir (TGR) could
34 trigger big earthquakes (*Zou et al., 2014; Zhang et al., 2014; Mei et al., 2013; Hua et al., 2013;*
35 *Yi et al., 2012*). The occurrence of the 2013 M5.1 Badong earthquake that struck the TGR area
36 on December 16, 2013, seems to have confirmed the hypothesis. Scientists around the world are
37 now wondering the possibility of subsequent micro-seismicity or even bigger events triggered by
38 this largest manmade structure, and how the hazard mitigation can be alleviated if they come to
39 truth in near future. In this study we carry out a detailed numerical analysis using a coupled
40 three-dimensional poroelastic finite element method to quantitatively evaluate this open problem.

41 TGR, the world's largest power station in terms of the installed power capacity (22,500 MW),
42 was completed on Yangtze River in July 2012. The reservoir is 660 km in length, 1.12 km in
43 width and 185 meters in depth. Its water storage capacity reaches $39.3 \times 10^9 \text{ m}^3$ with a total water
44 surface area of 1,045 square kilometers from the western part of Hubei province to the eastern
45 part of Chongqing municipality (Mao et al., 2008) (See the upper left panel in Figure 1). Because
46 of its capacity and typical geological settings, many researchers have considered its seismicity
47 risks related to the regional stress state, rock stratum, faults and fracture systems(Chen, 2002).

Broadband seismic stations were densely deployed to monitor the seismicity immediately upon its completion(Che et al., 2010; Ma et al., 2010). However, because of lacking of adequate data, the results of earlier research were controversial and inconclusive. For examples, some believed that the micro-seismic activities might gradually weaken or even disappear over time, while others argued that regional earthquakes would not stop, and the magnitude of earthquakes happened in the reservoir-head region (Dam-Miaohe section) and in the head-mid-reservoir region (Jiuwanxi-Fairy mountain section and Zigui-Badong section) would be $M_s \leq 5.0$ and $M_s \leq 5.5$, respectively(Liao et al., 2009; Sun et al., 1996).

After the first impoundment of the TGR on June 7, 2003, the water head raised sharply. There were over 7,000 micro-earthquakes occurred in the upstream area (Chen et al., 2007b). The magnitudes of these events were mostly less than $M_L 2.0$, with their distribution pattern closely correlated with the water coverage and water level fluctuations, indicating that they were essentially reservoir triggered events. Moreover, two big earthquakes with $M_L 3.7$ and $M_s 4.1$ occurred in the reservoir-head region on September 27 and November 22, 2008 during its third impoundment (Che et al., 2009, 2010), and they were followed by a powerful $M 5.1$ earthquake in Badong County on December 16, 2013, right after the water level of the TGR reached its annual highest record. The epicenter of this event was 5.5km away from the upper stream boundary and 100km from the dam. The focal depth of this earthquake was 5km, and the focal mechanism revealed that it was a right-lateral normal dip-slip fault. Later on, two major events with magnitudes of $M 4.3$ and $M 4.7$ also occurred in Zigui County on March 30, 2014. These two events are also closely associated to the impoundment of the TGR.

In this paper, we adopt a fully coupled poroelastic theory (Rice and Cleary, 1976) to evaluate both the instantaneous change of elastic stress caused by reservoir water load itself, and the

subsequent pore pressure change and the corresponding stress change in the crust beneath the TGR and its vicinity. By taking full account of the observational data, including the high resolution topography, water level fluctuations and water depth variation history, flood zone boundaries and fault geometry parameters, we attempt to explain the triggering mechanisms of M5.1 Badong earthquake through adopting high resolution finite element modeling and quantitative analysis. In the following sections, we explain the finite element model of the TRG. This model enables us to flexibly and efficiently handle different kinds of boundary conditions and complex geometries. The model also allow us to quantitatively estimate the ground deformation for model verification against available GPS observations, the Coulomb failure stress change (ΔCFS) at the hypocenter for evaluating the earthquake triggering potential, and the total accumulated strain energy by water load itself. And finally, discussions and concluding remarks are given in the last section.

Geological and geophysical settings of the TGR

The occurrence of RTE is closely related to the background tectonic stress field, fault-fracture system and rock strength. Thus it is necessary to consider the tectonic setting of the model (Shi et al., 2013). In the TGR region, fold and fault structures are well developed. There are two large tectonic units in this region. One is the Qinling fold belt on the north, the other is the Yangtze platform on the south (Sun et al., 1996). Most of the TGR area is located within the Yangtze platform, which in turn is subdivided into four smaller units, known as the Huangling block, the Shennongjia block, the Zigui block and the faulted block of the Hubei Province, respectively (Li et al., 2009; Sun et al., 1996). Seismic tomography shows high velocity anomalies down to 20km beneath the Huangling block, and partially molten substances of the upper mantle beneath the

Badong-Zigui block and its adjacent regions (Li et al., 2009; Zhao et al., 2007). Chen et al. (2007a) presented that the elastic wave speed ratio (V_p/V_s) increased before the occurrence of micro-earthquakes and decreased during the dilatation-diffusion phase.

Three kinds of rocks, granite, limestone and detrital stone, are exposed in the TGR area (Chen, 1999). The first segment of TGR area, from Sandouping to Miaohe, which belongs to Huangling block with Pre-Sinian complexes, consists predominantly of strong granodiorite with low permeability. The second segment, from Miaohe to Fengjie, which passes through the vicinity of Huangling block, is formed by Pre-Sinian and Upper Cambrian limestone and detrital rock with higher permeability. Finally, the third segment, upstream Fengjie, is mainly composed of carbonatite, sandstone and shale of Triassic age (Mao et al., 2008; Wang et al., 2013). The Badong region is located at the junction of the Huangling block and the Shennongjia block. Faults and fractures are well developed under strongly compressive stress state (Han and Rao, 2004).

Three groups of fractures and faults, mostly distributed in the east of TGR area, can be recognized, as shown in Figure 1. The NWW fault-group, including the Fairy Mountain fault, the Tianyangping fault and the Wuduhe fault, extending tens of kilometers with a trend of $N10^{\circ}\sim40^{\circ}W$. The NNE fault-group, including the Jiuwanxi fault, Xinghua fault and Niukou fault, ranges from tens of kilometers to 100 km with a trend of $N20^{\circ}\sim30^{\circ}E$. The NEE fault-group, covering the Gaoqiao fault, extending over 40km with a trend of $N45^{\circ}\sim60^{\circ}E$. These three major fault groups dominate the regional geological settings and crustal deformation, as well as the nucleation of moderate earthquakes. Ma et al. (Ma et al., 2010) proposed that the micro-earthquakes concentrating around the northern end of Fairy Mountain fault and Jiuwanxi fault, were probably due to the infiltration of reservoir water into the crust underneath.

Methodology

Coulomb failure stress change (ΔCFS)

The concept of ΔCFS is a widely accepted tool to analyze the mechanism of earthquake triggering (Stein et al., 1997; Stein et al., 1992). It is also used in the analysis of tidal triggering (Heaton, 1975; Perfettini and Schmittbuhl, 2001) and reservoir triggering (Cheng et al., 2012; Gahalaut and Hassoup, 2012; Ge et al., 2009). As limited by lacking of reliable measurement techniques of full stress in earth's crust, the tectonic stress field of the crust beneath the reservoir cannot be determined in advance. In this study, we introduce the Coulomb failure stress change of Mohr-Coulomb theory and the Hook-Brown strength criteria to quantitatively investigate the influence of the reservoir on the earthquake triggering (Gahalaut and Hassoup, 2012; King et al., 1994; Stein et al., 1992). On an existing fault plane, the ΔCFS is the derivative of the Coulomb stress, which can be expressed as

$$\Delta CFS = \Delta \tau + \mu (\Delta \sigma_n + \Delta p) + \Delta \mu (\sigma_n + p), \quad (1)$$

where, $\Delta \sigma_n$ is the normal stress change, $\Delta \tau$ represents the shear stress change along the slip direction, p and Δp denote the pore pressure and its change, and μ defines the inner friction coefficient. The third term in the right-hand side may be negligible since there is little experimental data for $\Delta \mu$ during the fault-slip process (Cocco and Rice, 2002). Eq. (1) is simplifies as

$$\Delta CFS = \Delta \tau + \mu (\Delta \sigma_n + \Delta p). \quad (2)$$

According to Eq. (2), the fault is prone to slip if ΔCFS is positive. On the other hand, if ΔCFS is negative, the fault becomes more stable. Thus, in principle, we can determine from the calculated ΔCFS if an existing fault becomes safer or more dangerous assuming that the regional stresses are in a critical state. If the fault geometry is unknown, we could calculate the optimal

ΔCFS at every nodal point in the 3-D space.

Fully coupled poroelastic theory

In this study, we adopt the poroelastic theory of Biot (Biot, 1941) and Rice et al. (Rice and Cleary, 1976) to obtain the stress change under the impoundment and drainage of the reservoir. The crust beneath the TGR is considered as water saturated continuous porous media under quasi-static state. Thus, the governing equation in terms of the elastic stress σ_{ij} and pore pressure p , obeys the equilibrium equation as

$$\sigma_{i,j} + f_i = 0, \quad (3)$$

where, σ_{ij} denotes the stress tensor and f_i represents the body force. The constitutive law of continuous poroelastic model is given by

$$\sigma_{ij} = 2G\varepsilon_{ij} + \frac{\nu}{1+\nu}\sigma_{kk}\delta_{ij} - \frac{3(\nu_u - \nu)}{B(1+\nu)(1+\nu_u)}p\delta_{ij} \quad (4)$$

in which, ε_{ij} is the strain tensor, p is the pore pressure in solid porous rock, and $\sigma_{kk} = 1/3\sigma_{ki}\delta_{ik}$ is the effective bulk stress, respectively. The relationship between σ_{kk} and the bulk strain ε_{kk} in a solid structure is $\sigma_{kk} = 3K\varepsilon_{kk}$, where δ_{ik} is the Kröneckers delta tensor, and G denotes the shear modulus. ν and ν_u represent the Poisson's ratios when the material is deformed under drained and undrained conditions, respectively. B is the Skempton's coefficient (Kuempel et al., 1991; Roeloffs and Rudnicki, 1984; Skempton, 1954), which usually is allowed to vary between 0.5 to 0.9~0.95, depending on the types of the crustal rocks (Roeloffs, 1996; Wang et al., 2012). As aforementioned, there are three kinds of rocks, i.e., granite, limestone and detrital stone, in our study area, for simplicity, we choose the value of the B as 0.8.

As to the porous solid material, the fully coupled governing equation satisfies

$$\nabla^2 \cdot (\sigma_{kk} + \frac{3}{B} p) - \frac{1}{c} \frac{\partial}{\partial t} (\sigma_{kk} + \frac{3}{B} p) = 0. \quad (5)$$

Here, c is the diffusion coefficient (m^2/s) and can be calculated from

$$c = \frac{k}{\eta} \left[\frac{2\alpha(1-\nu)}{1-2\nu} + \frac{B^2(1-2\nu)}{9(\nu_u - \nu)} \frac{1+(\nu_u)^2}{1-(\nu_u)} \right], \quad (6)$$

where, η is the fluid rheology in a porous solid fault zone.

Finite element model of the TGR

The occurrence of RTE is closely correlated with the geological settings, regional tectonic stress state, reservoir water level fluctuations and physical properties of the rocks and faults (Shi et al., 2013; Simpson et al., 1990). To capture these physical phenomena, we construct a full 3D finite element model of the TGR with the data of realistic geometry of the fault system, as shown in Figure 2. The domain of our numerical model is $110.0 \sim 111.5^\circ\text{E}$, $30.3 \sim 31.8^\circ\text{N}$ in horizontal. The vertical depth is from the surface down to -20km . The width of the fault zone is less than 7km . At the same time the TGR locates in a canyon with elevation variation of hundreds of meters between the water level and the local mountains. It is obvious insufficient if the topographic effect is not considered (Cao and Shi, 2011). Thus, in this study, we consider the topography in our model. The whole model consists of 17 sub-layers, with 968,949 triangular prismatic type of finite elements composed of 518,886 nodes. The total simulation period is from June 2003, when the first impoundment of the TGR was getting started, until May 2014. The time step is one month, and the total time steps are 132. From the assumption of poroelastic theory, the initial pore pressure is assumed as hydrostatic pressure in water-saturated state of equilibrium. The pore pressure on top surface of the reservoir's

bedrock is assigned as of the water head from the water depth impounded, and the pore pressure on both the lateral and the bottom surfaces are given by a hydrostatic pore pressure with the depth. The normal displacement and the tangential shear stress on the lateral boundaries of the whole model are fixed. While, the normal stress and pore pressure of the reservoir bottom are assigned as hydrostatic pressure varying with the water level fluctuations during the impoundment and drainage processes.

Hydraulic parameters, especially the diffusion coefficient, are closely related to the pore pressure and varying with respect to time in poroelastic problems. Unfortunately, there are few hydraulic parameters data of TGR area available. Here, according to the method of Talwani et al. (2007), we calculated the seismic diffusion coefficients of different subdomains based on the seismic activities and seismic stagnant time windows after the impoundment of TGR (Xu, 2010). The average diffusion coefficient is $0.2\text{m}^2/\text{s}$ and its maximum value is $2.0\text{m}^2/\text{s}$. For comparison, we assign Model 1 as homogeneous medium with diffusion coefficient as $0.2\text{m}^2/\text{s}$. Because of the high diffusion of fault and Zigui block with distributed carbonate rock, Model 2 is assigned as inhomogeneous medium, the fault systems and Zigui block designated as $2.0\text{m}^2/\text{s}$. At the same time, the selection of elastic parameters are based on the in-situ geological survey of V_p and V_p/V_s ratio of different depths (Li et al., 2009; Li et al., 2010; Zhao et al., 2007), the detailed elastic parameters are listed in Table 1 (Simpson et al., 1990).

Simulation results

Deformation induced by the TGR

Since 1998, advanced dense GPS network has been deployed to monitor the horizontal and vertical displacement of the TGR area. Later on, through numerical and analytical models of

homogeneous materials, researchers examined the elastic displacement of the TGR and its adjacent regions under the gravitational load of reservoir water (Liang and Hu, 2008; Wu et al., 2009). In order to verify our 3D numerical model, we first calculate the displacement of the TGR area when the water level is 135m, as shown in Figure 3(a). The maximum subsidence displacement is ~35mm, which is in good agreement with the GPS measurement by Liang and Hu (2008), confirming that our numerical model results are reliable. At the same time, the subsidence is mainly concentrated in the center of the reservoir at the Xiangxi segment and gradually decreases to zero upon the boundaries of the reservoir. The deformation of the Zigui Block, where the TGR passes through, is relatively bigger than that of other areas. The surface deformation near the Badong area is 5mm. Figure 3(b) demonstrates the vertical displacement when the water level reaches 175m. We see the maximum surface deformation is up to 70mm. But in the Badong area, the maximum surface deformation is ~10mm.

Temporal variations of stress at the hypocenter

After the impoundment of the TGR, many micro-earthquakes occurred around the reservoir region and were concentrated in the Badong area and the Fairy mountain-Jiuwanxi fault zone, exhibiting linearized or mass-like clustering patterns, as shown in Figure 1. Therefore, herein, we not only focus on the M5.1 earthquake in the Badong region, but also analyze the Ms4.1 earthquake on November 22, 2008, which have been seen as the second biggest RTE by the TGR, as comparison.

Figure 4(a) shows the pore pressure and ΔCFS at the hypocenter of the M5.1 earthquake. Both of them increase gradually along with the water level arising, and the increase of pore pressure is much larger than the elastic stress after the impoundment of the TGR. The ΔCFS caused by the TGR water load is close to 1.5kPa when the M5.1 earthquake occurred, indicating that the water

load leveraged the risk of fault activation and facilitated the fault plane to rupture. More strikingly, when pore pressure effect is considered, ΔCFS can reach up to 8.0~11.0kPa when the friction coefficient is 0.6, indicating that the effective pore pressure is relatively significant. Most probably, pore pressure predominated the triggering mechanism of this seismogenic faults towards destabilization.

By comparing the homogeneous model (Model 1) with the inhomogeneous model (Model 2), we get: (1) After the initial impoundment of the TGR, the pore pressure change of Model 1 is bigger than that of Model 2, which is calculated with higher diffusion coefficient. This phenomenon suggests that the undrained response is instantaneous, and its subsequent diffusion effect should not to be neglected, especially when its diffusion coefficient is low. For the undrained response, pore pressure change is owing to the elastic bulk deformation of the solid porous skeleton. Meanwhile, the additional water load also leads to elastic deformation and stress of the solid porous skeleton. Combining the instantaneous effects of undrained response, and elastic stress of the solid porous skeleton by water load, we can explain why some micro-earthquakes appeared around the reservoir area immediately after the onset of the impoundment. (2) With the time passing, additional water head escalates the pore pressure diffusing through the faults and fractures beneath the water reservoir (diffusive response), and increases the pore pressure at the hypocenter gradually. Apparently, during this procedure, the crust's diffusion coefficient exhibits a predominant effect on the total pore pressure changes at the hypocenter. This is the mechanism of which the pore pressure of Model 2 exceeds that of Model 1 eventually.

The Ms4.1 earthquake, occurred on the Fairy mountain thrust fault, was the first relative big event after the water level of the TGR reached 175m. Its epicenter is nearly 1.0km from the bank

of TGR and less than 30km from TGR dam. Figure 4(b) shows the variation of pore pressure and ΔCFS at its hypocenter. Comparing the Ms4.1 earthquake to the M5.1 earthquake, although both of these two earthquakes occurred when water level reached the highest annual water level, they were significantly different. Firstly, the ΔCFS of the Ms4.1 earthquake's hypocenter induced by the water load is negative while positive of M5.1 earthquake, suggesting that the impoundment of TGR actually stabilized the faults and prevented the hypocenter from rupturing when the occurrence of Ms4.1 earthquake. Given this, we can preliminarily conclude that, if the reservoir is located above the hanging wall of the steeply dipping reverse fault or shallowly dipping thrust fault, the impoundment of the reservoir makes the thrust fault more stable, but may lead the normal fault to be more dangerous. On the contrary, the drainage of the reservoir lead the normal fault to more stable, but makes the thrust fault may be more dangerous. That is to say, the effect of reservoir impoundment depends on where it is located and the nature of the local seismogenic fault system. Secondly, as for the Ms4.1 earthquake, when the pore pressure effect is considered for the homogenous model, the ΔCFS can only reach up to -1.0kPa in model 1, revealing that the impoundment of the TGR may not trigger the occurrence of earthquake when adopting the homogenous model. However, when adopting the heterogeneous model, the maximum ΔCFS at the hypocenter is around 5.0kPa. These results confirm that the computational values are highly sensitive to RTE model parameters, especially, the values of the diffusion coefficient. When the geological background is considered, the calculated results could be consistent with the actual situations. This means, it is very necessary to adopt high-resolution heterogeneous geological model to analyze the realistic effects of reservoir loading in future studies. Moreover, ΔCFS value at the time of the impoundment may not be a good indicator of RTE and the evaluation of earthquake risk must consider the long-term effect due to pore pressure diffusion.

Furthermore, by comparing the difference between these two earthquakes, their patterns of the pore pressure increasing are slightly different, as shown in Figure 4. The Ms4.1 earthquake does not locate in the Zigui block with high diffusion coefficient, the pore pressure of model 2 is always larger than model 1. It confirms that their triggering mechanisms are slightly different too.

More generally, at the beginning of the impoundment, undrained and elastic effects are significant in response to the fast water load increasing. The diffusive response gradually become predominant over time and may overtake the undrained and elastic effects eventually, mainly depending on the permeability of the crust as well as the nature (normal/thrust/reverse) and geometry of the seismogenic fault systems beneath the reservoir. During the impoundment or drainage of the reservoir, the tradeoff between undrained and diffusive effects constitutes a process of dynamic responses. More specifically, when the diffusion coefficient is small, undrained response is more obvious, and when the diffusion coefficient increases, diffusive response gradually increases with respect to time. Essentially, at the hypocenter of the seismogenic fault, whether the undrained response or diffusive response is predominant depends on the fault geometry, the focal depth and permeability of the crust beneath the reservoir.

Accordingly, we come to the preliminary conclusions that: (1) During initial impoundment or drainage process, while the change in water level is fast, the micro-earthquakes are more elastic and undrained response related. The magnitudes of these earthquakes are small and their occurrences are relatively frequent and exhibit a spatially intensive pattern. (2) After the crust undergoes with the diffusive effect over a long time, the triggered seismicity is finally attributed to the delayed dynamic process of pore pressure redistribution under the water head. And typically, this kind of triggered seismicity is spatially and temporally sparse, and its magnitude is

relatively larger.

Stress changes at different depths with water level fluctuation

The water level of the TGR underwent from 135m in 2003 to 156m in September 2006, and reached up to its highest value of 175m in November 2010, and then fluctuated with the seasons. For focal depths of most micro-RTES were around 5km (Ma et al., 2010), Figure 5(a-c) demonstrate the pore pressure change (Δp) at the depth of 5km of these three time windows mentioned above. As the diffusion of the pore pressure Δp obviously increases with time, the pore pressure changes at the reservoir center area and gradually spread around. At the beginning of the impoundment, Δp between Miaohe and Xiangxi evidently and rapidly increases, and then Δp from Xiangxi to Badong increases at a larger rate after November 2010. But due to the different geometries of the Gaoqiao fault and Fairy mountain fault, the seismicity around Badong area increases more faster than that of the Zigui area at the beginning of impoundment. These results are closely correlated with the seismic activities of the Zigui area, whose reservoir seismicity, owing to its high permeability, become more intensive with respect to time.

Figure 5(d-f) clearly reveal that ΔCFS varied with different depths in December 2013. In most river channels, ΔCFS reaches up to 65.0kPa at the depth of 3km, while only exceeding 20.0kPa at Badong, the Zigui Block and the segment of Xiangxi to Miaohe at the depth of 5km, respectively. The ΔCFS attenuates rapidly with the depth, only slightly larger than 20.0kPa at the depth of 11km in the Xiangxi to Zigui segment. Comparing the distribution pattern of 119 micro-earthquakes (Xu, 2010), that occurred from March 2009 to December 2009, we can infer that most of these earthquakes are well located in the regions with positive ΔCFS , suggesting that the micro-earthquakes occurred around the TGR have direct correlation with the impoundment of the reservoir. At the same time, most of micro-earthquakes had shallow depth (less than 6km)

and were located in the Badong area.

Strain energy potential accumulation induced by the TGR

After the impoundment of the TGR, strain energy potential was accumulated in the crust beneath the reservoir and its adjacent regions. For the sake of analyzing the effect of the reservoir impoundment rate on the earthquake occurrence, the elastic strain energy potential accumulation induced by the reservoir is calculated. Basically, the elastic strain energy potential is the integration of elastic strain energy density function over spatial and temporal domains (Li et al., 2010) as

$$U = \int_v w(x, y, z; t) dv dt = \int_v \frac{1}{2} \sigma_{ij} \varepsilon_{ij} dv dt, \quad (8)$$

where, $w(x, y, z; t)$ is the strain energy density rate. Based on the estimation of our numerical simulation results for the M5.1 earthquake, the mechanical strain energy accumulation of the entire TGR and its adjacent regions (about $5.5 \times 10^4 \text{ km}^3$) is around $1.7 \times 10^{12} \text{ J}$. However, according to the estimation criterion of the seismic wave energy released by the seismic waves (Bath and Duda, 1964), as shown by

$$\log E = (12.24 \pm 1.35) + (1.44 \pm 0.20)M, \quad (9)$$

the seismic wave energy released by the M5.1 earthquake is about 10^{19} J . Thus, the contribution of the mechanical strain energy induced by the TGR is merely less than 0.01% of the total energy released by the M5.1 earthquake, signifying that the impoundment of the reservoir only triggered, rather than providing the strain energy for this RES.

Discussions

Reservoir-triggered-earthquake (RTEs) is one of the significant issues in the earthscience community (Talwani, 2007; Wang and Manga, 2009; Richard A. Kerr and Richard Stone, 2009;

345 Ge et al., 2009). Worldwide, there have been more than 140 RTEs reported by over 70 countries
346 (Mao et al., 2008; Talwani et al., 2007). Among them, 4 reservoir regions had been stricken by
347 RTEs with magnitudes $M \geq 6.0$. Most of the existing investigations confirm that there is a close
348 correlation between the reservoir water level fluctuation and seismicity (Chen and Talwani, 1998;
349 Gupta, 1985; Wu et al., 2009). The current understanding of the mechanical processes following
350 reservoir impoundment suggests two major phases. First, a rapid change of elastic stress coupled
351 with undrained pore pressure dissipation, owing to the bulk deformation of the solid skeleton of
352 the crust under the load of the water body. This leads to quick response of weak faults with
353 planes oriented at a critical angle (Simpson et al., 1988; Talwani, 1997). An example of this type
354 of response is the many shallow micro-earthquakes occurred immediately after the impoundment
355 of the Kariba Reservoir since its impoundment in December 1958 (Gough and Gough, 1970a;
356 Gough and Gough, 1970b). Second, the pore pressure state in the crust beneath the reservoir and
357 its adjacent regions changes due to its diffusive effect. Consequently, not only the undrained pore
358 pressure in the fracture-fault system gradually dissipating into its surroundings, but also the pore
359 pressure at the focal depth gradually increases due to diffusion from the reservoir bed by the
360 water head. This could lead to large earthquakes after a certain period of time following the
361 impoundment. For example, the $M_L 5.7$ Aswan Reservoir earthquake occurred nearly 17 years
362 after its first impoundment (Gahalaut and Hassoup, 2012). These two physical processes indicate
363 that the stress change at the hypocenter can rise up rapidly from a coupled elastic response due to
364 compaction of the porous space (elastic deformation and undrained response), or more slowly
365 with the diffusive effect of water head from the reservoir's bed (diffusive response). Overall, the
366 stress change at the hypocenter or on a fault plane is closely associated with the coupled effects
367 of all the different mechanisms mentioned above. According to the theory of rock mechanics,

changes in either the elastic stress (decreased normal stress or increased shear stress) or decreased effective normal stress due to increased pore pressure may facilitate the failure of faults with a critical orientation.

Heated arguments occurred after the 2008 Ms8.0 Wenchuan earthquake on whether the impoundment of the Zipingpu reservoir, which is located close to the LongmenShan fault zone, triggered the occurrence of this huge devastating event (Ge et al., 2009; Kerr and Stone, 2009, 2010). Many scholars have continued to study the tectonic activities and seismicity beneath this reservoir in relation to the earthquake. Reviews of the more recent studies were proposed by Ma and Zhou et al. (Ma et al., 2012; Zhou et al., 2012).

Upon the occurrence of the M5.1Badong earthquake, the micro-earthquakes with magnitudes less than M2.0 became more active. Moreover, comparing to the Ms6.1 earthquake happened in Xinfengjiang Reservoir in 1962, which is well acknowledged as the largest RTE in China so far, the ΔCFS we obtained at its hypocenter is about 3.0kPa (Cheng et al., 2012). The primary results of our simulations suggest that the ΔCFS of the hypocenter of the M5.1 Badong earthquake varies from 8.0~11.0kPa, suggesting that the impoundment of the TGR mostly possibly triggered the occurrence of this event. On the other hand, because the regional tectonic stress background upon this event is still not clear and the ΔCFS we obtained here is still too small. We cannot rule out the possibility of model uncertainty, for examples, fault geometric parameters, boundary conditions and initial conditions of pore pressure. So it cannot be directly concluded that there must be a direct connection between the TGR impoundment and the occurrence of this earthquake. However, because the GPS observation of crustal motion of the Xinfengjiang reservoir area is larger than that of the TGR (Gan et al., 2007), tectonically, the TGR region is not as active as that of the Xinfengjiang reservoir region. So, maybe the magnitudes of future

earthquakes triggered by the impoundment of TGR are less than that of the 1962 Xinfengjiang earthquake.

In this study, at the hypocenter, the mechanism of elastic stress change induced by the water load is different in accordance with the different typical characteristics of seismogenic faults. In the case of a thrust fault, the elastic stress change from the impoundment of reservoir usually makes it more stable, whereas the normal fault may become more dangerous. The seismogenic faults of the November 2008 M4.1 and the Wenchuan earthquakes are both thrust types of faults, and their Δ CFSs induced by the elastic stress change are all negative. However, Δ CFSs induced by the elastic stress change of the December 2013 M5.1 and Xinfengjiang Ms6.1 events are all positive.

Conclusions

The Δ CFS at the hypocenter of the M5.1 Badong earthquake is positive at the impoundment of the reservoir. Both pore pressure and the Δ CFS at the hypocenter gradually increased with time. At the occurrence of the earthquake, pore pressure at the hypocenter reaches 13.0~17.0kPa and Δ CFS is around 8.0~11.0kPa, which is above the threshold value of stress changes for the occurrence of reservoir triggered earthquake, as proposed by King et al. (1994). Thus the occurrence of the earthquake could be due to the impoundment of the TGR. On the other hand, the Δ CFS at the hypocenter of the M4.1 earthquake in November 2008 in the Zigui Country (*Mei et al., 2013*) is negative during the impoundment. Diffusion of pore pressure cause the Δ CFS to gradually increase, reaching up to ~5.0kPa upon the occurrence of the M4.1 earthquake. These examples show that the Δ CFS at the time of the impoundment may not be a good indicator of RTE, and evaluation of earthquake risk must consider the long-term effects due to pore pressure

diffusion.

Scientists are now wondering if other large earthquakes may be triggered by this large manmade structure and how the related hazards may be alleviated. Our simulation shows that the elastic strain energy released by this earthquake is very small. On the other hand, the stresses continued to change due to pore pressure diffusion, which accounts for the predominant increase of the ΔCFS . Thus we cannot exclude the possibility of the occurrence of subsequent big reservoir-triggered events in the TGR area in the future. Long-term simulation of the ΔCFS on the major faults beneath the TGR may be needed to evaluate future seismic risks in this area.

Data and Resources

The topographical data used in this paper was obtained from the SRTM <http://dds.cr.usgs.gov/srtm/> (last accessed March 2014). The coordinates of hypocenter and focal mechanism solutions of the M5.1 Badong earthquake were downloaded from China Earthquake Administration (www.ceic.ac.cn) (last accessed December 2013). The details of the Ms4.1 earthquake was from the Seismological Bureau of Hubei Province, China. <http://www.eqhb.gov.cn/> (last accessed May 2014).

Acknowledgment

This research is partial supported by National Basic Research Program of China under grant number 2014CB845906, and National Science Foundation of China (41590864, 41274103 and 41404078). It is also partially supported by the CAS/CAFEA International Partnership Program for creative research teams (No.KZZD-EW-TZ-19 and KZZD-EW-TZ-15).

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Figure 1. The geological structure and the distribution of the main faults around the TGR. I-IV represent Shenongjia block with Pre-Sinianage, Zigui block with Jurassic age, Huangling block with Pre-Sinianage, and other area with Triassic-sinianage, respectively. ①-⑨ denote Wudouhe Fault, Xinhua Fault, Xingshan-Maliang Fault, Fairy mountain Fault, Tianyangping Fault,

536 Gaoqiao Fault, Niukou Fault, Shuitianba Fault and Jiuwanxi Fault, respectively. The upper left
537 panel shows the Yangtze River and the location of the Three Gorges Reservoir. The shadow
538 indicates the TGR region.

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Figure 2. The high-resolution finite element model of TGR. I-IV represent the geological blocks, and ①-⑨ show faults in the TGR region the same as in Figure 1.

Figure 3. Numerical calculation of the vertical displacement distribution after the impoundment of TGR when the water level reached 135m (a) and 175m (b), respectively. The two focal mechanism beach ball diagrams represent the epicenters of the M5.1 earthquake in the Badong region (left) and the Ms4.1 earthquake on November 22, 2008 (right).

Figure 4. Variation of pore pressure and Coulomb Failure Stress change at the hypocenter in terms of the TGR water level fluctuation. (a) ΔP and ΔCFS at the hypocenter of the M5.1 Badong earthquake. The parameters of the corresponding seismogenic fault planes are referenced by the previous geological field investigation, for examples, the strike angle is 74° , the dip angle is 56° , and the rake angle is -178° . (b) ΔP and ΔCFS of the hypocenter at the Ms4.1 earthquake. The calculation parameters of seismogenic fault are: strike angle= 213° , dip angle= 81° and rake angle= 110° (Xu, 2010).

574 Figure 5. The distribution of the pore pressure changes at the depth of 5km with water level, and
 575 Coulomb Failure Stress changes varies with different depths during the occurrence of Ms5.1
 576 earthquake in model 2. The inner frictional efficient is 0.6, the strike angle is 74° , the dip angle is
 577 56° , and the rake angle is -178° , respectively. The focal mechanisms of the micro-earthquakes
 578 are adopted from (Xu, 2010). The magnitude of these 119 micro-earthquakes are larger than 1.0
 579 from March 2009 to December 2009. Among them, the focal depths of 59 micro-earthquakes are
 580 less than 4.0km in Figure 5(d), the focal depths of 43 micro-earthquakes are less than 7.0km and
 581 larger than 4.0km in Figure 5(e), and the focal depths of 17 micro-earthquakes are larger than
 582 7.0km and less than 11.0km in Figure 5(f).

585 Table 1. The values of physical parameters in our finite element model

Block	Model1	Model2				
Depth(km)	E(10^{10} Pa)	ν	Vp	Vp/Vs	C(m^2/s)	
SNJ	0-2	6.58	0.23	5.50	0.35	
	2-5	6.94	0.27	5.76	0.32	
	5-11	7.62	0.25	5.87	0.33	0.2
	11-20	9.19	0.26	6.32	0.32	
ZG	0-2	4.97	0.23	4.97	0.35	
	2-5	5.22	0.27	5.20	0.32	
	5-11	6.99	0.25	5.69	0.33	2.0
	11-20	7.64	0.26	5.92	0.32	
HL	0-2	8.47	0.23	6.02	0.35	
	2-5	8.34	0.27	6.15	0.32	
	5-11	9.46	0.25	6.34	0.33	0.2
	11-20	10.1	0.26	6.53	0.32	
OTHER	0-2	6.58	0.23	5.50	0.35	
	2-5	6.55	0.27	5.64	0.32	
	5-11	8.10	0.25	6.00	0.33	0.2
	11-20	9.19	0.26	6.32	0.32	
FAULT		3.00	0.22	3.00	-	2.0

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