Are reservoir earthquakes man-made?

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Abstract

A debate on whether the Wenchuan Mw7.9 earthquake is triggered by the nearby Zipingpu reservoir has drawn the attention of both the scientific community and the general public. High performance computation provides a powerful new tool to quantitatively evaluate stresses produced by the weight of impoundment of reservoirs and the changes of pore pressure due to water diffusion along faults to the hypocenter. We calculated Coulomb stress changes of a number of reservoirs: including the hotly debated Zipingpu reservoir, the well known reservoir earthquake of Xinfengjiang in 1962, and the reservoir earthquake of Aswan in 1981. We have reached several main conclusions: Elastic energy increase due to the weight of impounded water is usually very small in comparison with seismic wave energy released by earthquakes of magnitude 6 or greater, these reservoir earthquakes are improper to be called man-made, but they are human activity triggered. Geological background and tectonic stresses control the occurrence of such large reservoir earthquakes. Stresses due to weight of impoundment may promote or prevent the occurrence of reservoir earthquakes determined by the location and nature of the earthquake fault. Pore pressure increase due to water penetration along permissive fault, however, always increases the risk of reservoir earthquakes. There seems no definite threshold value of Coulomb stress to trigger earthquake, it may varies from several kPa to 0.1MPa, depending on the magnitude of tectonic stresses and strength of the fault. The occurrence time of reservoir earthquakes after impoundment also varies from months to years depending on the permeability and stress of the fault zone. Geological surveys and numerical simulations may improve risk estimates before reservoir construction.
Keywords: reservoir-triggered earthquake, Coulomb failure stress (CFS), Zipingpu reservoir, Wenchuan earthquake, Xinfengjiang reservoir, Aswan reservoir.

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1 Introduction

Genesis of reservoir triggered earthquake (RTE) is an important problem and has drawn a lot of attentions [1–6]. A debate has lasted five years about if the Mw7.9 Wenchuan earthquake, May 12, 2008, is related to impoundment of the Zipingpu Reservoir or not, since the reservoir is only about 10 km from the epicenter. Soon after the occurrence of Wenchuan earthquake, Fan [7] claimed that the Zipingpu earthquake might have triggered the Wenchuan earthquake based on qualitative criterion. Lei *et al*. [8] estimated the impact of the impoundment of Zipingpu reservoir to the Wenchuan earthquake through calculating the changes of Coulomb failure stress (ΔCFS). They drew the conclusion that Zipingpu reservoir acts an obvious impact on Longmenshan faults and the ΔCFS of the coseismic fault is larger than 0.1MPa in the upper 10km below the reservoir and a few tens of kPa at the focal depth, which means the Zipingpu reservoir could induce the occurrence of Wenchuan earthquake. Kerr and Stone [9] reported this kind of opinions. It is then interpreted as "Chinese earthquake may have been man-made, say scientists" by the news media (*http://www.telegraph.co.uk/news/worldnews/asia/china/4434400/Chinese-earthquake-may-have-been-man-made-say-scientists.html*). A senior Chinese scientist Chen [10] diametrically opposed to this view and qualitatively discussed five features of the Wenchuan earthquake which are not consistent with the typical characters of common reservoir triggered earthquakes. However, qualitative arguments could not convince either side, the debate had been going on. Quantitative analysis is necessary. Unfortunately, although many researchers studied on this issue, their quantitative results are different, because of differences in models, parameters and methods of computation. For example, Ge *et al*. [11] used 2-D numerical models to calculate pore pressure and static load, they concluded that the impoundment of the Zipingpu reservoir changed the ΔCFS by −0.01 to 0.05 MPa at the earthquake hypocentre and potentially hastened the occurrence of this earthquake by tens to hundreds of years. Using 3-D analysis method, Ghaulaut and Ghaulaut [12] suggested that the reservoir produces negative Coulomb stress about -0.1kPa, therefore, plays no role in the occurrence of the earthquake. Deng *et al*. [13] used 2-D model to calculate the pore pressure with grid size greater than 1km, and analytical solution for a 3-D static load; they concluded that at the focal depth, ΔCFS is 0.01kPa, and therefore negligible. Lei [14] insisted his results that Coulomb stresses reach a few tens of kPa at the focal depth, and they are large enough to modulate the secular stress buildup of a few kPa/yr in the Longmenshan thrust zone. Facing the divergences in computation, we need do more detailed investigation on the reservoir triggered earthquake. Firstly, we calculate numerical solution by finite element method (FEM) of simple problems and compare them with analytic solutions as benchmark to guarantee the code is valid and sufficient number of element is used for accuracy. Secondly, we discussed the difference between 2D and 3D. Then, by taking the consideration of the precise topography and dynamic water level, a three-dimensional poroelastic finite element model was constructed about Zipingpu reservoir. Finally, for comparison, we also applied the poroelastic FEM to the M_L5.7

earthquake in Aswan reservoir in 1984 and the Ms6.1 earthquake in Xinfengjiang reservoir in 1962, which is well accepted as the largest reservoir-induced earthquake in China.

2 The physical mechanism of RTE

After the impoundment of reservoir, changes in stresses and pore pressure may influence the earthquake occurrence of the region originally under significant tectonic stresses. We adopt here Coulomb failure stress changes (ΔCFS) to quantify the influence of the reservoir on the earthquakes. The ΔCFS formula can be expressed as eqn (1) (Shi and Cao [15]).

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

where, $\Delta\sigma_v$ is the normal stress change and $\Delta\tau$ is shear stress change along the fault slip direction, μ the friction coefficient, following the principle of elasticity, tensile stress is positive in this paper. ΔP is the pore pressure change, increase of pore pressure is expressed as positive. A positive ΔCFS is in favor of the fault slip, and negative ΔCFS means the fault becomes safer.

The rock mass and faults are poroelastic. When large reservoirs are built, three main physical mechanisms may affect the Coulomb stresses on the nearby fault: (1) elastic load due to the weight of reservoir water; (2) pore pressure increase responding to the volumetric compression; (3) diffusive pore pressure change with time. ΔCFS is affected by the three contributions and is used to study the trend whether the fault becomes safer or more risky [1, 11–13, 16–18].

2.1 The effect of elastic load of impoundment and drainage of Zipingpu reservoir

2.1.1 Using analysis method to estimate the magnitude of ΔCFS due to the elastic load

Because different authors report Coulomb stresses at different order of magnitude, therefore we first approximate the reservoir water load as a point load to see the overall stress state at the focal depth before we go to detailed numerical study. Based on the solution of Boussinesq's problem, the result indicates (Figure 1) that the ΔCFSs for thrust fault beneath the reservoir are mostly negative and decays rapidly with distance and depth to the load. The negative ΔCFS means the vertical compressive stress actually prevent the slip of thrust. At the hypocenter by CEA (China Earthquake Administration), the normal stress, shear stress and ΔCFS are -1.6, -2.8 and -3.8kPa, respectively. These values give a reference level to benchmark the numerical computations.

The point load model can not reflect the complex stress changes within a few kilometers below reservoir. According to digital topography, we build a model with consideration of geometry of the reservoir and realistic water depth. We divided the Zipingpu reservoir into 2000 girds and integrate the point load at each grid. The results provide a more realistic view of stress distribution near the reservoir. Figure 2 shows Coulomb stress changes due to unloading, because the water level in the Zipingpu reservoir was reduced 80 meters 4 months before the main shock. The results confirms previous ΔCFS computations, that at the focal depth, elastic loading tend to prevent the thrust slip and drainage of Zipingpu reservoir is in favor of the occurrence of the earthquake. The magnitude of the ΔCFS decays rapidly with depth, is about 3 kPa at the hypocenter.

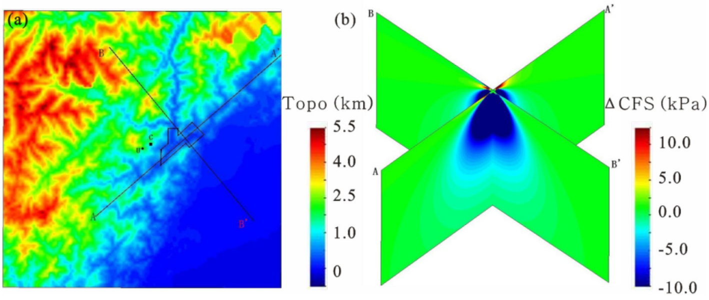

Figure 1: (a) the topography of Zipingpu reservoir area; (b) the ΔCFS of profile AA’ and BB’; Point U stands for the focus provided by USGS and Point C stands for the focus by CEA (China Earthquake Administration); the site of Zipingpu dam was the interaction of the profile AA’ and BB’; the capacity of Zipingpu is 1.112 km^3 and the height of dam is 156m and the reserve-water-level is 877m; the horizontal scale is 100km and the vertical scale is 50km [19].

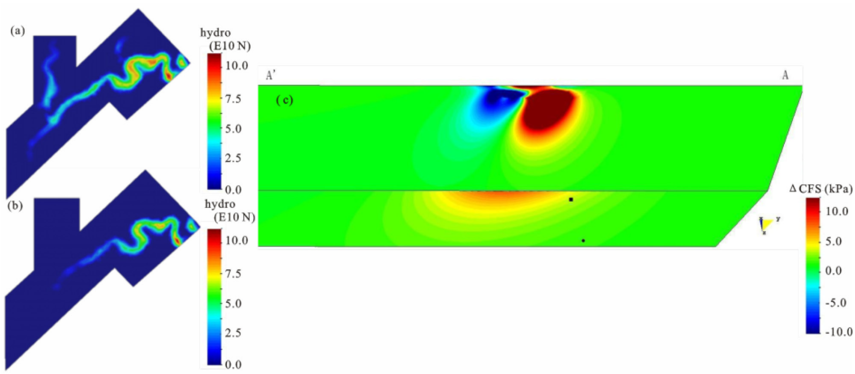

Figure 2: (a) hydraulic pressure when Zipingpu reservoir water level is 877m; (b) hydraulic pressure when Zipingpu reservoir water is 817m; (c) the ΔCFS of the faults when water level reduced from 877m to 817m; profile AA’ stand for the direction of the seismic fault [19].

2.1.2 Comparison of numerical method with analytic method

Using half elastic space analytic method, results can be quickly attained. However, for consideration of more realistic data with heterogeneous geological features such as fault zones, strata, and topography, 3-D numerical model are necessary. We build 3-D models and compare the simple ones with analytic solution to guarantee sufficient accuracy of the code. Triangular prism elements were used in the FEM mesh; it is divided into twenty-seven layers and encrypted in the reservoir area. Total number of elements exceeds 910,000. Figure 3 shows the model and the calculated ΔCFS at two profiles. The value of ΔCFS at focal depth below the reservoir is also negative about 3.0 kPa, consistent with the analytic results.

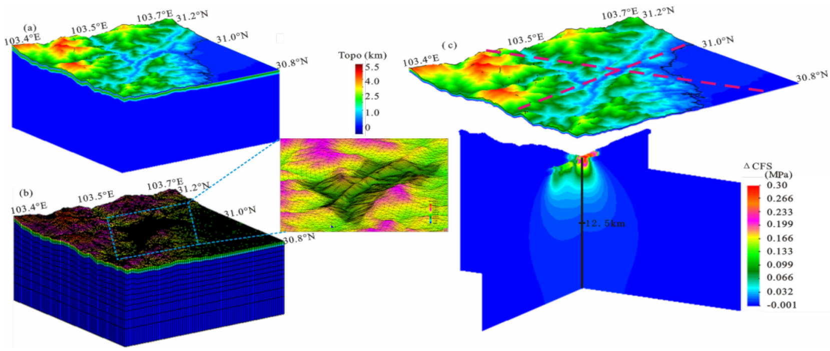

Figure 3: The 3D FEM model of Zipingpu Reservoir. (a) The 3D model and topography; (b) the FEM model mesh in the Zipingpu reservoir area; (c) the ΔCFS at the two profiles labeled above [20].

According to the above results, we can confirm that the impoundment of Zipingpu reservoir make the coseismic fault more stable, while rapid water level decline make the fault more fragile. The magnitude of Coulomb stresses at focal depth due to elastic loading is about a few kPa.

2.2 The effect of Zipingpu Reservoir on the Wenchuan earthquake

Based on above description and discussion, a 3D poroelastic FEM model of the Zipingpu area is constructed to calculate the complete effects of elastic loading and pore pressure during the entire operation of the reservoir. The model includes the fault zone, topography, heterogeneous geological survey data, and dynamic water level change of the Zipingpu reservoir from the beginning of the impoundment to the occurrence of the Wenchuan earthquake (Figure 4). Hydraulic parameters, especially diffusion coefficient and permeability are very important. Though drilling and other exploration can provide some parameters of the shallow rock mass, however, the deep parameters are not clear. Therefore, within a reasonable range, models of different diffusivity of faults and rock mass are calculated and compared to investigate their influences. The results show that the elastic modulus has little effect on the Coulomb stress, while the ΔCFS at the hypocenter increase with the increase of diffusivity, as shown in Figure 4(b) and 4(c). If fault diffusivity exceeds 5.0m/s, ΔCFS at the hypocenter can reaches ~+1 kPa on the eve of the Wenchuan earthquake occurrence. Otherwise, the ΔCFS is negative. It is noticed that elastic contribution of impoundment of water makes the thrust fault more stable, but drainage of water is in favor of trigger the slip. While diffusive increase of pore pressure always tend to increase the seismic risk. It is interesting that the sudden increase of Coulomb stress before the Wenchuan earthquake is directly related to the drainage of water level 5 months before the quake. Figure 4(c) show that the distributions of small earthquakes around the Zipingpu area after the impoundment. They show a tendency occurring in region of increased positive Coulomb stress. Our results indicate the Zipingpu reservoir may not trigger the Wenchuan earthquake if the fault permeability is not sufficiently high. Even the permeability is high enough, however, it is still in doubt that if a small increase in ΔCFS of +1 kPa can trigger the occurrence of the Wenchuan earthquake.

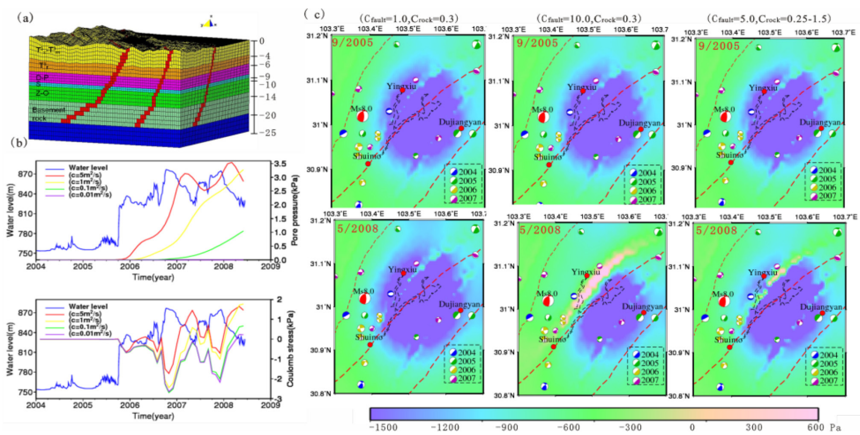

Figure 4: The 3D FEM model of Zipingpu area and the results of calculation; (a) the FEM model mesh in the Zipingpu reservoir area; (b) variation of pore pressure and ΔCFS with the water level at the hypocenter of Wenchuan earthquake [21]; (c) distribution of ΔCFS at the depth of 13km for different combination of fault and rock properties, with small earthquakes from 2004 to 2008 labeled.

2.3 The differences between 2D and 3D

Some researchers based on 2D model to analyze the influence of reservoir on the occurrence of the earthquake are in favor of the possibility of the Zipingpu reservoir triggering [11, 19]. Actually, the 2D model means taking infinite linear loads instead of a load in limited area. It may exaggerate the loading effect. Using FEM method, we compare the differences of 2D and 3D models. Figure 5 shows that the results of 3D model is only 1/3 to1/4 of that of 2D model. At the same time, we found that the results of 2D model are more sensitive to the diffusion coefficient. When we choose different diffusion coefficients, the difference of peak pore pressure in 2D and 3D are 10 and 2kPa, respectively. So, using the 3D model is more reasonable in the absence of the measured diffusion coefficient.

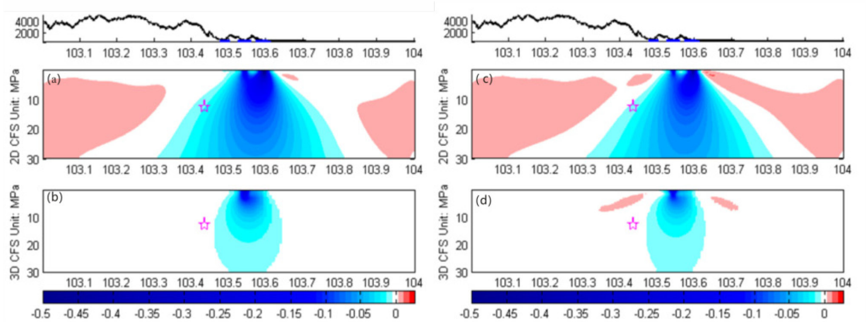

Figure 5: The differences between the 2D and 3D models; (a) the ΔCFS due to the elastic load only in 2D; (b) the ΔCFS due to the elastic load only in 3D; (c) the ΔCFS due to the elastic load and pore pressure in 2D; (d) the ΔCFS due to the elastic load and pore pressure in 3D [22].

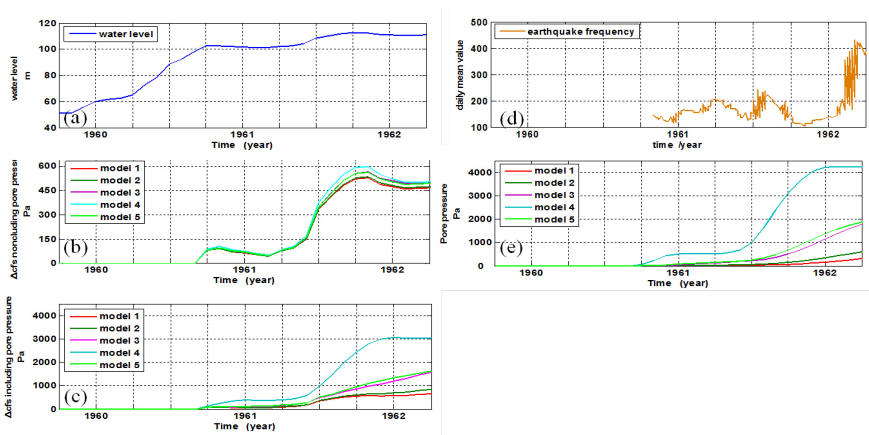

Figure 6: Variation of pore pressure and Coulomb stress with changing water level at the *M*s6.1 hypocentre in Xinfengjiang Reservoir area. (a) Xinfengjiang Reservoir water level; (b) Coulomb stress due to elastic load only (pore pressure not included); (c) Coulomb stress at the focal depth; (d) the earthquake frequency in Xinfengjiang Reservoir area; (e) the pore pressure changes at the seismic source [23].

2.4 The effect of Xinfengjiang reservoir on Ms6.1 earthquake

Coulomb stress calculation of Zipingpu reservoir is marginal positive in favorable permeability conditions. For comparison, we try several other reservoirs to investigate if Coulomb stress needs to reach some threshold value to trigger reservoir earthquakes. Frequent seismic activities occurred since the impoundment of the Xinfengjiang Reservoir, Guangdong, China in October 1959. Two and half years later, an *M*s 6.1 earthquake broke on 19 March 1962, well acknowledged as the largest reservoir-induced earthquake in China. A 3-D Xinfengjiang model was established. The diffusion coefficients of stratum in Xinfengjiang are uncertain. On the basis of the predecessors' study, we give five models of different diffusivity to discuss the effect of the impoundment of Xinfengjiang reservoir on the Ms6.1 earthquake.

The variations of pore pressure and ΔCFS with water level are both increased with increasing water level, shown in Figure 6. Permeability of rock and fault plays a significant role in the pore pressure pervasion. Elastic stress induced by the water load had only a little effect on the stability of the fault system. Pore pressure makes the main contribution to changes of Coulomb stress. The ΔCFS at the hypocenter was 0.7~3.0 kPa in different models.

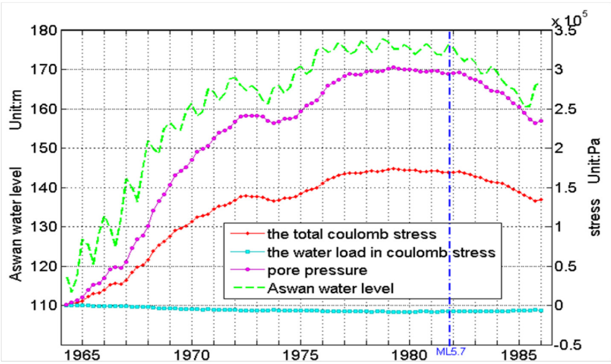

Figure 7: Variations of pore pressure and ΔCFS at the hypocenter with changing water level [20].

2.5 The M_L5.7 earthquake in Aswan reservoir

The Aswan Reservoir, the world's second largest reservoir, is located in southern Cairo in Egypt. The first impoundment of the Aswan Reservoir occurred in 1964 [24]. Maximum water depth was up to 177.48 m in November 1978. On November 14, 1981, four days after the water level reached seasonal maximum, an M_L5.7 earthquake occurred. Three large foreshocks and two aftershocks occurred following the main shock. Faults are well developed in the reservoir area. A 3D Aswan Reservoir FEM poroelastic model was established. Figure 7 shows variations of pore pressure and ΔCFS of the hypocenter. The pore pressure is about 300kPa at the time of the occurrence of M_L5.7 earthquake. ΔCFS caused only by reservoir loads is negative and relatively small compared with pore pressure. ΔCFS reaches 0.17 MPa before the main shock. Moreover, a dynamic lag in pore-pressure diffusion is encountered and is found to correspond with reservoir water level. Aswan Reservoir water level reached a peak in 1972, and pore pressure and ΔCFS corresponding to the peak reached their highest points in 1973.

3 Is there a threshold value of ΔCFS to trigger earthquake?

King *et al*. [25] suggested that notable seismic activity could be observed if the stress change reaches 0.01MPa, or 10kPa. In this study, for Zipingpu, Xinfengjiang and Aswan reservoir, the values of ΔCFS at the hypocenters immediately before the earthquake are about 1.0kPa, 3.0kPa and 100kPa, respectively. The time interval between the impoundment of reservoir and the earthquake occurrence varies from several months to nearly 17 years. Although the Ms6.1 earthquake in Xinfengjiang reservoir area is widely accepted as the largest reservoir earthquake in China, the magnitude of the ΔCFS in our model is 3.0KPa only, smaller than the 10kPa value proposed by King. While the Aswan earthquake did not occur until the Coulomb stress increased to 100kPa after 17 years. Therefore, it seems that there is no definite threshold value for triggering reservoir earthquakes. The occurrence of reservoir triggered earthquakes is closely related to the background tectonic stress field and fault or rock strength. Even though the ΔCFS is small, if tectonic stresses are already close to the strength, reservoir impoundment and drainage can trigger reservoir earthquakes. Therefore, in the future study of RTE, state of tectonic stresses should be explored carefully.

4 Strain energy due to the impoundment of reservoir

The impoundment of reservoir could lead to rock mass deformation. So we can calculate the elastic strain energy produced by water loading, and it can be compared with seismic wave energy released during the earthquake. We calculated the maximum vertical subsidence due to impoundment of Xinfengjiang reservoir is 17.5mm, in well agreement with the observed 15.0mm. The strain energy induced by Zipingpu, Xinfengjiang and Aswan reservoir are about 4.0×10^{11} J, 7.3×10^{11} J and 1.12×10^{15}J, respectively, comparing with the energy released by the seismic wave energy of Mw7.9, Ms6.1 and M_L5.7 earthquakes, they are less than 0.001%, 1% and 0.01%. This result shows that the impoundment of the reservoir only triggered the earthquake. Most energy released by the earthquake has been stored there due to tectonic loading for tens or hundreds of years. The reservoir triggered earthquake with magnitude 6.0 or greater cannot be called man-made. They are only triggered by human activity.

5 Discussion and conclusion

Since Carder [2] investigated the relationship between the Denver Reservoir and local earthquake activity in the 1940s, many scientists have focused on reservoir triggered seismicity and obtain some physical mechanisms of RTE [1–6, 26–27]. However, after the *Mw*7.9 Wenchuan earthquake, there exists a heated argument about whether the Zipingpu reservoir triggered the occurrence of the Wenchuan earthquake [9–14, 28–30]. We therefore carried out investigations on the reservoir triggered earthquake by constructing numerical models and calculating the ΔCFSs for the *Mw*7.9 Wenchuan earthquake, *Ms*6.1 Xinfengjiang earthquake and M_L5.7 Aswan earthquake. We get the following conclusions: (1) the direct elastic effect of impoundment loading at Zipingpu reservoir makes the thrust fault more stable, while rapid water level decline make the fault more fragile. (2) Pore pressure increases due to water penetration along permeable fault, always increases the risk of reservoir earthquakes. Diffusivity of fault zones is of critical importance. (3) With reasonable values of diffusivity, we found the ΔCFS at the hypocenter of Wenchuan earthquake ranges at a marginal value from a few kPa negative to only ~+1kPa on the eve of the Wenchuan earthquake occurrence. There is no solid evidence to support that Wenchuan earthquake is triggered by the Zipingpu reservoir impoundment, however, it is also too early to exclude the possibility of triggering effect, because the Coulomb stress may be positive in favorable conditions, and the earthquake occurred when drainage rapidly after a long period of high water level. (4) For *Ms*6.1 Xinfengjiang earthquake, the reservoir impounding increases both the pore pressure and ΔCFS. The diffusion of pore pressure is the main factor that triggered earthquake, while the elastic water load is small. The ΔCFS values at the hypocenter can be about 3.0kPa, depending on the fault diffusivity. In Aswan reservoir area, both pore pressure and Coulomb stress of seismogenic fault have been gradually increasing with the raising water level, and the maximum values can reach 0.01MPa to trigger the earthquake. (5) Coulomb stresses calculated from 2D model have been exaggerated. For the case of Zipingpu reservoir, the results of 3D models are only 1/3 to1/4 of those of 2D models. (6) The elastic strain energy due to reservoir impoundment is very small compared with seismic wave energy for earthquakes of magnitude 6 or greater. Therefore major reservoir earthquakes are triggered by water impoundment, but it is improper to call them man-made. (7) There seems no definite threshold value of Coulomb stress to trigger earthquake, it may varies from several ~kPa to 0.1MPa, depending on the magnitude of tectonic stresses and strength of the fault. The occurrence time of reservoir earthquakes after impoundment also varies from months to years depending on the permeability and stress of the fault zone. (8) Geological surveys, stress measurement and numerical simulations may improve risk estimates before reservoir construction.

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