# Research on Faulting Response to Reservoir-induced Seismicity*

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Abstract: Reservoir-induced seismicity (RIS for short) is the result from reservoir impounding. According to the research during past half century, the cause of RIS may be complex. However, based on the tectonic analysis of some RIS samples in the world and China, there existed obvious faulting response to RIS, which were shown as the heterogeneous distribution of the RIS epicenters, the RIS epicenters centralizing in a belt, the uncertain position relationship between the reservoir and RIS belt, and RIS belt being controlled by some faults in the reservoir area.

Key words: reservoir-induced seismicity; genetic mechanism; faulting response

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## 1 About the Genesis of RIS

The general idea is that the seismicity in the reservoir area should be changed after water storage. This phenomenon is so called reservoir-induced seismicity, or RIS (Gupta, 1992; Ding, 1989; Rothe, 1968).

During the middle of the 20th century, some strong earthquakes occurred in some reservoir areas, such as Xinfengjiang, China, Reservoir, etc., and caused severe damage and casualties. After that, the research on RIS has been paid more attention to. As the reason of data, the conclusions on RIS genesis are different due to different periods and different researches (Hu, 1983).

Packer et al. (1979) and Baecher (1982) statistically analyzed 234 big reservoirs in the world (the dam height ≥ 90 m and capacity ≥ $1\times10^9$ $m^3$), and concluded that only at 29 reservoirs occurred RIS. Based on the analysis on rock style, water depth, capacity, tectonic stress and faults, they thought that the correlation is obvious between reservoir depth, capacity and RIS in the reservoir area where the rock is sedimentary and tectonic stress is strike-slide.

Rothe (1973) concluded that the depth of a reservoir is more important than capacity to RIS. RIS may be easily occurred at the reservoir whose depth is deeper than 100 m.

Simpson (1976) concluded that the seismic response is different in different reservoirs and the relationship between the RIS and parameters of reservoir is not obvious, because that the RIS was not occurred in some big reservoirs but occurred in some small ones.

Based on the statistics of correlation among RIS and built year, dam style, water depth, capacity, area of water surface, impounding process, geology and tectonics, Sturrt-Alexander (1976) concluded that more obvious factors to influence RIS are water depth and capacity. As the water depth is deeper than 90 m, the existence and activity of fault don't influence RIS. Metamorphic rock is more important to RIS than magmatic and sedimentary rock.

Castle et al. (1980) studied the geological background of 41 reservoirs in which RIS occurred and some reservoirs in which RIS hadn't occurred, and

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concluded that the existence and style of fault and elastic strain accumulation along fault are very important to RIS. Generally, the RIS occurred along the normal or strike-slip faults which parallel to reservoir bank, and with large dip angle and strain.

Keith et al. (1982) studied the RIS at Nurek, USSR, Reservoir. Based on the fault location and offset style, they concluded that whether a reservoir induces earthquake not only depends on fault but mainly on water injecting into fault.

In the early 1980's, based on the study of 13 RIS samples in China, Hu[①] concluded that the probability of occurring RIS in a reservoir doesn't increase with increasing seismic intensity in the reservoir area. The relationship among RIS, regional tectonic activity and natural seismicity in the reservoir area is not very agreement as there are not much data to support the relationship between RIS and large active fault, because RIS hasn't occurred at some reservoirs built on large active faults where earthquakes occurred before the reservoirs impounding. 11 of 13 RIS samples are related to Karst, 2 occurred in magmatic area. The Karst is related to RIS. Hu also concluded that according to previous studies the probability of RIS in a reservoir increase with increasing dam height and reservoir capacity. Different researchers gave different conclusions on the relationship between RIS and geological environment. The major reason should be that for every reservoir the data of dam height and capacity maybe get more easily and certainly than geological data, because the accuracy of focus locating, relationship between RIS and particular geological factors may be difficult to determine.

By the late 1980's, Ding (1989) studied some RIS samples in China, including Xinfengjiang Reservoir, etc., and concluded that RIS is just a probable phenomenon and not a necessary result of reservoir impounding. The RIS occurrence should be determined by multifarious reasons including regional seismicity, the characters of the faults developed in reservoir area, rock petrology, geothermal condition, etc. The seismic inducing role of reservoir includes water load, pore fluid pressure, hydrochemical and physical factors, and microearthquake. The effects of water load and pore fluid pressure are major mechanism of RIS. Because water load decreases the pressure of fault, which promotes the water diffusion, chemical-physical action and effect of pore fluid pressure.

Gupta (1992) studied 70 RIS samples in the world in the early 1990's and concluded that the mechanism of RIS is mainly the effects of water load and pore fluid pressure.

Chen (1998) studied the 19 RIS samples in China, and concluded that 15 of 19 samples occurred in Karst area, 4 occurred in granite area, diffusion of pore pressure and hydrochemical dissolution are the reasons of RIS.

Marcelo (2002) studied 16 RIS determined in Brazil, the rock in these reservoir areas is granite, basalt and metamorphic rock. He believed that not only deep reservoirs may induce earthquake, but also shallow ones may do, and concluded that the RIS research on small reservoir should be emphasized.

From above introduction we can see, the interpretation on RIS mechanism is multitudinous up to now. Geologically, some researchers thought that RIS might not relate to the fault developed in reservoir area. But some researchers concluded that there are no relationship between RIS and the fault developed in reservoir area. Water impounding causes water diffusion along fault, thus changing the stress along some fault or producing an incremental stress field. This process promotes the water diffusion, hydrochemical dissolution, decreasing the pore fluid pressure along fault (Marcelo, 2002).

## 2 Faulting Factor of RIS

RIS is divided into tectonic style and Karst style. The genesis of tectonic RIS is interpreted as the seismicity change in reservoir area caused by water

① Hu Y L, 1983. Progress on reservoir induced seismicity study. Seismogeology Translation Collection.

impounding which changes the stress field and tectonic movement process of reservoir area, inducing fault's seismic rupturing. At present, different researches have different conclusions on the relationship between fault and mechanism of RIS.

Keith (1982) believed that the site of RIS is determined by existence of fault, not by whether the water injecting into fault.

Simpson (1976) concluded that the correlation between RIS and fault developed in the reservoir area is from the stress action of water load; the normal fault and strike-slide fault should be easy to induce earthquake, but reverse fault should not. The reservoir built on normal or strike-slide fault should is more possible to trigger earthquake.

Simpson (1990) also concluded that the mechanism of the process from water impounding—pore pressure increasing—fault surface weakening and stable loss—RIS occurrence, had not been comprehended. He gave a model on RIS in which under the reservoir there is a weakened and water seeped layer or fault in dip state. But it is pity that the model still hasn't been discussed and evidenced by numerous and complex RIS samples.

Jacob (1979) concluded that the normal and strike-slide faults should promote the RIS, the reverse fault should decrease the seismicity of reservoir area, and outlined the analysis models under this idea.

Ding (1989) concluded that more than half the RIS in the world were related with the shallow fault developed in reservoir area and its vicinity. The fault on different scales and developed in the basement of reservoir may be not only the rupturing factor of RIS but also the basic condition of water diffusion. The fault with large length and depth scale and big dip angle, and the active fault parallel to the reservoir bank or transversely cutting through the reservoir, are important conditions of strong RIS occurrence. The normal and strike-slip fault are easy to rupture. The reservoirs in tectonic tension area may be easier to induce earthquake than those in tectonic compression area.

At present, we have understood the RIS-fault relationship to some degree and been paying more attention to it, but there are still some arguments about detail genesis of RIS-fault relationship or tectonic genesis mechanism of RIS.

## 3 Performance of Faulting Response to RIS

Based on above study, it may be concluded that there is fault factor in some RIS events. If the fault rupturing mechanism can't be concluded, it should be understood that there exists faulting response phenomena in RIS.

According to the RIS data of the reservoirs on various scales and in different regions, different regional seismicity and RIS, the faulting response to RIS has following performances.

### 3.1 Heterogeneity of RIS Epicenter Distribution

Almost all of the RIS samples whose maximum magnitudes larger than 6, including Xinfengjiang Reservoir of China, etc., RIS epicenters distributed heterogeneously. The heterogeneous distribution phenomenon also appeared in some RIS samples whose maximum magnitude between 5.0 and 5.9, such as Aswan Reservoir of Egypt, etc., and some samples whose maximum magnitude between 4.0 and 4.9, such as Shuikou Reservoir of China and Nurek Reservoir of USSR, etc., as well as some samples whose maximum magnitude small than 3, such as Menticello Reservoir of USA and Tuoktuogul Reservoir of USSR, etc. These heterogeneity samples distributed at different countries, on different reservoir scale, and with different magnitude of mainshock, it means that the RIS may not be the occasional or probable event.

### 3.2 RIS Epicenters Convergence in belt

Based on the heterogeneity, RIS epicenters generally concentrate in some special area and usually form seismic belt in reservoir area. The number, scale and figure of RIS epicenter belts are usually various in different reservoirs. For example, 5 RIS belts formed in the Xinfengjiang Reservoir area. Among them, the epicenters in left bank are most dense, the mainshock and some big aftershocks occurred there. 3 RIS areas separately formed at north bank, south bank and west end of Nurek Reservoir. One 10 – km – long RIS belt formed in Aswan Reservoir, which located in the Geleb Marawa Mountain near the mouth segment of the reservoir. The maximum magnitude of RIS is more than 2 at Menticello, Huangshi and Tuoktuogul reservoirs, their RIS epicenters also distributed in belt. The RIS epicenters at Menticello Reservoir also formed 3 seismic areas at north end, middle part and south end of the reservoir, which strikes in NW.

3.3 Uncertain Position Relationship Between Reservoir and Its RIS Belt

The most obvious character of the relationship between reservoir and its RIS belt or area is that the RIS epicenter belt or area generally located at the reservoir bank area or some special site outside the reservoir, in the inner basin of reservoir the RIS is little or lack comparatively. It is said that there was not the sample which the RIS epicenters belt or area covers all of the reservoir area. This should be very important to understand the genesis mechanism of RIS. For some reservoirs, the strike of RIS belt is the same as the strike of the reservoir, such as Xinfengjiang Reservoir, etc. Some RIS belts crossed the reservoir obliquely, such as the Wuxijiang (China), Aswan and Menticello reservoirs, etc. Also the two cases occurred in a same reservoir, such as Nurek Reservoir, etc. In the relationship between RIS belt and reservoir segment, some RIS belts are located at the head segment of the reservoirs or the vicinity of the dams, such as the Aswan, Toktogul, Tena and Yingzhidu reservoirs. In some reservoirs, the RIS belt is located at the end of the reservoir, such as Huangshi Reservoir of China, etc; in other reservoirs, the RIS belt is located in the middle part of the reservoir, such as the Danjiangkou, Wuxijiang and Shuikou reservoirs of China, etc. This relationship characters between RIS belt and reservoir segment are also showed by Brazil RIS (Marcelo, 2002).

3.4 RIS Belt Controlled By Some Faults Developed in Reservoir Area

Generally the seismic ground rupture caused during earthquake near the fault is the direct evidence of tectonic genesis of quake, thus the fault rupture genesis of RIS whose magnitude is larger than 6.0 may be understood, including Koyna, India RIS, etc. As some reasons, the genetic relationship between mid-small RIS activity and fault rupture is still in disputation.

In order to further study the genetic relationship between RIS activity and fault rupture, we give the tectonic characters of some RIS reservoirs in the world and China in Table 1 and Table 2, separately.

Only the reservoirs listed in Table 1 and Table 2, their RIS should be related to some faults developed in reservoir area. In one hand, their RIS distributed heterogeneously and in belt, and had complicated location relationship with the reservoirs, but these characters may not be logically understood and interpreted by the non-tectonic factors including reservoir scale, petrology, water diffusion along fault or fissure, and change of reservoir water level, etc. In the other hand, according to the relative data reported, the these RIS have following characters:

(1) one or more than one faults run through the seismic belt or its vicinity. In the RIS area of Xinfengjiang Reservoir, the Heyuan, Renzhishi and Dengta-Kejia faults are developed (Gupta, 1992; Wei, 1976; Wang, 1976; Xiao, 1984). The epicenters of M5.3 mainshock and its aftershocks that occurred in Aswan Reservoir mainly distributed along the 10 km segment of Kalabsha fault (Issawi, 1969). Dangjiang fault, Shangshi fault and Junyun fault run through the RIS area of Danjiangkou Reservoir (Gupta, 1992; Yan et al., 1994; Gao, 1983; Wang et al., 2003).

(2) The extension direction of RIS belt is the same as the strike of fault running through the belt. This phenomenon is obvious in Xinfengjiang Reservoir, Aswan Reservoir and Nurek Reservoir, etc., in which there were many earthquakes occurred.

(3) The mainshock or earthquake sequence usually centralized at a special tectonic environment. The epicenters of mainshock and lot of aftershocks of RIS in Xinfengjiang Reservoir occurred at the east bank of the reservoir near the dam, where the NE-trending

Table 1 Tectonic Characters of Some RIS Reservoirs in the World

| No. | Country | Reservoir Name | Maxi Magnitude of the RIS | Possible Expression of Faulting Response | Data Source |
|---|---|---|---|---|---|
| 1 | USA | Mead | 4.6 | The epicenters mainly distributed along southeastern and southwestern Mead Lake. The faults are developed along the southeast and southwest bank of Mead Lake. The faults developed in the southeast bank include Mead Slope fault and Fortification fault. There is obvious concordance between the fault strike and the fault plane solutions of the earthquakes. | Gupta (1992), Rogers et al. (1976), Rogers et al.① |
| 2 | | Oroville | 5.6 | A new 3.8-km-long surface rupture zone was formed in N-NNW direction. The surface fault is consistent in the position, orientation and manner of slip with the fault zone defined from the distribution of aftershock activity, focal mechanism, deformation inferred by survey. | Gupta (1992), Clark et al. (1976), Bufe (1976) |
| 3 | | Monticello | 2.8 | Some researchers concluded that the earthquakes were caused by the thrust slip of tectonic fractures. | Zoback et al. (1982), Talwani et al. (1987) |
| 4 | India | Koyna | 6.4 | Tectonic ruptures are developed in the reservoir area. The LANDSAT imagery linements in the seismic area are developed. The distribution of the earthquakes is consistent with the imagery linements. A 3-km-long surface fissures and cracks zone was formed by the earthquake. | Gupta (1992), Rastogi et al. (1980), Sykes (1970) |
| 5 | | Bhatsa | 4.9 | The faults very developed in the RIS area, including Talekhan Fault, Kengri Fault and F7, etc. | Rastogi et al. (1986) |
| 6 | | Osman Sagar | 3.5 | The RIS epicenters mainly distributed along the NS-striking fault developed in the north of the reservoir. | Rastogi et al. (1986) |
| 7 | USSR | Nurek | 4.5 | The earthquakes distributed along the north bank, south bank and south end of the reservoir. The NE-trending Sarikamar fault developed along the north bank and the NE-trending Gulizindan fault developed along south bank. At the dense epicenter area in the south end of the reservoir may develop a NS-trending fault which runs through this area. | Keith et al. (1982), Leith et al. (1981) |
| 8 | | Toktogul | 4.7 | Talas-Fergana Fault and Karasu Fault run through the north and east of the RIS area. The Naryn river on which the dam is located also flows along the strike of an active fault extending from the dam to Talas-Fergana Fault and the fault runs through the RIS region. | Gupta (1992), Simpson (1988), Simpson (1981) |
| 9 | Canada | LG3 | 3.7 | The LG3 fault runs through the earthquake area of 1983. | Anglin (1985) |

Heyuan and Renzishi faults and NW-trending Shijiao-Xingang-Baitian fault belt flock together. The M4.3 epicenter of the Shukou RIS located at the vicinity of the crossing site of NE-NEE fault zone and NW-trending faults. In the epicenter dense area of Nurek Reservoir, the NE-trending Sarikamar fault developed along the north bank and the NE-trending Gulizindan fault along the south bank may meet together with a NS-trending fault which be conjectured (Keith et al., 1982; Leith et al., 1981). At Toktogul Reservoir, the RIS epicenters mainly distributed at the intersecting area of WE-rending Talas-Fergana fault and NE-trending Karasu fault (Gupta, 1992; Simpson, 1988, 1981).

(4) The fault plane solutions of RIS agree with some faults. Based on the foci mechanism analysis of some RIS, including Aswan (M5.3), Koyna (M6.5), Xinfengjiang (M6.1) etc., not only the fault plane solutions of their mainshocks agree with some fault running through the earthquake areas, but also the solutions of some aftershocks agree with them (Wang, 1976).

(5) Besides above features, based on measurements of hydraulic fracturing stress and seismic stress drop, Zoback et al. (1982) concluded that the microshocks in Menticello Reservoir were caused by the offset of tectonic fractures.

Based on above analysis, just as same as the natural earthquake, there is also obvious tectonic relationship between RIS and the fault developed in

① Rogers A M, Gallanthine S K. 1974. Seismic study of earthquakes in the Lake Mead region. Environmental Research Corporation, USA.

Table 2　Tectonic Characters of Some RIS Reservoirs in China

| No. | Reservoir Name | Maxi M of the RIS | Faults developed in reservoir area: Fault Name | Property | Possible Fault Response Performance | Data Source |
|---|---|---|---|---|---|---|
| 1 | Danjiangkou | 4.7 | Danjiang fault | normal | Control the distribution of the epicenters | Ding(1989) |
| | Hubei | | Shangshi Fault | reverse | | Yan et al. (1994) |
| | | | Junyun fault | reverse | | Gao(1984) |
| | | | Hanjiang fault | reverse | | Wang et al. (2003) |
| | | | Dashiqiao Fault | normal | Control the distribution of the epicenters | |
| 2 | Xinfengjiang | 6.1 | Heyuan fault | reverse | Control the distribution of the epicenters and mainshock | Ding(1989) |
| | Guangdong | | Renzishi fault | reverse | Control the distribution of the epicenters | Wei(1976) |
| | | | Dengta-Kejia fault | reverse | | Wang(1976) |
| | | | Daping fault | reverse | Control the distribution of the epicenters | Xiao(1984) |
| | | | Guolongshi fault | reverse | Control the distribution of the epicenters | |
| | | | Longmen fault | reverse | Control the distribution of the epicenters | |
| | | | Shijiao-Xingang-Baitian fault | | Control the distribution of the epicenters and mainshock | |
| | | | Dongyuan-shuangtang fault | | Control the distribution of the epicenters and mainshock | |
| 3 | Huangshi | 2.3 | Jinglongqiao fault | reverse | Control the distribution of the epicenters | Dai(1997) |
| | Hunan | | GUangdongshan fault | reverse | | Kong(1984a) |
| 4 | Yingzhidu Guizhou | V (intensity) | Xiaba fault | reverse | Run through the earthquake area | Wang(2003) |
| 5 | Wuxijiang | 3.4 | Yishanhuangnilin fault | reverse | Control the distribution of the epicenters | Kong(1984b) |
| | Zhejiang | | Gaoshan-Changyun fault | reverse | | |
| | | | F6 fault | | Control the location of mainshock | |
| 6 | Shuikou | 4.3 | NW trending faults | reverse | Control the isoseismals of mainshock and the epicenters of the microshocks | Peng(1997) Guo(1998, 1997) |
| | Fujian | | NE trending faults | tension | | Chen(2002) Xu(2004a, 2004b) |
| 7 | Chanwo | 4.8 | NE faults | | Major seismic tectonics | Ding(1989) |
| | Laoning | | NNE faults | | | |
| | | | NW faults | | | |
| 8 | Zheling | 3.2 | NE faults | | | Huang(1984) |
| | Jiangxi | | Wuning fault | normal | Control the distribution of the epicenters | |
| | | | Shatiangang fault | normal | Control the intension distribution of some earthquakes | |
| 9 | Wujiangdu | 3.5 | Bailiushui fault | reverse | | Wang(1984) |
| | Guizhou | | Malaoshi fault | reverse | | Tan(1994) |
| | | | Xiaotianba fault | reverse | | |
| 10 | Nanshui | 3.0 | F3, F4, F5 | normal | The M3.0 earthquake locates at the conjugate site of F3, F4 and F5 | Xiao(1984) |
| | Guangdong | | F6, F7, F8, F9, F10 | normal | | |

reservoir area, especially the local faults. So RIS should also have obvious faulting response characters. On the other hand, the tectonic relationship between RIS and the fault should be more complex. It means that not on all faults developed in a reservoir area will occur earthquake or not all faults in the reservoir area have response behavior to RIS.

## 4　Discussion and Major Conclusion on Faulting Response to RIS

(1) The fault is the result of rock rupture caused by tectonic movement and is a general geological trace that is kept in the shallow crust (Mogi, 1967). Based on different ideas, the faults are classified into lithosphere fault and crust fault, large fault and small fault or fracture, active fault and nonactive fault, normal fault and reverse fault, strike-slip fault and dip-slip fault, tension fault and press fault, etc.

(2) Because of inner and outer earth dynamical action, the relation between fault and geomorphy is intimate. Not only the regional landform features are controlled by large fault, but also the local mini ground relief may relate with small fault. The river is a usual geomorphic sign on the Earth, the genesis and evolution of which are controlled not only by re-

gional neotectonic movement of crust but also by the fault or active fault. Therefore, the reservoir related to river is usually located at a special geological and tectonic environment. Based on the geological data of some reservoirs that can be collected, not only may the big fault run through but also some small faults that have not been noticed exist in reservoir area or vicinity. Because of this reason it should be a general situation that some small-scaled faults may exist in reservoir area.

(3) Among the reservoirs in the world, only some of them had the RIS reports. In these samples, the mainshocks or biggest earthquakes of 4 RIS more than 6.0, those of 36 RIS from 4.5 to 5.9, those of 43 RIS from 3.0 to 4.4, those of 51 smaller than 3.0. According to the statistics of the RIS reports before 1980's, Packer et al. (1979) and Baecher et al. (1982) concluded that the RIS took 12% of the total. Even if the RIS records may not be complete, up to now there is still no evidence to prove that RIS are the certain result of reservoir building and water impounding. Therefore, according to Table 2, just like the relationship between RIS and petrology, dam height, and reservoir capacity, there may not be universal correlation between the faults developed in reservoir area and RIS events. It is means that even if there are faults in reservoir area, the earthquake doesn't always occur at the reservoir.

(4) Based on some geological dada of RIS reservoirs, the RIS certainly relates to some faults, the major reasons should be supported by that RIS usually distributed at some special sites heterogeneously, these sites are not all in the limestone area and dam area, but all of the RIS areas have fault (s) running through the seismic belt, and the dense epicenter areas are usually located at special fault area. The fault plane solutions of some RIS focus mechanism analysis agree with some special geological faults that run through reservoir area.

(5) RIS only relates to some special faults developed in reservoir area. This indicates that the RIS-fault relation is not only intimate but also complex. Beside the scale, activity, tectonic steadiness determined by rock strain accumulation, dynamic property and slide manner, maybe the dynamic relation between the fault supplement stress state caused by water impounding and inherent or original stress state of fault is more important genetic factor of fault response to RIS, which determined by relative location relationship between fault and reservoir basin.

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# 水库诱发地震中的断层响应分析 *

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摘要：通过对过去近半个世纪水库诱发地震资料的分析，认为水库诱发地震的诱发因素尽管复杂，但一些国内外水库诱发震例表明，水库诱发地震的断层响应现象是明显的，这种现象由水库诱发地震的非均匀分布性、集中呈带性、地震带与水库位置关系的非确定性、地震带沿库区某些断层展布等方面所反映。

关键词：水库诱发地震；地震机理；断层响应