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Reservoir-induced Seismicity in China

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Abstract—A review of case histories of reservoir-induced seismicity (RIS) in China shows that it mainly occurs in granitic and karst terranes. Seismicity in granitic terranes is mainly associated with pore pressure diffusion whereas in karst terranes the chemical effect of water appears to play a major role in triggering RIS. In view of the characteristic features of RIS in China, we can expect moderate earthquakes to be induced by the construction of the Three Gorges Project on the Yangtze River.

Key words: Reservoir-induced seismicity in China, mechanism of reservoir-induced seismicity.

Introduction

Since the earliest, and one of the most destructive cases of reservoir-induced seismicity (RIS), the M_s 6.1 earthquake in Xinfengjiang in 1962, there have been 18 other cases of RIS in China. These have ranged in magnitude between M_s 4.8 and 2.2, and have occurred in different geologic zones and have been associated with a large range of impoundment histories and water levels. The RIS at these reservoirs has been the subject of non-uniform studies, ranging from detailed studies at Xinfengjiang and Danjiangkou Reservoirs, to very few studies at Shenjiaxia and Shuikou. Very few details are available in English and most accounts are only available in various technical reports, journals and books in Chinese.

Two large hydroelectric projects, the Three Gorges Project on the Yangtze River and the Xiaolangdi Project on the Yellow River (Fig. 1) are currently under construction. When completed, they will be among the largest in the world and in view of the incidence of RIS in China, it is important to understand and assess their seismic potential. In order to do so, it is necessary to understand the nature of the RIS that has been observed to date. Towards that end, in this paper we review the lithology of hypocentral areas where RIS has been observed, their filling history and reservoir characteristics.

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Mechanism of RIS

Recently TALWANI (1997) reviewed our current understanding of the nature of RIS. The emphasis was on the physical effect of impoundment on triggering RIS. The strength changes (S) are governed by the Coulomb criterion, $S = S_0 + \mu(\sigma_n - p)$ where S_0 is cohesion, μ the coefficient of friction, σ_n the normal stress and p the pore pressure. Increase in pore pressure, or a decrease in the coefficient of friction and cohesion results in weakening the rocks and leading them to failure.

The elastic response to impoundment is instantaneous and manifests itself by an increase in the normal stress. It results in stabilizing the regions below the deepest part of the reservoir, resulting in little or no activity there. The impounding of a reservoir also results in an instantaneous increase in pore pressure, due to Skempton's effect. This effect is usually short-lived. As the pore pressure diffuses away, there is a cessation in seismicity. The delayed effect of pore pressure diffusion from the reservoir to hypocentral depths is most widely observed. Pore pressures increase away from the reservoir (thus weakening the rocks), resulting in a delay between the filling and the onset of seismicity. The seismicity occurs on the periphery of the reservoir and is usually associated with outward migration of epicenters along faults. Thus, delayed seismicity is most commonly observed.

In recent years we have come to recognize that the impoundment of a reservoir can reduce the strength of rocks by reducing the coefficient of friction, μ, or by

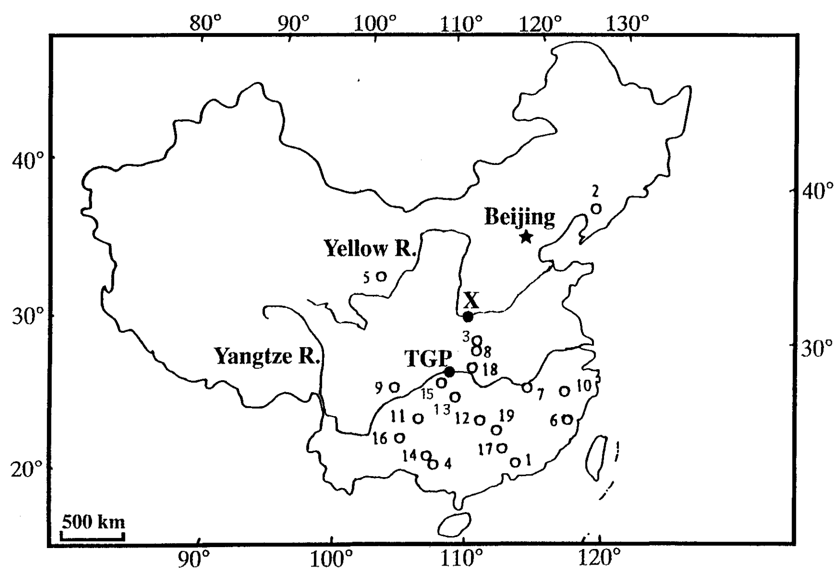

Figure 1
Map showing the locations of RIS cases in China and the Three Gorges and Xiaolangdi Projects (modified from HU *et al.*, 1996). TGP, Three Gorges Project; X, Xiaolangdi Project.

reducing the cohesive strength of rocks, S_0. Introduction of water or an increase in pore pressure in clayey gouge leads to a lowering of μ (TALWANI and ACREE, 1984/85). The cohesive strength decreases due to stress corrosion and dissolution on carbonate rocks. Chemical dissolution for carbonates occurs in the crust according to the following chemical reaction (FYFE *et al.*, 1978) $CaCO_3 + CO_2 + H_2O = Ca(HCO_3)_2$. When water diffuses to greater depths in carbonate rocks, and there is an increase in the CO_2 content, dissolution occurs. Dissolution results in a decrease in cohesion (and sometimes the coefficient of friction). Failure also occurs because of karst cavity collapse, which results from dissolution of the carbonate rocks and the added load of the reservoir.

In China we find evidence that all these mechanisms play an important role in RIS. Next we review our knowledge of RIS in China.

RIS in China

Figure 1 illustrates the locations of RIS in China and the projects under construction; the Xiaolangdi and Three Gorges Projects. The height of the dam, reservoir volume, dates of impoundment, initial seismicity, and the magnitude and date of the largest event are given in Table 1. Most of the reservoirs are in granitic or in carbonate rocks (mostly karsts). The hypocentral lithology, presence of nearby active faults, and the depths of the main shock and depth range of predominant seismicity are given in Table 2.

Following the RIS near Xinfengjiang Reservoir (No. 1), there have been 18 more cases of RIS in China. Except for the Shenwo Reservoir (No. 2) in Liaoning Province and the Shengjiaxia Reservoir (No. 5) in Qinghai Province, all other cases of RIS occurred in South China (Fig. 1).

There are 348 reservoirs in China with a volume of 0.1 km^3 or greater, of these 15 (4.4%) are associated with RIS. Of these 348 "large" reservoirs, 82 have active faults within 3 km of the reservoir. Of these 82, five reservoirs (6.1%) (Table 2) have RIS associated with them (CHEN, 1995). Thus the fraction of "large" reservoirs with active faults and RIS is similar to the fraction of "large" reservoirs with RIS. Consequently the presence of nearby active faults is not a determining factor in anticipating RIS.

Earthquake Locations and Lithology

Two lithologies are prevalent in the hypocentral areas of the 19 cases listed in Tables 1 and 2. Except for Danjiangkou (No. 3) the rocks at hypocentral depths were the same as those at the epicenters. Correspondingly in Table 2, the lithologies are for hypocentral depths. The hypocentral areas lie in granitic (4) and carbonate

Table 1

General characteristics of RIS in China

No.	Reservoir name	Dam height (m)	Volume (km^3)	Initial filling	Initial activity	Largest M_s (Io*)	Earthquake date	Reference no.
1	Xinfengjiang	105	11.5	Oct. 20 1959	Nov. 1959	6.1 (VIII)	Mar. 19 1962	(1)
2	Shenwo	50.3	0.54	Nov. 1 1972	Feb. 1973	4.8 (VI)	Dec. 22 1974	(2)
3	Danjiangkou	97	19	Nov. 1967	Jan. 1970	4.7 (VII)	Nov. 29 1973	(3)
4	Dahua	74.5	0.42	May 27 1982	Jun. 4 1982	4.5 (VII)	Feb. 10 1993	(4)
5	Shengjiaxia	35	0.004	Oct. 1980	Nov. 1981	3.6 (VI)	Mar. 7 1984	(5)
6	Shuikou	101	2.35	May 1993	Jul. 1993	3.2 (VI)	Jan. 12 1994	(5)
7	Zhelin	62	7.17	Jan. 31 1971	Feb. 1971	3.2 (V)	Oct. 14 1972	(6)
8	Qianjin	50	0.02	May 1970	Oct. 20 1971	3.0 (VI)	Oct. 20 1971	(7)
9	Tongjiezi	74	0.03	Apr. 5 1992	Apr. 6 1992	2.9 (V)	Jul. 17 1992	(8)
10	Hunanzhen	129	2.06	Jan. 12 1979	Jun. 28 1979	2.8 (V)	Oct. 7 1979	(9)
11	Wujiangdu	165	2.14	Nov. 20 1979	Mar. 1980	2.8 (V)	Mar. 7 1985	(5)
12	Nanchong	45	0.015	1969	1969	2.8 (VI)	Jul. 25 1974	(10)
13	Huangshi	40.5	0.61	Jan. 1970	May 1973	2.8 (V)	Sept. 21 1974	(11)
14	Yantan	110	2.43	Mar. 19 1992	Mar. 29 1992	M_L3.5 (V)	Jun. 21 1994	(4)
15	Geheyan	151	3.4	Apr. 1993	Apr. 1993	2.6 (V)	May 30 1993	(9)
16	Lubuge	103	0.11	Nov. 21 1988	Nov. 24 1988	M_L3.4 (VI)	Dec. 17 1988	(12)
17	Nanshui	81.5	1.22	Feb. 1969	Jan. 1970	2.3 (V)	Feb. 26 1970	(13)
18	Dengjiaqiao	12	0.0004	Dec. 1979	Aug. 1 1980	2.2 (V)	Oct. 30 1983	(14)
19	Dongjiang	157	8.12	Aug. 2 1986	Nov. 1986	M_L3.2 (>V)	Jul. 20 1991	(15)

*Io: Epicentral Intensity: (1) DING *et al.* (1987), (2) ZHONG *et al.* (1981), (3) GAO and YING (1980), (4) GUANG (1995), (5) HU *et al.* (1996), (6) HUANG and KONG (1984), (7) GAO *et al.* (1984), (8) GUO (1994), (9) HU *et al.* (1986), (10) HU and CHEN (1979), (11) KONG (1984), (12) JIANG and WEI (1995), (13) XIAO and PAN (1984), (14) LIU and LI (1981), (15) HU *et al.* (1995).

(15) rocks (Table 2). We have adequate data for only two of the four locations in granitic rocks, Xinfengjiang and Hunanzhen Reservoirs (Nos. 1 and 10). RIS at Xinfengjiang Reservoir has been the subject of several detailed studies and we will

address it in a later section. Of the 15 cases in carbonate rocks we have adequate data for 14 reservoirs. In 13 of these the hypocenters were in carbonate rocks.

As the nearest station was about 60 km distant, the location of the Shenwo earthquake (No. 2) is not well constrained. The macroscopic epicenter is about 7 km from the instrumentally determined epicenter. They both lie in middle Ordovician limestone (ZHONG *et al*., 1981). The instrumentally determined depth, ~6 km and the depth of the predominant seismicity (4 to 8 km) all lie in Proterozoic dolomites.

A nine station seismic network was installed at Danjiangkou Reservoir (No. 3) after the *M* 4.7 earthquake in January 1970. The depth of the subsequent seismicity is accurate to about ±1 km and lay between 2 and 5 km in Precambrian dolomites. The depth of the main shock (5 to 9 km) is not well constrained and the main shock may have occurred in the underlying Proterozoic metamorphic rocks. The columnar stratigraphy is from YANG *et al*. (1986).

A five station seismic network was installed before the impoundment of Dahua (No. 4) and the nearby Yantan (No. 14) reservoirs. The hypocentral depths are

Table 2

Geological settings and focal depths of RIS in China

No.	Reservoir name	Hypocenter lithology	Active faults	Earthquake depths (km) predominant	main shock	accuracy	Reference no.
1	Xinfengjiang	Granite	Y	4–11	5	±1	(1)
2	Shenwo	Carbonate		4–8	6	±several	(2)
3	Danjiangkou	Carbonate Metamorphics	Y	2–5	5–9	±1–2	(3)
4	Dahua	Carbonate	Y	1–7	3.1–3.5	±2	(4)
5	Shengjiaxia	Granite					(5)
6	Shuikou	Granite					(5)
7	Zhelin	Carbonate	Y	3–6	6–7	±several	(6)
8	Qianjin	Carbonate		<1	2	±1	(7)
9	Tongjiezi	Carbonate		1–4	1.2	±1–3	(8)
10	Hunanzhen	Granitoid		0.3–0.4		±0.5	(9)
11	Wujiangdu	Carbonate		<0.5		±0.5	(5)
12	Nanchong	Carbonate		<1			(10)
13	Huangshi	Carbonate		<2			(11)
14	Yantan	Carbonate		1–7		±2	(4)
15	Geheyan	Carbonate	Y	<1			(5)
16	Lubuge	Carbonate		<3		±2	(12)
17	Nanshui	Carbonate					(13)
18	Dengjiaqiao	Carbonate		<0.5			(14)
19	Dongjiang	Carbonate		3–4		±0.5–0.6	(15)

(1) DING *et al*. (1987), (2) ZHONG *et al*. (1981), (3) GAO and YING (1980), (4) GUANG (1995), (5) HU *et al*. (1996), (6) HUANG and KONG (1984), (7) GAO *et al*. (1984), (8) GUO (1994), (9) HU *et al*. (1986), (10) HU and CHEN (1979), (11) KONG (1984), (12) JIANG and WEI (1995), (13) XIAO and PAN (1984), (14) LIU and LI (1981), (15) HU *et al*. (1995).

considered accurate to about 2 km. The hypocenters of the main shocks and the pursuant seismicity at these two locations (1 to 7 km) are located in Carboniferous and Devonian limestones (GUANG, 1995). The macroscopically determined epicenter of the Zhelin earthquake (No. 7) is located in Cambrian limestone, whereas the main shock (inferred depth of 6 to 7 km) and subsequent seismicity (3 to 6 km) are located in Precambrian limestone and clastic rocks (HUANG and KONG, 1984). A portable seismograph network was deployed at Qianjin Reservoir. The seismicity was very shallow with (*S*-*P*) times of 0.1 to 0.2 s and was accompanied by loud earthquake sounds. The main shock ($\sim$2 km depth) and subsequent seismicity (a few hundred meters deep) are located in Proterozoic and Precambrian limestones, respectively (GAO *et al*., 1984).

The main shock and subsequent seismicity at Tongjiezi (No. 9) were determined by a dense network of portable stations. Tongjiezi Reservoir was impounded on April 15, 1992 and earthquakes occurred the next day near the dam. Earthquakes in Tongjiezi were shallow (1 to 4 km deep). The main shock was 1.2 km deep and located in Carboniferous limestones (GUO, 1994).

The seismicity at Hunanzhen (No. 10) was located using a dense network of portable seismographs. It occurred at depths of a few hundred meters in granitoid rocks (HU *et al*., 1986). The seismicity at Wujiangdu (No. 11) was located on a dense portable seismic network. It was very shallow, and events with magnitudes ≈ 0 were associated with loud sounds. The seismicity was located in Permian and Triassic limestones (HU *et al*., 1996). No seismic stations were deployed at Nanchong (No. 12). However from macroscopic data and loud sounds the hypocenter was considered to be in the top 1 km in middle Devonian limestone (HU and CHEN, 1979).

There were no seismic stations at Huangshi (No. 13) and the depths (<2 km) were estimated from macroscopic data. The seismicity lies in Cambrian and Ordovician limestones. Seismicity at Geheyan (No. 15) was recorded on a local seismic network. The seismicity was shallow ($\sim$few hundred meters deep) and occurred in Permian and Triassic limestones (HU *et al*., 1996).

Lubuge Reservoir (No. 16) was impounded on November 21, 1988, and by the third day after impoundment, earthquakes with M_L 1.0 began to occur. On the fourth day an earthquake with M_L 2.9 occurred accompanied with rumbling noise. The focal depth was 3.0 km (JIANG and WEI, 1995). The seismicity was located on a local network and the depths are considered accurate to about 1 km. The seismicity was located in upper Carboniferous limestones (JIANG and WEI, 1995).

The seismicity at Dengjiaqiao (No. 18) was very shallow and based on macroscopic data. It was located at depths of a few hundred meters in Cambrian limestones.

The seismicity at Dongjiang (No. 19) was located on a dense seismic network. The depths are considered accurate to $\sim$0.5 km. The seismicity was located between depths of 3 to 4 km and was located in lower Carboniferous and Devonian limestones (HU *et al*., 1995).

No data are available for Shengjiaxia (No. 5), Shuikou (No. 6) and Nanshui (No. 17) reservoirs. The lithology in the epicentral area at these locations is granite for the first two and carbonates for Nanshui.

For the 18 reservoirs where RIS occurred after Xinfengjiang, the magnitudes of the main shocks range between M_s 2.2 and 4.8. There were three earthquakes with magnitudes between 4.5 and 4.8. They occurred at Shenwo (*M* 4.8), Danjiangkou (*M* 4.7) and Dahua (*M* 4.5) (Table 2). Very shallow focal depths (<1 km) accompanied by loud sounds were observed at Qianjin (No. 8), Hunanzhen (No. 10), Wujiangdu (No. 11), Nanchong (No. 12) and Dengjiaqiao (No. 18).

The dam heights and reservoir volumes vary significantly from only 12 m and 4×10^{-4} km^3 for Dengjiaqiao (No. 18) to 165 m high for Wujiangdu (No. 11) and 19 km^3 for Danjiangkou Reservoirs (No. 3). In some reservoirs seismicity began soon after impoundment, whereas at others there was a delay in seismicity of a few years after impoundment. For example, seismicity occurred a day after impoundment started at Tongjiezi Reservoir (No. 9) and three days after the impoundment of Lubuge Reservoir (No. 16). Although the depths are not well constrained they were shallow. The main shock was at a depth of 1.2 km at Tongjiezi and shallower than 3 km at Lubuge. These observations suggest that increased pore pressure due to Skempton's effect is the likely mechanism of RIS. On the other end, the initial seismicity at Danjiangkou (No. 3) and Huangshi (No. 13) was two and three years respectively after impoundment (Table 1). The depth of the main shock at Danjiangkou is not well constrained and lies between 5 and 9 km, whereas the pursuant seismicity was shallower (GAO and CHEN, 1981). At Huangshi the seismicity was shallower than 2 km, yet it occurred three years after impoundment (KONG, 1984). These observations suggest that chemical effects probably played an important role in weakening the carbonate rocks in the karstic environment. Seismicity associated with karst cavity collapse was suggested for Zhelin, Huangshi and Dongjiang Reservoirs (Nos. 7, 13 and 19) (KONG, 1984; HUANG and KONG, 1984; HU *et al.*, 1995).

Four Examples

We present information regarding four examples of RIS in China. These include Xinfengjiang Reservoir; the best studied and the location of the largest earthquake. Next we present information pertaining to Danjiangkou Reservoir where the location of RIS was controlled by lithology. Then we present data relative to RIS near the Shenwo Reservoir, where the temporal pattern displayed interesting association with the large earthquake near Haicheng. The fourth example is of the smallest reservoir known to have been associated with RIS.

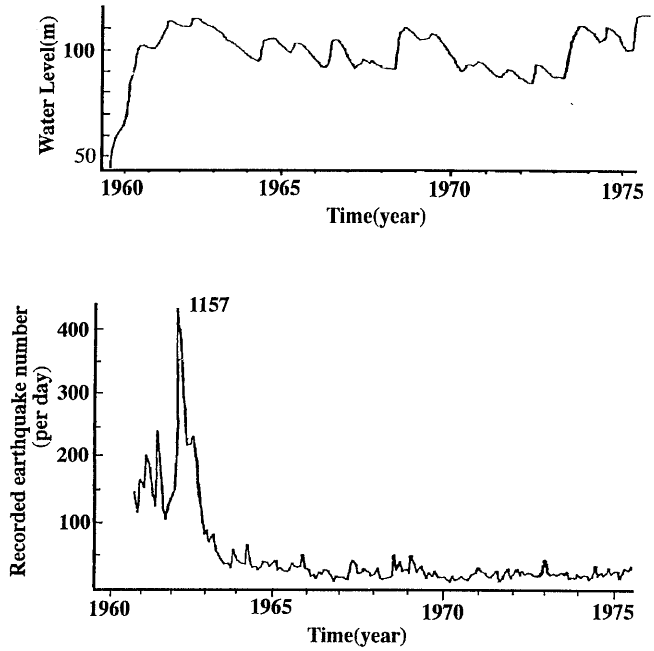

Figure 2
Relation between water level and earthquake frequency at Xinfengjiang Reservoir (modified from DING *et al.*, 1987). The upper figure shows water level curve and the lower figure shows the earthquake frequency.

a. Xinfengjiang Reservoir

The RIS at Xinfengjiang Reservoir has been well documented (see for example WANG *et al.*, 1976; and GUPTA, 1992), and we will present more recent data and other observations relevant to the mechanism of RIS. The main shock at Xinfengjiang is one of the four examples of RIS worldwide with a magnitude greater than 6.0. The details presented below have been taken from an exhaustive study by DING *et al.* (1987). Xinfengjiang dam is one of the four dams in China whose reservoirs are located in granitic rock. The 105 m high concrete dam impounds a reservoir with a volume of 11.5 km^3. Impoundment began on October 20, 1959 and seismicity started a month later. During the first few years (1961–1966), the earthquake frequency followed the reservoir levels (Fig. 2). The main shock M_s 6.1, occurred on March 19, 1962.

The dam and reservoir are located in a Mesozoic granitic batholith, with three well developed sets of faults striking NNW, NNE and NEE (Fig. 3). The main shock occurred near the intersection area of the NNW and NEE trending faults (Fig. 3). Joints are well developed in the epicentral area and divide the granite batholith into several blocks. By the end of 1987, 337,461 earthquakes were recorded by the reservoir network, 13,643 earthquakes with magnitude $M_s \geq 1.0$, 313 with magnitude $M_s \geq 3.0$ and 49 earthquakes with magnitude $M_s \geq 4.0$. There were two aftershocks with magnitude greater than M_s 5. The main shock registered a magnitude M_s 6.1, the focal depth of 5 km. The main shock encompassed a meizoseismal area of 28 km^2 and epicentral intensity VIII. The main shock caused extensive damage to houses and generated cracks in the river bank. It also generated cracks in the dam.

All the epicenters were near the reservoirs, outside the deepest part of the reservoir within 5 km of the reservoir. The earthquakes were distributed in four areas, area A, B, C and D (Fig. 4). Area A is located in a gorge area downstream of the dam. It is about 12 km long and 8 km wide. More than 90% of the earthquakes occurred in this area, most of the earthquakes with $M_s \geq 3.0$ were also located here. The main shock and the two earthquakes with $M_s > 5.0$ also occurred here. Seismicity continued in this area when the earthquakes stopped in B, C and D areas. Figure 4 displays all $M_s \geq 2.0$ earthquakes that occurred between July,

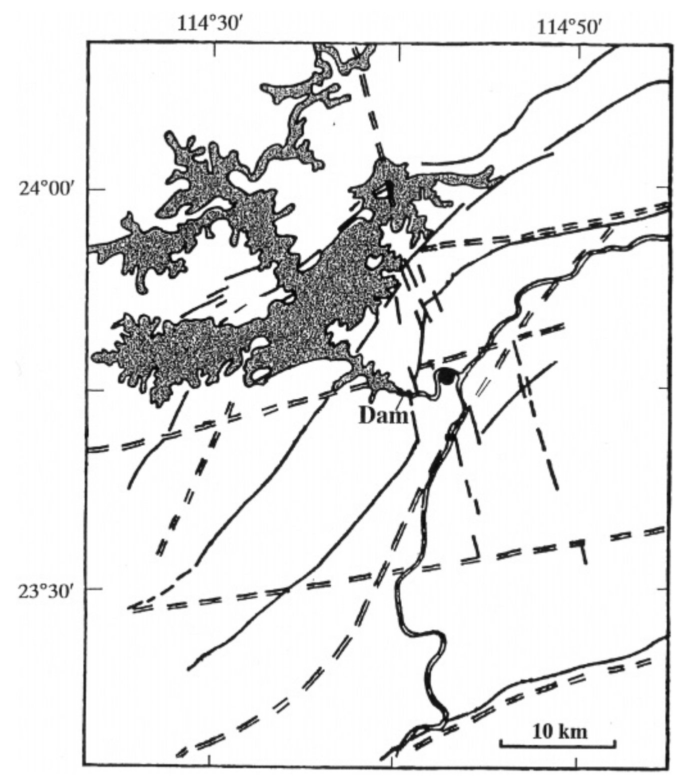

Figure 3
Major faults in the Xinfengjiang Reservoir area. Faults exposed on the surface are shown by single lines, whereas deeper, buried faults are shown by double lines (modified from DING *et al.*, 1987).

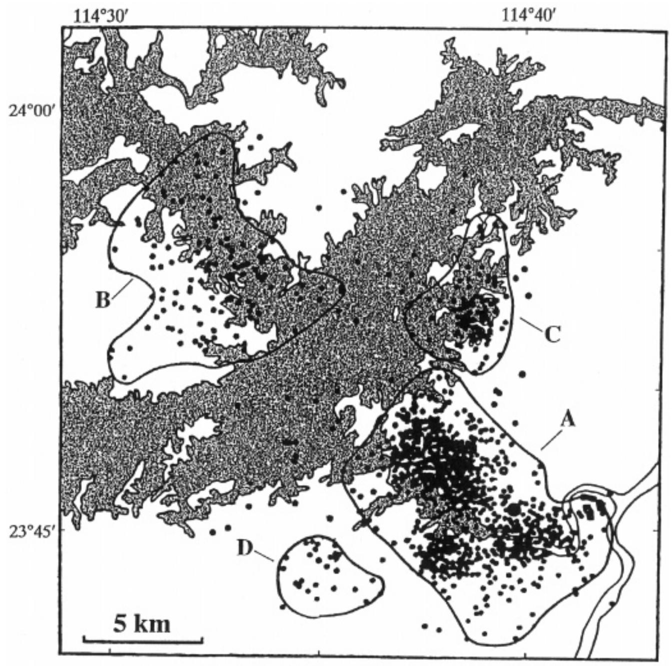

Figure 4
Distribution of earthquakes with magnitude $M_s \geq 2.0$ in Xinfengjiang Reservoir (July 1961–December 1978). The main shock occurred in area A (modified from DING *et al.*, 1987).

1961 and December, 1978. The seismicity in the A area occurred mainly during the period October, 1959 to November, 1962, including the most intense period, March–April, 1962. The seismicity in area B mainly occurred during the period October, 1961 to May, 1962, with the most intense activity in November–December, 1961. The seismicity in area C is for the period October, 1961 to December, 1963 with the most intense seismicity in June–November, 1962. The seismicity in area D covers the period April, 1962 to February, 1963, with the most intense seismicity arising in August, 1962. Therefore we note that the different areas "lighted" up at different times, attesting to the presence of a non-uniform set of fractures in the area.

The epicentral area increased with time. Figure 5 shows the temporal change in the epicentral area. From July 8, 1961 to March 18, 1962, most of the earthquakes were located in the A area. From March 19 to December 31, 1962, there were also earthquakes in areas C and D, and the epicentral area of A more than doubled.

All the earthquakes in Xinfengjiang were shallower than 15 km, the predominant depth being 4–11 km. The hypocentral depths increased with time (DING *et al.*, 1987). After the main shock, the predominant focal depths were 7–8 km before 1976 and 8–9 km after 1976. The location of seismicity on the periphery of the reservoir, distant from the deepest part of the reservoir, and the epicentral and hypocentral growth suggest that RIS was associated with pore pressure diffusion. Based on the assumption that the diffusion of pore pressure was associated with the increase in epicentral area, the hydraulic diffusivity was estimated (see e.g., TALWANI and ACREE, 1984/85). The hydraulic diffusivity was found to be 1.25×10^4 cm^2/s, a value consistent with other locations of RIS (TALWANI and ACREE, 1984/85).

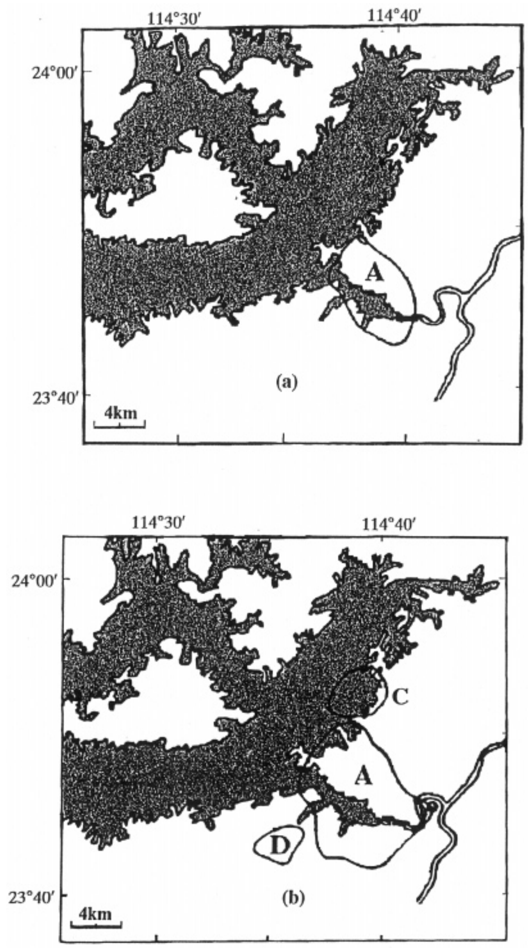

Figure 5
Temporal patterns of seismicity for two time periods in Xinfengjiang Reservoir. (a) July 8, 1961–March 8, 1962; (b) March 19, 1962–December 31, 1962 (modified from DING *et al.*, 1987).

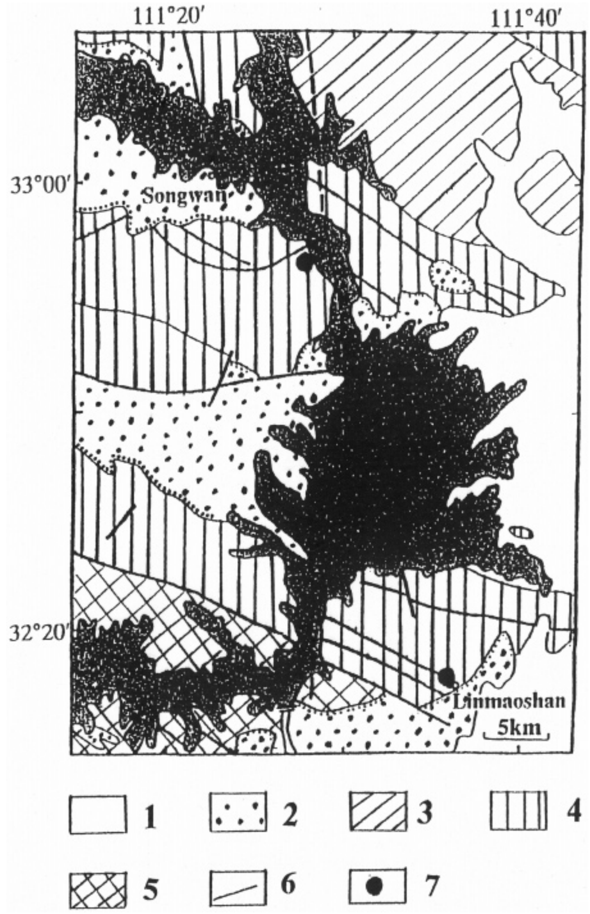

Figure 6
Tectonic map of Danjiangkou Reservoir area which consists of two reservoirs. The Danjiang Reservoir extends from the northwest to the center of the map, whereas the Hanjiang Reservoir extends further to the southwest of the map (modified from DING *et al.*, 1987). 1. Quaternary Alluvium; 2. Eocene-Cretaceous clastic rocks; 3. Carboniferous, Devonian and Silurian clastic rocks; 4. Ordovician, Cambrian and Precambrian carbonate rocks; 5. Proterozoic metamorphic rocks; 6. Fault; 7. Epicenters of main shocks.

b. Danjiangkou Reservoir

The 97-m high Danjiangkou dam impounds a reservoir with a volume of 19 km^3. Impoundment began in November 1967, and seismicity began in January 1970. The reservoir is composed of two branches (Fig. 6), Danjiang and Hanjiang Reservoirs to its southwest, occupying 48% and 52% of the volume, respectively. The Hanjiang Reservoir is located on Proterozoic schists and metavolcanic rocks and Cretaceous to Tertiary age sandstones and conglomerates. No earthquakes occurred in the shallower metamorphic terrane in which the Hanjiang Reservoir is located. The main body of the Danjiang Reservoir consists of Cretaceous to Tertiary sandstones, red beds and mudstones. Here also no earthquakes occurred. The epicenters were located in the Ordovician, Cambrian and Precambrian carbonates, especially the karst areas near Songwan Gorge to the northwest and Linmaoshan Gorge to the southeast of the Danjaing Reservoir (Fig. 6). The $M_s = 4.7$, 4.2 and 4.6 earthquakes occurred on November 29, 1973 in the Sonwang area. The depths of these earthquakes were not well constrained at about 9 km, and they could possibly have occurred in the underlying Proterozoic metamorphic rocks. The focal depth of other earthquakes was about 3–5 km or shallower and these occurred in Precambrian dolomites.

This example of RIS at Danjiangkou Reservoir illustrates how the epicentral location of RIS was controlled by the availability of karsts, although the main shock may have occurred in the underlying metamorphic rocks.

c. Shenwo Reservoir

Shenwo Reservoir has a dam height of 50.3 m and impounds a volume of 0.54 km^3 (Table 1). Impoundment began in November 1972 and earthquakes initiated in February 1973. The main shock had a magnitude M_s 4.8, and it occurred over 10 km upstream of the dam on December 22, 1974. The focal depths ranged from 4 to 8 km and the main shock reached a focal depth of 6 km. The fault-plane solution showed that faulting occurred along a NE fault in the reservoir.

The epicenter of the Shenwo main shock is about 100 km from the epicenter of the February 4, 1975 Haicheng M 7.3 earthquake (Fig. 7), and both sites are under the same regional stress field. Figure 8 shows the water levels and seismicity in Shenwo Reservoir. We note that there were no earthquakes with magnitude $M \geq 1.0$ in the reservoir area for one month following the Haicheng earthquake.

The Shenwo Reservoir is located in the dilatational quadrant of the Haicheng earthquake. It appears that there was a static stress drop in the Shenwo Reservoir area due to the Haicheng earthquake. KING *et al.* (1994) demonstrated that the 1992 M 7.3 Landers earthquake caused static stress change of 0.2–0.3 bars in the areas 100 km away. They showed that stress increases of less than one-half bar appeared sufficient to trigger earthquakes, and stress decreases of a similar amount were sufficient to suppress them. Therefore, the small reduced static stress in the Shenwo area, caused by the Haicheng earthquake, may be responsible for the quiescence in seismicity in Shenwo Reservoir area immediately following the Haicheng earthquake. Since the Shenwo main shock occurred about forty days before the Haicheng earthquake, it could also have had a triggering effect on the Haicheng earthquake, although the effect is less because of the smaller magnitude of the Shenwo earthquake.

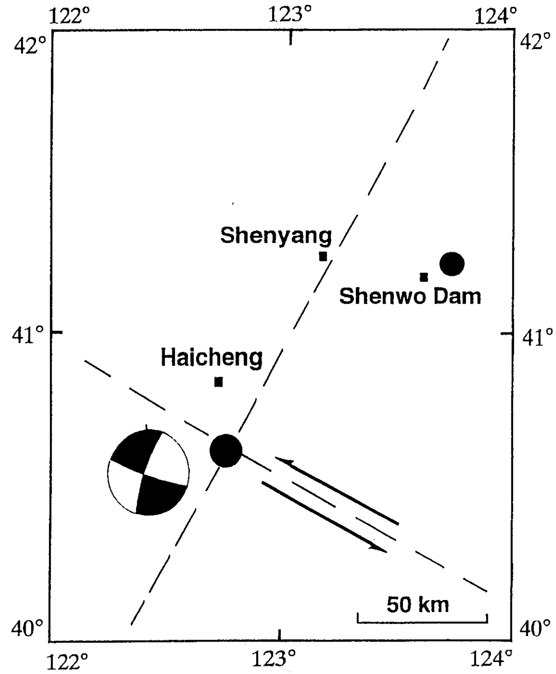

Figure 7
Map showing the location of Haicheng and Shenwo and the strike directions of the nodal planes of Haicheng earthquake (dashed lines). The fault plane solution is from Wu *et al.* (1979).

d. Dengjiaqiao Reservoir

Dengjiaqaio Reservoir has a dam height of 12 m and a volume of 3.5×10^5 m^3 (Table 1). Impoundment began in December 1979 and heavy rain fell in June and

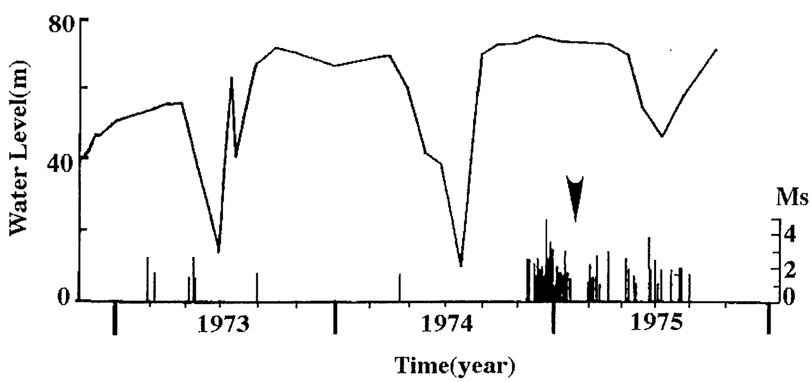

Figure 8
Water level and seismicity in Shenwo Reservoir (modified from Zhong *et al.*, 1981). The time of Haicheng earthquake is shown by the thick arrow.

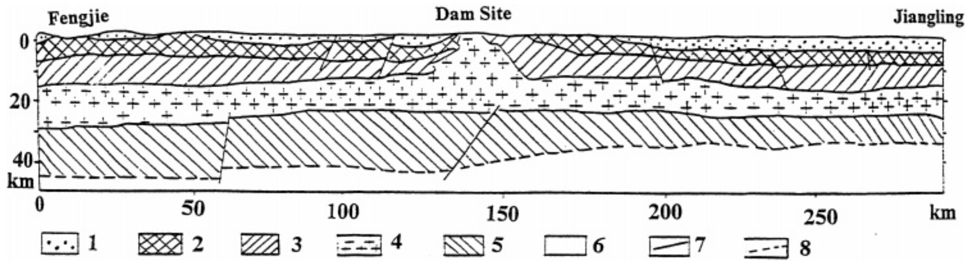

Figure 9
Cross-section from Fenjie to Jiangling along Yangtze River (modified from Yangtze River Water Resource Committee). The Three Gorges dam will be located on the granite core. 1. Alluvium, sandstone and shale; 2. Limestone; 3. Base metamorphic rocks; 4. Granite; 5. Diorite and Gabrro; 6. Olivine; 7. Fault; 8. Mohorovicic boundary (no vertical exaggeration).

July 1980, and the reservoir was full on July 31, 1980. Earthquakes were first felt on August 1, 1980, and a M_L 1.9 earthquake occurred that day. On October 30, 1983, another earthquake with magnitude M_L 2.2 occurred after another sizable rain storm. Both the earthquakes had shallow focal depths and small felt areas, and were associated with loud sounds.

The reservoir is located on the hanging wall of a NE-striking normal fault which is less than 1 km away from the reservoir. The reservoir area consists of limestones, dolomites and dolomitic limestones, with well developed karsts. Both the felt earthquakes occurred shortly after extensive rainfalls. One possible mechanism responsible for the earthquakes is that the loading effect of the reservoir and the substantial rainfall caused the hanging wall of the normal fault to move downward. Another possible mechanism is that there was a collapse of a cavity in the karst.

Seismicity Potential at the Three Gorges Project and Xiaolangdi Project

The Three Gorges Project under construction on the Yangtze River (Fig. 1) will have a dam height of 175 m and a reservoir volume of 39.3 km^3. It will be one of the largest multi-purpose projects in the world. The dam will be built in granitic rock. The granitic rock forms a core within carbonate rocks. The upstream area of the reservoir will lie on both the granitic core and on the upstream limestone beds, with an active fault separating them. A cross section from Fengjie (upstream) to Jiangling (downstream) of the Three Gorges Project is shown in Figure 9. We note that the reservoir lies over both granitic rocks and limestones, which have been associated with RIS. The Three Gorges Project lies in an area of ambient seismicity. Thus the empirical evidence suggests that we can anticipate moderate RIS in the reservoir area, especially upstream of the dam.

The Xiaolangdi Reservoir is under construction and is located on the Yellow River (Fig. 1). It will have a dam height of 154 m and a volume of 12.65 km^3 upon completion. A seismic network has already been in operation (LIN *et al.*, 1995), and no significant seismicity has thus far been detected.

Conclusions

There are 19 cases of RIS in China, including the Xinfengjiang Reservoir which was associated with a M_s 6.1 event in 1962. Most of the cases of RIS occurred in South China and are predominantly in karst terrane. The cases of RIS in granitic rocks, e.g., Xinfengjiang Reservoir appear to be caused by pore pressure diffusion in fractured rocks. That lithology controls the location of seismicity is illustrated by the example of RIS in Danjiangkou Reservoir. The temporal association of RIS with filling showed that in some cases, shallow, small earthquakes are associated with reservoir impoundment (Skempton's effect). Several examples illustrate that the chemical effect of water in dissolution is responsible for RIS.

The presence of faults in the granitic core where the Three Gorges Project is under construction, and the presence of outlying carbonate rocks upstream, suggest the possibility of moderate earthquakes when the reservoir is impounded.

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