Advances in the identification of reservoir-induced earthquakes

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Abstract: Due to the construction of large hydropower stations and the impoundment of reservoirs, the earthquakes occurred in or around the reservoir area are called reservoir-induced earthquakes, which have the characteristics of low magnitude, shallow source and high intensity. The construction of large reservoirs plays an important role in promoting the local economic development, improving the water conditions of the people and affecting people's life and property. Therefore, the identification, prediction and judgment of reservoir induced earthquake is an important technical support to ensure the construction and operation safety of hydropower stations. Over the years, many scientific and technological personnel have carried out active and large amount of research. This paper reviews and sorts out the macroscopic identification of reservoir induced earthquakes, including the mechanism of reservoir induced earthquakes, the cases of reservoir induced earthquakes, and the identification of reservoir induced earthquakes. Some problems and future research directions of reservoir induced earthquakes are discussed.

1. Introduction
Reservoir-induced earthquake is caused by reservoir impoundment or water level change[1]. This kind of earthquake has the characteristics of small magnitude, high intensity, shallow source and long period. And the reservoir-induced earthquake is often accompanied by landslide, debris flow and other secondary geological disasters, which seriously threaten the lives and property safety of the people around the reservoir area[2].

China is one of the early countries to study reservoir-induced earthquakes. On March 19, 1962, a Ms6.1 destructive earthquake occurred in Heyuan City, Guangdong Province. In the same year, the Institute of engineering mechanics, Chinese Academy of Sciences (now the Institute of engineering mechanics, China Earthquake Administration) established the first strong earthquake observation station in Xinfengjiang Reservoir in China, which initiated the cause of strong motion observation in China[3]. After some reservoir-induced earthquakes with strong destructiveness and high earthquake magnitude, this kind of special earthquake has attracted the attention of scientific, engineering and social public. A series of research activities and academic conferences have been held in the world. In 1970, UNESCO set up a research work on "earthquake phenomena related to large reservoirs". The UNESCO working group of large reservoirs held its first meeting in December of the same year to evaluate the earthquake cases of 30 large reservoirs[4].
The discrimination of reservoir-induced earthquake is mainly based on the change of seismicity characteristics and its correlation with each stage of reservoir impoundment. This kind of relationship usually includes: correlation between time and space, correlation of water level change, permeability, b value, quality factor Q, seismic dispersion[5]. In the early stage of the study, researchers have done a lot of research on the correlation between time and space, water level change correlation and permeability. Simpson et al. proposed that the time distribution of seismicity after large earthquake impoundment shows two types of response: immediate response and delayed response. D I Gough et al. conducted statistical research on the Kariba Lake and found that the main shock occurred about 5 weeks after the reservoir water level reached the highest level[6]. Rastogi B K et al. Found that after the seismic level of Koyna reservoir area decreased and the Warna reservoir at 25km to the south began to store water, the seismicity began to shift southward to the zone between Koyna and Warna[7].

Talwani and Acree proposed a "seismic diffusivity" (slope of L²-T diagram), which is in the range of 104-105cm²/s, and proposed that the "seismic diffusivity" determined by this method should be in the same order of magnitude as the real hydraulic diffusivity[8]. Although this kind of research method can well reflect the characteristics of reservoir-induced earthquake, it is difficult to identify reservoir-induced earthquake more directly because of the coupling of many factors. With the construction and improvement of digital seismic network all over the world, abundant digital seismic waveform data are provided for researchers, and because there are many and mature processing methods for seismic waveform, it is possible to directly identify through digital waveform data[9]. Chen Shuqiao et al. Conducted time-frequency analysis on seismic activity of Zipingpu Reservoir by using wavelet transform method, and found that reservoir-induced earthquake has the characteristics of narrower frequency range, lower frequency center, smaller frequency radius and more gentle trend of frequency attributes than tectonic earthquake[10]. Saadella h et al. analyzed the seismicity of Aswan reservoir by waveform inversion and source spectrum analysis, and found that the stress drop of reservoir-induced earthquake is smaller than that of ordinary tectonic earthquake, and there is a significant non-DC component[11]. Since the recognition of the relationship between the water storage of Lake Mead and seismic activity in the early 1940s[12], researchers have done much detailed work about reservoir-induced earthquakes. In this paper, a branch of reservoir-induced earthquake research: the identification of reservoir-induced earthquake is described, and the research methods commonly used for this work are described, the shortcomings and improvements of the existing research methods are described.

2. Features and typical cases of reservoir-induced earthquake

2.1. Features of reservoir-induced earthquake

The magnitude of reservoir-induced earthquakes are mainly weak earthquakes and microseisms. The statistics of magnitude of reservoir-induced earthquakes in China is shown in figure 1. Only four cases of reservoir-induced earthquakes with magnitudes exceeding Ms6 in the global scope[1]. Although the magnitude is very low, but because the focal depth of reservoir-induced earthquake is very shallow (usually less than 15km), so the seismic intensity is very high. For example, the epicenter intensity of Xinfengjiang reservoir-induced earthquake reaches VIII, which causes great damage to the surrounding residents and buildings. According to Xia QiFa et al.[13], in all cases of reservoir-induced earthquakes in the world, the percentage of Ms≥6.0 earthquakes was 2.98%; the percentage of 6.0>Ms ≥4.5 earthquakes was 26.12%; the percentage of earthquakes at 4.5>Ms ≥ 3.0 was 30.60%; The percentage of earthquakes with Ms<3.0 was 40.30%. The ratio of magnitude of reservoir-induced earthquake in China is very close to that in this paper.
According to the statistics of Chang Tinggai et al.[1], reservoir capacity and the dam height are closely related to the induced earthquakes. In foreign cases of reservoir-induced earthquake, reservoirs with capacity greater than billion m$^3$ account for about 85% of the total, and this number is 86.5% in China. What’s more, in foreign cases of reservoir-induced earthquake, there were 66 reservoirs whose dam height was more than 100m, accounting for 60.55% of the total. Of the cases of reservoir-induced earthquakes in China, 22 have dams over 100 meters high, accounting for 59.46% of the total. Therefore, the larger the reservoir capacity and the higher the dam height, the more likely to induce the earthquake. The source mechanism of earthquake induced by reservoir is generally divided into two types: one is dip slip, slide surface dip Angle is steep, the main compressive stress axis is close to the vertical, equivalent to the high Angle of normal fault dislocation type; The other is strike sliding, the sliding surface is also steep, the main compressive stress axis is close to the level, it is equivalent to the plane inferred layer type of steep inclination Angle. But the mechanism of reverse fault dislocation is rare[1].

2.2. Four typical reservoir-induced earthquakes
Since the early 1940s, people realized that the seismicity around Lake Mead in the United States is related to its impoundment period, there are about 150 cases of reservoir-induced earthquakes in the world, but different people have different understanding and statistical methods, so the statistical data are slightly different. Among them, 4 large reservoir-induced earthquakes are recognized as Xinfengjiang in China (Ms6.1-1962.03.19), Koyna in India (Ms6.3-1967.12.10), Kremasta in Greece (Ms6.2-1965.02.05) and Kariba in Zimbabwe (Ms6.1-1963-09-23). Table 1 lists the relevant information of the four reservoir-induced earthquakes.

Table 1. Four typical reservoir-induced earthquakes

| Number | Name       | Earthquake Date | Area   | Ms   | Capacity/ billion m$^3$ | Rock Types | Seismicity Activity before injection | Depth (KM) | Seismicity Types |
|--------|------------|-----------------|--------|------|------------------------|------------|-------------------------------------|------------|------------------|
2.2.1. Reservoir-induced earthquakes in Xinfengjiang. Xinfengjiang reservoir is located in the west of Heyuan City, Guangdong Province, China. It was built in 1959 with a maximum dam height of 105m and a designed capacity of 14 billion m$^3$. The reservoir was impounded on October 20, 1959. One month later, seismicity occurred around the reservoir area, and the main earthquake of Ms6.1 occurred in March 1962. By the end of 1978, 337461 events were recorded by the reservoir network, of which 13643 events with Ms \(\geq 1.0\), 313 events with Ms \(\geq 3.0\), 49 events with Ms \(\geq 4.0\), and 2 aftershocks with magnitudes greater than Ms5.0[14]. The earthquake caused a lot of casualties and economic losses, and directly led to an 82 meters long crack in the concrete dam of the reservoir.

The dam is located in a Mesozoic granite bedrock. The joints are well developed in the epicenter area, and divided the granite into several blocks. There are three faults in the reservoir area: NNE fault, NNW fault and NEE fault[15]. Among them, NNE fault is the most developed, with dip angle of 30° to 40° and multi-stage activity characteristics. NEE fault dip angle is relatively steep, with more lateral slip activities, moreover, the reservoir area is mainly NEE structure, and NNW fault dip angle is 60° to 90° with a characteristics of tensile shear activity[16]. According to the statistics of Ding Yuanzhang et all. The focal depths of earthquakes around the reservoir are all less than 15km, and the common depths are between 4 and 11km, the focal depths increase with time[15].

2.2.2. Reservoir-induced earthquakes in Koyna and Warna. Koyna is located in Maharashtra state in the west of India. In the 50 years after the initial impoundment in 1962, 170 earthquakes with Ms \(\geq 4\) and 10 events with Ms \(\geq 5\) occurred in this area. Since 1985, the construction of Warna reservoir at about 35km to the south of Koyna dam was started, and the water storage depth reached 60m in 1992, from August 1993 to December 1994, the area closer to the Warna reservoir between Koyna and Warna also occurred a series of earthquakes in the vicinity. Due to the close quarters between Koyna reservoir and Warna reservoir, earthquakes in this area are often characterized by coupling of two reservoirs, which is more complex than other reservoir-induced earthquakes in the world[17]. Because of the volcanic activity, Koyna-Warna area is covered with basalt flow of about 2km thick. Although it is difficult to find faults in volcanic rocks, there is a cliff (watershed) of Western Ghats mountain in this area. Some geologists believe that such cliff is controlled by faults[7]. Langston interpreted the fault map of Koyna area by using Landsat Image, which showing the dominant faults from NNE to NNW in Kyona area[18]. After relocation of the earthquakes in Koyna, Rastogi and Talwani found that the epicenter strike was mainly along NNE and NW directions, which was in good agreement with Langston's conclusion. On this basis, the fault plane inferred from the composite fault surface interpretation showed the left lateral strike on the NNE plane Slip movement and NW normal fault activity[17].

2.2.3. Reservoir-induced earthquakes in Kremesta. The Kremesta Reservoir was built for water storage in 1965 and is located in the upper reaches of the Alerovos River in Western Greece. This area is located in the Alps seismicity zone. Historically, there have been frequent earthquakes. From 1963 to 1965, 49 earthquakes with Ms5.3 or higher occurred, including 28 earthquakes with Ms7.1 or higher. The nearest earthquake occurred in the valley area about 40 km downstream of the dam[19]. However, no earthquakes with Ms5 or higher have occurred in the reservoir area itself before.

The seismic activity in the reservoir area increased significantly after the reservoir start to impounding in 1965, from November 1965 to January 1966, the reservoir water level rose.
dramatically for the first time, and 17 events with Ms3.4 or higher occurred immediately around the reservoir area. On February 5, 1966, when the reservoir water level reached 120m, a major earthquake with Ms6.2 magnitude was induced, followed by a high-magnitude (including five aftershocks of Ms5 or higher) aftershock attenuation[19].

Kremesta Reservoir is located in the Pindus geosyncline area of Himalayas. Due to geological activities, regional NNW folds and faults have formed in this area, as well as Pindus Mountains and Pindus thrust faults[20]. Because of the active geological structure and long-term seismic activity in the reservoir area, it is easy to induce earthquakes due to the elastic pore response caused by the reservoir body and the penetration of reservoir water after the completion of reservoir construction. At the same time, the seismic response has strong correlation with reservoir impounding. Therefore, such earthquakes are very typical reservoir-induced earthquakes.

2.2.4. Reservoir-induced earthquakes in Kariba. Lake Kariba is the largest artificial lake in the world, located on the Zambia River and formed by the Kariba Dam blocking the Zambia River in the Kariba Valley. The Kariba Reservoir began to close off and store water in December 1958. Until the main earthquake M6.1 on September 23, 1963, there were many small earthquakes in this area, and the number of earthquakes increased gradually. Until 1974, there were 13 earthquakes with Ms>4.9[21]. The Kariba area is part of the paleo-platform which with the Precambrian system as basement and leveled by long-term weathering and denudation. After activation, the platform has formed depressions and split towards NE direction. Then tension continues to develop deep into the bottom of the karroo rocks, which is controlled by NE trending faults and forms graben structure[20]. Although part of the East African Rift Valley, before the Kariba Reservoir was built, there was no earthquake in the Kariba area for a long time and it was considered as a seismic-free area. However, after the reservoir was built for impounding, the gravity of the reservoir water and the reservoir body caused the pore-elastic response of the fracture under the reservoir. Meanwhile, the reservoir water penetration intensified the fracture response and finally triggered the main earthquake of Ms6.1.

3. Earthquake Mechanisms
Reservoir-induced earthquake is caused by many factors. In the early stage of the study, the statistical analysis of the reservoir-induced earthquake cases show that: after relocated the sources, the area formed by the positioning point is always consistent with the fault strike in the area. At the same time, the worse the geological condition is, the greater the probability of induced earthquake occurs in the reservoir area. Therefore, it can be determined that the geological condition is one of the causes of the reservoir-induced earthquakes. In addition, a series of studies also show that the rate of water storage and discharge and the depth of water storage also have an important impact on the induced earthquake.

3.1. Rock failure
The integrity failure of rock is one of the direct causes of reservoir-induced earthquake. Because the rock under the reservoir area often becomes broken and loses its integrity, this change destroys the original stress balance, and then releases strain energy to cause earthquake.

After studying the earthquake induced by Xinfengjiang Reservoir in 1960, Shen Chonggang pointed out that once the rock mass in the fault fracture zone of the reservoir area is mudding to form a "weak intercalation", the integrity of the rock mass in this area will be destroyed and with different strength. At the same time, it will form a network channel of underground water circulation in the rock mass, and the cohesion and internal friction angle on the weak structural plane will decrease[22], this series of changes make the groundwater circulation in this area more developed, the reservoir water seepage is also more and more deep and far, at the same time, it makes the fault prone to shear slip induced earthquake. D I Gough and W I Gough analyzed the earthquakes induced by Kariba lake, they found that: the induced-earthquakes of Kariba Lake occurred on the rocks with low strength and pre rupture[23], because the rocks had pre fracture, after building a reservoir, a certain external force was applied to the rock and the effect of reservoir water diffusion was applied, and finally the earthquake
was induced.

3.2. Hydrochemical reaction

Hydrochemical reaction refers to the chemical reaction between reservoir water and carbonated rocks in the process of seepage. Such chemical reaction accelerates the destruction of rocks, and with the occurrence of hydrochemical reaction, the seepage rate of reservoir water accelerates, which in turn intensifies the hydrochemical reaction and finally induces earthquakes.

Linyue Chen and Pradeep Talwani studied reservoir-induced earthquakes in China, and found that the introduction of water or the increase of pore pressure in clay bearing fault resulted in the decrease of friction coefficient, because the cohesion strength decreased due to stress corrosion and dissolution of carbonate rocks. According to the chemical reaction: \( \text{Ca}_2\text{CO}_3 + \text{CO}_2 + \text{H}_2\text{O} = \text{Ca} (\text{HCO}_3)_2 \), the chemical dissolution of carbonate occurred in the crust\[14\]. When the water extends deeper into the carbonate rock, the content of \( \text{CO}_2 \) increases, and the dissolution of carbonate rock continues, which makes the cohesion strength and friction coefficient decrease. Due to the series of dissolution reactions and the increase of reservoir load, karst collapse occurs under the reservoir, and then earthquake is induced. Pradeep Talwani and Steve Acree believe that the hydration of clay minerals plays an important role in stress erosion when pore pressure increases, which is an important factor in reservoir-induced earthquakes\[8\]. The erosion of reservoir water in the process of seepage destroys rocks, forms "weak layer" and lubricates rock, which reduces its friction coefficient and induces earthquake.

3.3. The influence of impounding

In the process of reservoir impoundment, the gravity action of water and reservoir often changes the original stress state of fault by exerting vertical stress. At the same time, as the reservoir water penetrates into the stratum, it will also destroy the original stress state of the stratum, and then induce earthquake. Therefore, to a certain extent, the impoundment of reservoir is related to the induced-earthquakes, and the correlation can be more clear and direct through statistical model.

D. I. Gough and W. I. Gough studied the earthquakes induced by Kariba lake, found that the occurrence of earthquakes often follows the rapid changes of reservoir water level\[7\]. Pradeep Talwani believes that impounding will induced earthquakes, but will not influence the magnitude\[24\]. M. Lee bell and Amous Nur thinks that the impoundment leads to the sudden increase of vertical stress, the increase of pore pressure and the decrease of effective stress, which leads to the reduction of friction force between faults and the occurrence of fault failure. When the vertical stress increases to greater than the pore pressure, it shows the effect of stabilizing the fault, but the sudden decrease of the increased vertical stress (sudden change of reservoir water level) will make the stability effect disappear suddenly, and then caused the fault failure\[25\]. D. W. Simpson and S K Negmatullaliev studied the induced earthquake of Nurek reservoir in Tajikistan (USSR), the normal stress increased when the water level rose, which played a stabilizing role in the fault stress state. Therefore, when the reservoir reached the high water level, the number of earthquakes was less; but when the water level of the reservoir rapidly decreased, the normal stress decreased, and the pore pressure was still in the water in the state of the highest water level, therefore, the destructive effect of pore pressure on the fault stress state is greater than that of the stabilizing effect from the normal stress under the gravity of water and reservoir, so there will be more earthquakes when the water level drops rapidly; when the reservoir water level increases rapidly, the pore pressure increases rapidly, but the normal stress produced by the gravity of reservoir and water has not yet fully acted on the fault at this time, the destructive effect of pore pressure is greater than the stabilizing effect of normal stress, which is easy to induce earthquake\[26\]. According to D W Simpson and W. S. Leith et al. There are two types of earthquake induced by reservoir impoundment: instantaneous response and delayed response. After the establishment of the reservoir, under the gravity of the reservoir and water storage, the elastic stress under the underground elastic space model increases; due to the compression of the underground pore volume, the water can’t be filled in time, resulting in the increase of pore pressure, which makes
the effective stress at the fault decrease, and the fault sliding causes earthquakes[27]. Water storage gravity usually has two effects on the faults below the reservoir. Before the water diffuses, the direct gravity will increase the vertical stress on the fault surface, increase the effective stress, and stabilize the fault; with the reservoir water diffusion, when the pore stress at the fault increases to greater than the vertical stress level, the effective stress at the fault decreases and the fault slides, and then the earthquake is induced.

4. Identification of reservoir-induced earthquakes

Reservoir-induced earthquakes have many characteristics different from ordinary earthquakes, such as: strong correlation between earthquake frequency and reservoir water storage situation, long earthquake period, shallow source, high intensity, swarm characteristics and so on. These characteristics enable researchers to identify reservoir-induced earthquake through field investigation, numerical simulation and other methods; what’s more, reservoir-induced earthquake usually occurs in the area of water conservancy projects, once the earthquake occurs, it is easy to have a destructive impact on the water conservancy and hydropower projects, and then affect the surrounding villages and residents. Therefore, it is necessary and urgent to identify the reservoir-induced earthquake. Effective and accurate identification is conducive to better carry out the post earthquake rescue action and formulate the development mode after the earthquake.

The current identification methods include analysis of seismic activity and geological parameters (permeability, seismic spectrum characteristics, etc.), analysis of fault friction stability, aftershock attenuation coefficient P, correlation between temporal and spatial characteristics of earthquakes and reservoirs, etc.

4.1. Seismic activity and geological parameters

Because there are some different features between reservoir-induced earthquakes and tectonic earthquakes, we can judge whether the earthquakes belong to the reservoir-induced earthquakes by analyzing the mechanism of the earthquake and comparing with the relevant characteristics.

4.1.1. Permeability. The reservoir water seepage is an important reason for inducing earthquakes. After impounding, reservoir water will often seep into underground space due to seepage. If the rock under the reservoir is carbonate rock or karst terrain, the introduction of water will reduce the friction coefficient and cohesion strength of rock[14], the reduction of formation friction coefficient will make the stability of the formation decline, and then cause fault sliding, the decrease of cohesion strength of rock will induce karst collapse, both of which will induce earthquake. Although reservoir water penetration plays an important role in inducing earthquakes, it is not easy for us to measure the depth and distance of water seepage in our work. Therefore, some scholars[28-30] put forward a calculation method of permeability by analyzing the distance between reservoir area and seismic source and the delay time between water storage and earthquake occurrence. Talwani analyzed many examples of reservoir-induced earthquake and pointed out that (almost all of the permeability of them is in the order of 104cm²/s[8].) Therefore, the specific reservoir water permeability can be used as one of the identification criteria for reservoir-induced earthquakes.

Permeability of water not only reflects the degree of fracturing of strata below the reservoir area, but also is an important reason for delayed seismic response. After impounding, due to the permeability, the main shock will be delayed to a certain extent, the delay time is related to reservoir water permeability. The more fractured the formation, the higher the reservoir water permeability, the shorter the delay time is, on the contrary, the more complete the formation is, the longer the delay time is. But not all reservoir-induced earthquakes will be delayed. Some reservoirs are characterized as non-delayed earthquakes due to relatively complete strata and no fractured zone. Such earthquakes are usually induced by gravity of reservoir rather than pore pressure changes caused by permeation, formation erosion and rock cohesion reduction.
4.1.2. Characteristics of source spectrum. Source spectrum is an important tool to reflect the information of earthquake origin and mechanism. Due to the difference in the mechanism between reservoir-induced earthquake and tectonic earthquake, the differentiated source spectrum can also be used to distinguish reservoir-induced earthquake and tectonic earthquake.

Lu Lijuan et al. found that the spectrum of earthquakes induced by Longtan Reservoir in Guangxi is different to tectonic earthquakes: the corner frequency of reservoir-induced earthquake is significantly smaller than that of tectonic earthquake, and the corner frequency of reservoir-induced earthquake has better correlation with water level in time[31]. When studying the spectrum of Shanxi reservoir-induced earthquake and tectonic earthquake, Zhou Xin et al. found that there is a big difference in P-wave spectrum between them. Compared with tectonic earthquake, the main frequency of P-wave of reservoir-induced earthquake is lower than that of tectonic earthquake, but the frequency is more abundant, and there are several strong frequency bands in the energy density spectrum, at the same time, the peak value of P wave energy intensity of reservoir-induced earthquake appears earlier in the whole wave train than that of tectonic earthquake, and the energy attenuation is faster[9]. When Cao Siyuan et al. studied the Zipingpu reservoir-induced earthquakes, they conducted time-frequency analysis on source wave spectrum through wavelet transform, and found that before and after impoundment, about 50% of the data showed that the frequency center of the seismic curve decreased, the frequency band range decreased, and the frequency attribute changed gently after the earthquake[32].

Many scholars[11,33] studied reservoir-induced earthquakes by extracting two parameters of tensor moment and stress drop, they found that the stress drop of reservoir-induced earthquake is smaller than that of tectonic earthquake, and there is a significant non-DC component. This may be related to the higher pore fluid pressure caused by the complex cross faults in the reservoir area. Because these two parameters have a high degree of identification in the comparison of reservoir-induced earthquakes and tectonic earthquakes, it is theoretically feasible to identify reservoir-induced earthquakes by these two parameters. However, the calculation of these two parameters is closely related to the geological conditions of the earthquake source. If we want to identify them, it’s necessary for us to screen the data carefully to avoid a wrong identification caused by excessive difference in geological conditions.

4.1.3. Analysis of P-wave velocity structure. The analysis of P-wave velocity structure refers to the method of three-dimensional crustal velocity inversion by seismic tomography technology.

Due to the seepage of water, the rock saturation under the reservoir is in an increasing state at early time. According to the research of Shi Ge et al., when the rock saturation is low and gradually increasing, the P-wave velocity through the rock will show a significant decrease[34]. This may be due to the softening effect of water on the rock, which reduces the rock stiffness. In addition, Zhong Yuyun et al. have studied the joint inversion of velocity and focal point of Shanxi reservoir in Wenzhou, which shows that there is an obvious abnormal area of low P-wave velocity in Shanxi reservoir[35]. This study confirms that reservoir induced earthquakes can be identified by analyzing the characteristics of velocity structure.

Although the rock saturation can reflect the influence of the reservoir on the underground rock stratum, Geogery et al. also showed that the P-wave velocity of the fully water saturated rock is significantly higher than that of the partially water saturated rock, and has little effect on the shear wave velocity[36]. Therefore, when using the P-velocity structure characteristic analysis to identify the reservoir-induced earthquake, if the reservoir is built soon, and the groundwater in the reservoir area is not developed, the corresponding rock stratum is in dry or medium water saturated state; this method is more effective and can be used for identification. However, if the construction time is long and the water permeability is far and deep, that is, the underground rock stratum is in water saturated state, this method may cause a large deviation.
4.2. Relative position of fault zone and reservoir
The existence of fault zone is necessary for reservoir-induced earthquake. If the fault zone passes through the reservoir directly, it is easy to induce earthquake under the action of reservoir load and water seepage. However, a large number of cases have proved that even if there is no fault zone under the reservoir, earthquakes can also be induced. Chang Tinggai et al. believe that if the fault zone maintains a certain hydraulic connection with the reservoir water through secondary lateral fault zones and cross fault layers, earthquakes can also be induced[1].

4.3. Friction stability of faults
There are three types of reservoir-induced earthquakes: tectonic type, surface unloading type and karst type. Tectonic type refers to reservoir-induced earthquakes by water passing through seismically critical faults that under or close to the reservoir, these earthquakes are induced by undrained effects caused by the combined gravity of reservoir and reservoir water and changes in fault stress state caused by permeation.

Bell and Nur put forward the formula for the change of the total strength along the original fault plane due to the impoundment of the reservoir[25]:

$$\Delta S = \mu[(\Delta \sigma - \Delta P_p \pm \Delta \tau)]$$ (1)

Where: $\Delta S$ is the total strength change value along the fault plane; $\Delta \sigma$ is the normal stress generated by reservoir load; $\Delta \tau$ is the shear stress increment caused by reservoir load; $\Delta P_p$ is the pore pressure change value under reservoir load; and $\mu$ is the friction coefficient of the fault.

Based on that, R Chander and Kalpna proposed (2) which transformed from (1) in three-dimensional level[37]:

$$S_a(t) = [\sigma_a(t) - P_a(t)]\tan \phi(t) - \sigma(t)$$
$$S_r(t) = [\sigma_r(t) - P_r(t)]\tan \phi(t) - \sigma(t)\cos \Theta(t)$$
$$S(t) = S_a(t) + S_r(t)$$ (2)

Where: $S(t)$ is the stability of fault, $\sigma(t)$ is the normal stress, $P(t)$ is the pore pressure, $\tau(t)$ is the shear stress, $\tan \phi(t)$ is the friction coefficient, $\Theta(t)$ is the angle measured in the plane of fault between resolved shear stresses due to reservoir and ambient causes. (1) The subscript a here refers to the strength and stress under the condition of considering only the ambient effect, and the subscript r refers to the strength and stress situation under the action of the reservoir only. (2) The stress and strength positions mentioned in the formula are on the fault at the source. (3) The above symbols all change with time.) If $S_r(t) < 0$, it can be judged that reservoir action promotes the failure of fault strength, if $S_r(t) > 0$, it can be judged that reservoir action inhibits fault strength failure. According to (2), it can be determined whether the earthquake belongs to reservoir-induced earthquake after obtaining the parameters on the fault at the source.

4.4. Time correlation between earthquakes and reservoir water level
Reservoir-induced earthquakes often occurred with the change of water storage rate, and it is often induced when the water level reaches the peak or the water level changes too fast. A large number of studies have shown that reservoir-induced earthquakes usually occur after drastic changes in reservoir water level. Therefore, the correlation between earthquake frequency and reservoir water level can be used to identify reservoir-induced earthquake.

D. W. Simpson and A A Gharib et al. studied the earthquakes induced by Aswan reservoir in Egypt, and found that the main shock occurred on Nov.4 1981, which followed the seasonal maximum water level in the reservoir, and the maximum aftershock occurred on Aug.20 1982, which followed the seasonal minimum water level. During the period from July 1, 1982 to July 22, 1989, it was found that the earthquake occurrence rate changed with the depth of water and the rate of water level change[38]. It should be noted that although there is a strong correlation between seismicity and water level, but the response can be divided into two forms: instantaneous response and delayed response. The
instantaneous response means that the earthquake occurs immediately after the initial impoundment of the reservoir, the seismicity is mainly the low magnitude earthquake swarm activity, and generally occurs around the reservoir, which has a significant positive correlation with the change of reservoir water level. Delayed response refers to the obvious delay of seismicity after the initial impoundment. This kind of earthquake often has a larger magnitude and can exceed the scope of the reservoir. Although it is not immediately related to the change of reservoir water level, it often occurs after the reservoir water level has a significant change[27]. The differences between the two response are listed in table 2.

Table 2. The types of time-distribution responses to reservoir-induced earthquakes

| Response types | Mechanism | Definition | Features | Typical cases | Reference |
|----------------|-----------|------------|----------|---------------|----------|
| Instantaneous response | Instantaneous elastic response and undrained response. | The type of seismicity that increases immediately after the initial impoundment of reservoir or changes rapidly after the rapid change of water level. | Water injection has a strong correlation with the change of seismicity, generally occurs around the reservoir, and the magnitude is small, most of them are swarm seismicity. | Monticello, Manico-3, Nurek, Kariba, Kremesta et al. | D W Simpson (1988)[27] |
| Delayed response | Increase of pore pressure caused by permeability. | It is only after a period of reservoir impoundment that the seismicity changes regularly. | No significant correlation between water injection and seismicity, the time delay is obvious, the magnitude is generally large, and the earthquake occurrence point is not limited. | Koyna, Aswan, Oroville et al. | |

Among them, Monticello, Manico-3, Nurek, Kariba and Kremesta et al. show instantaneous response type. The research of these reservoir-induced earthquakes shows that the increase of elastic stress is an important reason for induced earthquake after the first impoundment of reservoir. And Koyna, Aswan and Oroville are of delayed response type. Through data comparison, we find that the focal location distribution of earthquakes induced by these reservoirs is often close to the fault strike near the reservoir area, and the phenomenon of the reduction of effective normal stress caused by water seepage induced earthquakes in this area is obvious.

4.5. Spatial correlation between seismicity and reservoir

The spatial activity range of reservoir-induced earthquake is small, which is generally limited in the range that reservoir water can affect[5]. The scope of the impact is about 30km. Since the seismicity is limited to the surrounding area of the reservoir (see table 3 for details), it can be roughly judged whether it is a reservoir-induced earthquake by the location of seismic activity.

The epicenter of the main earthquake induced by Xinfengjiang reservoir is only 1.1km away from the dam, and all the seismicity after the reservoir impoundment is limited to 30km around the dam. The epicenter of the main earthquake induced by Koyna reservoir is located about 3km to the south of the dam. In the past one year after the occurrence of the main earthquake, there were about 12 earthquakes with Ms5.0 and above and several thousand small earthquakes below Ms3.0. The epicenters of these earthquakes were distributed in the range of 2.5km to the south of the dam. The epicenter of the main earthquake induced by Kariba reservoir is about 13km away from the dam. The epicenter of the earthquake induced by Kremesta reservoir is located 25km away from the dam at the left bank of the reservoir tail. After the reservoir impounded greatly from November 1965 to January 1966, the frequency of earthquakes near the reservoir area increased sharply, and 17 sensitive earthquakes with Ms3.4 and above occurred successively, and the epicenter of these earthquakes was located near the reservoir area[13].
Table 3. The focal location of some reservoir-induced earthquakes

| Name       | Magnitude | Epicenter location      | Distance between dam and epicenter | Reference |
|------------|-----------|-------------------------|-----------------------------------|-----------|
| Xinfengjiang | Ms6.1     | Northeast side of dam   | 1.1KM                              | [22]      |
| Koyna      | Ms6.3     | South side of dam       | 3.0KM                              | [17]      |
| Kariba     | Ms6.1     | Southwest side of dam   | 13KM                               | [23]      |
| Kremesta   | Ms6.2     | Right bank of reservoir tail | 25KM                             |           |
| Mead       | Ms5.0     | Northeast side of dam   | 25KM                               | [13]      |
| Nurek      | -         | Upstream of the dam     | 15KM                               |           |
| Danjiangkou | Ms4.7     | Upstream of the dam     | 37KM                               | [19]      |
| Wujiangdu  | Mi2.6     | Upstream of the dam     | 40KM                               | [10]      |
| Shanxi     | M1i.4.4   | Downstream of the dam   | 20KM                               | [16]      |
| Wuxijiang  | Ms2.8     | Upstream of the dam     | 20KM                               | [41]      |

4.6. Attenuation coefficient (p) of the aftershock frequency
Aftershock attenuation refers to that after the occurrence of the main shock, the general trend of aftershock tends to weaken gradually in a certain time space and intensity range[42]. The time evolution of aftershock sequence can be described by modified Oromi formula[43,44]:

\[
r = \frac{dN}{dt} = \frac{K}{(c + t)^p}
\]

Where r is the occurrence rate of aftershocks with magnitudes greater than m, N is the number of aftershocks after the main shock, K, c, p are empirical constants, and t is the time starting from the main shock. The p value is called the sequence attenuation coefficient, the larger the p value, the faster the sequence attenuation[44].

According to the statistics of Utsu et al. among the more than 200 P values published in the world during 1962-1995, their distribution ranges from 0.6 to 2.5, with an average of 1.1[45]. According to the statistics of Shen Chonggang et al. the P values of Xinfengjiang, Koyna, Kariba, Kremesta are 0.9, 0.78, 1.0 and 1.0, respectively, which are all lower than the average value of 1.1 by Ustu et al.[22]. Therefore, in theory, the attenuation coefficient P of aftershock sequence can be used as a factor for the identification of reservoir-induced earthquakes. However, due to the different statistics of different people, the attenuation coefficient P of the average aftershock sequence in mainland China, such as Zhao Zhixin et al. is 0.9[45]. Therefore, when the attenuation coefficient P of aftershock sequence is used to identify reservoir-induced earthquake, the P value obtained from the earthquake occurred in the reservoir area should be compared instead of blindly using the P value in a wider area. But generally speaking, the aftershock attenuation coefficient P value of reservoir-induced earthquake is smaller than that of tectonic earthquake.

5. Conclusion
To sum up, it is of great significance to explore the cause of reservoir-induced earthquake and identify after the earthquake. However, the earthquake is induced by a variety of coupling effects, so it is necessary to conduct in-depth exploration in combination with seismic engineering, geological tectonics, statistics, elastic-plastic mechanics and other disciplines. Although many achievements have
been made through the continuous efforts of researcher, there are still many deficiencies in the identification of reservoir induced earthquakes:

1) Although reservoir-induced earthquakes are different from tectonic earthquakes in many seismological parameters, due to the complexity and uncertainty of earthquakes, it is still a probabilistic method to distinguish reservoir-induced earthquakes by some specific seismological parameters. At the same time, this probability method is still extremely empirical and can’t be discriminated under special circumstances. Therefore, this method can’t completely distinguish reservoir-induced earthquake from tectonic earthquake.

2) Although the probability of reservoir induced earthquake can be identified, there is still no perfect solution. For example, what kind of reservoir is easy to induce earthquake and whether it needs to be demolished? Is it necessary to avoid building a certain type of reservoir in the future construction? What kind of reservoir will be built under what geological conditions? And so on, we need to put forward solutions.

3) Since there are fewer examples of reservoir-induced earthquakes compared with tectonic earthquakes, the accumulated data are insufficient, the discrimination method is relatively single and there is no experimental method for the time being, so only existing cases can be analyzed before there is no new reservoir-induced earthquakes, and the richness of induced cases is insufficient. If an independent model of each reservoir is established and a large database is aggregated according to different geological conditions, capacity and storage time during reservoir construction, not only the reservoir operation can be monitored in real time, but also sufficient data can be provided for scientific researchers who carry out reservoir research. In the long run, it will greatly promote the development of reservoir-induced earthquake research.

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