Application of Statistical Prediction Model to the Reservoir Induced Seismic Risk Analysis of Aqing Hydropower Station in Xizang

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Abstract. Based on field seismic geological survey and previous research results, this paper analyzed tectonic background, seismicity and hydrogeological conditions of Aqing hydropower station in Xizang respectively, then calculated the probability of reservoir induced seismicity. The results showed that it is possible for the reservoir induced seismicity occurring, whose probability is 0.455. In detail, the probabilities of occurring moderate-strong, weak, and micro earthquake are 0.089, 0.070, and 0.296 respectively. Under these circumstances and based on the intensity attenuation relationship of reservoir induced seismicity, it can be deduced that the moderate-strong earthquake would occur with epicentral intensity VII, and the lengths of major axis and minor axis are 6.5 km and 3.3 km respectively.

Keywords. Reservoir induced seismicity (RIS), aqing hydropower station, statistical prediction model, inducing factor, epicentral intensity.

1. Introduction
Reservoir induced seismicity (simplified as RIS) refers to the phenomenon of occurring new earthquake or obvious change (aggravation or weakening) of original seismicity in dam area, reservoir basin or nearshore area on account of reservoir impoundment under the premise of seismogenic conditions (regional active fault structure, good water seepage channel, developed karst system, etc.). Since the 1960s, strong earthquakes (Ms≥ 6) have occurred in reservoirs such as Xinjiang in Guangdong, China, Kariba in Zambia, Kremasta in Greece, and Koyna in India. Although the probability of reservoir induced seismicity is relatively low, the risk is generally greater than that of peer tectonic earthquakes. Therefore, it is necessary to pay attention to its impact. By analyzing and studying some RIS examples, the researchers have put forward different methods to do the risk evaluation, such as geological structure identification, probability prediction, regression fitting of reservoir comprehensive impact parameters, comprehensive fuzzy judgment, gray system prediction, pattern recognition, hierarchical analysis (AHP), neural network and so on [1-4].

The Aqing hydropower station is located in Zanda County, Ngali Prefecture, Tibet Autonomous Region. The hub is 15 km upstream of Zanda County, 243 km away from Shiquanhe town where the administrative office of Ngali Prefecture is, 1450 km away from Lhasa city and 1290 km away from Kargilik County, Xinjiang. The Aqing hydropower station is an annual regulating reservoir with the normal storage level of 3812 m, the backwater length of about 16.88 km, and the total storage capacity of 276.2 million m³. The main task of the reservoir is to generate electricity. Its foundation is of great significance, which has momentous strategic and political influence on maintaining social stability in
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ethnic areas and consolidating border areas. Based on the analysis of tectonic background, seismicity and hydrogeology conditions of the Aqing hydropower station, this paper analyzes and calculates the probability of reservoir induced seismicity, laying a foundation for the further seismic monitoring and disaster mitigation.

2. Regional Geological Background

2.1. Topographic and Geomorphic Features
The cross section of the river valley in the reservoir area is U-shaped, with gentle slope angle and the width of 0.1 km to 1.2 km. In common water period, the water level fluctuates from 3715 m to 3732 m, and the width of water surface ranges from 40 m to 100 m. Erosional base terraces of grade II-V are developed on both sides of the river, whereas the terrace of grade I is missing. The terraces of grade II, III and IV on both banks are asymmetric, and the left bank is more developed than the right one. There are developed and deep gullies on both sides of the reservoir. The bottom and both sides of the gullies are mostly bedrocks, and the proluvials at the mouth of the gullies are less distributed, and some gullies have small-scale alluvial fans.

2.2. Tectonic Features
The near-field region is mainly composed of structure of basin and mountain. The west side of the NW-trending Ayiliaru Mountain is Zanda Basin, and the east side of it is the southern part of the Gar Basin. The quaternary active faults are developed along the border of the basins and mountains.

There are many developed fractures in the near-field region, which mainly strike NW, such as the Karakoram fault zone (figure 1). The outcrop in the near-field region belongs to the southeast segment of the fault zone, which extends about 40 km in the reservoir area, strikes NW, and dips NE. The fault has the characteristics of normal and right-lateral strike-slip fault. It is comprehensively determined that the active period of the fault in the near-field section is mostly in the Late Pleistocene-Holocene. The activity in this region is relatively strong, which can be clearly shown in the field outcrops and remote sensing images.

![Figure 1. Regional tectonic map.](image-url)
2.3. Formation Lithology
The lithology on both sides of the reservoir area is mainly slate of Triassic Xiukang formation (T3xk), which is gray black, hard and dense, with palimpsest structure and plate structure. The surface rock mass has strong unloading weathering and is relatively broken. Slate is continuously distributed on both sides of the reservoir area, which is the main rock mass forming the terrace base.

2.4. Hydrogeological Conditions
The main types of the groundwater in the reservoir area are porous phreatic water and bedrock fissure water. The porous phreatic water migrates through the loose layers with good water permeability on both sides of the river, which is always recharged by melting ice and snow, atmospheric precipitation, or bedrock fissure water. The source of recharging is poor and the water volume is insufficient. It is mainly discharged into the Xiangquan River and its tributaries in the form of runoff. The bedrock fissure water migrates along the bedrock fissures, which is always recharged by melting ice and snow and atmospheric precipitation and discharged into the Xiangquan River and its tributaries.

3. Assessment Method of Reservoir Induced Seismic Hazard
There are two kinds of methods mainly used in reservoir induced seismic hazard assessment, which are qualitative or semi-quantitative analogy analysis and method of quantitative prediction via using various models. The former refers to the seismic geological analogy analysis method, while the latter uses more methods such as comprehensive parameter discrimination of reservoir elements, probabilistic method and grey system analysis [5].

This paper uses the statistical prediction method to evaluate the reservoir induced seismic hazard of Aqing hydropower station [6, 7].

3.1. Reservoir Induced Seismic Statistical Prediction Model
Reservoir induced seismicity is affected by many factors. At present, the genetic mechanism of reservoir induced seismicity is still controversial. As a result, it is impractical to take all the factors into account [8]. In view of the previous researches and specific situation of the hydropower station, the probability prediction of magnitude and intensity is carried out by using eight inducing factors, including reservoir water depth (D), regional tectonic stress state (S), fault activity (F), rock type (G), seismic activity background (B), reservoir water permeability depth (FD), communication relationship with reservoir water (FC) and karst development degree (SK) (table 1).

| Inducing Factors | State Classification |
|------------------|---------------------|
| (D)              | >140 m              |
| (S)              | Reverse fault       |
| (F)              | Active              |
| (G)              | Blocky rock         |
| (B)              | Strong              |
| (FD)             | >2000 m             |
| (FC)             | Direct contact      |
| (SK)             | Strong              |

|                | 1        | 2        | 3        |
|----------------|----------|----------|----------|
|                | 90~140 m | <90 m    |
|                | Normal fault | Strike-slip fault |
|                | Inactive    |
|                | Layered rock | Carbonate rock |
|                | Moderate    |
|                | 500~2000 m  |
|                | Indirect contact | Non-contact |
|                | A little   |

According to Bayes Theorem, the prediction model can be expressed as

\[
P(M_i/A) = \frac{P(A/M_i) P(M_i)}{P(A)}
\]

(1)

P(A) Refers to the total probability of reservoir induced seismicity; P(A/M_i) refers to the conditional probability of different magnitudes under the circumstances of combination of various
inducing factors; $M_i$ refers to the magnitude of the predicted reservoir induced seismicity, which can be separated into five types: strong, moderate-strong, weak, microseismic, and aseismic.

According to the data of 251 large reservoirs in the world, including 46 large reservoirs with earthquakes and 205 large reservoirs without earthquakes, the earthquake occurrence probabilities are summarized (table 2). The prior probabilities of earthquake intensity ranked with strong, moderate-strong, weak, microseismic and aseismic earthquakes are $P(M_4) = 0.02$, $P(M_3) = 0.04$, $P(M_2) = 0.05$, $P(M_1) = 0.07$ and $P(M_0) = 0.82$, respectively [9]. Based on the prior probabilities, the conditional probabilities can be calculated with the below equations (2-5).

$$P(A|M_i) = P(i)/P(A) \ (i = 0, 1, 2, 3, 4) \quad (2)$$

And,

$$P(A) = P(0) + P(1) + P(2) + P(3) + P(4) \quad (3)$$

$$P(i) = P(M_i)P(D, S, F, G, B, FD, FC, SK/M_i) \quad (4)$$

$$P \left(D, S, F, G, B, FD, FC, SK/M_i \right) =$$

$$P(D/M_i)P(S/M_i)P(F/M_i)P(G/M_i)P(B/M_i)P(FD/M_i)P(FC/M_i)P(SK/M_i) \quad (5)$$

**Table 2.** The prior probabilities of earthquake occurring inducing factors in different states.

| Inducing Factors | Classification of Magnitude |
|------------------|-----------------------------|
|                  | $M_4$ $(M \geq 6.0)$ | $M_3$ $(6.0 > M \geq 4.5)$ | $M_2$ $(4.5 > M \geq 3.0)$ | $M_1$ $(M < 3.0)$ | $M_0$ $(M = 0)$ |
| (D)              | 1 0.00 0.22 0.46 0.36 0.18 |
|                  | 2 1.00 0.70 0.46 0.54 0.60 |
|                  | 3 0.00 0.08 0.08 0.10 0.22 |
|                  | 1 0.00 0.10 0.23 0.32 0.17 |
| (S)              | 2 0.40 0.41 0.62 0.50 0.68 |
|                  | 3 0.60 0.49 0.15 0.18 0.15 |
|                  | 1 0.90 0.70 0.38 0.21 0.10 |
| (F)              | 2 0.10 0.30 0.62 0.79 0.90 |
|                  | 1 0.70 0.48 0.46 0.21 0.48 |
| (G)              | 2 0.05 0.10 0.15 0.47 0.36 |
|                  | 3 0.25 0.42 0.39 0.32 0.16 |
|                  | 1 0.25 0.20 0.31 0.21 0.24 |
| (B)              | 2 0.25 0.40 0.46 0.53 0.47 |
|                  | 3 0.50 0.40 0.23 0.26 0.29 |
|                  | 1 0.75 0.60 0.57 0.31 0.21 |
| (FD)             | 2 0.20 0.30 0.38 0.50 0.28 |
|                  | 3 0.05 0.10 0.05 0.19 0.51 |
| (FC)             | 2 0.80 0.80 0.69 0.61 0.38 |
|                  | 3 0.10 0.10 0.23 0.29 0.31 |
| (SK)             | 1 1.00 0.42 0.55 0.50 0.16 |
|                  | 2 0.00 0.33 0.35 0.17 0.34 |
|                  | 3 0.00 0.25 0.10 0.33 0.50 |
4. Probability Analysis of Reservoir Induced Seismicity of Aqing Hydropower Station in Xizang

4.1. Determination of State of Inducing Factors

The Aqing hydropower station is a canyon type cascade hydropower station, whose comprehensive reservoir depth is about 110 m, hence, D2 should be chosen as the reservoir water depth. The lithology of reservoir and dam area is interbedded sandstone and limestone, which means the rock type in reservoir area is layered rock, so it is right to choose G2 as the rock type.

There are many fractures developed in the dam site and reservoir area. Many fractures passing through the reservoir area have direct contact with the reservoir water, which mainly strike NW. Dipping NE, the NW trending Karakoram fault zone extends about 40 km in the reservoir area, which is of the characteristics of normal fault and right-lateral strike-slip movement. The active tectonic trace of the fracture is obvious in the late Quaternary, and there are hot springs exposed in many places, showing the characteristics of a large fracture. It is comprehensively determined that the fracture is a Quaternary Holocene active fracture, as a result, it is better to choose FC1 and F1 as the communication relationship with reservoir water and the fault activity.

According to the state description of inducing factors, the topography of the Aqing hydropower station can be regarded as a deep U-shaped Valley. It is reasonable that choosing FD1 as the reservoir water permeability depth due to the high level of the cutting depth and the permeability depth of the reservoir water.

It is shown that the focal stress field of regional seismic focal mechanism solutions is consistent. The orientation of the maximum principal compressive stress P-axis is mainly NE and NW, and the angle of elevation is mostly greater than 60°; the orientation of the maximum principal strain stress T-axis is mainly NNE and NW, and the angle of elevation is mostly less than 30°. The regional stress field is mainly dominated by the strong extrusion stress field near NE-SW direction, thus, S1 should be chosen as the regional tectonic stress state.

According to the earthquake records, there have been four destructive earthquakes in the near-field region of the project site. The largest recorded earthquake is the M6.5 earthquake in the west of Zanda, Xizang in 1752, with the epicentral intensity VIII. Therefore, B1 should be chosen as the seismic activity background. There is no karst in the dam site, in consequence, SK3 should be chosen as the karst development degree.

4.2. Calculation Results and Attenuation Law of Magnitude and Intensity Influence Field

After determining the state of inducing factors of reservoir, the probability of reservoir induced seismicity and the influence field of magnitude and intensity are calculated (table 3).

The probabilities of earthquake of M4 (M≥6.0), M3 (6.0>M≥4.5), M2 (4.5>M≥3.0), M1 (M<3.0), M0 (M=0) are 0.0, 0.089, 0.070, 0.296 and 0.545, respectively.

**Table 3.** Comprehensive results of probability analysis of magnitude in reservoir area.

| Division of Predicted Areas | State of Inducing Factors | Statistical Model Prediction Results | Possible Magnitude Scale |
|-----------------------------|---------------------------|------------------------------------|--------------------------|
| Reservoir area              | D2, S1, F1, G2, B1, FD1, FC1, SK3 | M4 0.000  M3 0.089  M2 0.070  M1 0.296  M0 0.545 | M0, M1, M3               |

According to the research data of some scholars on the attenuation law of actual reservoir induced seismicity in recent years, it is evident that reservoir induced seismicity has the characteristics of shallow source, high intensity, heavy disaster, fast attenuation and small influence range. The attenuation of seismic intensity on the surface of the earth presents a certain geometric shape. At present, there are two kinds of reservoir seismic intensity attenuation models, circular and elliptical, most commonly used, especially the latter one. Fitting the elliptical seismic intensity attenuation
model, the attenuation relationship is obtained based on the data of typical reservoir induced seismic cases such as Koyna, Xinfengjiang, Danjiangkou, Shenwo, Qianjin, Dahua, Shanxi, and so forth [10].

\[
\begin{align*}
\text{Major axis} & \quad I_a = 5.002 + 0.9722M - 1.3241\ln(R + 6) \quad \sigma = 0.614 \\
\text{Minor axis} & \quad I_b = 4.425 + 0.9028M - 1.2041\ln(R + 4) \quad \sigma = 0.537
\end{align*}
\]

Comparing the intensity attenuation curves of reservoir induced seismicity and tectonic earthquake (figure 2), it can be seen that the epicentral intensity of reservoir induced seismicity is obviously higher than that of tectonic earthquake at low magnitude. With the increase of magnitude, the difference of epicentral intensity between them fade away. When the magnitude reaches Ms6, the epicentral intensity of the two kinds of earthquakes is very close, which reflects the characteristics of low magnitude and high intensity of RIS. Therefore, the attenuation relationship in the paper is suitable for the hazard prediction and evaluation.

![Figure 2. Comparison of major and minor axis intensity attenuation curves between reservoir induced seismicities and tectonic earthquakes in central and southern China.](image)

Based on the attenuation relationship, the influence field of reservoir induced seismicity is calculated (table 4). The evaluation results of intensity influence field show that the probability of moderate-strong earthquake with magnitude fluctuating from 4.5 to 6.0 in the reservoir area is 0.089 (table 3). When this kind of earthquake occurs with epicentral intensity VII, the lengths of major axis and minor axis are about 6.5 km and 3.3 km.

| Division of Predicted Areas | Possible Magnitude Scale | Epicentral Intensity | Major Axis (km) | Minor Axis (km) |
|-----------------------------|--------------------------|---------------------|----------------|----------------|
| Reservoir area              | M₀, M₁, M₃              | VII                 | 6.5            | 3.3            |

5. **Comprehensive Evaluation of Reservoir Induced Seismic Hazard of Hydropower Station**

In conclusion, the reservoir induced seismic hazard of the Aqing hydropower station in Xizang can be comprehensively evaluated. Based on the analysis of topography and geomorphology, valley morphology, formation lithology, geological structure, hydrogeological conditions, and seismic activity background, it is suggested that the occurrence of moderate-strong earthquake in reservoir area is possible. The results show that there is no possibility of an earthquake with magnitude 6.0 or above in the reservoir. The probabilities of moderate-strong earthquake with magnitude fluctuating from 4.5 to 6.0, earthquake with magnitude fluctuating from 3.0 to 4.5, micro-earthquakes with magnitude below 3.0 are 0.089, 0.070, 0.296, respectively. And the aseismic probability is 0.545.
Based on the results of deterministic analysis, it is comprehensively evaluated that with the extension of impoundment time, the reservoir of Aqing hydropower station in Xizang has the possibility of inducing moderate-strong earthquake with epicentral intensity VII. It is suggested that relevant departments should pay attention to it in the process of dam design and construction.

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