STUDY ON METHODS OF RESERVOIR INDUCED SEISMICITY PREDICTION OF THE THREE GORGES RESERVOIR

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ABSTRACT :
Based on the analysis of seismogeological background, the Three Gorges Reservoir area is divided into 31 units according to different combined conditions of induced earthquake, together with 8 influencing factors, to give the prediction on probability and magnitude of RIS by adopting statistical prediction model, fuzzy mathematics and gray system model as well as artificial neural network model respectively. The results show as follows: in 31 units, the slight differences exist in results among three predictive methods, especially distinction between mathematics statistics models and artificial neural network model, which is also quite coincident with past macroscopical analogical prediction. The results are not only in accord with the past researchers' basically, but also confirm with each other better: (1)from dam site to Miaohe segment, due to its geologic background, superficial fracture dislocation type of RIS may be triggered mainly, and the maximum (ultimate) magnitude will not exceed 3.0; (2) it is possible to trigger 4.5-6.0 earthquake in three places, including limestone area of southern Badong, near reservoir segment of Longchuanhe limestone area and far from reservoir segment of Gaoqiao Fracture limestone area; (3) it's quite likely that the certain activity of Gaoqiao Fracture trigger tectonic reservoir induced earthquake.

KEYWORDS:RIS; mathematic model, influencing factors, magnitude, prediction, the Three Gorges Reservoir

1. INTRODUCTION

The construction of large-scale reservoirs has caused a series of environmental and geological issues in reservoir area, especially reservoir induced seismicity (RIS), which is not only related to the change of human ecological environment, but also may threat directly to the regular operation of hydraulic buildings. The reservoir induced seismicity is known as the earthquake triggered by reservoir impounding, it has been more than 70 years since the issues discovered. As early as 1931, the first RIS has been detected in Marathon Reservoir of Greece, following more than 100 reservoirs were detected to trigger earthquakes in succession, several earthquakes exceed 6 to cause severe results. Therefore, the prediction is of great significance for RIS.

At present, the main methods to predict the magnitude of RIS are as follows: probability forecasting model method (G.B.Beacher et al., 1982), fuzzy comprehensive evaluation prediction method and comprehensive parameter method (Chang, 1992), logic information method (Yu, 1987), hierarchical analysis method (Li et al., 1995), grey cluster method (Yang et al.,1996; He et al., 2001) and neural network model (Xu et al., 1996), which study the possibility and intensity of RIS from different aspects.

Lack of data and issue complexity limit our understanding, together with the utilization of single method, which all affect the predictive effect. Therefore, according to different geological conditions, the Three Gorges Reservoir area is divided into 31 units to predict the probability and magnitude of RIS(Fig.1), by adopting statistical prediction model, fuzzy mathematics and gray system model as well as artificial neural network model respectively, which is of great significance for safe operation of Yangtze Three Gorge reservoir and prevention research of seicmic hazard.

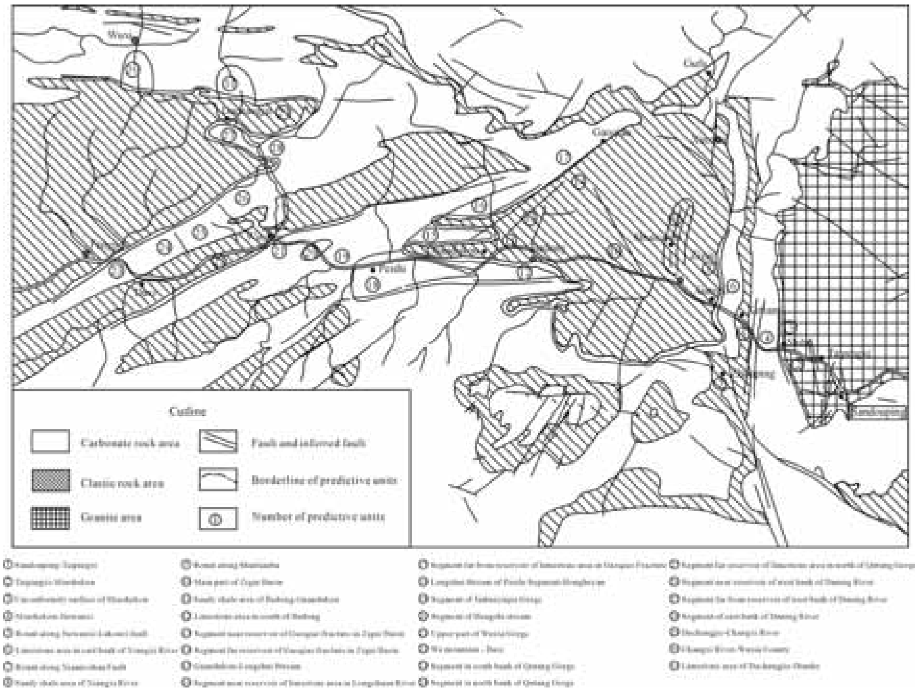

Figure 1 Schematic map of predictive unit division of RIS around the Three Gorges

2. MATHEMATICS MODEL OF RIS PREDICTION

2.1. Statistical predictive model

Statistical predictive method (probability predictive method), proposed by G.B.Beacher et al. in 1982, is a statistical analysis on factors which is likely to have close relationship with induced earthquake in large-scale reservoirs. The RIS is influenced by several factors, so its formation condition and genetic mechanism have not addressed with satisfaction, under this circumstances, it is more actual to regard the influencing factors as stochastic ones than unchangeable ones, and the process of reservoir induced seismicity is taken as multifactor function, after the data of combination environment (condition) and activity characteristics (results) of reservoir induced seismicity are obtained truly and comprehensively, the functional relation between condition and result are calculated through different mathematic models, such as probability statistics. According to the statistical data, combining with the geological structural condition of Three Gorges reservoir area, the conditional probabilities of induced earthquake factors under different status belonging to five magnitudes are calculated respectively.

According to Bayes's conditional probability theory, the statistical model for predicting reservoir induced seismicity is:

$$P(Mi/D,G,S,F,K,H,C,E)=\frac{P(Mi)P(D,G,S,F,K,H,C,E/Mi)}{\sum_{i=0}^{4}P(Mi)P(D,G,S,F,K,H,C,E/Mi)} \quad (2.1)$$

where P(Mi) is prior probability of earthquake in different magnitude, according to the data of domestic and foreign reservoirs, including 46 large-scale reservoirs with earthquake and 205 large-scale aseismic reservoirs, the prior probabilities of different magnitudes are as follows: P(M4) ＝0.02；P(M3) ＝0.04；P(M2) ＝0.05；P(M1) ＝0.07；P(M0) ＝0.82.

Where P(D,G,S,F,K,H,C,E /Mi) is conditional probability of different magnitude under various combinations of influencing factors, namely:

$$P(D,G,S,F,K,H,C,E/Mi)=(D/Mi)\cdot P(G/Mi)\cdot P(S/Mi)\cdot (F/Mi)\cdot P(K/Mi)\cdot P(H/Mi)\cdot P(C/Mi)\cdot P(E/Mi) \quad (2.2)$$

2.2. Gray system model

The parameter information of RIS prediction is not known completely, which may include other dispersive information influenced by many human factors. According to gray system theory, the quantity with uncertain information is regarded as gray quantity. Gray cluster method is known as a prediction based on it own gray target. Through white number, clustering objects to different clustering indexes are classified according to grey class, that is taking each weight of samples on statistical methods, then the corresponding weight of predicted object value on actual index is found in whitening weight functions to judge its category (Sun, 1995).

The magnitudes of RIS are regarded as clustering category, denoted by ML, represents L-th seismic category (L=1,2,3,…,s); Let induced earthquake factors be clustering index, denoted by Xi , is i-th predictive index (i=1,2,3,…,n); Taking reservoir segments as clustering object, denoted by YK, is the k-th predicted object (K=1,2,3,…,s).

If Zk(dij) is K-th sample of predicted reservoir to Xij, fLi(Zk(dij)) is the weight of Zk(dij) to whitening function of L-th Reservoir induced Seismicity:

$$f_{Li}\left\{Z_k(d_{ij})\right\}=\begin{cases}Y_L(x_{ij}/x_i) & Z_k(d_{ij})=Y_L(x_{ij}/x_i)\\ 0 & Z_k(d_{ij})\neq Y_L(x_{ij}/x_i)\end{cases} \quad (2.3)$$

Where YL(xi) is statistical number of i-th index in L-th reservoir earthquake category, YL(xij) is j-th sub-index's statistical number in i-th index of L-th reservoir earthquake category.The predicting vector is as follows:

$$Z_K(Y_L)=\{Z_K(Y_1),Z_K(Y_2),...,Z_K(Y_S)\}=\sum\sum f_{Li}(Z_k(d_{ij})) \quad (2.4)$$

If the category of predicted RIS is denoted by L*, while

$$Z_K(Y^*_L)=\max(Z_K(Y_1))=Z_k(Y_m) \quad (L^*=m) \quad (2.5)$$

When L* equal to m, the predicted RIS belongs to m-th reservoir earthquake category.

2.3. Artificial neural network model

The integrated physical theoretical model have not been established integrally in regard to its too many relative factors of triggering earthquake, complexity of generation, nonlinearity in preparation process and difficulty in understanding. So it has to describe the correlated physical parameters accurately by means of analyzing, summarizing and deducing the observed related phenomenon. It has been proved that the complex and nonlinear relations among variables can't be stated by simple algebraic equation, but the neural network theory just solve the problem because it is a nonlinear system combined organically by a lot of neurons, moreover, the analyzed objects are not asked to satisfy certain rules, so it is quite an effective method in seismic prediction. The neural network theory and examples are seen in relevant papers (Xu,1996).

3. PREDICTION ON TENDENCY OF RIS AROUND THREE GORGES RESERVOIR AREA

Three Gorges Reservoir, located at the lower section of upper Yangtze River, is a valley type long-narrow reservoir with total area of 55000 km^2; the reservoir is 660 km long, 1.0~1.5 km wide and 1048 km^2 of water area in total. The normal water level is 175 m with total storage capacity of 3.93×10^{10} m^3, in front of dam, the water head has increased nearly 110 m, so it belongs to the large reservoir with a high dam. The Three Gorges Reservoir has undergone two processes of impoundment: Since 24th May, 2003, With the Three Gorges Reservoir impounded to 135 m, in7th July, an earthquake with ML2.1 was occurred in Guandukou Town of Badong County, 2 km far from reservoir, and following 9th July, a serious of microearthquake happened; since September 20, 2006, the seismic activity intensified obviously when water level rose up to 156 m. During the impoundment of Three Gorges Reservoir from July, 2003 to December 2007, more than 3377 earthquakes have taken place in key monitoring areas, which are concentrated in Badong segment with maximum magnitude of about ML3.5.

3.1. Selection of triggering factors for reservoir induced seismicity and status

On the basis of past research(Gupta,1985;Gao et al.,1992;Jonathan et al.,1996; Wang et al.,2003;Xia,2006),, according to statistics and analysis on data of 251 reservoirs at home and abroad, 8 induced earthquake factors are chosen to predict the seismic risk of Three Gorges reservoir, which are listed as follows: depth of reservoir water (D), geological condition in reservoir area (G), tectonic stress environment (S), fault activity (F), Karst development degree (K), permeable height of reservoir water (H), communication relationship with reservoir water (C), earthquake activity background (E), and the authors classify them into three kinds of status (fault activity only has two kinds) for quantifying the model calculation(table 1).

In the process of establishing model, the way to select status of influencing factors is as follows: the dam of Three Gorges reservoir is 185m high but each segment around reservoir increases dissimilarly after impoundment, taking into account of the maximum water depth in every unit, ranged from 165 m to 120 m, which belongs to types of D1 and D2. However, the branch and units far away from reservoir aren't classified temporarily into corresponding status according to the water depth of the nearest segment.

Modern tectonic stress environment of the Three Gorges area is strike-slip fault primarily, therefore, the most reservoir segments are calculated as S3 while the Jiuwanxi-Lukouzi Fault segment as S2 and Xiannvshan Fault segment as S1. With regard to fault activity, few faults still active today exist in reservoir area expect slight activity occurred in route of Jiuwanxi-Lukouzi Fault, Xiannvshan Fault and Gaoqiao Fracture, therefore the former two faults are considered as F1; Tianziya Fault, more than 40 km long, passes across two branches on south bank which is also treated as F1, Shuitianba Fault and other faults in reservoir head area belong to inactivity status (F2). In limestone area of southern Badong, the Badong Fault goes through interface of limestone and sandy shale which is taken F1 and F2 as fault activity factors nowadays. And the Gaoqiao Fracture passes through clastic rock and limestone area which is selected F1 and F2 as activity.

According to the different types of outcropping metamorphic rock, magmatic rock, clastic rock and Carbonate rock in each segment, the authors classify them into three types of G1,G2 and G3. The stratum in certain segments distributes too complicatedly to ascertain its dominant lithology which is only taken G2 (stratified rock mass) and G3 (carbonate rock mass). In the meantime they are classified into K1, K2 and K3 according to karst development degree.

In this area, there is not deepwater hydrogeological structural plane, considered from the worst disadvantage, the faults of Jiuwanxi, Xiannvshan and Shuitianba are calculated as H1 while faults of Badong and Tianziya as H2, then the other segments all as H3.

The possible connection between reservoir water and fracture exists in faults of Jiuwanxi, Badong, Gaoqiao, Tianziya which are treated as C1; and same as Wuxia Gorge segment, Qutang Gorge segment, south segment of Daning River which have karst underground watercourse. limestone area in east section of Xiangxi River, Badong –Guandukou sandy shale area, Segment far from reservoir of limestone area of Gaoqiao fracture, Shiduan and west bank of Daning River have communication with reservoir water, which belong to C2, and the remaining are C3. Because of the small earthquake environment in Three Gorge reservoir area, therefore the earthquake activity background is all taken E3.

Table 1 Influencing factors of reservoir induced seismicity and status

Influencing factors	status		
	1	2	3
Depth of reservoir water (D)	＞150m	92~150m	＜92m
Geological condition in reservoir area (G)	blocked rock mass	stratified rock mass	carbonate rock mass
Tectonic stress environment (S)	reverse fault environment	normal fault environment	strike-slip fault environment
Fault activity (F)	activity	inactivity	
Karst development degree (K)	strong	weak	no karst
Permeable depth of reservoir water (H)	depth of water conductance＞2000m	depth of water conductance 500~2000m	depth of water conductance＜500m
Communication relationship with reservoir water (C)	contact directly	contact indirectly but with communication	no communication
Earthquake activity background (E)	strong	medium	weak

3.2. Magnitude classification of reservoir induced seismicity

According to the induced earthquake probability, analyzed from the data of domestic and foreign 46 large-scale reservoirs with earthquake while 205 large-scale reservoirs without earthquake, the forecasting magnitude of reservoir induced seismicity is divided into five statuses as strong, moderate-strong, small, micro and aseismic.

The criterions are as follows: the magnitude of strong reservoir induced seismicity (M_4) should be ≥6.0, the moderate-strong one (M_3) should be ≥4.5 and＜6.0, the small one (M_2) should be ≥3.0 and ＜4.5, the micro-earthquake (M_1) should be ＜3.0 and no earthquake (M_0).

Table 2 Status of induced earthquake factors and forecasting results of statistical model

Division of forecasting units	Division of forecasting units	Forecasting results of statistical predictive	Forecasting results of gray system	Forecasting results of neural network
1	D1G1S3F2K3C3H3E3	M_0	M_0	M_0
2	D1G1S3F2K3C3H3E3	M_0	M_0	M_0
3	D1G1S3F2K3C2H3E3	M_0	M_0	M_0
4	D1G3S3F2K2C1H3E3	M_0	M_0	M_0
5	D1G2S2F1K2C1H1E3	M_0、M_2	M_2	M_2
6	D1G3S3F2K2C2H3E3	M_0	M_0	M_1
7	D1G3S1F1K2C3H1E3	M_2、M_0	M_3	M_3
8	D1G2S3F2K3C3H3E3	M_0	M_0	M_1
9	D1G2S3F2K3C1H1E3	M_0	M_0	M_1
10	D1G2S3F2K3C2H3E3	M_0	M_0	M_1
11	D1G2S3F2K3C1H2E3	M_0	M_1	M_2
12	D1G3S3F1K1C1H2E3	M_3	M_3	M_3
13	D2G2S3F1K3C1H3E3	M_0	M_0	M_1
14	D2G2S3F2K3C3H3E3	M_0	M_0	M_1
15	D2G3S3F1K2C1H2E3	M_3	M_3	M_3
16	D2G3S3F2K2C1H2E3	M_0	M_1	M_2
17	D2G3S3F1K1C2H3E3	M_0、M_3	M_3	M_3
18	D2G3S3F2K2C2H3E3	M_0	M_0	M_0
19	D2G3S3F2K2C1H3E3	M_0	M_0	M_0
20	D2G2S3F2K3C3H3E3	M_0	M_0	M_0
21	D2G3S3F2K2C1H3E3	M_0	M_1	M_1
22	D2G2S3F2K3C1H3E3	M_0	M_0	M_0
23	D2G2S3F2K3C1H3E3	M_0	M_0	M_1
24	D2G3S3F2K1C1H3E3	M_0	M_2	M_1
25	D2G3S3F2K1C3H3E3	M_0	M_0	M_1
26	D2G3S3F2K1C1H3E3	M_0	M_2	M_1
27	D2G3S3F2K1C2H3E3	M_0	M_0	M_0
28	D2G3S3F2K1C1H3E3	M_0	M_2	M_1
29	D2G2S3F2K3C3H3E3	M_0	M_1	M_1
30	D2G3S3F2K1C3H3E3	M_0	M_1	M_1
31	D2G3S3F2K1C2H3E3	M_0	M_0	M_0

3.3. Predictive results

3.3.1 Statistical predictive results

Based on the statistical data, combining with the geological structural condition of reservoir area in Three Gorges, the conditional probability of each factor in different status belongs to five magnitudes respectively. According to different geological conditions of induced earthquake, the reservoir head area is divided into 31 forecasting units of engineering geological part, which are calculated respectively. The author calculates their probabilities by MATLAB which belong to five magnitudes respectively (showed in table 2), and takes the biggest value as the forecasting magnitude. Because of the uncertainty of original data, when the two status with biggest probability are close to each other (the difference of probability is not bigger than 0.10), list them into forecasting results simultaneously, and the one with bigger probability is in front (table 2).

The probability value of micro-earthquake and no earthquake ranged from 0.5 to 0.97 is bigger in each unit around Three Gorges reservoir, which reflects the stability in these units. However, the probability of M2 exists in some units, and indicates where might occur frequent small earthquake even moderate-strong earthquake. It is quite possible to trigger Ms4.5-6.0 earthquake in three places, including limestone area of southern Badong, Guandukou-Lengshuixi segment and far from reservoir segment of Gaoqiao Fracture limestone area.

3.3.2 Predictive results of gray system

After whiting function weights of each unit gray cluster are calculated, inserting them into Eq.(2) to calculate the predictive vector of each unit. From the results of gray clustering method, the maximum magnitude of induced earthquakes around reservoir area is between 4.5 and 6.0, which are concentrated in limestone area of southern Badong, Guandukou-Lengshuixi segment and far from reservoir segment of Gaoqiao Fracture limestone area, the active Xiannvshan Fault with medium developed karst may trigger $4.5 \le M < 6.0$ earthquake. Several places, such as Jiuwanxu-lukouzi Fault, segmment of Qutang Gorge north bank, segment near the reservoir of Daning River west bank and segment of Daning River east bank, may trigger $3.0 \le M < 4.5$ earthquake. In other segment, there are $M \le 3.0$ or no earthquake.

3.3.3 Predictive results of neural network

From the results of neural network prediction, the $4.5 \le M < 6.0$ earthquake occurs in route along Xiannvshan Fault, limestone area of southern Badong, Guandukou-Lengshuixi segment, far from reservoir segment of Gaoqiao Fracture limestone area. In some places, it may trigger earthquakes with $3.0 \le M < 4.5$, including route along Jiuwanxi-Lukouzi fault, Badong- Guandukou sandy shale area, near reservoir segment of Longchuanhe limestone area. the magnitude of earthquake occurring in other segments are all less than 3.0.

4. CONCLUSIONS

In short, the results from three different predictive methods are quite same with each other, especially distinction between mathematics statistics model and artificial neural network model, which is also conform to past macroscopical analogical prediction, it is proved that the neural network method to predict the seismic tendency is of certain significance. The results are obtained in so harsh condition, which show the preferable selection of induced earthquake factors, to certain degree, it also reflects the basic characteristics of induced earthquake mechanism.

Compared with past predictive results, our results are same basically without great deviation: (1) From Three

Gorges dam site to Miaohe segment, it lies in crystalline rock area where has not deeply regional fracture and large hydrogeological structural plane without middle or strong earthquake in history, after the impoundment of reservoir, the water here has increased about 69 m, however, the induced earthquakes are also seldom and the magnitude is quite small. (2) According to the analysis of earthquakes at home and abroad, the RIS takes place mainly in carbonatite and igneous rock, and concentrates in karst developing segment, yet it is little possible that earthquake happens in clastic rock area. From the predictive results, it is possible to trigger Ms4.5-6.0 earthquake in three places, including limestone area of southern Badong, near reservoir segment of Longchuanhe limestone area and far from reservoir segment of Gaoqiao Fracture limestone area. (3) Around the Gaoqiao Fracture, it's quite likely to take place tectonic reservoir induced earthquake, through the geological research, Longhuiguan Ms5.1 earrhquake in 1979 may be related to the Gaoqiao Fracture with certain activity, during the early period of reservoir impounding, the maximum magnitude of earthquake happening around the Gaoqiao Fracture reaches to 3.3. The bigger earthquakes might be induced in near reservoir segment of Gaoqiao fracture area, along with the water storing to the designing level.

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