第9卷 第1期 西北地震学报 Vol.9,No.1
1987年3月 NORTHWESTERN SEISMOLOGICAL JOURNAL March,1987

TWO MATHEMATIC MODEL FOR PREDICTION OF RESERVOIR INDUCED SEISMICITY

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With the expansion of human engineering activity both in scale and in sphere, there appears an accompaning new problem---induced seismicity in these decades especially in the last two decades.Many activities would intensify seismicity, such as impoundmen water in reservoir, large scale opencut mining and underground mining , waste liquid disposal, geothermal power generation as well as filling of high pressure water into the ground for a second time of petrolium exploitation, large scale drawing of underground water in cities and the post effect of underground nuclear detonation, ets.Since induced seismicity are accompanying engineering projects and occur near the large engineering projects triggering them, obvious social and ecnomic consequences would be incurred.therefore even as weak as M = 5 magnitude, an earthquake has to be taken into account. Among various kinds of induced seismicity already known, reservoir induced seismicity (usually called reservoir earthquake) is most worth heeding. The Xinfengjiang Reservoir in China, the Kremasta Reservoir in Greese, the Kariba Reservoir in the border area between Zambia and Zinbabwe and the Koyna in India, all had triggered strong earthquakes of more than 6 magnitude one after another in 1960s, and such earthquake is most serious in Xinfengjiang and Koyna.

Exploitation of hydroelectric resources is one of the most important ways to ease the energy problem for the world and especially for China. Many seismologists have been extensively information on the cases of reservoir earthquake (according to statistics, about 100 cases throughout the world and more than 10 cases in China), identifying their features, cases and trigger mechanism to find prediction methods and engineering countermeasures.

The end result of these efforts is to find out whether earthquakes would be induced after a reservoir is filled and what would be their intensities and location. And this is also one of the key seismological problems determining the rational operation of a reservoir and its accesory facilites.

Up to recent, owing to the restriction by the inadquate exposure of the natural phenomenon and the complicity of the problem, thus the people's poor understanding of it, extreme countermeasures have often been taken in engineering practice[1]. In view of the low occurance probability especially for strong earthquake, some people advocate to take no consideration of the risk while others hold that the highest magnitude so far (Koyna, Ms6.5) be adopted as a general seismic protection standard for all large reservoir to be built. However, from the viewpoint to solve the contradiction between safety and economics, these two ideas both seem a little too extreme.

The scholar of different fields suggested many empirical or semi-empirical prdiction methods.[15].In this study, The author tries to use digitally processed data from existing reservoirs (including those induced or not induced seismicity) to establish a mathematical prediction model. Here a brief description is firstly given of the statistical examination model (SEM) proposed by Packer[13] and Beacher[14]. Then the author's fuzzy comprehensive estimation model (FCEM) is presented.It goes without saying that since this mathematic prediction model is based on the analysis of existing data, it is of limitation in nature. However it is still a method which may be used inconjuction with the above methods for comrpehensive judgement.

I. Statistical Examination Model for Reservoir Earthquake (SEM)

1. Used data

Since there are several hundred thausands of reservoirs in the world, it is impossible to collect all data from so numerous reservoirs. On the other hand, the seismic cases of existing reservoirs show that they (especially strong ones) occurred mostly at large reservoirs of only several hundreds in number. Also, once a large reservoir suffers an earthquake, disasterous effect would result. Therefore, data used in this analysis are limited to large reservoirs both induced (RIS)or not yet seismicity ($\overline{\text{RIS}}$). Of course, the predictive result thus obtained are also only applicable to" large reservoirs", while used on" small reservoirs" it is quite possible to overestimate the inductive risks.

Seirmoinductive factors (Table 1) used iu statistic analysis of large reservoirs are considered as in close relationship with seismoinductive effects and can be found in published literature. Other possibly related factors are not listed for the time being either because they not available or because their seismoinductive effects have already been included in other factors. Once data are complete, they can be introduced into the model without difficulties.

"Large reservoir" defined in SEM and in FCEM refers to a reservoir of more than 92 meter in depth (ont the dam hight) and/or more than 10^{10} cubic meters in volume. The number of reservoir, used in SEM, meeting the above difinition are 29 seismoinduced and 205 no seismoinduced.

For seismoinductive factors and their classification (called factor state) see Table 1.

Based on the data of the 29 seismoinduced and 205 no seismoinduced, the frequency of the reservoirs under different states and their likelihood are listed in Tadle 2.

Table 1 Inductive facrors and their states

factor	sstate		
	1	2	3
Depth(C)	d_1: <15.m	d_2: 92—150m	d_3: <92m
Volume(V)	v_1: $10^{10}m^3$	v_2: $(0.12—1)10^{10}$	v_3: $0.12 \cdot 1.^{10}m^3$
Stress field(D)	s_1: extensional (thrust fault circumstance)	s_2: extensional (thrust fault circumstance)	s_3: shear (shear fault circumstance)
Fault activity(F)	f_1: active	f_2: inactive	
Geology conditiop(G)	g_1: sedimentary	g_2: metamophic	g_3: igneous

Table 2 Factor states and their likelihood rates

factor		number of reservoirs	state		
			1	2	3
RIS	D	29	10(0.34)	18(0.62)	1(0.04)
	V	29	7(0.24)	11(0.38)	11(0.38)
	S	29	4(0.14)	18(0.26)	7(0.24)
	F	7	7(1.00)	0(0)	
	G	28	13(0.46)	8(0.29)	7(0.25)
$\overline{RIS}$	D	204	27(0.13)	144(0.71)	33(0.16)
	V	205	52(.25)	36(0.18)	117(0.57)
	S	203	34(0.17)	138(0.68)	31(0.15)
	F	6	4(0.67)	2(0.33)	
	G	165	57(0.35)	64(0.39)	44(0.26)

2.SEM

(1) single factor model

It is obuious that a reservoir earthquake can not be induced only by and single one of the above factor, but a single factor is the basis for multifactor prediction model. For a known factor state, for example d_i, according to Bayes's theorem, the the conditional probability p(RIS/d_i) will be

$$q(RIS/d_i) = \frac{p(RIS)p(d_i/RIS)}{p(RIS)p(d_i/RIS + p(\overline{RIS})p_i/\overline{RIS})} \quad (1)$$

where p(RIS) and p($\overline{RIS}$) are she pre-examination probabilities of RIS and $\overline{RIS}$ respectivery, and P(d_i/RIS) and p($d_i/\overline{RIS}$ are the conditional pobability of RIS and $\overline{RIS}$ versus d_i respectively.

Conditional probability (Table 3) for all single factor states can be calculated in the same way.

Table 3 conditional probability of single factor states

factor	state		
	1	2	8
D	0.26	0.11	0.03
V	0.12	0.23	0.09
S	0.10	0.12	0.18
F	0.18	0	
G	0.16	0.10	0.12

(2) Multi-factor Model

Like (1), taking all 5 factors into account, the conditional probability of earthquake occurance is

$$p(RIS/D,V,S,F,G) = \frac{p(RIS)p(D,V,S,F,G/RIS)}{p(RIS)p(D,V,S,F,G/RIS) + p(\overline{RIS})p(D,V,S,F,G/\overline{RIS})} \quad (2)$$

the conditional probability of RIS for multi-factor is

$$p(\overline{RIS}/D,V,S,F,G) = \frac{p(\overline{RIS})p(D,V,S,F,G/\overline{RIS})}{p(RIS)p(D,V,S,F,G/RIS) + p(\overline{RIS})p(D,V,S,F,G/\overline{RIS})} \quad (3)$$

Divide equation (2) by (3), we have

$$\frac{p(RIS/D,V,S,F,G)}{p(\overline{RIS}/D,V,S,F,G)} = \left[\frac{p(RIS)}{p(\overline{RIS})}\right]\left[\frac{p(D,V,S,F,G/RIS)}{p(D,V,S,F,G/\overline{RIS})}\right]$$

$$= \left[\frac{p(RIS)}{p(\overline{RIS})}\right] LR(D,V,S,F,G) \quad (4)$$

LR(D,V,S,F,G) in equation (4) is called likelihood ratio which can easily be obtained using figures in Table 2(see Table 4).

Table 4 likelihood ratio

factor	state		
	1	2	3
D	2.62	0.87	0.21
V	0.95	2.15	0.66
S	0.82	0.91	1.58
F	1.05	0	
G	1.34	0.74	0.94

Ⅰ.FCEM of RIS

It should be said that the above said statistical examination model (SEM) is rigorous in the sense of statistics, but the following problems are worth approaching.Firstly, the data used above of RIS and $\overline{RIS}$ are apparently not sufficient for the examination of a nutural phenomenon jointly caused by so numerous and complicated factors.At the mean time, it can hardly be expected to supplement more data by constructing a number of large reservoirs in few years, and then it is neccessary to do more subjective judgements.Secondly, according to some studies, different factors differ greatly from each other in the relationship with RIS, this indicates that the "contributions" of different factors to seismoinduction can not be regarded as equal, and different factors as well as their states should be attached with different weights as the case may be.Thirdly, this model gives only the risk probability of RIS and does not estimate the possible maximum intensity of RIS. Obviously if estimation of RIS intensity is given, design work would be greatly facilitated.Therefore we suggest a FCEM on the basis of ad ditional data, especial data from China.

1.Fuzzy relation analysis

As pointed out above, reservoir earthquakes are caused by the combined effect of numerous factors and the seismoinductive factors are not in very close relationship with induction risk as well as possible induced intensity.For example, while high-dam large reservoirs are liable to induce earthquake, strong induced earthquakes are also seen with low-dam small reservoirs. What is the meaning of "high and large", "low and small" concerned in respect of inductive effect, reservoir depth and reservoir volume can not but be two fuzzy variables. Also, if the fault activity at and near the reservoir area is very important for judging induction effect of the fault, then what amplitude and speed of fault motion with which fault activities were to be classified are also fuzzy variables, and so on and so forth. Therefore, for the purpose of calculation, while fuzzy variables are classified, as done in SEM, it is neccessary to take consideration of such fuzzy nature to further fuzzify them (see later). So, in view of the unfull exposure of this natural phenomenon plus the differences in contribution to inductive effect by different factors, it proves to be an effective method in practical comprehensive examination of fuzzy mathematics to give proper weights to different factors and their states according to the trend shown in existing data and the conception of the expert.

2.FCEM

The principl and methodology of reservoir earthquake prediction using FCEM had been presented elsewhere[15, 16], here given is only a chief descriotion of them.

Assumed is that the domain of intensity of reservoir induced earhquake (called intensity domain, for short)

$$\underset{\sim}{V} = \{ V_1, V_2, \cdots\cdots, V_m \} \quad (5)$$

and the domain of factor partcipating in seismoinduction (called factor domain, for short)

$$\underset{\sim}{U} = \{ U_1, U_2, \cdots\cdots, U_n \} \quad (6)$$

whare m (here m = 3 is taken) and n (here n = 5) are the classes of intensity domain and the number of induction participating factors respectively.

Also assumed is that the single factor examination by ith factor to various intensity classes is

$$\underset{\sim}{R_i} = (r_{i1}, r_{i2}, \cdots\cdots r_{im}) \quad (7)$$

where R_{ik} is the membership degree of the ith factor on the kth intensity class.If expressed by matrix, the fuzzy relationship will be

$$\underset{\sim}{R} = \begin{pmatrix} \underset{\sim}{R_1} \\ \underset{\sim}{R_2} \\ \vdots \\ \underset{\sim}{R_n} \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ & \vdots & & \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{pmatrix}, \quad (8)$$

To perform fuzzy examination of reservoir induced earthquake is in fact to investigate the fuzzy subset $\underset{\sim}{A}$ in domain $\underset{\sim}{U}$ and through fuzzy relation matrix $\underset{\sim}{R}$ to perform image on the fuzzy subset $\underset{\sim}{B}$ in intensity domain $\underset{\sim}{V}$.

The factors subset in domain U is expressed as

$$\underset{\sim}{A} = \frac{a_1}{\underset{\sim}{U_1}} + \frac{a_2}{\underset{\sim}{U_2}} + \cdots\cdots + \frac{a_n}{\underset{\sim}{U_n}} \quad (9)$$

where $a_1, a_2, \cdots, a_n$ are the membership degree of $U_1 \cdots U_n$ on $\underset{\sim}{A}$, that is the peoples weighting of the factors effects on seismoinduction and its possible intensity, or the contribution by them to the seismoinduction (weight distribution).

The fuzzy subset of intensity domain is assumed as

$$\underset{\sim}{B}=\frac{b_1}{\underset{\sim}{V_1}}+\frac{b_2}{\underset{\sim}{V_2}}+\cdots\cdots+\frac{b_m}{\underset{\sim}{V_m}} \qquad (10)$$

where $b_1 \cdots b_m$ are the membership degree of various intensity classes on the examined intensity, and are the answeer we require. The plus and division sign in (9) and (10) are Zadeh symbols.

Now the first stage of prediction model can be expressed simply as

$$\underset{\sim}{B}=\underset{\sim}{A}o\underset{\sim}{R} \qquad (16)$$

or

$$(b_1, b_2, \cdots, b_m) = (a_1, a_2, \cdots, a_n)\,o\begin{pmatrix} r_{11} & r_{12} & r_{1m} \\ r_{21} & r_{22} & r_{2m} \\ & \vdots & \\ r_{n1} & r_{n2} & r_{nm} \end{pmatrix} \qquad (12)$$

where "o" is the complex operation sign. In consideration of the nature of varion seismoinductive factors, here a pair of operators (• , ⊕) is used and "•" is the usual multiplication sign, "⊕" is bounded summation namely when weight vectors and the elements in relation matrix are normalized, the above operators will into a pair of operators (• , +) used in conventional summing and products.

$$\alpha \oplus \beta = \min(\alpha+\beta,\ 1)$$

Since the factors are classified into several factor states, it is very difficult to distribute weights to all factors at the same time.So Eq (11) and (12) are revolved into the second stage examination model

$$\underset{\sim}{B}=\underset{\sim}{A}o\underset{\sim}{R}=\underset{\sim}{A}\begin{pmatrix} \underset{\sim}{A_1} & o & \underset{\sim}{R_1} \\ \underset{\sim}{A_2} & o & \underset{\sim}{R_2} \\ & \cdots & \\ \underset{\sim}{A_n} & o & R_n \end{pmatrix} \qquad (13)$$

where A_1—A_n and the weight factors of various factor states

3.Factors and their states

To make comparision with SEM, factor states are changed a little, i.e., a 4 th state is added and g_4 is carbonatite in kind (see Table 1).

4.Difference examination of "pair of factor states" for strong induced earthquake of equal and more than $W_s \geqslant 5.0$ (M_{macro}) and weak induced earthquake less than $W_s < 5.0$ (M_{micro}).

Apparently, to predict actual intensity is difficult due to limited data, In viewpoint of engineeing, to divide induced earthquake into two order with M_s 5.0 as dividing threshold is a feasible approach.To do so, it is neccessary to perform difference examination of various factor of the known earthquake of $M_s \geqslant 5$ and $M_s < 5$. In other words, examination of order is possible only if the difference is great enough so that the induced intensites can be divided into two orders. Here we use X^2 examination. Examination of M_{macro} and M_{macro} can be made separately only when the value of actual examined X^2 for a factor state pair is greater than threshold value for 90-95% of confidence degree. Here X^2 is calculated by the formula

$$\left.\begin{aligned} X^2 &= \sum_i \sum_j \sum_k \frac{(n_{ij} - n_k p_i\, p_j)^2}{n_k\, p_i\, p_j} \\ p_i &= \sum_j \sum_k \frac{n_{ijk}}{n} \\ p_j &= \sum_i \sum_k \frac{n_{ijk}}{n} \end{aligned}\right\} \quad (14)$$

where i means the column in the determinant for factor states, j means the row, k_1 and k_2 are the data group of M_{macro} and M_{micro}, n_{ij} is the number of reservoir in column i and row j, n^k is the total number of reservoir of $M_{macro}^{(k=1)}$ or $M_{micro}^{(1-2)}$, i.e., $n = n_{k=1} + n_{k=2}$.

The results of difference examination are as follows (Table 5)

Table 5

Pair of factor states	X^2	degree of freedom	threshold value of $\alpha=0.1$	threshold value of $\alpha=0.05$
D—V	21.0	8	13.4	15.5
D—S	10.5	8	13.4	15.5
D—G	17.2	12	18.5	21.0
V—X	54.3	8	13.4	15.5
V—G	50.3	12	18.5	21.0
S—G	22.5	12	13.5	21.0

Erom the result in Table 5, it can be seen that the actual values of X^2 of almost all factor state pairs exeed the threshold value of correspo-nding degree of free-dom except that the signification of difference of C—S and D—G are a little lower than threshold value of 90% of confidence degree.Thus it maybe concluded that strong earthquake ($M_s \geqslant 5$) and weak earthquake may be examined separayely.

5.Membership degree of single factor state (relation matrix $\underset{\sim}{R}$)

Basing on the data in Attached Table 1 ($M_s \geqslant 5$ — M_{macro}) and Attached Table 2 (M_s<5—M_{micro}) of RIS and the data in Attached Table 3 of RIS (Attached tables omitted), relation matrixes shown in Table 6 are given by statistics, the figures in parentheses are the number of corresponding reservoirs.

Tabie 6 Membership degree of single factor states

factcr	state	M_{macro}	M_{micro}	M_o
R_D	d_1	0.200(2)	0.388(12)	0.129(26)
	d_2	0.600(6)	0.581(18)	0.693(140)
	d_3	0.200(2)	0.032(1)	0.328(36)
R_V	v_1	0.400(4)	0.233(7)	0.238(48)
	v_2	0.600(6)	0.267(8)	0.188(38)
	v_3	0(0)	0.500(15)	0.574(116)
R_S	s_1	0.200(2)	0.172(5)	0.212(42)
	s_2	0.400(4)	0.655(19)	0.641(127)
	s_3	0.400(4)	0.172(5)	0.146(29)
R_F	f_1	1.000(10)	1.000(8)	0.670(4)
	f_2	0(0)	0(0)	0.330(2)
R_G	g_1	0.400(4)	0.074(2)	0.218(37)
	g_2	0.200(2)	0.333(9)	0.355(60)
	g_3	0.300(3)	0.296(8)	0.278(47)
	g_4	0.100(8)	0.296(7)	0.148(25)

It should be pointed out that there are active faults at and nearthe areas of the 10 M_{macro} reservoirs according to data concerned and in-field investigations[13]; while for M_{micro} reservoirs, only a few of them were investigated in respect of fault activity (e.g.Aksombo of Ghana Clark Hill of USA, Keben of Turkey, Nurek and Toktokyer of USSR, Sefid of Iran Danjiangkou and Foziling of China, etc.), in and near reservoir area So Rf of M_{micro} are also taken as 1.0(f_1) and O(f_2).

As said above, for reservoir depth and volume, being also fuzzy continuous variables, it is not reasonable enough to perform definite subjective clarification, for example, why 151 meter and 149 meter of depth are classified as d_1 and d_2 respectively and not in other way? Therefore, in consideration that maximum magnitude did not always occurred with highest water level and corresponding valume, a fuzzy classification membership function μ_i is difined in the calculation of depth and volume membership degree,

$$\mu_i=\begin{cases}1 & n=i\\ 0.7 & n=i-1,\ i+1\\ 0.3 & n=i-2,\ i+2\end{cases} \tag{15}$$

Also, stress state, fault activity and medium condition are of fuzzy nature when they are determined from data concerned, for example, stress state are not so clear as those listed in Table 1; strike-slip with dipslip component is classified as strike-slip circumstance; it is difficult to ascertain what medium condition is prevailing for the predominant structure of a reservoir, and so on and so forth. Therefore a fuzzily classified membership function μ_i is also defined for these factors,

$$\mu_i=\begin{cases}1 & n=i\\ 0.5 & n\neq i\end{cases} \tag{16}$$

In this way, after calculation, data in Table 6 are converted into those in Table 8.

Table 7

factor	state	M_{macro}	M_{micro}	M_0
R_D	d_1	0.304(5.8)	0.360(24.9)	0.293(134.8)
	d_2	0.392(8.8)	0.392(27.1)	0.399(183.4)
	d_3	0.304(6.8)	0.248(17.2)	0.308(141.8)
R_V	v_1	0.366(8.2)	0.271(17.1)	0.261(109.4)
	v_2	0.393(8.8)	0.370(23.4)	0.365(152.8)
	v_3	0.241(5.4)	0.359(22.7)	0.374(157.0)
R_S	s_1	0.300(6)	0.293(17)	0.303(120)
	s_2	0.350(7)	0.414(24)	0.410(162.5)
	s_3	0.350(7)	0.293(17)	0.287(113.5)
R_F	f_1	0.667(10)	0.667(18)	0.556(5)
	f_2	0.333(5)	0.333(4)	0.444(4)
R_G	g_1	0.280(7)	0.215(14.5)	0.244(103)
	g_2	0.240(6)	0.267(18.0)	0.271(114.5)
	g_3	0.260(6.5)	0.259(17.5)	0.256(108)
	g_4	0.220(5.5)	0.259(17.5)	0.229(977)

6. weight vector of factor and weight vector of state

In the light of the tendences of experts abroad, reported in publicized literature and the recognition of the author, here the weight vector of factor, $\underset{\sim}{A}$, is taken as

$$\underset{\sim}{A}=\{0.35(D),\ 0.25(V),\ 0.20(S),\ 0.10(F),\ 0.10(G)\} \tag{17}$$

Making reference to the published or unpublished data, weight vector of factor states is taken as

$$\left.\begin{aligned}
&\qquad\ d_1 \quad\ d_2 \quad\ d_3 \\
\underset{\sim}{A}_D &= \begin{pmatrix}0.20&0.60&0.20\\0.45&0.52&0.03\\0.12&0.70&0.18\end{pmatrix}\begin{matrix}M_{macro}\\M_{micro}\\M.\end{matrix} \\
&\qquad\ v_1 \quad\ v_2 \quad\ v_3 \\
\underset{\sim}{A}_V &= \begin{pmatrix}0.30&0.60&0.10\\0.24&0.31&0.45\\0.23&0.19&0.58\end{pmatrix}\begin{matrix}M_{macro}\\M_{micro}\\M.\end{matrix} \\
&\qquad\ s_1 \quad\ s_2 \quad\ s_3 \\
\underset{\sim}{A}_S &= \begin{pmatrix}0.20&0.40&0.40\\0.21&0.58&0.21\\0.21&0.63&0.16\end{pmatrix}\begin{matrix}M_{macro}\\M_{micro}\\M.\end{matrix} \\
&\qquad\ f_1 \quad\ f_2 \\
\underset{\sim}{A}_F &= \begin{pmatrix}1.00&0\\0&1.00\\0.67&0.33\end{pmatrix}\begin{matrix}M_{macro}\\M_{micro}\\M.\end{matrix} \\
\underset{\sim}{A}_G &= \begin{pmatrix}0.30&0.30&0.30&0.10\\0.09&0.35&0.30&0.26\\0.22&0.36&0.27&0.15\end{pmatrix}\begin{matrix}M_{macro}\\M_{micro}\\M.\end{matrix}
\end{aligned}\right\} \qquad (18)$$

Ⅱ. Predictive tables of two models (SEM and FCEM)

1. Predictive table for SEM

Basing on the figures in Table 4 and using Fq.(4), the seismoinductive probability of combination of 162 (3 × 3 × 3 × 2 × 3) factor states, assuming varoius seismoinductive factors are probabilistic independent (last row), are calculated.

2. Predictive table fro FCEM

Basing on the relation matriex in Table 7 and the factor weight vector (Eq.17) and factor weight matrix (Eq. 18), the predictive results of the seismoinductive possibility and possible inducing intensity for combination of 216 (3 × 3 × 3 × 2 × 4) factor states are calculated (last two row in Table 8. Also, the normalized membership degree of b_2 and b_3 of various classes on the fuzzy comprehensive evaluation are given in Table 8. So, not only predictthe intensity classes, but also may known the risk of various intensity class based on their membership degree.

Having the two predictive tables, the predictive result may be examined at once, once the states of five seismoinductive factors of a large reservoir to be predictd are determined.

In order to examinate the success of two models, according to

Table 8

			d_1 v_1					d_1 v_2					d_1 v_3				
			b_1	b_2	b_3	FCEM prediction	SEM prediction	b_1	b_2	b_3	FCEM prediction	SEM prediction	b_1	b_2	b_3	FCEM prediction	SEM prediction
s_1	f_1	g_1	0.416	0.465	0.119	Mmicro	0.358	0.436	0.449	0.083	Mmacro	0.558	0.343	0.408	0.190	Mmicro	0.280
		g_2	0.410	0.471	0.119	Mmicro	0.235	0.461	0.454	0.085	Mmicro	0.411	0.338	0.473	0.189	Mmicro	0.176
		g_3	0.417	0.470	0.113	Mmicro	0.282	0.468	0.453	0.079	Mmacro	0.470	0.346	0.472	0.182	Mmicro	0.214
		g_4	0.413	0.479	0.108	Mmicro		0.465	0.401	0.074	Mmacro		0.340	0.481	0.179	Mmicro	
	f_2	g_1	0.307	0.386	0.307	Mmicro	0.271	0.404	0.375	0.221	Mmacro	0.457	0.199	0.394	0.407	Mo	0.205
		g_2	0.361	0.397	0.301	Mmicro	0.170	0.396	0.385	0.219	Mmacro	0.317	0.197	0.405	0.398	Mmicro	0.125
		g_3	0.314	0.396	0.290	Mmicro	0.207	0.406	0.384	0.210	Mmacro	0.371	0.210	0.403	0.387	Mmicro	0.153
		g_4	0.304	0.409	0.287	Mmicro		0.400	0.394	0.206	Mmacro		0.198	0.416	0.386	Mmicro	
s_2	f_1	g_1	0.375	0.472	0.153	Mmicro	0.382	0.423	0.457	0.120	Mmicro	0.584	0.311	0.475	0.213	Mmicro	0.301
		g_2	0.370	0.476	0.154	Mmicro	0.255	0.418	0.461	0.121	Mmicro	0.436	0.308	0.480	0.212	Mmicro	0.192
		g_3	0.377	0.475	0.148	Mmicro	0.303	0.424	0.460	0.116	Mmicro	0.496	0.315	0.479	0.206	Mmicro	0.232
		g_4	0.372	0.483	0.144	Mmicro		0.421	0.467	0.112	Mmicro		0.310	0.486	0.204	Mmicro	
	f_2	g_1	0.272	0.414	0.313	Mmicro	0.292	0.354	0.401	0.244	Mmicro	0.483	0.186	0.421	0.394	Mmicro	0.223
		g_2	0.269	0.422	0.309	Mmicro	0.186	0.349	0.409	0.242	Mmicro	0.340	0.185	0.429	0.386	Mmicro	0.136
		g_3	0.279	0.421	0.300	Mmicro	0.225	0.358	0.408	0.235	Mmicro	0.396	0.195	0.428	0.377	Mmicro	0.167
		g_4	0.271	0.432	0.298	Mmicro		0.352	0.417	0.231	Mmicro		0.186	0.438	0.376	Mmicro	
s_3	f_1	g_1	0.441	0.466	0.094	Mmicro	0.518	0.487	0.450	0.063	Mmacro	0.709	0.369	0.470	0.161	Mmicro	0.428
		g_2	0.434	0.471	0.095	Mmicro	0.373	0.480	0.455	0.065	Mmacro	0.573	0.364	0.474	0.162	Mmicro	0.292
		g_3	0.441	0.470	0.089	Mmicro	0.430	0.486	0.454	0.060	Mmacro	0.631	0.371	0.473	0.155	Mmicro	0.344
		g_4	0.437	0.478	0.084	Mmicro		0.484	0.462	0.055	Mmacro		0.367	0.482	0.151	Mmicro	
	f_2	g_1	0.357	0.395	0.248	Mmicro	0.418	0.437	0.383	0.180	Mmacro	0.619	0.252	0.404	0.343	Mmicro	0.332
		g_2	0.350	0.405	0.245	Mmicro	0.284	0.429	0.392	0.179	Mmacro	0.473	0.249	0.413	0.337	Mmicro	0.216
		g_3	0.361	0.404	0.235	Mmicro	0.335	0.438	0.391	0.171	Mmacro	0.532	0.260	0.412	0.327	Mmicro	0.259
		g_4	0.353	0.416	0.231	Mmicro		0.433	0.401	0.160	Mmacro		0.251	0.424	0.325	Mmicro	

Table 8 续表

			d_2 v_1					d_2 v_2					d_2 v_3				
			b_1	b_2	b_3	FCEM prediction	SEM prediction	b_1	b_2	b_3	FCEM prediction	SEM prediction	b_1	b_2	b_3	FCEM prediction	SEM prediction
s_1	f_1	g_1	0.392	0.346	0.262	Mmicro	0.156	0.441	0.343	0.215	Mmacro	0.295	0.327	0.352	0.321	Mmicro	0.114
		g_2	0.336	0.353	0 260	Mmacro	0.093	0.436	0.350	0.214	Mmacro	0.188	0 323	0.359	0.318	Mmicro	0.066
		g_3	0.393	0.353	0.254	Mmacro	0.115	0.442	0.350	0.208	Mmacro	0/227	0.330	0.358	0.311	Mmicro	0.083
		g_4	0.389	0.360	0.251	Mmacro		0.438	0.356	0.206	Mmacro		0.325	0.365	0.310	Mmicro	
	f_2	g_1	0.289	0.220	0.491	Mo	0.110	0.375	0.235	0.390	Mo	0.219	0.198	0.235	0.567	Mo	0.079
		g_2	0.284	0.236	0 480	Mo	0.064	0.369	0.248	0.083	Mo	0.133	0.197	0.249	0.653	Mo	0.045
		g_3	0.295	0.235	0.470	Mo	0.080	0.377	0.248	0.375	Mmacro	0.164	0.208	0.249	0.544	Mo	0.057
		g_4	0.287	0.243	0.471	Mo		0.372	0.254	0.374	Mo		0.198	0.256	0.546	Mo	
s_2	f_1	g_1	0.358	0.369	0.273	Mmicro	0.171	0.404	0.365	0.231	Mmacro	0 317	0.301	0.375	0.324	Mmicro	0.125
		g_2	0.354	0.375	0.271	Mmicro	0.102	0.399	0.371	0.230	Mmacro	0.204	0.298	0.381	0.321	Mmicro	0.073
		g_3	0.360	0.375	0.265	Mmicro	0.126	0.405	0.370	0.225	Mmacro	0.246	0.304	0.380	0.316	Mmicro	0.091
		g_4	0.356	0.381	0.263	Mmicro		0.402	0.376	0.223	Mmacro		0.300	0.386	0.314	Mmicro	
	f_2	g_1	0.262	0.279	0.459	Mo	0.120	0.336	0.284	0.380	Mo	0.237	0.187	0.290	0.523	Mo	0.087
		g_2	0.260	0.290	0.450	Mo	0.071	0.332	0.294	0.374	Mo	0.146	0.187	0.300	0.513	Mo	0.050
		g_3	0.268	0.289	0.430	Mo	0.088	0.339	0.293	0.368	Mo	0.179	0.195	0.299	0.506	Mo	0.063
		g_4	0.261	0.296	0.443	Mo		0.334	0.299	0.367	Mo		0.187	0.306	0.507	Mo	
s_3	f_1	g_1	0.415	0.354	0.231	Mmacro	0.263	0.460	0.350	0.190	Mmacro	0.447	0.351	0.361	0.288	Mmicro	0.199
		g_2	0.410	0.361	0.230	Mmacro	0.165	0.454	0.357	0.189	Mmacro	0.308	0.348	0.367	0.385	Mmicro	0.120
		g_3	0.416	0 360	0.224	Mmacro	0.200	0.460	0.356	0.184	Mmacro	0.362	0.354	0.366	0.280	Mmicro	0.148
		g_4	0.413	0.366	0.221	Mmacro		0.457	0.362	0.181	Mmacro		0.349	0.373	0.278	Mmicro	
	f_2	g_1	0.322	0.243	0.424	Mo	0.192	0.406	0.254	0.340	Mmacro	0.350	0.244	0.257	0.499	Mo	0.142
		g_2	0.327	0.257	0.416	Mo	0.116	0.399	0.265	0.336	Mmacro	0.229	0.242	0.270	0.489	Mo	0.083
		g_3	0.337	0.256	0.407	Mo	0.143	0.402	0.265	0.328	Mmacro	0.274	0.251	0.269	0.480	Mo	0.104
		g_4	0.330	0.263	0.407	Mo		0.407	0.271	0.326	Mmacro		0.243	0.276	0.481	Mo	

Table 8 续 表

			d_3 v_1					d_3 v_2					d_3 v_3				
			b_1	b_2	b_3	FCEM prediction	SEM prediction	b_1	b_2	b_3	FCEM prediction	SEM prediction	b_1	b_2	b_3	FCEM prediction	SEM prediction
s_1	f_1	g_1	0.398	0.343	0.272	Mmacro	0.043	0.463	0.329	0.208	Mmacro	0.092	0.310	0.339	0.351	Mo	0.030
		g_2	0.391	0.340	0.269	Mmacro	0.024	0.455	0.338	0.207	Mmacro	0.053	0.305	0.349	0.346	Mmicro	0.017
		g_3	0.401	0.340	0.269	Mmacro	0.030	0.463	0.337	0.200	Mmacro	0.066	0.315	0.348	0.338	Mmicro	0.022
		g_4	0.395	0.339	0.257	Mmacro		0.459	0.345	0.196	Mmacro		0.305	0.348	0.327	Mmicro	
	f_2	g_1	0.229	0.103	0.670	Mo	0.029	0.375	0.152	0.473	Mo	0.063	0.084	0.136	0.780	Mo	0.021
		g_2	0.225	0.134	0.641	Mo	0.016	0.366	0.175	0.459	Mo	0.036	0.088	0.164	0.748	Mo	0.011
		g_3	0.243	0.133	0.624	Mo	0.021	0.379	0.175	0.446	Mo	0.045	0.106	0.119	0.731	Mo	0.015
		g_4	0.227	0.143	0.631	Mo		0.370	0.183	0.447	Mo		0.122	0.165	0.709	Mo	
s_2	f_1	g_1	0.353	0.364	0.284	Mmicro	0.048	0.412	0.359	0.229	Mmacro	0.101	0.279	0.371	0.350	Mmicro	0.033
		g_2	0.348	0.371	0.281	Mmicro	0.026	0.406	0.366	0.228	Mmacro	0.058	0.276	0.379	0.345	Mmicro	0.019
		g_3	0.356	0.371	0.274	Mmicro	0.034	0.413	0.365	0.222	Mmacro	0.073	0.284	0.378	0.338	Mmicro	0.023
		g_4	0.350	0.379	0.271	Mmicro		0.409	0.372	0.219	Mmacro		0.273	0.386	0.337	Mmicro	
	f_2	g_1	0.208	0.215	0.567	Mo	0.032	0.321	0.242	0.437	Mo	0.078	0.100	0.244	0.656	Mo	0.022
		g_2	0.206	0.243	0.551	Mo	0.018	0.315	0.256	0.428	Mo	0.039	0.103	0.260	0.637	Mo	0.013
		g_3	0.219	0.242	0.539	Mo	0.022	0.326	0.256	0.419	Mo	0.049	0.115	0.260	0.625	Mo	0.016
		g_4	0.207	0.252	0.541	Mo		0.318	0.264	0.418	Mo		0.102	0.269	0.630	Mo	
s_3	f_1	g_1	0.430	0.342	0.229	Mmacro	0.079	0.486	0.339	0.175	Mmacro	0.163	0.344	0.355	0.305	Mmicro	0.057
		g_2	0.422	0.351	0.227	Mmacro	0.046	0.478	0.348	0.175	Mmacro	0.097	0.339	0.361	0.301	Mmicro	0.032
		g_3	0.431	0.350	0.219	Mmacro	0.057	0.485	0.347	0.168	Mmacro	0.120	0.347	0.353	0.293	Mmicro	0.040
		g_4	0.427	0.359	0.215	Mmacro		0.482	0.354	0.164	Mmacro		0.341	0.301	0.291	Mmicro	
	f_2	g_1	0.307	0.156	0.537	Mo	0.064	0.421	0.190	0.391	Mmacro	0.115	0.171	0.183	0.646	Mo	0.038
		g_2	0.300	0.181	0.519	Mo	0.031	0.411	0.209	0.380	Mmacro	0.067	0.171	0.205	0.624	Mo	0.022
		g_3	0.316	0.180	0.504	Mo	0.038	0.422	0.208	0.370	Mmacro	0.083	0.185	0.205	0.610	Mo	0.027
		g_4	0.304	0.190	0.506	Mo		0.416	0.216	0.363	Mmacro		0.171	0.214	0.625	Mo	

Table 8, the two inspective "prediction" results for various large reservoirs are listed in the last two row.

It is not difficult to find out that SEM is less successful. According to its predictions, examination probabilites can reach or approach 0.5 only for 12 induced reservoirs, with a success rate of only about 40%, and at the same time seismoinductive intensity can not be predicted.

On the contrary, FCEM has a success rate of "prediction" of up to 70% for $M_s \geqslant 5$, 80% for $M_s < 5$ and 85% for M_o (assume that the fault activity is f_2). Therefore conclusion may be drawn that with the existing data-based FCEM, it is possible to estimate with 70-80% of certainty the seisminductive risk and the possible maxmum intensity of large new reservoirs.

Of couse, FCEM still has some aspects to be improved which are not to be discussed here.

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预测水库诱发地震的两个数学模式

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摘　　要

近几十年来，特别是近二十年来，随着人类工程活动的规模和领域的扩大，出现了伴生的新问题——诱发地震。水库蓄水、小规模的地面或地下采矿、处理废液、地热发电和石油开采及城市大量抽取地下水以及地下核爆破等都造成局部地震活动增强。由于诱发地震是伴随大型工程而发生的，且多发生于大型工程附近，所以即使5级左右的地震也应予以考虑。

国内外学者对水库地震的预测提出过许多方法。本文介绍了预测水库地震的统计检验预测模式和两级模糊综合评判模式，并用实际水库震例进行了检验。