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Reservoir induced seismic hazard using principal component analysis

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RESUMEN

Se calcularon funciones empíricas ortogonales (EOF) asociadas con los parámetros que contribuyen a la generación de sismicidad inducida en presas, con base en 37 casos en todo el mundo. Se encontró que la primera EOF explica el 54% de la varianza. Mostró una correlación de 0.38 con la magnitud máxima y tuvo una carga mayor respecto al volumen de la presa y el retraso en tiempo de la magnitud máxima desde su llenado inicial. La segunda EOF que explicó aproximadamente el 33% de la varianza, mostró sin embargo la carga máxima para la altura de la presa, pero tuvo una correlación de sólo 0.10. Incluyendo la magnitud sísmica máxima como el cuarto parámetro, las primeras dos EOF's explicaron sólo el 73% de la varianza comparada con el 87% usando tres parámetros. La influencia combinada del volumen de la presa y del retraso en tiempo resultan ser más importantes que la altura de la presa desde el punto de vista de la evaluación del peligro.

PALABRAS CLAVE: Sismicidad inducida, presas y temblores.

ABSTRACT

Empirical orthogonal functions (EOF) associated with the parameters conducive to reservoir induced seismicity have been computed based on 37 cases throughout the world. It was found that the first EOF explained 54% variance. It showed a correlation of 0.38 with the maximum magnitude of earthquakes and had large loadings for reservoir volume and the time lag of the occurrence of the largest earthquake since the filling of the reservoir. The second EOF which explained about 33% variance however, showed largest loading for the height of the reservoir but had a correlation of only 0.10 with these parameters. By including the maximum magnitude of the earthquake as the fourth parameter, the first two EOF's explained only about 73% variance as compared to 87% with the three parameters. The combined influence of the reservoir volume and the time lag appears to be more important than the height of the reservoir from the view of hazard assessment.

KEY WORDS: Induced seismicity, dams and earthquakes.

INTRODUCTION

Reservoir-induced seismicity has attracted the attention of geoscientists for about three decades. One of the earliest studies on the subject (Carder, 1945) associated seismicity variations with the filling of lake Mead reservoir, Colorado, USA. Based on more than 100 cases of reservoir-induced seismicity, Guha and Patil (1990) grouped them into three categories classifying them as intense ($M \geq 6.0$), moderate to mild (5.9 to 3.1) and microearthquake seismicity ($M \leq 3.0$). Gupta (1992) compiled more than 70 cases of reservoir induced seismicity in addition to a few cases of decrease in seismicity. Baecher and Kenney (1987) found from limited samples that the reservoir depth is the attribute which most discriminates circumstances that may or may not result in induced seismicity, and the next best is the reservoir volume. Taking into consideration the possibility of a time lag in the response of the earth's crust to the reservoir size and the largest magnitude earthquake, the influence of all such parameters needs to be explained using a larger data set, which is now available. In this paper, principal component analysis (PCA) has been applied to understand the contribution of different parameters to reservoir induced seismicity. Although this method has been extensively used in meteorology (Srivastava and Singh, 1994), its application for reservoir-induced seismicity is being reported for the first time.

METHODOLOGY

Principal component analysis is based on linear functions of the original variables

$$Z = a_1 x_1 + a_2 x_2 + \ldots + a_p z_p \qquad (1)$$

where $a_1, a_2 \ldots a_p$ are constants. As we change $a_1, a_2 \ldots a_p$, we get different linear functions and we can calculate the variance of any such linear functions. The first principal component (PC) is the linear function which has the maximum possible variance; the second PC is the linear function with the next highest variance uncorrelated with the first PC; the third PC is the linear function which maximizes variance subject to being uncorrelated with the first and second PCs, and so on. Thus, it is easy to construct p principal components providing optimal m-dimensional representation of the data for each m = 1, 2 ... p and for various different definitions of optimality. In general, the kth principal component is given by:

$$Z_k = a_{R1} x_1 + a_{R2} x_2 + \ldots a_{Rp} x_p \qquad (2)$$

for k = 1, 2 ... p. Here a_R are vectors consisting of the weights of different variables. We compute eigenvectors of the (p x p) co-variance matrix. Details are given by Preisendorfer (1988). The orthogonality condition on x_i

implies that the covariance matrix of x_m has zero off-diagonal terms (while that of x_m has both diagonal and off diagonal terms). The transformation from x-Z therefore, can be achieved by diagonalising the covariance matrix.

The empirical orthogonal function (EOF) is the set of coefficients appearing in the first PC. Similarly subsequent EOF's consist of coefficients of $x_1, x_2 \ldots x_p$ in each successive PC. The first eigenvalue is the variance of the first PC, and so on. To define the principal components only the normalization constant is imposed. The method of normalization used in this paper is given by:

$$\sum_{ij} a^2_{k_i} = \frac{1}{\lambda_i} \tag{3}$$

which makes Var $(Z_k)=1$ for all $k = 1, 2 \ldots p$.

In the first instance, we express the maximum magnitude of an earthquake as a linear combination of orthogonal functions of the other possible reservoir-induced seismicity parameters. Expressing parameters such as height, volume and time lag for different reservoirs, the eigenvectors of the co-variance matrix are computed. The loading factors corresponding to the three parameters are given in Table 2.

Table 1

Reservoir induced changes in seismicity (modified after Gupta, 1992)

No.	Name of the Dam	Country	Reservoir Height of dam (m)	Reservoir volume (10 m)	Year of impounding	Year of largest earthquake	Mag./ intensity
01	Hsinfengkiang	China (PRC)	105	13,896	1959	1962	6.1
02	Kariba	Zambia/Zimbabwe	128	175,000	1958	1963	6.2
03	Koyna	India	103	2,780	1962	1967	6.3
04	Kremasta	Greece	160	4,750	1965	1966	6.2
05	Aswan	Egypt	111	164,000	1964	1981	5.6
06	Benmore	New Zealand	110	2,040	1964	1966	5.0
07	Eucumbene	Australia	116	4,761	1957	1959	5.0
08	Hoover	USA	221	36,703	1935	1939	5.0
09	Marathon	Greece	67	41	1929	1938	5.7
10	Oroville	USA	236	4,400	1967	1975	5.7
11	Srinagarind	Thailand	140	11,750	1977	1983	5.8
12	Bajina Basta	Yugoslavia	90	340	1966	1967	4.8
13	Bhatsa	India	88	947	1981	1983	4.9
14	Camarillas	Spain	49	37	1960	1964	4.1
15	Canelles	Spain	150	678	1960	1962	4.7
16	Capivari-Cachoeira	Brazil	58	180	1970	1971	5.0
17	Danjiangkou	China (PRC)	97	16,000	1967	1973	4.7
18	Grandval	France	88	292	1959	1963	4.5
19	Kastraki	Greece	96	1,000	1968	1969	4.6
20	Kerr	USA	60	1,505	1958	1971	4.9
21	Kurobe	Japan	186	149	1960	1961	4.9
22	Lake Pukaki	New Zeland	106	9,000	1976	1978	4.6
23	Monteynard	France	155	275	1962	1963	4.9
24	P. Colombia/V. Grande	Brazil	40/56	1,500/2,300	1973/1974	1974	4.2
25	Piastra	Italy	93	13	1965	1966	4.4
26	Pieve de Cadore	Italy	116	69	1949	1950	5.0
27	Shenwo	China (PRC)	50	540	1972	1974	4.8
28	Vouglans	France	130	605	1968	1971	4.4
29	Blowering	Australia	112	1,628	1968	1973	3.5
30	Contra	Switzerland	220	86	1963	1965	3.0
31	Idukki	India	169	1,996	1975	1977	3.5
32	Itezhitezhi	Zambia	65	5,000	1976	1978	3.8
33	Jocasse	USA	107	1,431	1971	1975	3.2
34	Paraibuna-Paraitinga	Brazil	94/105	4,700	1975/1976	1977	3.0
35	Ajanjin	China (PRC)	50	20	1970	1971	3.0
36	Sriramsagar	India	43	32,000	1983	1984	3.2
37	Kuzuryu	Japan	128	353	1967	1972	6.0

The advantage of the principal component solution is its ability to compress the complicated variability of the original data set into temporally uncorrelated components.

Making use of the weights for the height, volume and the time lag (Table 2), we can compute the individual values of the first EOF for reservoirs in different regions. The correlation coefficient is, then, worked out using these values with the corresponding maximum magnitude of the earthquake (Table 2, last column). Similarly, the correlations with the second and third EOF are computed.

Table 2

Empirical orthogonal functions for three induced seismicity parameters

No. of EOF	Height	Volume	Time Lag	Percentage Variance	Correlation Coeff. with Max. Mag.
EOF 1	0.19	0.69	-0.70	54.0	0.38
EOF 2	0.98	-0.18	-0.08	32.7	0.10
EOF 3	0.07	0.70	-0.71	13.3	0.15

DATA ANALYSIS

The parameters conducive to reservoir-induced seismicity such as height, volume, time lag from the filling to the occurrence of a significant earthquake and maximum magnitude, were generally taken from the data published by Gupta (1992). Earthquakes of magnitude less than 3 were not considered. Among Japanese major artificial reservoirs, Kuzuryu and Ikari were included, which showed seismicity changes at a 90% level of significance (Ohtake, 1986). The Srinagarind (Thailand) earthquake of 1983 (Chung and Liu, 1992) which had a magnitude of 5.8, has also been included in this study. The data for reservoirs in the Indian peninsula included Koyna (1967) and Bhatsa (1983), which are the best documented cases (Srivastava *et al.*, 1991). Also, Sriramasagar and Idduki were included in view of the occurrence of earthquakes of magnitude more than 3. Mula, Nagarjunsagar, Parambikulum, Sharavatty, Kinnersain or Gundipet were excluded because the earthquakes were of magnitude less than 3.0. Historical and recent catalogues of earthquakes (Srivastava and Das, 1985, Srivastava and Ramachandran, 1985, Ramachandran and Srivastava, 1991), BARC Seismic Array and seismological networks in peninsular India show the occurrence of hundreds of small events (less than magnitude 3) in different parts of peninsular India, making it difficult to tell tectonic events from reservoir-induced ones. The data for reservoir-induced seismicity parameters used in this paper is given in Table 1. Note that although water level in the reservoir changes in time, we have considered the maximum capacity (volume) of the reservoir provided that it was filled at some stage before the occurrence of the earthquake.

RESULTS AND DISCUSSION

Table 2 shows that the first two EOF's explain 87% of the variance. The first EOF in this table showed a correlation of 0.38 with the maximum magnitude of the earthquake near the reservoir and had larger loading for the reservoir volume and the time lag of the maximum magnitude earthquake since the filling of the reservoir. Test statistics (Student's T-test) shows that the results are significant at the 95% level of confidence. While these features have loadings of opposite sign, the time delay in the occurrence of the maximum earthquake has a larger influence on the reservoir volume than the height of the reservoir. The second EOF, however, yields largest loading for the height of the reservoir with a correlation of 0.10 (Table 2). If we include the maximum magnitude of earthquakes near the reservoir as the fourth parameter, the results of the four EOF's are given in Table 3. It may be seen that the first two EOF's now explain only 72% of the variance. All three parameters (reservoir volume, time lag and maximum magnitude of earthquake) have similar loading with the least influence of height of reservoir for the first EOF. The loading due to the height of reservoir is significant for the second EOF but the loading of the remaining parameters are also larger as compared to the case where only three parameters are used. Thus, including the fourth parameter (Table 3) gives worse results as compared to only 3 parameters (Table 2). According to Coates (1981), 10% of the reservoirs deeper than 90 meters have induced seismicity while 21% of the reservoirs deeper than 140 meters induced significant earthquakes. This correlation is broadly supported by the second EOF in (Table 2) which shows the largest loading due to the height of the reservoir.

Table 3

Empirical orthogonal functions for four induced seismicity parameters

No. of EOF	Height	Volume	Time Lag	Maximum Magnitude	Percentage Variance
EOF 1	0.21	0.60	0.60	0.48	47.2
EOF 2	-0.90	0.21	0.29	-0.23	25.1
EOF 3	0.36	0.23	0.32	-0.84	17.7
EOF 4	0.08	0.71	-0.70	-0.04	10.0

Hudson (1991) observed that the maximum earthquake does not increase either with depth or volume. But the simple correlation coefficient of the maximum magnitude with the volume of the reservoir, based on data of our study, was found to be larger (0.38) than for height (0.18). This may be attributed to the fact that the reservoir volume includes the influence of ressure variations caused by the water load on the local seismic activity. Since the first and second EOF's are orthogonal, with a correlation coefficient of 0.38 for the first EOF (Table 2), the influence of the reservoir volume and of the time delay are more important than the height of the reservoir for assessing the earthquake hazard. This is also supported by the larger variance of 54% for the first EOF as compared to 33% for the second EOF (Table 2). The orthogonality criteria of the first and second EOF's also suggest that the physical process in inducing seismicity may be different for reservoir volume plus time lag, vs height of the reservoir. Physically, the opposite sign of loadings in the first EOF for reservoir volume and time lag would imply that the maximum magnitude may occur earlier if the volume of the reservoir is larger and vice versa (Table 2).

Talwani and Acree (1985) have studied the seismic hydraulic diffusivity of reservoir-induced seismicity from the growth of aftershocks; but this aspect could not be examined due to lack of data for many reservoirs. It has also been found that reservoir-induced seismicity is more common with strike slip or normal faults (Gupta and Rastogi, 1976), but there are exceptions, notably Nurek and Srinagarind reservoirs where thrust faulting is predominant (Keith *et al.*, 1982, Chung and Liu, 1992). The non availability of reliable fault plane solutions for several earthquakes of magnitude less than 5.0 to 5.5 prevents us from using this parameter for EOF study.

Howells (1974) has shown that the time required for significant pore pressure to migrate to a depth of 5 to 7 km could be several hundred days. This would allow us to exclude the cases where the response was immediate. However, if several cases with immediate response of induced seismicity were identified, a separate EOF analysis might be justified. It should be mentioned that the maximum rate of change of lake level (dH/dt) has been associated with significant earthquakes near some reservoirs (Gupta 1985, Guha 1990, Rastogi, 1990). This parameter could not be included in EOF analysis due to its being available for only a few dams. Also, the influence of this parameter has been found to be less marked after a few years in the case of continued seismicity such as Koyna reservoir (MERI reports). In conclusion, the new approach of analyzing reservoir-induced seismicity parameters through the Principal Component Analysis offers better insight through relative loadings and the extent of their interdependence. This study could be made more elaborate if additional data is available.

The seismic response of the filling of large reservoirs varies greatly from one reservoir to another, due to several factors including local geology and stress conditions. Baicher and Kenney (1982) have however, found a small correlations with such factors. Simpson *et al.* (1988) identified a type of induced seismicity in terms of temporal and spatial characteristics, featuring rapid response in which the seismicity is closely correlated with changes in water level. This seismicity tends to be shallow and of low magnitude. In this paper, we have considered only earthquakes of magnitude ≥ 3 which excludes the influence of changes in pore pressure and stress-related elastic compression. On the other hand, delayed response was attributed to diffusion-controlled increase in pore pressure. In the present study, the combined influence of reservoir height and volume, and of time delay in the first EOF implies a steady change in pore pressure through elastic deformation and coupled fluid response, depending upon the time taken by the water to physically move from the reservoir to the site of potential failure by diffusion (Simpson and Narasimhan, 1992). This appears to provide a better insight for earthquake hazard assessment through an improved correlation with the maximum magnitude of the earthquake (Table 2).

CONCLUSIONS

A study based on principal component analysis has brought out the following results:

(i) The first EOF explains 54% of the variance by reservoir volume and time lag of occurrence of the largest earthquake after the filling of the reservoir. A higher correlation coefficient of the EOF with the maximum magnitude of the earthquake suggests that this combined influence is more important than the height of the reservoir for inducing seismicity. These results provide an improved insight into earthquake hazard assessment for reservoir-induced seismicity.

(ii) The second EOF gave the highest loading to the height of the reservoir and explained about 33% of the variance, but the correlation with the maximum magnitude of the impending earthquake was only 0.10 which supports the interpretation given in (i) above.

Since the second EOF is orthogonal to the first EOF, the physical process in inducing seismicity may differ for reservoir volume plus time delay as against height of the reservoir alone.

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