

geofísica  
internacional

Geofísica Internacional

ISSN: 0016-7169

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México

Srivastava, H. N.; Dube, R. K.  
Reservoir induced seismic hazard using principal component analysis  
Geofísica Internacional, vol. 36, núm. 1, january-march, 1997, p. 0  
Universidad Nacional Autónoma de México  
Distrito Federal, México

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## Reservoir induced seismic hazard using principal component analysis

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Received: October 25, 1995; accepted: September 18, 1996.

### 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

$$Z = a_1 x_1 + a_2 x_2 + \dots + a_p x_p \quad (1)$$

where  $a_1, a_2 \dots a_p$  are constants. As we change  $a_1, a_2 \dots a_p$ , 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  $m = 1, 2 \dots p$  and for various different definitions of optimality. In general, the  $k$ th principal component is given by:

$$Z_k = a_{k1} x_1 + a_{k2} x_2 + \dots + a_{kp} x_p \quad (2)$$

for  $k = 1, 2 \dots p$ . Here  $a_k$  are vectors consisting of the weights of different variables. We compute eigenvectors of the  $(p \times p)$  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  $x$ - $X$  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  $x_1, x_2 \dots x_p$  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:

$$\sum_{ij} a_{k_i}^2 = \frac{1}{\lambda_1}$$

which makes  $\text{Var}(Z_k)=1$  for all  $k = 1, 2 \dots p$ .

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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 2. Loading factors for the first three principal components (PCs).

No.	Variable	Unit	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14	PC15	PC16	PC17	PC18	PC19	PC20	PC21	PC22	PC23	PC24	PC25	PC26	PC27	PC28	PC29	PC30	PC31	PC32	PC33	PC34	PC35	PC36	PC37	PC38	PC39	PC40	PC41	PC42	PC43	PC44	PC45	PC46	PC47	PC48	PC49	PC50	PC51	PC52	PC53	PC54	PC55	PC56	PC57	PC58	PC59	PC60	PC61	PC62	PC63	PC64	PC65	PC66	PC67	PC68	PC69	PC70	PC71	PC72	PC73	PC74	PC75	PC76	PC77	PC78	PC79	PC80	PC81	PC82	PC83	PC84	PC85	PC86	PC87	PC88	PC89	PC90	PC91	PC92	PC93	PC94	PC95	PC96	PC97	PC98	PC99	PC100	PC101	PC102	PC103	PC104	PC105	PC106	PC107	PC108	PC109	PC110	PC111	PC112	PC113	PC114	PC115	PC116	PC117	PC118	PC119	PC120	PC121	PC122	PC123	PC124	PC125	PC126	PC127	PC128	PC129	PC130	PC131	PC132	PC133	PC134	PC135	PC136	PC137	PC138	PC139	PC140	PC141	PC142	PC143	PC144	PC145	PC146	PC147	PC148	PC149	PC150	PC151	PC152	PC153	PC154	PC155	PC156	PC157	PC158	PC159	PC160	PC161	PC162	PC163	PC164	PC165	PC166	PC167	PC168	PC169	PC170	PC171	PC172	PC173	PC174	PC175	PC176	PC177	PC178	PC179	PC180	PC181	PC182	PC183	PC184	PC185	PC186	PC187	PC188	PC189	PC190	PC191	PC192	PC193	PC194	PC195	PC196	PC197	PC198	PC199	PC200	PC201	PC202	PC203	PC204	PC205	PC206	PC207	PC208	PC209	PC210	PC211	PC212	PC213	PC214	PC215	PC216	PC217	PC218	PC219	PC220	PC221	PC222	PC223	PC224	PC225	PC226	PC227	PC228	PC229	PC230	PC231	PC232	PC233	PC234	PC235	PC236	PC237	PC238	PC239	PC240	PC241	PC242	PC243	PC244	PC245	PC246	PC247	PC248	PC249	PC250	PC251	PC252	PC253	PC254	PC255	PC256	PC257	PC258	PC259	PC260	PC261	PC262	PC263	PC264	PC265	PC266	PC267	PC268	PC269	PC270	PC271	PC272	PC273	PC274	PC275	PC276	PC277	PC278	PC279	PC280	PC281	PC282	PC283	PC284	PC285	PC286	PC287	PC288	PC289	PC290	PC291	PC292	PC293	PC294	PC295	PC296	PC297	PC298	PC299	PC300	PC301	PC302	PC303	PC304	PC305	PC306	PC307	PC308	PC309	PC310	PC311	PC312	PC313	PC314	PC315	PC316	PC317	PC318	PC319	PC320	PC321	PC322	PC323	PC324	PC325	PC326	PC327	PC328	PC329	PC330	PC331	PC332	PC333	PC334	PC335	PC336	PC337	PC338	PC339	PC340	PC341	PC342	PC343	PC344	PC345	PC346	PC347	PC348	PC349	PC350	PC351	PC352	PC353	PC354	PC355	PC356	PC357	PC358	PC359	PC360	PC361	PC362	PC363	PC364	PC365	PC366	PC367	PC368	PC369	PC370	PC371	PC372	PC373	PC374	PC375	PC376	PC377	PC378	PC379	PC380	PC381	PC382	PC383	PC384	PC385	PC386	PC387	PC388	PC389	PC390	PC391	PC392	PC393	PC394	PC395	PC396	PC397	PC398	PC399	PC400	PC401	PC402	PC403	PC404	PC405	PC406	PC407	PC408	PC409	PC410	PC411	PC412	PC413	PC414	PC415	PC416	PC417	PC418	PC419	PC420	PC421	PC422	PC423	PC424	PC425	PC426	PC427	PC428	PC429	PC430	PC431	PC432	PC433	PC434	PC435	PC436	PC437	PC438	PC439	PC440	PC441	PC442	PC443	PC444	PC445	PC446	PC447	PC448	PC449	PC450	PC451	PC452	PC453	PC454	PC455	PC456	PC457	PC458	PC459	PC460	PC461	PC462	PC463	PC464	PC465	PC466	PC467	PC468	PC469	PC470	PC471	PC472	PC473	PC474	PC475	PC476	PC477	PC478	PC479	PC480	PC481	PC482	PC483	PC484	PC485	PC486	PC487	PC488	PC489	PC490	PC491	PC492	PC493	PC494	PC495	PC496	PC497	PC498	PC499	PC500	PC501	PC502	PC503	PC504	PC505	PC506	PC507	PC508	PC509	PC510	PC511	PC512	PC513	PC514	PC515	PC516	PC517	PC518	PC519	PC520	PC521	PC522	PC523	PC524	PC525	PC526	PC527	PC528	PC529	PC530	PC531	PC532	PC533	PC534	PC535	PC536	PC537	PC538	PC539	PC540	PC541	PC542	PC543	PC544	PC545	PC546	PC547	PC548	PC549	PC550	PC551	PC552	PC553	PC554	PC555	PC556	PC557	PC558	PC559	PC560	PC561	PC562	PC563	PC564	PC565	PC566	PC567	PC568	PC569	PC570	PC571	PC572	PC573	PC574	PC575	PC576	PC577	PC578	PC579	PC580	PC581	PC582	PC583	PC584	PC585	PC586	PC587	PC588	PC589	PC590	PC591	PC592	PC593	PC594	PC595	PC596	PC597	PC598	PC599	PC600	PC601	PC602	PC603	PC604	PC605	PC606	PC607	PC608	PC609	PC610	PC611	PC612	PC613	PC614	PC615	PC616	PC617	PC618	PC619	PC620	PC621	PC622	PC623	PC624	PC625	PC626	PC627	PC628	PC629	PC630	PC631	PC632	PC633	PC634	PC635	PC636	PC637	PC638	PC639	PC640	PC641	PC642	PC643	PC644	PC645	PC646	PC647	PC648	PC649	PC650	PC651	PC652	PC653	PC654	PC655	PC656	PC657	PC658	PC659	PC660	PC661	PC662	PC663	PC664	PC665	PC666	PC667	PC668	PC669	PC670	PC671	PC672	PC673	PC674	PC675	PC676	PC677	PC678	PC679	PC680	PC681	PC682	PC683	PC684	PC685	PC686	PC687	PC688	PC689	PC690	PC691	PC692	PC693	PC694	PC695	PC696	PC697	PC698	PC699	PC700	PC701	PC702	PC703	PC704	PC705	PC706	PC707	PC708	PC709	PC710	PC711	PC712	PC713	PC714	PC715	PC716	PC717	PC718	PC719	PC720	PC721	PC722	PC723	PC724	PC725	PC726	PC727	PC728	PC729	PC730	PC731	PC732	PC733	PC734	PC735	PC736	PC737	PC738	PC739	PC740	PC741	PC742	PC743	PC744	PC745	PC746	PC747	PC748	PC749	PC750	PC751	PC752	PC753	PC754	PC755	PC756	PC757	PC758	PC759	PC760	PC761	PC762	PC763	PC764	PC765	PC766	PC767	PC768	PC769	PC770	PC771	PC772	PC773	PC774	PC775	PC776	PC777	PC778	PC779	PC780	PC781	PC782	PC783	PC784	PC785	PC786	PC787	PC788	PC789	PC790	PC791	PC792	PC793	PC794	PC795	PC796	PC797	PC798	PC799	PC800	PC801	PC802	PC803	PC804	PC805	PC806	PC807	PC808	PC809	PC810	PC811	PC812	PC813	PC814	PC815	PC816	PC817	PC818	PC819	PC820	PC821	PC822	PC823	PC824	PC825	PC826	PC827	PC828	PC829	PC830	PC831	PC832	PC833	PC834	PC835	PC836	PC837	PC838	PC839	PC840	PC841	PC842	PC843	PC844	PC845	PC846	PC847	PC848	PC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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, Parambikulam, 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

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 or low magnitude. In this paper, we have considered only earthquakes of magnitude  $\geq 3$  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 suggest 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.

### ACKNOWLEDGMENTS

The authors are grateful to the Director General of Meteorology for providing the facilities. One of us (HNS) is thankful to the Council of Scientific and Industrial Research for financial support. Shri S. S. Singh, Director of India Meteorological Department extended help in the computational work.

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