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Prediction of Reservoir Induced Seismicity by Analytical Hierarchy Process and Regression Analysis

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ABSTRACT

This study is done to find out the equation for reservoir induced seismicity. The mechanism and histories of reservoir induced seismicity are studied first to find out the factors affecting reservoir induced seismicity. A questionnaire survey is done to get an opinion of an expert on the effect of all the factors affecting reservoir induced seismicity. The results obtained from this questionnaire survey is used to find out the respective weightages of the factors by analytical hierarchy process. In the second part of the study, seismic details of 20 seismic and aseismic dams are found out in a questionnaire survey format. These details along with the weights found out in the first part of the study is used to find out the equation for reservoir induced seismicity by regression analysis.

Keywords: Reservoir induced seismicity, Analytical hierarchy process, Regression Analysis.

INTRODUCTION

Earthquakes are one of the most devastating among the various natural hazards. In the last few decades, the world has been faced by a number of large earthquakes which has caused significant destruction of human life and property, earthquakes are the major natural disaster in our country too. The Indian subcontinent has suffered much due to earthquakes being one of the most earthquake prone regions of the globe. The damage to human life and property due to large earthquakes are significant, the rapid rate of urbanization and globalization has caused the construction of mega infrastructures to support people which has increased the potential of earthquakes to a greater extent[5,6].

A particular seismic event or earthquakes refers to the tremors associated with the damage of a rock mass below the surface of earth. The energy released is only a small portion of the energy which is released due to the rupture of the rock mass. A seismic event is caused by excess concentration of stress in discontinuities of rock mass which leads to failure of the rock mass, the excess stress concentration is caused due to stress redistribution. An earthquake or seismic activity is said to be completed when the energy dissipation is complete and the rocks moves from one stress state to another. Seismic activity may vary in intensity and in many events the energy dissipated may not reach the earth surface. But it will reach the earth surface in case of large earthquakes and cause considerable shaking[7,8].

The impoundment of large reservoirs especially ones with height above 100 m have caused earthquakes which are termed as reservoir induced earthquakes or reservoir triggered earthquakes. The first case of reservoir induced earthquake was that of marathon reservoir, Greece in 1931[7,11]. After that over 100 cases of reservoir induced earthquakes were recorded in which many of them had magnitudes greater than 6 and caused considerable damage[11,3].

This work focuses on predicting the reservoir induced seismicity due to the dam by statistical method of regression

Methodology

Evaluation of weightage of factors affecting reservoir induced seismicity by Analytical Hierarchy Process

The factors which are likely to affect reservoir induced seismicity are finalised from previous investigation papers and history of reservoir induced seismicity. Even though the factors affecting the RIS is complicated and the exact mechanism is net yet found out, this study focusses on seven factors which have a direct dependence on causing reservoir induced seismicity[3,10,11]. These factors are namely:

- Water load
- Geological condition of area
- Fault characteristics
- Fault activity
- Seismic zone
- Karst topography
- Water conductance of soil below

A questionnaire survey is created on the above given factors affecting reservoir induced seismicity to find out the importance of each of the factors. The questionnaire survey is to be answered by an expert geologist. The format of the questionnaire survey is based on the importance level proposed by analytical hierarchy process called the universal scale of absolute numbers. The questionnaire survey is shown below and the universal scale of absolute numbers[8] is shown in table 1.

Please register your opinion regarding the effect of the following factors in causing reservoir induced earthquakes(eg: if a factor has no contribution in causing reservoir induced earthquake mark as no importance & if a factor is an extremely important factor in causing reservoir induced earthquakes mark it as extreme importance)

Note: Please tick the correct option

Water load

o No importance o Moderate
o Strong o Very strong
o Extreme

Geological condition of reservoir area

o No importance o Moderate
o Strong o Very strong
o Extreme

Fault characteristics

o No importance o Moderate
o Strong o Very strong
o Extreme

Fault activity

o No importance o Moderate
o Strong o Very strong
o Extreme

***Karst topography**

o No importance o Moderate
o Strong o Very strong
o Extreme

Seismic Zone

o No importance o Moderate
o Strong o Very strong
o Extreme

Water conductance of soil below

o No importance o Moderate
o Strong o Very strong
o Extreme

*Karst topography is a landscape formed from the dissolution of soluble rocks such as limestone, dolomite, and gypsum. It is characterized by underground drainage systems with sinkholes, dolines, and caves[11].

Analytical Hierarchy Process

Analytical hierarchy process comes under a multiple criteria decision making approach which was first introduced by saaty in 1977 and 1994..In this process ,the input data are easy to obtain and the solution is found out easily by smooth mathematical properties[1,2]. The analytical hierarchy process is normally used to solve complex mathematical problems. It creates a multilevel hierarchy structure which consists of criteria, objectives, sub criteria and alternatives. The obtained data is solved by formation

Table 1:

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possibleorder of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals of Above	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal valuewhen compared with i	

of pair wise comparison matrix which provide weights of different criteria. It also provides mechanism to improve consistency if it's not perfect[8,9,10].

In our case, an expert opinion is used to create the comparison matrix which correlates the Relative importance of the seven factors affecting reservoir induced seismicity. The right eigen vectors of the matrix gives the weightages of the seven factors affecting reservoir induced seismicity[8,9,10].

From the expert opinion the pairwise comparison matrix is formed

Pairwise Comparison Matrix

$$\begin{bmatrix} 1 & 9/3 & 9/3 & 7/3 & 7/3 & 7/3 & 3/3 \\ 3/9 & 1 & 9/9 & 9/9 & 7/9 & 7/9 & 3/9 \\ 3/9 & 9/9 & 1 & 9/9 & 7/9 & 7/9 & 3/9 \\ 3/9 & 9/9 & 9/9 & 1 & 7/9 & 7/9 & 3/9 \\ 3/7 & 9/7 & 9/7 & 9/7 & 1 & 7/7 & 3/7 \\ 3/7 & 9/7 & 9/7 & 9/7 & 7/7 & 1 & 3/7 \\ 3/3 & 9/3 & 9/3 & 9/3 & 7/3 & 7/3 & 1 \end{bmatrix}$$

The right Eigen vectors of the pairwise comparison matrix gives the respective eights of

Weightage evaluation: Expert opinion of a geologist

Water load(W)	Moderate	3
Geological condition of reservoir area(G)	Extreme	9
Fault characteristics(F)	Extreme	9
Fault activity(A)	Extreme	9
*Karst topography(K)	Very strong	7
Seismic Zone(S)	Very strong	7
Water conductance of soil below(C)	Moderate	3

factors affecting reservoir induced seismicity. The right Eigen vectors of the above comparison matrix is calculated as follows

$$\begin{bmatrix} 0.26 \\ 0.087 \\ 0.0773 \\ 0.087 \\ 0.112 \\ 0.112 \\ 0.26 \end{bmatrix}$$

The values obtained were checked for consistency and were found to be consistent.

Calibration of equation of Reservoir induced seismicity magnitude by regression analysis

The second part of the study is the calibration of equation for magnitude of reservoir induced seismicity magnitude by regression analysis. This is done by collecting seismic data of seismic and aseismic dams across the nation. It is seen from previous studies and investigations that all the seven factors affecting seismicity can be divided each into four sub factors. These sub factors are incorporated when seismic detail of each dam is found out. All the sub factors are given weightages ranging from 1 to 4 with 1 causing the least chance of reservoir induced seismicity and 4 showing highest probability of causing reservoir induced seismicity. The factors affecting reservoir induced seismicity, their sub factors and their weightages are given in table 3.

The seismic data is collected in a questionnaire format as shown below

Please register your opinion regarding the following geological and geotechnical features of the dam area

Note: Please tick the correct option

Water Load (W)

o <10^5 m^3 o 10^5-10^7

o 10^7-10^9 o >10^9 m^3

Geological condition of reservoir (G)

o Igneous rocks o Metamorphic rocks

o Non-carbonate sedimentary rocks

o Carbonate sedimentary rocks

Fault characteristics (F)

o No Fault o Reverse fault

o Normal fault o Strike slip fault

Fault activity (A)

o Inactive o Very less active

o Moderately active o Highly active

***Karst Topography (K)**

o Underdeveloped o Poorly developed

o Developed o Well developed

Seismic zone(S)

o 2 o 3 o 4 o 5

Table 3

Factors affecting seismicity	Sub factors	
Water load	1.	<10^5 m^3
	2.	10^5-10^7
	3.	10^7-10^9
	4.	>10^9 m^3
Geological condition of reservoir area	1.	Igneous rocks
	2.	Metamorphic rocks
	3.	Non-carbonate
	4.	sedimentary rocks
	5.	Carbonate sedimentary rocks
Fault characteristics	1.	No Fault
	2.	Reverse fault
	3.	Normal fault
	4.	Strike slip fault
Fault activity	1.	Inactive
	2.	Very less active
	3.	Moderately active
	4.	Highly active
Karst topography	1.	Underdeveloped
	2.	Poorly developed
	3.	Developed
	4.	Well developed
Seismic zone	1.	2
	2.	3
	3.	4
	4.	5
Water conductance	1.	<100m
	2.	<500m
	3.	500-2000m
	4.	>2000m

Water conductance (in depth of water conductance)(C)

o <100m o <500m

o 500-2000m o >2000m

*Karst topography is a landscape formed from the dissolution of soluble rocks such as limestone, dolomite, and gypsum. It is characterized by underground drainage systems with sinkholes, dolines, and caves.[11]

Regression Analysis

The seismic details that is the seven factors with the corresponding recorded seismicity is collected from the cases of seismic and aseismic dams around the country. Each of the dam details that is the seven factors affecting reservoir induced seismicity is multiplied by their corresponding weights obtained from part 1 of the study. This weighted details along with the corresponding seismicity value is used for regression analysis to obtain the equation for reservoir induced seismicity. The process of regression analysis is done by Microsoft excel[4,12].

Dam Details

W	G	F	A	K	S	C	Seismicity
4	3	2	1	2	2	1	5.3
2	3	1	3	2	3	2	4.5
1	2	3	2	4	3	1	3.2
3	2	4	3	1	2	4	5.1
2	4	3	2	1	4	3	4.5
4	3	2	4	2	3	1	6.1
4	2	3	2	1	4	2	5.9
1	2	3	4	2	4	2	3
2	3	2	4	2	3	1	3.2
2	4	3	2	1	4	3	4.5
3	2	4	1	3	2	4	4.5
4	2	3	1	2	4	2	4.8
4	3	1	2	4	3	4	6.2
4	2	3	4	3	4	3	6
2	3	4	2	1	3	2	2.1
4	2	3	4	1	2	3	3
2	3	1	4	3	2	1	2.1
4	2	3	1	4	3	2	4.8
4	2	3	1	2	3	3	4.5
2	3	1	2	1	2	3	4.9
4	2	3	1	4	3	2	5

Weighted Dam Details

W	G	F	A	K	S	C	Seismicity
1.04	0.261	0.1546	0.087	0.224	0.244	0.26	5.3
0.52	0.261	0.0773	0.261	0.224	0.366	0.52	4.5
0.26	0.174	0.2319	0.174	0.448	0.366	0.26	3.2
0.78	0.174	0.3092	0.261	0.112	0.244	1.04	5.1
0.52	0.348	0.2319	0.174	0.112	0.488	0.78	4.5
1.04	0.261	0.1546	0.348	0.224	0.366	0.26	6.1
1.04	0.174	0.2319	0.174	0.112	0.488	0.52	5.9
0.26	0.174	0.2319	0.348	0.224	0.488	0.52	3
0.52	0.261	0.1546	0.348	0.224	0.366	0.26	3.2
0.52	0.348	0.2319	0.174	0.112	0.488	0.78	4.5
0.78	0.174	0.3092	0.087	0.336	0.244	1.04	4.5
1.04	0.174	0.2319	0.087	0.224	0.488	0.52	4.8
1.04	0.261	0.0773	0.174	0.448	0.366	1.04	6.2
1.04	0.174	0.2319	0.348	0.336	0.488	0.78	6
0.52	0.261	0.3092	0.174	0.112	0.366	0.52	2.1
1.04	0.174	0.2319	0.348	0.112	0.244	0.78	3
0.52	0.261	0.0773	0.348	0.336	0.244	0.26	2.1
1.04	0.174	0.2319	0.087	0.448	0.366	0.52	4.8
1.04	0.174	0.2319	0.087	0.224	0.366	0.78	4.5
0.52	0.261	0.0773	0.174	0.112	0.244	0.78	4.9
1.04	0.174	0.2319	0.087	0.448	0.366	0.52	5

The weighted dam details are used and regression analysis is done in Microsoft excel. It is seen that the p value of all factors affecting RIS except W and C are found to be above .15 therefore only W and C are used for calibrating the equation. The coefficient of W and C are 2.597 and 4.088 respectively

Thus the magnitude of reservoir induced seismicity in any dam is given as M= 0.26 x 2.597 x W + 0.26 x 4.088 x C

RESULTS AND DISCUSSIONS

Reservoir induced seismicity is a phenomena whose exact mechanism and factors affecting it has not yet been found out. In this study, an attempt is made to find out the equation for reservoir induced seismicity by use of statistical information and expert opinions. The tools of analytical hierarchy process and regression analysis is used to find out the equation. The first part of the work consists of evaluation of weightage of factors affecting reservoir induced seismicity by an expert opinion followed by analytical hierarchy process. The weightages of the factors are found out as shown below:

W=0.26
G=0.087
F=0.0773
A=0.087
K=0.112
S=0.112
C=0.26

The weightages of the factors are used in the seismic data of test dams. The weighted seismic data is used for regression analysis to find out the equation for reservoir induced seismicity.the equation found out is as follows

M= 0.26 x 2.597 x W + 0.26 x 4.088 x C

It can be said that the equation found out is accurate to a certain respect with respect to the statistical data and can be used in predicting reservoir induced seismicity.

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