International Journal of Technical Innovation in Modern Engineering & Science (IJTIMES)
Impact Factor: 3.45 (SJIF-2015), e-ISSN: 2455-2585
Volume 4, Issue 03, March-2018

STATISTICAL ANALYSIS OF RESERVOIR INDUCED SEISMICITY AT A RESERVOIR SITE

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ABSTRACT: This paper presents a statistical probability method to find the probability of a particular intensity of earthquake at a reservoir site which can be used to assign degree of risk associated with the site. Reservoir impoundment at certain sites leads to increase seismicity at the site which makes the structures in the vicinity of the reservoir vulnerable to earthquake forces which might not have been considered according to conventional seismic design, thus it becomes important to include the effect of Reservoir Induced Seismicity (RIS) in the design of structure which are in proximity to the reservoir site. So we are presenting a modified earthquake design for a site which is suspected to be in the category of RIS by using additional parameters along with conventional parameters of earthquake design. The nature of our design where seismicity have been induced due to reservoir impoundment is a slightly different from tectonic earthquake design considering the fact that this particular design is well supplemented with a rational statistical analysis hence requiring us to design the structures for increased design forces to fulfil the basic earthquake design criteria.

Keywords: - Bayes conditional probability, Proximity factor, RIS factor, Statistical probability, Reservoir Induced Seismicity.

INTRODUCTION

Purpose

The purpose of this paper is to provide guidance for designing structures at a reservoir site both normal occupancy structures and important structures (hydraulic, building, hospitals etc.). Since finding suitable sites for dams is very difficult task in itself hence it might not be possible to reject a site just on the basis of RIS. Hence it will be more practical to follow a modified earthquake design to ensure the safety of a structure that is going to be constructed near a reservoir site.

Scope

A rational statistical work has been proposed to analyze the nature, causes and intensity of Reservoir induced seismicity.

(a) To present a statistical probability method giving probability of a particular intensity of earthquake at a reservoir site using data of reservoir sites experiment this phenomena in the past.
(b) To formulate Risk factor associated with a reservoir site using probability and energy of a particular magnitude of earthquake.
(c) To formulate RIS factor and proximity factor to be included in the seismic design.

LITERATURE REVIEW

The first incidence of reservoir induced seismicity was observed as early as 1931 in Marathon reservoir of Greece. As of today, over 90 sites have been globally identified where earthquakes have been triggered by filling of water reservoirs. The phenomenon of earthquakes induced due to impoundment of reservoirs has been addressed and reviewed in a number of paper and books. The most significant contribution in this field is by a leading Harsh Kumar

Gupta [1] who defines the occurrence as: "earthquake occurring in the vicinity of artificial water reservoir as a consequence of impoundment." (Gupta, H.K, 2002)

The study conducted by H K Gupta [2] highlights the following points:

1. Depth of water in the reservoir and the volume of water play an important role in triggering an earthquake.
2. One characteristic of RIS is that the magnitude of the foreshock is higher than the magnitude of the aftershock and both values are generally higher than in cases of natural earthquakes.
3. The effect of RIS can be rapid (following the initial impoundment of reservoir) or delayed (Occurring later in the life of reservoir).

Another study was done by Jauhari V.P to find out the mechanism of RIS. He wrote the following about RIS in a paper prepared for the world commission on Dams. "The most widely accepted explanation of how dams cause earthquakes is related to the extra Water pressure created in the micro-cracks and fissures [5] in the ground under and near a reservoir. When the pressure of water in the rocks increases it acts to lubricate faults which are already under tectonic strain but are prevented from slipping by the friction of the rock surfaces."

METHODOLOGY ADOPTED

1. Use of statistical probability and bays conditional probability theory to find the probability of a particular intensity of earthquake at a reservoir site.
2. Development of risk factor using probability and energy of earthquake.
3. Classification of a reservoir site with reference to low, moderate and high risk.
4. To propose the seismic design changes for normal occupancy structures and important structures at a reservoir site.

FACTORS AFFECTING RESERVOIR INDUCED SEISMICITY

Using study conducted in the past it can be deduced that not all reservoirs are capable of triggering seismicity in an area instead there are certain geological, tectonic, and reservoir characteristics [3] whose mutual interaction results in enhanced seismic response of the reservoir site. There are seven factors considered in this study:

1. Depth of reservoir water
2. Geological condition in the reservoir area.
3. Tectonic stress environment
4. Fault activity
5. Karst development degree
6. Communication relationship with reservoir water.
7. Earthquake activity background.

Table 1: Influencing factors for reservoir induced seismicity

Influencing factors	**1**	**2**	**3**
Depth of reservoir water(D)	Less than 100m	100-150m	Greater than 150m
Geological condition in the 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
Communication relationship with reservoir water	Contact directly	Contact indirectly but with communication	No communication
Earthquake activity background	Strong	medium	Weak

STATISTICAL ANALYSIS OF RESERVOIR DATA

This part includes the reservoir characteristics of ninety reservoirs from all over the world which have experienced the phenomena of reservoir induced seismicity in the past.

Table 1: Factors affecting reservoir induced seismicity

Reservoir/ Dam	Height	Magnitude	Site Coordinate	Reservoir/ Dam	Height	Magnitude	Site Coordinate
Hsinfengkiang	105	6.10	$D_2G_1S_3F_1K_3C_1E_2$	Dhamni	59	3.80	$D_3G_2S_2F_1K_3C_2E_3$
Kariba	128	6.20	$D_2G_1S_3F_1K_3C_1E_1$	Donjiang	157	3.20	$D_1G_1S_3F_1K_3C_3E_3$
Koyna	103	6.30	$D_2G_1S_3F_1K_3C_1E_2$	Emborcacao	158	3.01	$D_1G_1S_3F_1K_3C_2E_2$
Kremasta	160	6.20	$D_2G_3S_2F_2K_1C_2E_1$	Emmosson	180	3.00	$D_1G_3S_3F_1K_1C_2E_3$
Aswan	111	5.60	$D_2G_3S_3F_1K_1C_1E_1$	Fierza	167	3.00	$D_1G_2S_3F_1K_2C_1E_2$
Benmore	110	5.00	$D_2G_2S_3F_1K_2C_3E_2$	Gandipe	36	3.50	$D_3G_3S_3F_2K_1C_1E_3$
Charvak	148	5.30	$D_2G_3S_1F_2K_1C_2E_2$	Grancarevo	123	3.00	$D_2G_2S_3F_1K_2C_1E_2$
Eucumbene	116	5.00	$D_2G_2S_2F_1K_1C_1E_2$	HendrikVerwo	66	3.00	$D_3G_3S_3F_2K_1C_2E_3$
Geheyan	151	4.00	$D_1G_3S_1F_1K_2C_1E_3$	Huangshi	40	3.00	$D_3G_1S_1F_2K_3C_3E_1$
Hoover	221	5.00	$D_1G_1S_3F_1K_3C_1E_2$	Hunanzhen	129	3.00	$D_2G_1S_3F_1K_3C_1E_3$
Marathon	67	5.70	$D_3G_1S_1F_2K_2C_3E_3$	Idukki	169	3.50	$D_1G_1S_2F_1K_3C_3E_2$
Oroville	236	5.70	$D_1G_2S_2F_1K_2C_1E_1$	Itezhitezhi	65	3.80	$D_3G_1S_3F_2K_3C_3E_3$
Srinagarind	140	5.90	$D_2G_3S_3F_1K_1C_1E_2$	Jocasse	107	3.20	$D_2G_1S_3F_1K_3C_2E_3$
Warna	80	5.00	$D_3G_1S_3F_1K_1C_1E_1$	Kamafusa	47	3.00	$D_3G_2S_3F_1K_2C_2E_2$
Aksombo Main	136	5.00	$D_2G_1S_3F_2K_3C_3E_3$	Katse	185	3.10	$D_1G_3S_1F_2K_1C_1E_1$
BajinaBasta	90	4.5-5	$D_3G_2S_3F_1K_2C_2E_2$	Keban	212	3.50	$D_1G_2S_2F_1K_2C_2E_2$
Bhatsa	88	4.90	$D_3G_1S_2F_1K_1C_1E_3$	Kouris	124	3.00	$D_2G_2S_3F_1K_2C_3E_2$
Brastk	100	4.20	$D_2G_1S_2F_1K_3C_2E_1$	Kurupsai	100	3.00	$D_2G_1S_3F_1K_3C_2E_2$
Camarillas	49	4.10	$D_3G_3S_1F_2K_1C_3E_3$	Lake Gordon	140	3.00	$D_2G_1S_3F_1K_3C_2E_3$
Canelles	150	4.70	$D_1G_2S_2F_2K_2C_1E_3$	LG 3	80	3.70	$D_3G_3S_3F_2K_1C_1E_2$
CapivariCachore	58	6.00	$D_3G_2S_3F_1K_2C_2E_2$	Lubuge	103	3.40	$D_2G_1S_1F_3K_2C_2E_2$
Clark Hill	60	4.30	$D_3G_2S_1F_1K_1C_1E_2$	Makio	105	3.00	$D_2G_1S_1F_1K_3C_3E_1$
Dahua	74.5	4.50	$D_3G_2S_3F_2K_3C_3E_3$	Monticello	129	3.00	$D_2G_1S_1F_1K_3C_3E_1$
Danjiangkou	97	4.70	$D_3G_3S_3F_2K_2C_1E_3$	Mula	56	3.00	$D_3G_3S_2F_2K_1C_1E_3$
Foziling	74	4.50	$D_3G_3S_3F_2K_1C_2E_3$	Nagawado	155	3.00	$D_2G_1S_3F_1K_3C_1E_3$
Grandval	88	5.00	$D_1G_2S_1F_2K_3C_3E_3$	Nanchong	45	3.00	$D_3G_2S_1F_1K_2C_2E_2$
HoaBinh	125	4.90	$D_2G_3S_3F_1K_1C_2E_2$	Nanshui	81	3.00	$D_3G_1S_2F_2K_3C_3E_2$
Kastraki	96	4.60	$D_3G_2S_2F_1K_2C_1E_1$	Novo Ponte	48	3.70	$D_3G_1S_3F_2K_3C_3E_3$
Kerr	60	4.90	$D_1G_1S_3F_1K_2C_2E_2$	OuedFodda	101	3.00	$D_2G_2S_3F_1K_2C_2E_3$
Komani	130	4.20	$D_2G_1S_3F_2K_3C_1E_2$	Paraibuna	94/105	3.00	$D_2G_1S_3F_1K_3C_1E_3$

Kurobe	186	4.90	$D_1G_3S_3F_1K_1C_1E_2$	Qianjin	50	3.00	$D_3G_1S_3F_2K_3C_2E_3$
Lake Baikal	160	4.0-4.8	$D_1G_2S_2F_1K_2C_1E_2$	Ridracoli	103	3.50	$D_2G_1S_3F_1K_3C_1E_2$
Lake Pukaki	106	4.60	$D_2G_1S_2F_1K_3C_1E_3$	Salanfe	165	2.50	$D_1G_3S_2F_1K_1C_1E_2$
Manicouagan 3	108	4.10	$D_2G_2S_1F_1K_2C_2E_3$	Schlegeis	117	2.00	$D_2G_1S_3F_1K_3C_3E_2$
Marimbondo	94	4.00	$D_3G_3S_1F_2K_3C_1E_2$	Shasta	183	3.00	$D_1G_3S_3F_2K_1C_1E_2$
Monteynard	155	4.90	$D_1G_3S_2F_1K_1C_1E_1$	Shengjiaxia	35	3.60	$D_3G_1S_3F_1K_3C_3E_2$
Nurek	317	4.60	$D_1G_3S_3F_1K_1C_1E_2$	Shuikou	101	3.20	$D_2G_3S_2F_1K_1C_2E_2$
P. Colombia	40/56	4.20	$D_3G_2S_2F_1K_3C_2E_3$	Sobradinho	43	3.00	$D_3G_1S_3F_1K_3C_2E_1$
Piastra	93	4.40	$D_3G_2S_1F_2K_1C_1E_2$	Sriramsagar	43	3.20	$D_3G_2S_3F_2K_2C_3E_2$
Pieve de Cadore	116	5.00	$D_2G_2S_2F_1K_2C_1E_3$	Talbingo	162	3.50	$D_1G_1S_1F_2K_3C_1E_3$
Shenwo	50	4.80	$D_3G_3S_3F_2K_2C_1E_2$	Thomson	153	3.00	$D_1G_2S_2F_1K_3C_2E_3$
Vouglans	130	4.40	$D_2G_2S_2F_1K_2C_2E_3$	Toktogul	215	3.00	$D_1G_3S_3F_1K_3C_2E_3$
Acu	31	3.00	$D_3G_1S_3F_1K_1C_2E_2$	Tongjiezi	74	3.00	$D_3G_2S_2F_2K_1C_1E_3$
Blowering	112	3.50	$D_2G_1S_3F_1K_3C_2E_2$	Tucurui	100	3.40	$D_2G_1S_1F_2K_3C_1E_2$
Capivara	59	3.70	$D_3G_1S_3F_2K_3C_1E_2$	Vajont	262	3.00	$D_1G_1S_3F_1K_3C_1E_2$
Carmo doCajuru	22	3.70	$D_3G_3S_2F_2K_1C_1E_3$	Zhelin	62	3.20	$D_3G_2S_3F_1K_2C_1E_3$
Contra	220	3.00	$D_1G_1S_1F_2K_1C_1E_2$	Wujiangdu	165	3.00	$D_1G_3S_3F_1K_1C_1E_2$
				Yantan	110	3.50	$D_2G_3S_3F_1K_1C_2E_2$

Table 2: Probability of a particular intensity of earthquake

Earthquake category	**Probability of occurrence**
Strong (M_6)	0.04
Moderate strong (M_5)	0.11
Moderate (M_4)	0.29
Small (M_3)	0.55

Table 3: Conditional probability for M>6

Site condition	**1**	**2**	**3**
Depth of reservoir water(D)	0.25	0.75	0.0
Geological condition in the reservoir area (G)	0.75	0.0	0.25
Tectonic stress environment(S)	0.0	0.25	0.75
Fault activity (F)	0.75	0.25	0.0
Karst development degree(K)	0.25	0.0	0.75

Communication relationship with reservoir water	0.75	0.25	0.0
Earthquake activity background	0.5	0.5	0.0
Depth of reservoir water(D)	0.3	0.5	0.2
Geological condition in the reservoir area.(G)	0.3	0.3	0.4
Tectonic stress environment(S)	0.2	0..2	0.6
Fault activity(F)	0.8	0.2	0.0
Karst development degree(K)	0.4	0.4	0.2
Communication relationship with reservoir water	0.7	0.1	0.2
Earthquake activity background	0.3	0.5	0.2

Table 4: Conditional probability for 4<M<5

Site condition	1	2	3
Depth of reservoir water(D)	0.32	0.28	0.39
Geological condition in the reservoir area.(G)	0.21	0.46	0.32
Tectonic stress environment(S)	0.18	0.36	0.46
Fault activity(F)	0.71	0.28	0.0
Karst development degree(K)	0.28	0.43	0.28

Table 5: Conditional probability for 3<M<4

Site condition	**1**	**2**	**3**
Depth of reservoir water(D)	0.35	0.29	0.36
Geological condition in the reservoir area.(G)	0.52	0.19	0.29
Tectonic stress environment(S)	0.63	0.19	0.17
Fault activity(F)	0.57	0.42	
Karst development degree(K)	0.31	0.23	0.46
Communication relationship with reservoir water	0.36	0.41	0.21
Earthquake activity Background	0.06	0.52	0.42

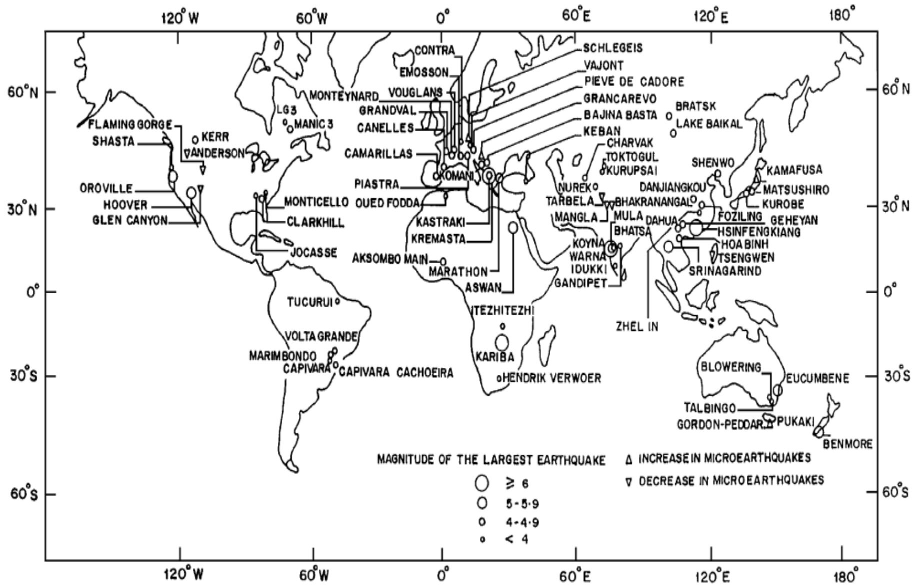

Fig. 1. Worldwide distribution of reservoir-triggered changes in the seismicity. The figure is updated from Gupta (1992) to include all sites where triggered earthquakes of $M>4$ occurred. Sites where RTS events of $M<4$ occurred are too numerous and not updated. For details, please see Table 1.

Figure 1: seismicity induced sites in the world

APPLICATION OF THE ANALYSIS TO A RESERVOIR WITH ASSUMED GEOLOGICAL, TECTONIC, AND RESERVOIR CHARACTERISTICS

According to bayes conditional probability theory [4] the statistical model for predicting reservoir seismicity is:

$$P(Mi/Di,Gi,Si,Fi,Ki,Ci,Ei)=[P(Mi)P(Di,Gi,Si,Fi,Ki,Ci,Ei/Mi)]\div[\sum P(Mi)P(Di,Gi,Si,Fi,Ki,Ci,Ei/Mi)] \quad (1.1)$$

Where,

$P(Di,Gi,Si,Fi,Ki,Ci,Ei/Mi)=P(Di/Mi)P(Gi/Mi)P(Si/Mi)P(Fi/Mi)P(Ki/Mi)P(Ci/Mi)P(Ei/Mi)$ $P(Mi/Di,Gi,Si,Fi,Ki,Ci,Ei)$is the probability of an earthquake of magnitude of intensity Mi under given condition of depth of reservoir ,geological condition in the reservoir area ,tectonic stress environment,faultactivity,Karst development degree, communication relationship with reservoir waterand activity background.

- P (Mi) is the probability of earthquake of magnitude Mi.
- P (Di,Gi,Si,Fi,Ki,Ci,Ei/Mi) is the probability of given conditions of depth of reservoir, geological condition in the reservoir area ,tectonic stress environment, fault activity,Karst development degree, communication relationship with reservoir water and activity background such that they have triggereda earthquake of magnitude M in the past.
- P(Di/Mi) is the probability that the depth of reservoir is Di such that it triggered an earthquake of magnitude Mi
- P(Gi/Mi) is the probability that the geological condition at the reservoir site is Gisuch that it triggered an earthquake of magnitude Mi
- P(Si/Mi) is the probability that the tectonic stress environment is Si such that it triggered an earthquake of magnitude Mi
- P(Fi/Mi) is the probability that the fault activity is Fi such that it triggered an earthquake of magnitude Mi
- P(Ki/Mi) is the probability that the Karst development degree is Ki such that it triggered an earthquake of magnitude Mi
- P(Ci/Mi) is the probability that the communication relationship with reservoir Cisuch that it triggered an earthquake of magnitude Mi
- P (Ei/Mi) is the probability that the earthquake activity background is E is such that it triggered an earthquake of magnitude Mi.

Table 6: Site condition

Depth of reservoir water(D)	250m
Geological condition in the reservoir area.(G)	Stratified rock mass
Tectonic stress environment(S)	Reverse fault
Fault activity(F)	Active
Karst development degree(K)	weak
Communication relationship with reservoir water	Contact indirectly but with communication.
Earthquake activity background	Strong

Now the conditional probability of occurrence of reservoir induced earthquakes of different categories are as follows-
Strong- 0
Moderate strong- 0.0798
Moderate – 0.633
Small - 0.287

FORMULATION OF RISK FACTOR AND RIS CLASSIFICATION
Risk factor is the classification factor which is determined by combining the probability of earthquake at the reservoir site and the energy of a particular magnitude of earthquake.

Risk factor = $P_1E_1+P_2E_2+P_3E_3+P_4E_4$ 1.3

The range of risk factor comes out to be 2-180

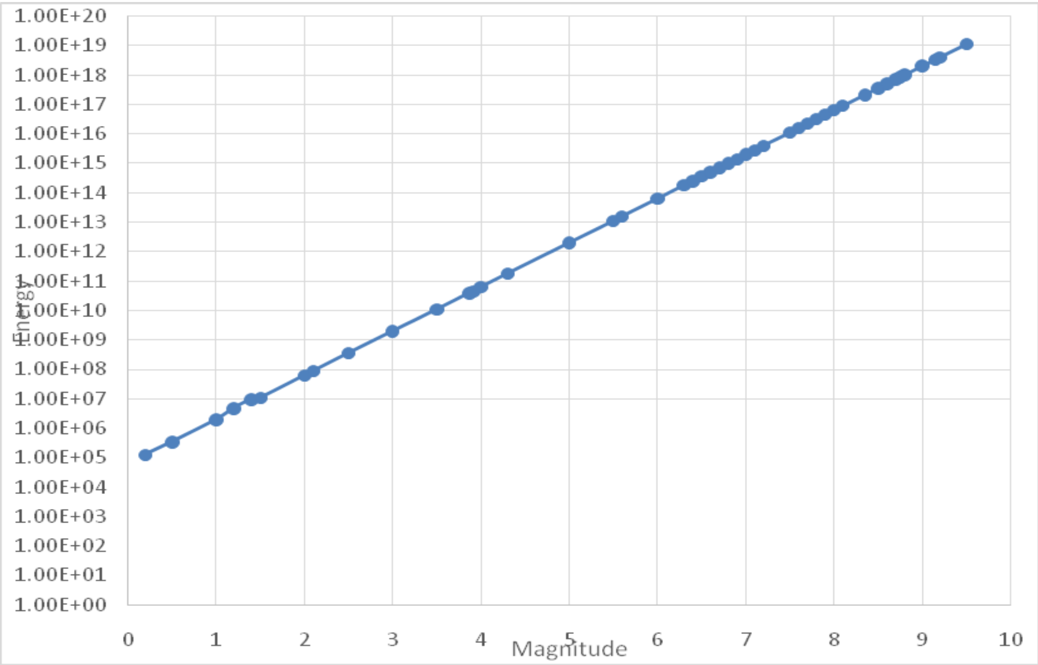

Figure 3: Energy Vs. Magnitude

International Journal of Technical Innovation in Modern Engineering & Science (IJTIMES)
Volume 4, Issue 03, March-2018, e-ISSN: 2455-2585, Impact Factor: 3.45 (SJIF-2015)

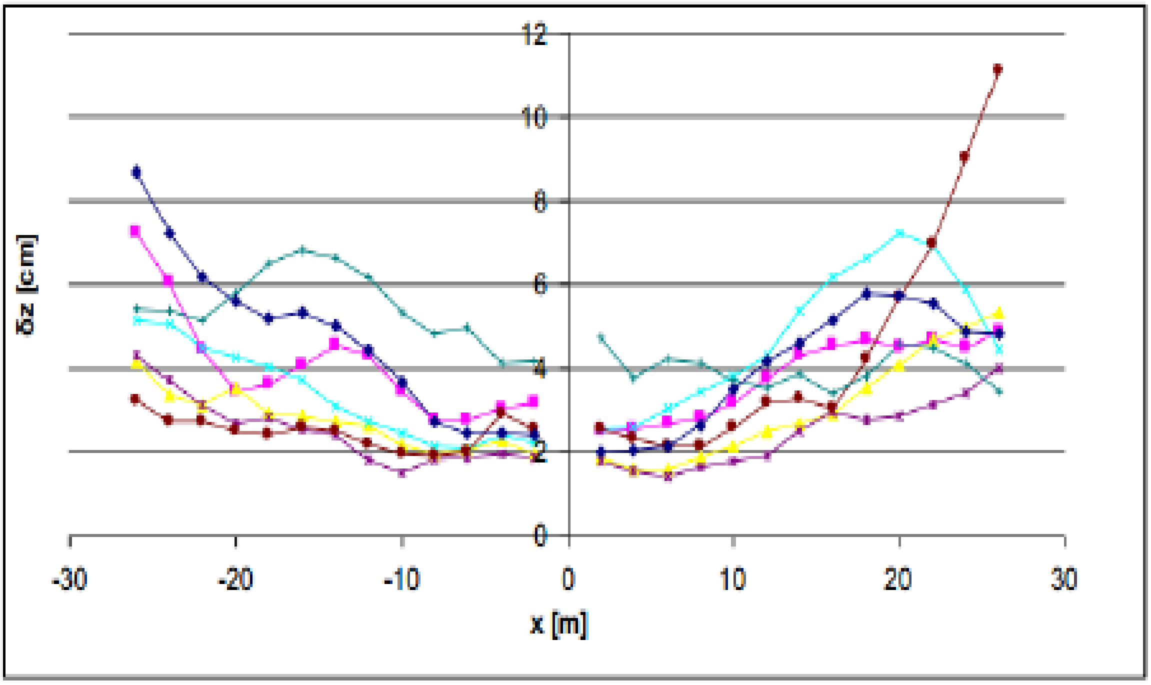

Figure 2: Standard deviation root-mean squared with mean difference from DTM as a function of cross track distance, mean depth equal to 8.5m.

Table 7: Classification of a site depending upon the value of risk factor

Reservoir site classification	Risk factor
Low	<2
Moderate	2-63
High	63-180

MODIFIED SEISMIC DESIGN AT THE RESERVOIR SITE

In order to find out the design seismic forces at a reservoir site the horizontal acceleration coefficient A_h is required to be modified and to fulfil this purpose three additional parameters along with conventional parameters are required to be incorporated in the design.

1. Z+1 Factor

This factor is included in the design of every structure where it is located in the region of high, medium and low reservoir. Thus it is the minimum safety factor we are providing in a building subjected to seismic loading for the earthquake induced by reservoir impoundment.

2. RIS Factor (F_R)

This factor has been introduced in the design to quantify the extent of reservoir induced seismicity risk as it is the only factor which will take into account the low, moderate , high reservoir induced seismicity risk categories. RIS Factor has been given a value 1-2 in case of normal occupancy structure and value of 1.5-3 in case of important structures. These value are not based on any rational analysis but on earthquake design philosophies where we are reducing the risk by different magnitudes so as to increase the factor of safety.

3. Proximity Factor (F_P)

The factor used in the design is a reduction factor because of the fault that the effect of RIS is in contradistinction to a tectonic earthquake. So we can't design each and every structure located in particular earthquake zone by this prior analysis .Thus this factor is introduced to limit the boundary within which this particular design is to be followed. Since the extent of this boundary will vary from place to place depending upon tectonic and reservoir conditions. Hence for every site this detailed analysis is to be done and using this particular boundary is to be defined:

Development of proximity factor:

Within RIS boundary : 1
Without RIS boundary : $0.5F_R$

CONCLUSIONS

The analysis based upon rational data and engineering judgement provides a method to ensure the safety of hydraulic structure as well as building in its vicinity by giving simple approach to be followed whenever a dam site is chosen. When it comes to design of dam or structure in the vicinity of dam. RIS never got the importance. It should have been given considering the fact; it is already too difficult to find a suitable site for dam. Since it is quite imperative that nobody is going to change the site because of this phenomenon. But we hope that we will prove beneficial not only in finding the severity of reservoir site for inducing earthquake activities but also in providing a solution by modifying design keeping in view that in any case the collapse of the structure is to be prevented. Even though this particular work might not be significant during present time where not much attention is given to its effects. But this ignorance can't be justified in coming years where huge numbers of dams are being built with outmost fervour risking life of so many numbers of people. This work will see the light of day when there is considerable awareness among the engineering community about the devastating effects of RIS.

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