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Dynamic Analysis of Hirakud Dam Due to Seismic Forces

Gaurva Verma[*], Dr.M.K.Verma[**], Dr.R.K.Tripathi[***]

[*] Research Scholar, Deptt.of Civil Engg., NIT, Raipur, (C.G.) 492010, India.
[**] Professor, Deptt.of Civil Engg., NIT, Raipur, (C.G.) 492010, India.
[***] Associated Professor, Deptt.of Civil Engg., NIT, Raipur, (C.G.) 492010, India.

Abstract- The present study investigates and analyses the behavior of a concrete gravity dam during the strong ground horizontal motions due to an earthquake with CADAM. The model in thesis is the structure of Hirakud gravity dam. Hirakud dam across river Mahanadi in eastern India is a composite structure of earth, concrete and masonry. Length of the main dam is 4.80 Km, flanked by 21 km earthen dykes on left and right sides, making a total length of 25.8km. Two concrete spillways of average height 45.75 m and maximum height 60.96 m are located in the two arms of the river. Hirakud dam has been built at Latitude 21^0-32' N and Longitude 83^0-52'E across river Mahanadi at about 15 km upstream of Sambalpur town. This is the first post independence major multipurpose river valley project in India. It hasn't ever shakes under the influence of powerful ground motions in the area. Because of lowness and special firmness of the structure it behaves like a solid body, therefore the structure should be compared with many different earthquake accelerations and then the maximum vibration of the body is considerable. After linear dynamic analysis with CADAM the results show the stresses on the body of the dam are relative to particularity of each earthquake like magnitude, epicenter distance and PGA .The body of dam is modeled two dimensional in CADAM. The procedure of analyses is linear response spectra analysis. The acceleration records of ground motions in the CADAM dynamic response spectra analysis are real records of occurred earthquakes. The other data which are used in CADAM modeling are approximately unreal and exaggerated and they are used for magnifying the influence of earthquake on the dam's body.

Index Terms- Dynamic Analysis, Concrete Dam, Seismic Forces Simulating

I. Introduction

Historically Odisha has experienced very few moderate to large earthquakes. Some events with magnitudes in excess of 5.0 have originated in the Bay of Bengal off the coast of the state. Several faults have been identified in the region and some have shown evidence of movement during the Holocene epoch. The Brahmani Fault in the vicinity of Bonaigarh is among then. The Mahanadi also flows through a graben structure. Several deep-seated faults are situated beneath the Mahanadi Delta. However, it must be stated that proximity to faults does not necessarily translate into a higher hazard as compared to areas located further away, as damage from earthquakes depends on numerous factors such as subsurface geology as well as adherence to the building codes.

Recognizing an earthquake behavior is of high importance. Previous earth quake experiences has shed light on the fact that in order to decrease the damages caused by earthquakes is only possible through in depth studies of previous earth quakes and also taking into consideration quake behavior of important structures. Concrete dames are of great importance because any damage can cause irreparable financial and causalities. Dynamic analysis of the concrete weight dams against external and internal forces has been the center of attention for Scientists and experts.

Present study is focused on dynamic analysis of concrete dam against difference forces caused by recent earthquakes. HassanMirza-Bozorg and MehdiVarmarziar in 2009 did a study in which they studied the effect of earthquake on the linear response of the concrete dam. The purpose of this study was to study the effect of non-uniform instigation tremulous on tremulous response of concrete dam and to compare it to uniform instigation which is common in analyzing and designing dams using the ABAQUES software. Chopra in 1991 studied the effect of earthquake on a weight dam conditional of the fact that there is a shaking floor under the dam. In this study the effect of earthquake on a rigid dam and a flexible dam was studied and several graphs were shown. Several problems that are a result of static analysis method are addressed. Various drawbacks include not considering: the structural elasticity, damping forces, variation of the foundation acceleration over time, and the alternation and short duration characteristics of the seismic loading. In Response Spectra analysis method the history of the structures behavior under the accelogram of the earthquake was studied and the forces, stresses and movements were calculated. In this study CADAM was used which is considered to be powerful software of this kind. For the purpose of response spectra records of real earthquakes such as earthquake on 12 June 2001 - Konokjora-Sundargarh area, Odisha, Mw 4.7, is used.

HISTORY: Dynamic analysis of concrete dam is more complicated compared to other buildings under the same conditions. ICOLD recommendations are followed while evaluating the seismic parameters (ICOLD, 1989), therefore an Operating Basis Earthquake (OBE) and a Maximum Credible Earthquake (MCE) are considered. The seismic input is defined in terms of maximum horizontal accelerations and unified response spectra. Artificial acceleration time histories which are compatible with the response spectra are also provided and can be employed especially for non-linear analyses. McGuire´s relationship between magnitude, distance and ground

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acceleration is used when evaluating the maximum horizontal acceleration which is based on the earthquake-catalogue (Lenhardt, 1995). For the OBE, a return period of 200 years is selected with a minimum value of 0.6 m/s2. For the MCE, not only the results of extreme-value statistics are considered, but also the global geology and long-term tectonic processes are taken into account. The resulting ground accelerations could be considered as approximate values only and, in general, more detailed studies including the local geological situation are necessary for a specific site. The maximum acceleration of the vertical excitation is defined as 2/3 of the respective maximum horizontal acceleration.

A pseudo-dynamic seismic analysis is based on the response spectra method. It is conceptually similar to a pseudo-static analysis except that it recognizes the dynamic amplification of the inertia forces along the height of the dam. However, the oscillatory nature of the amplified inertia forces is not considered. That is the stress and stability analyses are performed with the inertia forces continuously applied in the same direction. Since the pseudo-dynamic method does not recognize the oscillatory nature of earthquake loads it is also appropriate to perform the safety evaluation in two phases: (a)the stress analysis using peak spectral acceleration values, and (b) the stability analysis using sustained spectral acceleration values. It is assumed in these analyses that the dynamic amplification applies only to the horizontal rock acceleration. The period of vibration of the dam in the vertical direction is considered sufficiently small to neglect the amplification of vertical ground motions along the height of the dam.

THE EQUATIONS GOVERNING THE LINEAL DYNAMIC ANALYSIS OF STRUCTURES

For three-dimensional seismic motion, the typical modal Equation is written as:

$$\ddot{y}(t)_n + 2\zeta_n\omega_n\dot{y}(t)_n + \omega_n^2\, y(t)_n = p_{nx}\, \ddot{u}(t)_{gx} + p_{ny}\, \ddot{u}(t)_{gy} + p_{nz}\, \ddot{u}(t)_{gz}$$

where the three Mode Participation Factors are defined by

$$\boldsymbol{p}_{ni} = -\emptyset_n^T M_i$$

in which i is equal to x, y or z. Two major problems must be solved to obtain an approximate response spectrum solution to this equation. First, for each direction of ground motion, maximum peak forces and displacements must be estimated. Second, after the response for the three orthogonal directions has been solved, it is necessary to estimate the maximum response from the three components of earthquake motion acting at the same time. This section addresses the modal combination problem from one component of motion only.

For input in one direction only, Equation (15.1) is written as:

$$\ddot{y}(t)_n + 2\zeta\omega_n\dot{y}(t)_n + \omega_n^2\, y(t)_n = p_{ni}\, \ddot{u}(t)_g$$

Given a specified ground motion $\ddot{u}(t)_g$, damping value and assuming Pni = -1.0, it is possible to solve the Equation at various values of ω and plot a curve of the maximum peak response $(\omega)_{MAX}$. For this acceleration input, the curve is by definition the displacement response spectrum for the earthquake motion. A different curve will exist for each different value of damping.

A plot of $\omega y(\omega)_{MAX}$ is defined as the pseudo-velocity spectrum and a plot of $\omega^2 y(\omega)_{MAX}$ defined as the pseudo-acceleration spectrum.

The three curves- displacement response spectrum, pseudo-velocity spectrum, and pseudo-acceleration spectrum are normally plotted as one curve on special log paper. However, the pseudo-values have minimum physical significance and are not an essential part of a response spectrum analysis. The true values for maximum velocity and acceleration are calculated from the solution of Equation (15.2). There is a mathematical relationship, however, between the pseudo-acceleration spectrum and the total acceleration spectrum. The total acceleration of the unit mass, single degree-of-freedom system, governed by Equation (15.2), is given by:

$$\ddot{u}(t) = \ddot{y}(t) + \ddot{u}(t)_g$$

Equation (15.2) can be solved for $\ddot{y}(t)$ and substituted into Equation (15.3) to yield:

$$\ddot{u}(t)T = -\omega^2(t) - 2\,\xi\omega\dot{y}(t)$$

Therefore, for the special case of zero damping, the total acceleration of the system is equal to $\omega^2 y(t)$. For this reason, the ***displacement response spectrum*** curve is normally not plotted as modal displacement $y(\omega)MAX$ versus ω. It is standard to present the curve in terms of $S(\omega)$ versus a period T in seconds,

where:

$$S(\omega)a = -(\omega)^2 y(\omega)MAX$$

and

$$T = \frac{2\pi}{\omega}$$

The pseudo-acceleration spectrum curve, $S(\omega)a$, has the units of acceleration versus period that has some physical significance for zero damping only. It is apparent that all response spectrum curves represent the properties of the earthquake at a specific site and are not a function of the properties of the structural system. After an estimation is made of the linear viscous damping properties of the structure, a specific response spectrum curve is selected.

MODELING THE DAMS SYSTEM AND FOUNDATION: The Hirakud Dam is a composite structure of earth, concrete and masonry. Ten km north of Sambalpur, it is the longest major earthen dam in the world, measuring 24 km including dykes, and stands across the river Mahanadi. The main dam has an overall length of 4.8 km spanning between two hills; the Lamdungri on the left and the Chandili Dunguri on the right. The dam is flanked by 21 km earthen dykes on both the left and right sides, closing the low saddles beyond the adjoining hills. The dam and dykes together measure 25.8 km. It also forms the biggest artificial lake in Asia, with a reservoir holding 743 km² at full capacity, with a shoreline of over 640 km.

The building of the dam in spite of its great height and its hardness shows a strong behavior under horizontal movements, because of this in the below study the modeling was done under the acceleration of several earthquakes so that we can study the maximum vibration.

The study area lies between 17° to 24°N, 78°o 88°E and a simplified geology map (Sarkar, 2001) with main tectonic elements (GSI, 2000) is shown in Fig. 1. The Bastar craton [BB] is separated from the Dharwar [DB] and Singhbhum cratons [SB] by the Godavari [GG] and Mahanadi [MG] Gondwana grabens respectively; with the Eastern Ghat Mobile belts [EGMB] lying to the south east. From detailed geological, petrological and structural studies the Central Indian shear (CIS, Yedekar *et al.*, 1990) has been identified, which separates the Bastar block from the northern (Bundelkhand) block. The western side of this shear is buried under alluvium and traps while to the east it forks into two parts with the northern part coming close to the Tan shear. From geological and geochronological data the other arm is conjectured to extend eastwards below the Gondwana sediments and merge with the Singhbhum shear [8] (Yedekar *et al.*, 1990). The Tan shear [3] is believed to extend below the cover (Yedekar *et al.*, 1990) and possibly joins the Barabhum shear [7] within the Singhbhum block [SB]. Due to the extensive surface cover of the Mahanadi Graben [MG] by the Gondwana sediments, the subsurface extension of these structures needs to be verified. The north-western part of the study region and the northern part of the Godavari Graben are covered by Deccan flood basalts. The Bastar craton consists of two Proterozoic basins (Chattisgarh [C] and Indravati [I]). The Central Indian Tectonic zone (CITZ) (Yedekar *et al.*, 1990) lying to the north of the CIS is marked by several sub-parallel ENE trending faults: Narmada North and South [11 and 12], Tapti fault [1], Gavilgarh fault [2], Tan shear [3], Bamni-Chilpa fault [5] and Tatapani fault [6]. The Tatapani area has several thermal springs that are responsible for the high heat flow in Central India (Ravi Shankar, 1991). The Singhbhum Block [SB] to the east is separated from the rest of the Indian Peninsular Shield by the Mahanadi Graben [MG] occurring to its west and the Sukinda thrust (Mahadevan, 2001) to the south. Tectonically, this block includes the Singhbhum granite (which includes banded iron formation) to the south, and the Proterozoic Singhbhum mobile belt in the middle separated from the Chotanagpur Granite Gneiss terrain in the north by the Barabhum shear [7]. The Eastern Ghat Mobile Belt (EGMB) is a high-grade NE-SW metamorphic belt to the south of the Singhbhum block. The EGMB is separated from the adjoining blocks by a major shear/thrust called Sileru shear zone

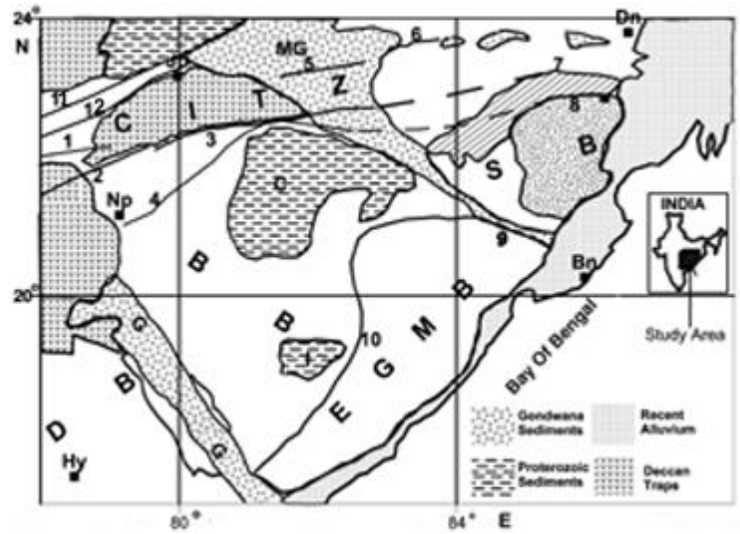

Fig. 1. Simplified geology and tectonic map of the study area redrawn from Sarkar (2001) and GSI (2000). DB-Dharwar block, BB-Bastar block, SB-Singhbhum block, CITZ-Central Indian Tectonic zone,EGMB-Eastern Ghat Mobile Belt, GG-Godavari graben, MG-Mahanadi graben, I-Indravati basin, C-Chattisgarh basin, 1-Tapti fault, 2-Gavilgarh fault, 3-Tan shear, 4-Central Indian shear, 5-Bamni-Chilpa fault,6-Tatapani fault, 7-Barabhum shear, 8-Singhbhum shear, 9-Sukinda thrust, 10-Sileru shear, 11-North Narmada fault, 12-South Narmada fault. Hy-Hyderabad, Bn-Bhubhaneswar, Dn-Dhanbad, Jb-Jabalpur, Np-Nagpur

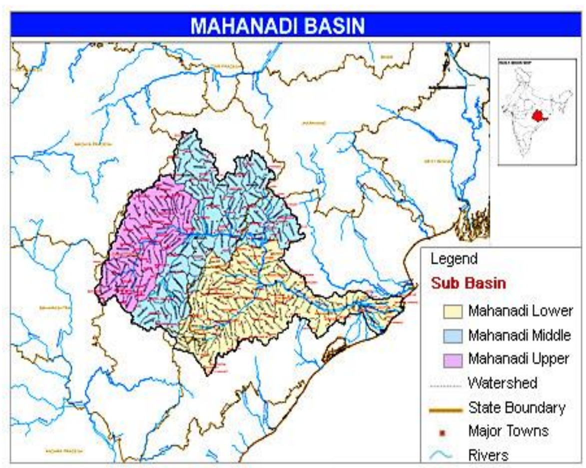

Fig 2: Figure showing the Mahanadi Basin

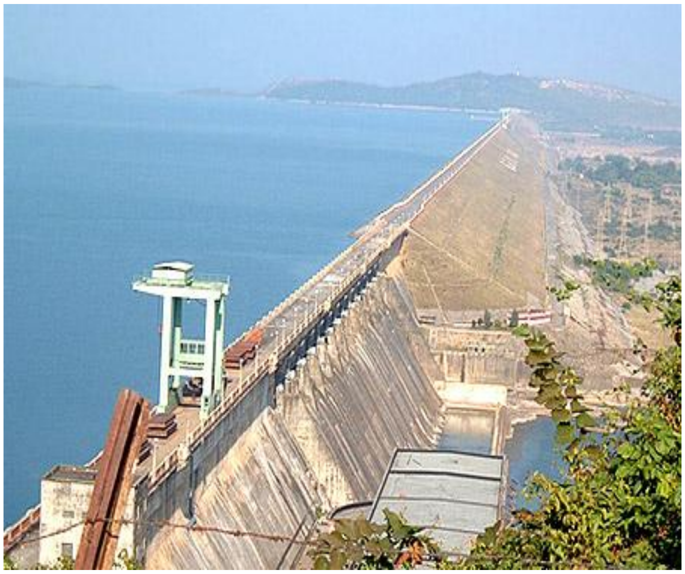

Fig. 3: A view of the dam

Since the pseudo-dynamic method does not recognize the oscillatory nature of earthquake loads it is also appropriate to perform the safety evaluation in two phases: (a) the stress analysis using peak spectral acceleration values, and (b) the stability analysis using sustained spectral acceleration values. It is assumed in these analyses that the dynamic amplification applies only to the horizontal rock acceleration. The period of vibration of the dam in the vertical direction is considered sufficiently small to neglect the amplification of vertical ground motions along the height of the dam.

To ensure the accuracy of the pseudo-dynamic method, the structure is divided in thin layers to perform numerical integrations. Number of divisions up to 301 can be specified. The weight of the concrete is 2630Kg/m^3.The Poisson's coefficient was 0.2. The dynamic flexibility of the structure is modeled with the dynamic concrete Young's modulus (Es) 27400MPa. The dam damping on rigid foundation without reservoir interaction is considered to be 0.05. Any change to these basic parameters affects the fundamental period of vibration and the damping of the dam-foundation-reservoir system. Thus the spectral accelerations are evaluated. The wave reflection coefficient (α) is the ratio of the amplitude of the reflected hydrodynamic pressure wave to the amplitude of a vertical propagating pressure wave incident on the reservoir bottom. A value of $\alpha = 1$ indicates that pressure waves are completely reflected, and smaller values of α indicate increasingly absorptive materials .The value of α is considered to be 0.5. The velocity of pressure waves in water is in fact the speed of sound in water. Generally it is assumed at 1440 m/sec (4720 ft/sec).

Because the maximum response in the natural vibration mode and in higher modes doesn't occur at the same time, a modal combination has to be considered. Four options are offered to the user: (i) Only the first mode; (ii) Only the static correction computed for higher modes; (iii) SRSS (square-root-of-the-sum-of-squares of the first mode and static correction for higher modes); or the (iv) Sum of absolute values which provides always conservative results.

The SRSS combination is considered for the study.

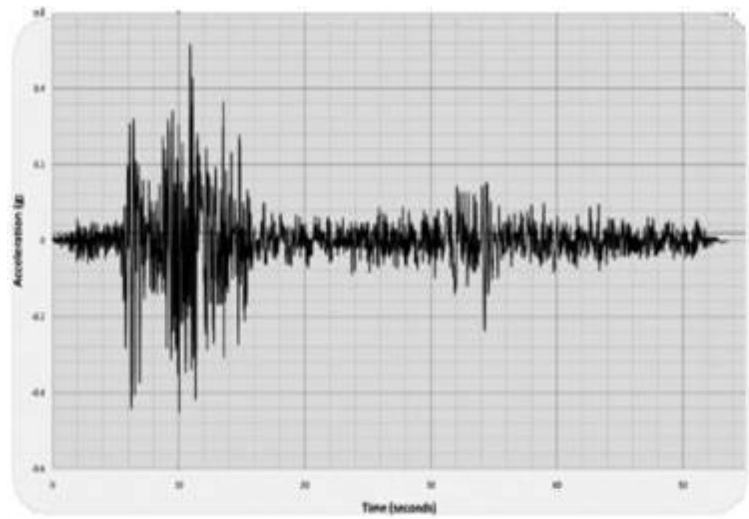

Fig 4: Accelograph for
12 June 2001 - Konokjora-Sundargarh area, Odisha, Mw 4.7 earthquake

II. Analysis and Results

Dynamic Analysis of the dam section has been performed using CADAM with the parameters of the dam as input. The dam section has been checked for various load combinations .The result of stress and stability analysis for usual combination had been presented through Table 1 and Table 2 respectively whereas Table 3 and Table 4 depicts the results of stress and stability analysis for flood combination. It is evident from the results that the stress are within the permissible limits on all the joints and the Factor of safety for Overturning and Sliding is quite higher than the desired/safe values as per the code. The results of stress and stability analysis for peak acceleration values and sustained acceleration values for Seismic 1(OBE) has been presented through Table 5-8 It is observed that the dam section is safe for all seismic combinations and the dam is safe against stresses, sliding and overturning at all the joints considered.

The overall results can be summarized as follows. The dam section is found to be safe for the present PGA values of 0.16g and no further retrofitting measures are required for the section presently. The FOS for sliding and overturning are observed as 8.974 and 6.258 for usual combination where as required is 1.00. For flood combination the FOS is observed as 5.385 and 5.939 whereas required is greater than1. For seismic 1 combination FOS is 19.707 and 4.336 when required is 1.1 . The Static, Pseudo-Static and Pseudo Dynamic Loads with the position of application are summarized from Table 9 to Table 16.

TABLE 1: Usual combination (stress analysis)

joint		Stresses						
		Normal stresses		Allowable stresses		Shear		
ID	Upstream Elevation(m)	U/s (kPa)	D/s (kPa)	Tension	compression	u/s (kPa)	maximum (kPa)	D/s (kPa)
1	60.000	-23.544	-23.544	0.000	-9990.000			
2	50.000	-299.908	-170.263	0.000	-9990.000			
3	40.000	-565.245	-15.875	0.000	-9990.000	0.000	12.588	12.588
4	30.000	-653.789	-35.684	0.000	-9990.000	0.000	58.710	28.297
5	20.000	-696.683	-114.696	0.000	-9990.000	0.000	121.565	90.951
6	10.000	-717.814	-221.321	0.000	-9990.000	0.000	195.466	175.402
7	Base	-872.986	-342.992	0.000	-9990.000	0.000	280.541	271.984

TABLE 2: Usual combination (stability Analysis)

Joint		Safety Factors					Resultants				Uplift
ID	Upstream Elevation	Sliding Peak	Sliding residual	Overturning Toward u/s	Overturning Toward d/s	uplifting	Normal kN	Shear KN	Moment KN	Position % of joint	Final Force kN
1	60.000	> 100	> 100	> 100	> 100	> 100	-215.2	0.0	0.0	50.000	
2	50.000	> 100	> 100	> 100	> 100	> 100	-2381.7	0.0	-1108.9	45.404	
3	40.000	> 100	40.973	12.909	11.994	12.592	-5247.8	128.1	-14933.7	34.244	50.000
4	30.000	33.034	8.001	5.892	4.876	5.651	-8960.0	1119.9	-34795.1	35.059	45.404
5	20.000	16.566	4.450	4.760	3.403	4.294	-13761.2	3092.7	-55802.8	38.045	34.244
6	10.000	11.085	3.250	4.369	2.779	3.727	-19651.5	6046.5	-72464.9	41.189	35.059
7	Base	8.974	3.032	6.258	3.184	5.101	-30265.7	9981.2	-109446.0	42.736	38.045
Required		>1.00	>1.000	>1.000	>1.000	>1.000					

TABLE 3: Flood combination (stress analysis)

joint		Stresses						
		Normal stresses		Allowable stresses		Shear		
ID	Upstream Elevation(m)	U/s (kPa)	D/s (kPa)	Tension	compression	u/s (kPa)	maximum (kPa)	D/s (kPa)
1	60.000	-23.544	-23.544	0.000	-15000.00			
2	50.000	-191.114	-207.443	0.000	-15000.00	0.000	-22.397	164.497
3	40.000	-293.961	-167.575	0.000	-15000.00	0.000	132.883	132.883
4	30.000	-288.830	-281.060	0.000	-15000.00	0.000	222.874	222.874
5	20.000	-269.627	-422.169	0.000	-15000.00	0.000	334.770	334.770
6	10.000	-247.919	-571.632	0.000	-15000.00	0.000	453.290	453.290
7	Base	-411.487	-724.370	0.000	-15000.00	0.000	574.407	574.407

TABLE 4: Flood combination (stability Analysis)

Joint		Safety Factors					Resultants				Uplift
ID	Upstream Elevation	Sliding Peak	Sliding residual	Overturning toward u/s	Overturning toward d/s	uplifting	Normal kN	Shear KN	Moment KN	Position % of joint	Final Force kN
1	60.000	> 100	> 100	> 100	> 100	> 100	-215.2	0.0	0.0	50.000	
2	50.000	47.116	7.724	9.462	4.269	6.565	-2018.9	261.4	139.7	50.683	362.8
3	40.000	15.509	2.839	4.707	2.526	3.720	-4167.9	1468.0	-3435.6	45.436	1532.6
4	30.000	9.512	2.026	4.177	2.033	3.128	-7405.9	3655.6	-437.4	49.773	3480.3
5	20.000	7.083	1.719	4.044	1.819	2.891	-11733.0	6824.3	14626.2	53.675	6206.0
6	10.000	5.782	1.563	3.998	1.702	2.766	-17149.2	10973.9	47247.1	56.583	9709.5
7	Base	5.385	1.755	5.939	2.033	4.016	-28271.5	16104.5	64611.4	54.591	9374.0
Required		>1.0000	>1.000	>1.000	>1.000	>1.000					

TABLE 5: Seismic #1 combination-Peak accelerations (Stress Analysis)

joint		Stresses						
ID	Upstream Elevation (m)	Normal stresses U/s (kPa)	Normal stresses D/s (kPa)	Allowable stresses Tension	Allowable stresses compression	Shear u/s (kPa)	Shear maximum (kPa)	Shear D/s (kPa)
1	60.000	-28.061	-24.050	0.000	-27270.000	0.000	-9.068	0.000
2	50.000	-485.349	-34.973	0.000	-27270.000	0.000	-68.147	27.733
3	40.000	-797.246	0.000	0.000	-27270.000	0.000	-45.624	0.000
4	30.000	-841.444	0.000	0.000	-27270.000	0.000	26.446	0.000
5	20.000	-878.089	-46.114	0.000	-27270.000	0.000	63.312	36.567
6	10.000	-960.965	-115.083	0.000	-27270.000	0.000	98.155	91.258
7	BASE	-1204.610	-172.699	0.000	-27270.000	0.000	138.375	136.946

TABLE 6: Seismic #1 combination-Peak accelerations (Stability Analysis)

Joint		Safety Factors					Resultants				Uplift
ID	Upstream Elevation	Sliding Peak	Sliding residual	Overturning Toward u/s	Overturning Toward d/s	uplifting	Normal kN	Shear KN	Moment KN	Position % of joint	Final Force kN
1	60.000	> 100	4.310	38.973	> 100	> 100	-238.1	-55.3	-27.9	48.717	
2	50.000	32.229	6.437	4.619	> 100	> 100	-2635.7	-409.5	-3852.3	35.574	48.6
3	40.000	63.373	13.106	3.801	14.598	13.936	-5855.8	-446.8	-14337.2	27.112	452.7
4	30.000	95.377	23.863	3.999	5.662	6.254	-10121.2	424.1	-40580.1	30.853	1926.3
5	20.000	33.843	9.830	4.103	3.872	4.752	-15674.7	1594.6	-79772.5	34.997	4177.8
6	10.000	23.665	7.492	3.656	3.187	4.124	-22516.4	3005.3	-123459.6	36.898	7207.2
	Base	19.707	7.089	4.336	3.700	5.645	-34281.2	4835.9	-213093.8	37.513	7379.7
Required		>1.000	>1.000	>1.00	>1.00	>1.00					

TABLE 7: Seismic #1 combination-Sustained accelerations (Stress Analysis)

joint		Stresses						
		Normal stresses		Allowable stresses		Shear		
ID	Upstream Elevation(m)	U/s (kPa)	D/s (kPa)	Tension	compression	u/s (kPa)	maximum (kPa)	D/s (kPa)
1	60.000	-25.491	-23.167	0.000	-27270.000	0.000	-5.267	0.000
2	50.000	-405.094	-80.749	0.000	-27270.000	0.000	-58.450	64.032
3	40.000	-694.229	0.000	0.000	-27270.000	0.000	-32.352	0.000
4	30.000	-781.563	0.000	0.000	-27270.000	0.000	27.458	0.000
5	20.000	-824.091	-22.546	0.000	-27270.000	0.000	90.646	17.878
6	10.000	-854.207	-127.713	0.000	-27270.000	0.000	150.389	101.273
7	Base	-1026.093	-240.301	0.000	-27270.000	0.000	218.551	190.553

TABLE 8: Seismic #1 combination-Sustained accelerations (StabilityAnalysis)

Joint		Safety Factors					Resultants				Uplift
ID	Upstream Elevation	Sliding		Overturning toward		uplifting	Normal kN	Shear KN	Moment KN	Position % of joint	Final Force kN
		Peak	residual	u/s	d/s						
1	60.000	> 100	6.929	62.817	> 100	> 100	-222.4	-32.1	-16.2	49.204	
2	50.000	48.511	9.221	6.952	> 100	> 100	-2461.1	-266.9	-2774.3	38.873	
3	40.000	79.350	16.094	4.571	13.316	13.012	-5437.8	-337.9	-14197.9	28.913	452.7
4	30.000	90.446	21.348	3.717	5.310	5.840	-9322.8	436.7	-37068.9	30.597	1926.3
5	20.000	24.279	6.693	3.573	3.662	4.437	-14359.2	2145.4	-76854.7	34.221	4177.8
6	10.000	14.504	4.363	3.537	2.972	3.851	-20546.8	4709.6	-106034.4	37.669	7207.2
7	Base	11.298	3.898	4.781	3.397	5.271	-31520.5	8086.4	-162269.2	39.658	7379.7
Required		>1.000	>1.000	>1. 00	>1.00	>1.00					

TABLE 9: Static Loads (1/1)

		Self Weight		Normal Operating Level			
Joint		Dam		Upstream Reservoir		Uplift	
ID	Upstream Elevation	Vertical load		Horizontal Load		Normal Load	
		D(kN)	Position x	Hnu(kN)	Elevation(m)	Un(kN)	Position I(m)
1	60.00	-215.2	4.570				
2	50.00	-2381.7	4.600				
3	40.00	-5700.5	6.133	128.1	41.703	452.7	6.020
4	30.00	-10886.3	6.515	1119.9	35.037	1926.3	8.664
5	20.00	-17939.0	11.090	3092.7	28.370	4177.8	11.307
6	10.00	-26858.7	13.721	6046.5	21.703	7207.2	13.950
7	Base	-37645.4	16.370	9981.2	15.037	7379.7	16.593

TABLE 10: Static Loads (2/2)

		Flood Level	
Joint		Upstream Reservoir	Uplift
ID	Upstream	Horizontal Load	Normal Load

	elevation				
		Hnu(kN)	Elevation(m)	Un(kN)	Position I(m)
1	60.00				
2	50.00	261.4	52.433	362.8	3.377
3	40.00	1468.0	45.767	1532.6	6.020
4	30.00	3655.6	39.100	3480.3	8.664
5	20.00	6824.3	32.433	6206.0	11.307
6	10.00	10973.9	25.767	9709.5	13.950
7	Base	16104.5	19.100	9374.0	16.593

TABLE 11:Pseudo-Static Loads (Seismic Coefficient)-Stress Analysis

JOINT		Inertia Load				Reservoirs (Operating Level)	
		Dam				Upstream	
ID	Upstream elevation	Horizontal Load		Vertical Load		Horizontal Load	
		Qh (Kn)	Elevation (m)	Qv (kN)	Position x(m)	Hdu (kN)	Elevation (m)
1	60.00	-34.4	60.500	-23.0	4.570		
2	50.00	-381.1	55.469	-254.0	4.600		
3	40.00	-912.1	49.101	-608.1	6.133	-66.1	42.044
4	30.00	-1741.8	42.241	-1161.2	8.515	-336.2	36.044
5	20.00	-2870.2	35.376	-1913.5	11.090	-720.3	30.044
6	10.00	-4297.4	28.551	-2864.9	13.721	-1190.9	24.044
7	Base	-6023.3	21.762	-4015.5	16.370	-1734.3	18.044

TABLE 12:Pseudo-Static Loads (Seismic Coefficient)-Stability Analysis

JOINT		Inertia Load				Reservoirs (Operating Level)	
		Dam				Upstream	
ID	Upstream elevation	Horizontal Load		Vertical Load		Horizontal Load	
		Qh (Kn)	Elevation (m)	Qv (kN)	Position x(m)	Hdu (kN)	Elevation (m)
1	60.00	-10.8	60.500	-7.2	4.570		
2	50.00	-119.1	55.469	-79.4	4.600		
3	40.00	-285.0	49.101	-190.0	6.133	-20.7	42.044
4	30.00	-544.3	42.241	-362.9	8.515	-105.1	36.044
5	20.00	-897.0	35.376	-598.0	11.090	-225.1	30.044
6	10.00	-1342.9	28.551	-895.3	13.721	-372.2	24.044
7	Base	-1882.3	21.762	-1254.8	16.370	-542.0	18.044

TABLE 13: Pseudo - Dynamic Loads (Chopra' S Method) - Stress Analysis (1 / 2)

JOINT	FIRST MODE			HIGHER MODES			MODAL COMBINATION
	DAM	RESERVOIR (UPSTREAM)	TOTAL	DAM	RESERVOIR (UPSTREAM)	TOTAL	SRSS
	HORIZONTAL LOAD	HORIZONTAL LOAD	HORIZONTAL LOAD	HORIZONTAL LOAD	HORIZONTAL LOAD	HORIZONTAL LOAD	HORIZONTAL LOAD

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ID	Upstream Elevation (m)	Eq1 (kN)	elevation (m)	Hd1 (kN)	elevation (m)	Em1 (kN)	Elevation (m)	Eqs (kN)	Elevation (m)	Hds (kN)	Elevation (m)	Ems (kN)	Elevation (m)	Emc (kN)	Elevation (m)
1	60.00	-28.5	60.504			-28.5	60.504	47.3	60.506			47.3	60.506	-55.3	60.505
2	50.00	-246.6	56.009			-246.6	56.009	326.9	56.639			326.9	56.639	-409.5	56.411
3	40.00	-440.1	51.142	-12.5	41.880	-452.6	50.886	351.6	56.437	2.9	56.776	354.5	56.439	-574.9	53.066
4	30.00	-620.8	46.491	-61.0	36.260	-681.8	45.576	40.8	227.787	-179.4	33.763	-138.6	-23.386	-695.7	44.904
5	20.000	-754.2	42.751	-112.7	31.111	-866.9	41.238	-704.6	12.705	-517.2	27.833	-1221.8	19.109	-1498.1	28.502
6	10.000	-830.4	40.261	-159.3	26.432	-989.7	38.035	-1912.9	13.955	-962.7	21.822	-2875.6	16.589	-3041.2	19.981
7	Base	-855.0	39.293	-200.3	22.070	-1055.4	36.024	-3568.0	9.698	-1468.0	16.008	-5035.9	11.537	-5145.3	13.495

TABLE 14: Pseudo - Dynamic Loads (Chopra' S Method) - Stress Analysis (2 / 2)

JOINT		VERTICAL LOADS	
		DAM	
		VERTICAL LOAD	
ID	Upstream Elevation (m)	Eqv (kN)	Position x (m)
1	60.000	-28.5	60.504
2	50.000	-246.6	56.009
3	40.000	-440.1	51.142
4	30.000	-620.8	46.491
5	20.000	-754.2	42.751
6	10.000	-830.4	40.261
7	Base	-855.0	39.293

TABLE 15: Pseudo -Dynamic Loads (Chopra' S Method) - Stability Analysis (1 / 2)

JOINT		FIRST MODE						HIGHER MODES						MODAL COMBINATION	
		DAM		RESERVOIR (UPSTREAM)		TOTAL		DAM		RESERVOIR (UPSTREAM)		TOTAL		SRSS	
		HORIZONTAL LOAD		HORIZONTAL LOAD		HORIZONTAL LOAD		HORIZONTAL LOAD		HORIZONTAL LOAD		HORIZONTAL LOAD		HORIZONTAL LOAD	
ID	Upstream Elevation (m)	Eq1 (kN)	elevation (m)	Hd1 (kN)	elevation (m)	Em1 (kN)	Elevation (m)	Eqs (kN)	Elevation (m)	Hds (kN)	Elevation (m)	Ems (kN)	Elevation (m)	Emc (kN)	Elevation (m)
1	60.000	-28.5	60.504			-28.5	60.504	14.8	60.506			14.8	60.506	-32.1	60.504
2	50.000	-246.6	56.009			-246.6	56.009	102.2	56.639			102.2	56.639	-266.9	56.101
3	40.000	-	51.142	-12.5	41.880	-452.6	50.886	109.9	56.437	0.9	56.776	110	56.439	-466.0	51.216

		440.1										.8			
4	30.000	-620.8	46.491	-61.0	36.260	-681.8	45.576	12.8	227.787	-56.1	33.763	-43.3	-23.386	-683.2	45.508
5	20.000	-754.2	42.751	-112.7	31.111	-866.9	41.238	-220.2	12.705	-161.6	27.833	-381.8	19.109	-947.3	38.518
6	10.000	-830.4	40.261	-159.3	26.432	-989.7	38.035	-597.8	13.955	-300.8	21.822	-898.6	16.589	-1336.8	30.287
7	Base	-855.0	39.293	-200.3	22.070	-1055.4	36.024	-1115.0	9.698	-458.7	16.008	-1573.7	11.537	-1894.8	22.235

TABLE16: PSEUDO - DYNAMIC LOADS (CHOPRA' S METHOD) - STABILITY ANALYSIS (2/ 2)

JOINT		VERTICAL LOADS	
		DAM	
		VERTICAL LOAD	
ID	Upstream Elevation (m)	Eqv (kN)	Position x (m)
1	60.000	-7.2	4.570
2	50.000	-79.4	4.600
3	40.000	-190.0	6.133
4	30.000	-362.9	8.515
5	20.000	-598.0	11.090
6	10.000	-895.3	13.721
7	Base	-1254.8	16.370

III. CONCLUSIONS AND RECOMMENDATIONS

Results presented in this paper demonstrate that the response of concrete gravity dam-reservoir systems is significantly affected by various static and dynamic loading parameters. The design check of existing dam is performed, for the present PGA value of the earlier earthquake i.e. 0.16g, to assess whether seismic upgrading of Hirakud Dam is necessary from seismic safety point of view. It can be concluded from the present study that the dam section is safe for all possible load combinations and no further retrofitting measures are required for the section.

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AUTHORS

First Author – Gaurva Verma, Research Scholar, Deptt.of Civil Engg., NIT, Raipur, (C.G.) 492010, India, Email: gaurva.verma@gmail.com
Second Author – Dr.M.K.Verma, Professor, Deptt.of Civil Engg., NIT, Raipur, (C.G.) 492010, India, Email: mkseem670@gmail.com
Third Author – Dr.R.K.Tripathi, Associated Professor, Deptt.of Civil Engg., NIT, Raipur, (C.G.) 492010, India, Email: rajesh_tripath64@yahoo.co.in