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Finite Element Modelling and Seismic Response Evaluation of Large Concrete Gravity Dams - An Approach based on Indian Standard Codal Guidelines

Dr. K. Rama Mohan Rao [1], Nagul Nanne Shaik [2]

[1, 2]Department of Civil Engineering, JNTUH College of Engineering, Hyderabad, India.

Abstract: *Concrete Gravity Dams are important lifeline structures and represent the fragrance of people's standard of living. These are very complex structures and subjected to various types of forces both static and dynamic in nature. In the present study, a 63m height of Non Overflow section is considered and a two dimensional (2D) Finite Element Model is created to simulate both dam body and its foundation. All major load/forces are calculated and applied as primary load cases and load combinations are generated for the most adverse load combination A, B, C, D, E, F or G as per I.S 6512-1984. Dam-Water interaction is accorded by considering the Instantaneous hydrodynamic forces during the seismic conditions on the U/s surface of dam body by using Zanger's approach. Dam-Foundation interaction is taken into consideration in the analysis by finite element modelling of the foundation and assigning their properties, so as to evaluate the response of concrete gravity dam during the earthquake. Apart from the Normal Operating Conditions / Combinations, Seismic analysis is performed for both Static and Dynamic Methods. Seismic Coefficient Method as per IS 1893- 1984 for the Static Seismic analysis and Response Spectrum Modal Analysis Method as per IS 1893- 2002 for the Dynamic Analysis are followed. Natural Periods and Mode Shapes of the dam section are determined including the % of Mass Participation in each Mode, using Finite Element software StaadPro V8i. Six no. of Modes are considered in the analysis such that the sum total of modal masses of all modes considered is more than 90% of total seismic mass. The stress contour pattern and behaviour under various load combinations are evaluated and stress distribution is visualised. The maximum displacement of the dam crest is observed for the various load combinations. A comparative study is made between Static Vs Dynamic seismic analysis for maximum Compressive and Tensile stresses at Heel /Toe/ in dam body for the various load combinations as per I.S. Codal guide lines for 'dam with fixed base' and 'dam with foundation system'.*

Keywords: *Concrete Gravity Dam, Seismic Response, Finite Element Method, Seismic Coefficient Method, Response Spectrum Modal Analysis, Dam – Water – Foundation Interactions, Mode Shapes, Stress Contour.*

1. Introduction

Dam structures are barriers which create huge impounding reservoirs for various purposes such as hydropower, water supply and irrigation, flood protection, water storage cum diversion, navigation as well as recreation and aquatic ornamentation etc. Any major dam failure shall obviously be a disastrous in nature and create substantial loss of life and heavy destruction to properties. The structures which are directly linked with human lives are required to be safe and strong. This triggers to pay an immense attention towards the safety of dam from the design engineering stage itself. A Concrete Gravity Dam is a Solid Structure which takes care of all external forces simply by its own weight, shape and strength of concrete. These are complex structures and are subjected Static Type of loads viz., Dead loads, Reservoir and Tail water loads, uplift pressure, Earth and silt pressures etc., and Static Type of loads viz., Seismic forces, Wind forces etc. Seismic forces on structures depend largely on the ground motions during the earthquakes. The response of a dam subjected to seismic loading, exhibits a combined effect of the interaction among dam, reservoir and foundation systems. Hence, there is a significant importance in studying the various aspects influencing the seismic response of a large concrete gravity dams for safe and long lasting service to public domain. The magnitudes of maximum compressive/tensile stress at the heel/Toe/any other planes normal to the faces of the dam rapidly change and huge variation in stresses can be observed during the earthquakes. Hence, a paramount importance is gained for the dynamic seismic stress analyses with finite element procedures to obtain a clear insight into the response behaviour of concrete gravity dams.

The main aim of this study highlights on the response behaviour of an idealized large concrete monolith gravity dam with effect of foundation flexibility and reservoir interaction under the static and dynamic seismic forces. The main objectives of the present study are

- To evaluate compressive and tensile stresses occurring at the heel/ Toe/ any other planes normal to the faces of the dam considering the most adverse load combination A, B, C, D, E, F or G as per I.S 6512-1984.
- To visualise the stress contours pattern and distribution under various load combinations on to the screen.
- To evaluate the maximum displacement of the dam crest for the various load combinations.
- To evaluate Natural Periods and Mode Shapes of the dam section including the percentage (%) of Mass Participation in each Mode.
- A comparative study between Static Vs Dynamic seismic analysis for maximum Compressive and Tensile stresses at Heel /Toe/ in dam body for the various load combinations for 'dam with fixed base' and 'dam with foundation system'.

2. Previous Studies

Failure of dams occurs quite rapidly without adequate prior warning with a large potential of causing excessive calamity. According to Hazrat Ali et. Al (2012), based on a study of over 1600 dams, the identified causes and their contribution toward the failure of dams are, Foundation problems (40%), Inadequate spillway capacity (23%), Poor construction practices (12%), Uneven settlement (10%), High pore pressure (5%), Acts of war (3%), Embankment slips (2%), Defective materials (2%), Incorrect operation (2%) and Earthquakes (1%).

Mohammad Mehdi Heydari and Shiva Khosravi (Iran, 2013) have investigated to develop an efficient procedure to model a 2D Finite Element model with 11 defined geometry variables for optimal geometrical shape of Concrete gravity dams considering dam-reservoir-foundation rock interaction for the modal analysis with APDL language. Anil K. Chopra (USA, 2012) has investigated and discussed about the various factors that significantly influence the three-dimensional analysis of arch dams. some of identified factors are the semi unbounded size of the reservoir and foundation-rock domains, dam-water interaction, wave absorption at the reservoir boundary, water compressibility, dam–foundation rock interaction, and spatial variations in ground motion at the dam-rock interface. Brijesh Singh And Pankaj Agarwal (India, 2009) have investigated the earthquake response of high concrete gravity dam-reservoir-foundation system to study the effect of foundation flexibility and reservoir on the response of high concrete dam under transient dynamic analysis. The dam has been idealized by considering a separate monolith under plane stress conditions and foundation block as plane strain.

3. Model Description, Load Types and Load Combinations

In the present study, a 63m height of Concrete Gravity Dam of Non Overflow section having a base width of 46m is considered. A Two dimensional (2D) Finite Element Model is created to simulate both dam body and its foundation using StaadPro V8i software.

3.1. Hydraulic Data

Maximum Water Level : +245.200 m

Full Reservoir Level : +244.200 m

Maximum Draw down Level : +214.000 m

Road Top (Top of Dam) : +248.000 m

Ground Level : +193.000 m

Foundation Level : +185.000 m

3.2. Geometric Data

Top Bund Level (T.B.L) : +248.000 m

Top width of Dam : 5.000 m

U/s Batter of 1 in 20 starts at : +235.000 m

D/s Slope 1 (V) to 0.70 (H) starts at : +240.000 m

Max Height of the Dam : 63.000 m

Bottom Level of Foundation Gallery : +186.500 m

Dimensions of Gallery : 2.00 x 2.50 m

3.3. Dam Concrete Properties

Grade of Mass Concrete (Hearting) : PCC M15 with 80 MSA

Grade of Concrete (U/ 2.5m thick)
: PCC M20 with 80 MSA

Grade of Concrete (around galleries)
: RCC M20 with 20 MSA

Young's Modulus of Elasticity (E)
: 1.94 x 106 t/Sqm

Poisson's Ratio (μ) : 0.17

Density of Concrete : 2.40 t/Cum

Shear Modulus (G) : 0.946 x 106 t/Sqm

Damping : 5%

3.4. Dam Foundation Rock Properties:

The dam foundation is divided into 3 zones of strata and properties of each stratum are as follows.

Stratum 1

(0.00 to 13.5m below Reservoir Bed Level)

E : 2.54 x 105 t/Sqm

Poisson's Ratio (μ) : 0.277

Density of Rock : Mass Less

Shear Modulus (G) : 0.946 x 106 t/Sqm

Damping : 0.07

Stratum 2

(13.50 to 94.50m below Reservoir Bed Level)
Young's Modulus of Elasticity (E)
: 5.0 x 105 t/Sqm

Stratum 3

(94.50 to 117.50m below Reservoir Bed Level)

E : 8.157 x 105 t/Sqm

3.5. Finite Element Model of Dam and Foundation System:

Four Finite Element (FE) models are created using StaadPro V8i Finite Element software to study the Response behaviour.

These models are

- Model 1: Dam with Fixed base using Static Seismic analysis (IS 1893- 1984).
- Model 2: Dam with Fixed base using Response Spectrum Modal Analysis (IS 1893- 2002).
- Model 3: Dam with Foundation system using Static Seismic analysis (IS: 1893-1984).
- Model 4: Dam with Foundation system using Response Spectrum Modal Analysis (IS:1893- 2002)

The below figure shows a 2-D finite element mesh dam model with foundation, 353 elements are used to represent the dam section and (1743-353) 1390 elements for foundation geometry. The base width of the dam at foundation level is 46 m and height of dam is 63 m. The size of foundation block is 283m wide and 117m deep.

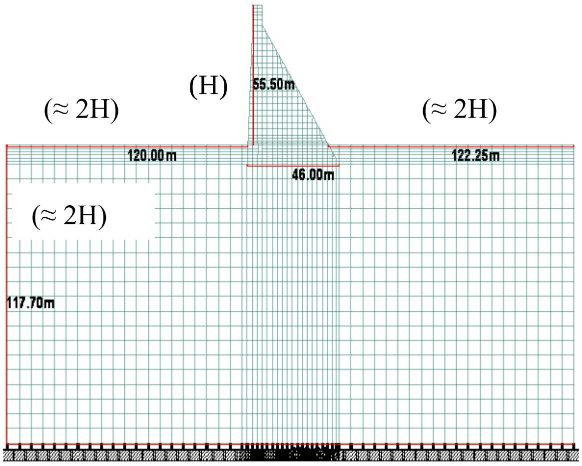

Figure 1. *Finite Element Model of Dam-Foundation System*

3.6. Primary Load Types

3.6.1. Dead Loads

The dead loads of a dam include its self weight. The total self weight of dam is worked out to 3498 t and is applied to Staad Model.

3.6.2. Reservoir and Tail Water Loads

The Reservoir loads are worked out for the both FRL & MWL conditions. The Hydro static pressure on U/s face of dam and vertical weight of water on the U/s inclined portion of dam are applied to Staad Model.

- The Hydro static pressure for FRL case is applied as a linearly varying load from FRL (0.0 t/Sqm) to the Bottom of Dam (59.00 t/Sqm).
- The Vertical Weight of water on U/s inclined portion for FRL case is applied as a linearly varying load from point of Inclination (9.0 t/Sqm) to the Bottom of Dam (59.00 t/Sqm) over a width of 2.50m.

- The Hydro static pressure for MWL case is applied as a linearly varying load from FRL (0.0 t/Sqm) to the Bottom of Dam (60.20 t/Sqm).

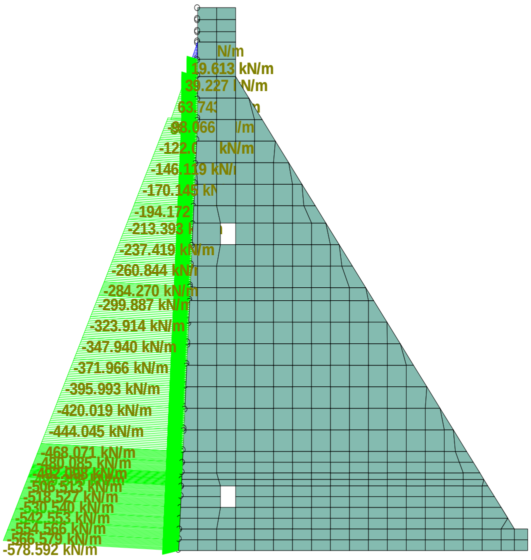

Figure 2.1 *Hydro Static Pressure (@ FRL)*

- The Vertical Weight of water on U/s inclined portion for MWL case is applied as a linearly varying load from point of Inclination (10.20 t/Sqm) to the Bottom of Dam (60.20 t/Sqm) over a width of 2.50m.
- Tail water load is not applicable here.

3.6.3. Uplift Pressure Loads:

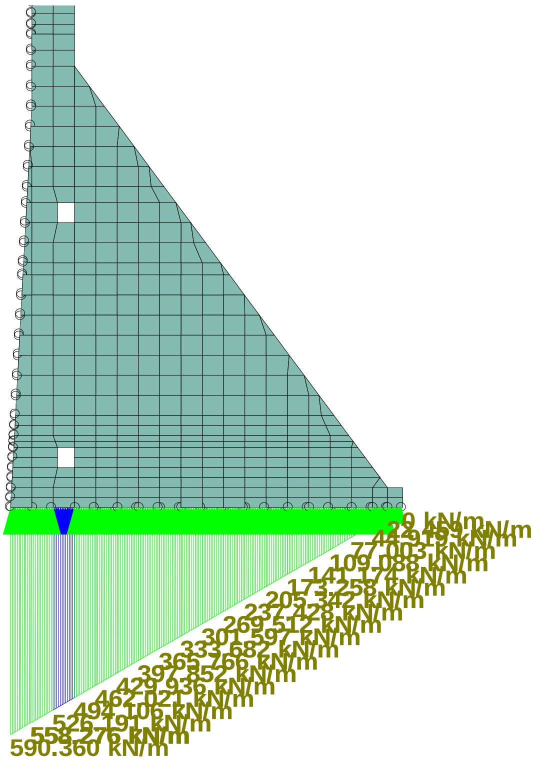

Figure 2.2 *Normal Uplift Pressure (@ FRL)*

The Uplift Pressure loads are worked out for the both FRL & MWL conditions for the Normal and Extreme conditions.

- The Normal Uplift Pressure under FRL case is applied as a linearly varying load from 0.0t/Sqm (at Toe) to 19.67t/Sqm (at drainage gallery line) and 59.00t/Sqm (at Heel of Dam).
- The Normal Uplift Pressure under MWL case is applied as a linearly varying load from 0.0t/Sqm (at Toe) to 20.07t/Sqm (at drainage gallery line) and 60.20t/Sqm (at Heel of Dam).
- The Extreme Uplift Pressure under FRL case is applied as a linearly varying load from 0.0t/Sqm (at Toe) to 59.00 t/Sqm (at Heel of Dam).
- The Extreme Uplift Pressure under MWL case is applied as a linearly varying load from 0.0t/Sqm (at Toe) to 60.20 t/Sqm (at Heel of Dam).

3.6.4. Reservoir Silt Loads

- The Horizontal silt pressure is applied as a linearly varying load from MDDL (0.0 t/Sqm) to the Bottom of Dam (0.36*29 =10.44 t/Sqm).
- The Earth pressure is not applied, since any significant influence.

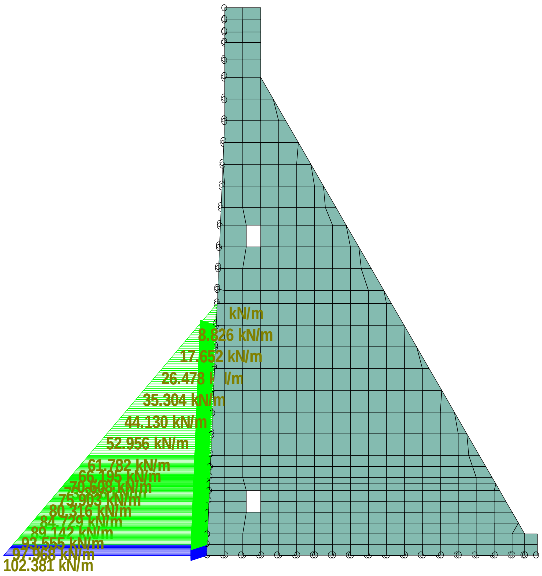

Figure 2.3. *Silt Pressure*

3.7. Seismic Loads/ Forces

3.7.1. Seismic Coefficient Method (IS: 1893 – 1984):

The design value of horizontal seismic coefficient α_h is computed by the following expression:

$$\alpha_h = \beta I \alpha_0 = 0.06$$

Where,

β = a Coefficient depending upon the soil foundation system = 1 (As per table 3 of IS 1893-1984)

I = a factor depending upon the Importance of the structure = 3 (As per table 4 of IS 1893-1984)

α_0 = Basic horizontal seismic coefficient = 0.02 (As per table 2 of IS 1893-1984)

3.7.2. Hydrodynamic Effects Due to Reservoir

Due to horizontal acceleration of the foundation and dam there is an instantaneous hydrodynamic pressure (or suction) exerted against the dam in addition to hydrostatic forces. The direction of hydrodynamic force is opposite to the direction of earthquake acceleration. The hydrodynamic pressure at depth y below the reservoir surface shall be determined as follows:

$$p = Cs\ \alpha h\ w\ h = 3.653 \text{ t/m}$$

Where

P = hydrodynamic pressure in kg/m at depth y,

Cs = coefficient which varies with shape and depth = 0.688

αh = design horizontal seismic coefficient

= 1.5*0.06 = 0.09

w = unit weight of water in t/m3 = 1 t/m3

h = depth of reservoir in m

= 59m under FRL

3.7.3. Response Spectrum Method (IS: 1893 – 1984):

The fundamental period of vibration of the dam (T) as per Cl: 7.3.1.1(b) of IS: 1893-1984,

$$T = 5.5 (H2/B) * Sqrt (wm/g/Es)$$

$$= 0.1684 \text{ sec}$$

Where

H = height of the dam =63m,

B = base width of the dam=46 m,

w_m = unit weight of dam material =2400 kg/m3,

g = acceleration due to gravity

The design value of horizontal seismic coefficient αh is computed by the following expression:

$$\alpha_h = \beta\ I\ F0\ Sa/g = 0.06$$

Where,

β = a Coefficient depending upon the soil foundation system = 1 (As per table 3 of IS 1893-1984)

I = a factor depending upon the Importance of the structure = 3 (As per table 4 of IS 1893-1984)

F_0 = Basic horizontal seismic coefficient

= 0.1 (As per table 2 of IS 1893-1984)

Sa/g = Average acceleration coefficient for appropriate Natural Time Period and Damping of the structure. (As per Fig 2 of IS 1893-1984) = 0.2

The base shear (V_B) may be obtained by the following formulae

$$V_B = 0.6\ W\ \alpha h$$

(ie., V_B = 0.036 W) = 125.90 t.

Where W = Total weight of concrete dam.

3.7.4. Response Spectrum Modal Analysis Procedure as per IS: 1893 – 2002:

Modal analysis is performed with software's and most software packages are equipped with this facility. Modal analysis technique used to compute the natural frequencies of vibration and corresponding mode shapes for specified modes.

In the present case Staad Pro V8i is used and as follows

The value for (Z/2*I/R) as factors for input spectrum are provided.

- As the R Value (Response Reduction Factor) for Concrete Dams is not available (In fact, The Dams & Embankments part 5-IS 1893 is under revision and still No draft code available) and Staad Pro V8i program calculates the design base shear (V_B) and it is compared with a base shear ($\tilde{V}_B$) calculated as per IS: 1893-2002 code using a Fundamental natural period of vibration (Ta), for the Response Spectrum Modal Analysis.

- Hence, the value for (Z/2*I/R =0.0144) factors are arrived by equating the Base shears (V_B = 0.6*0.06W = 0.036W) obtained from Response Spectrum Method of IS: 1893-1984 to the Base shear (V_B) using design horizontal seismic coefficient (Ah) and Response Spectra as per IS: 1893-2002: Equating the Base shears from both methods, keeping the parameters viz., Z, I, Sa/g values constant, The R Value (Response Reduction Factor) for dam in the present case is worked out to 2.4.
- All response quantities for each mode are calculated.
- In Response Spectrum Modal Analysis Method, the design base shear (V_B) shall be compared with a base shear ($\tilde{V}_B$) calculated using a Fundamental natural period of vibration (Ta). If VB is less than $\tilde{V}_B$, all the response quantities shall be multiplied by $\tilde{V}_B/V_B$. The response quantities include member forces, displacements, storey forces, storey shears and base reactions.
- The peak response quantities are then combined as per the specified method (SRSS, CQC, ABS, CSM or TEN) to get the final results.

3.8. Load Combinations

A Concrete Gravity dam design shall be based on the most adverse load combinations given below using the safety factors prescribed as per IS: 6512-1984. Depending on the scope and details of the various project components, site conditions and construction programme one or more of the following loading combinations may not be applicable and may need suitable modifications:

- Load Combination A (Construction Condition): Dam completed but no water in reservoir and no tail water.
- Load Combination B (Normal Operating Condition): Full reservoir elevation normal dry weather tail water, normal uplift, Ice and silt (if applicable)
- Load Combination C (Flood Discharge Condition): Reservoir at maximum flood pool elevation, all gates open, Tail water at flood elevation, normal uplift, and silt (if applicable).
- Load Combination D: Combination A + Earthquake.
- Load Combination E: Combination B + Earthquake but no ice.
- Load Combination F: Combination C + with Extreme uplift (drains inoperative).
- Load Combination G: Combination E + with extreme uplift (drains inoperative).

The above load combinations are applied to the Finite Element Staad Pro Model to perform the Analysis and Response Results are obtained.

4. ANALYSIS AND RESPONSE RESULTS:

All 4 Dam models are analysed with the Seismic Coefficient Method as per IS 1893- 1984 as a Static Seismic analysis and Response Spectrum Modal Analysis Method as per IS 1893- 2002 as a Dynamic Analysis, apart from the Normal Operating Conditions / Combinations using StaadPro V8i software.

The following Response Parameters are considered in the present case study

- The Maximum Stresses (Compressive / Tensile)
- Maximum displacement of the dam Crest
- Natural Periods
- Mode Shapes of the dam section
- Percentage (%) of Mass Participation in each Mode etc.

4.1. Response Results of Dam

4.1.1. Models 1 &2: Dam with Fixed base (Stress diagrams):

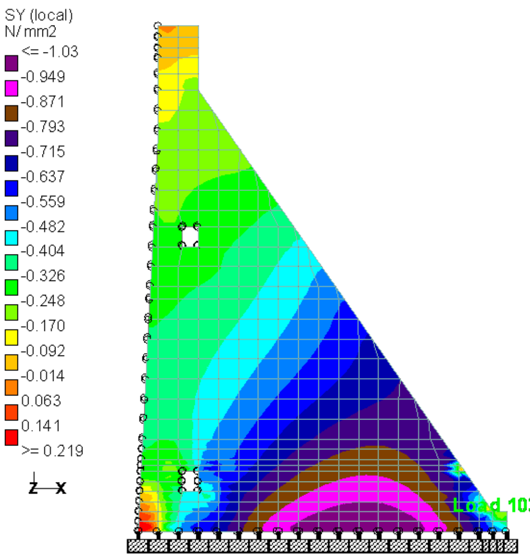

Figure 3.1 *Case - C (Flood Discharge Condition)*

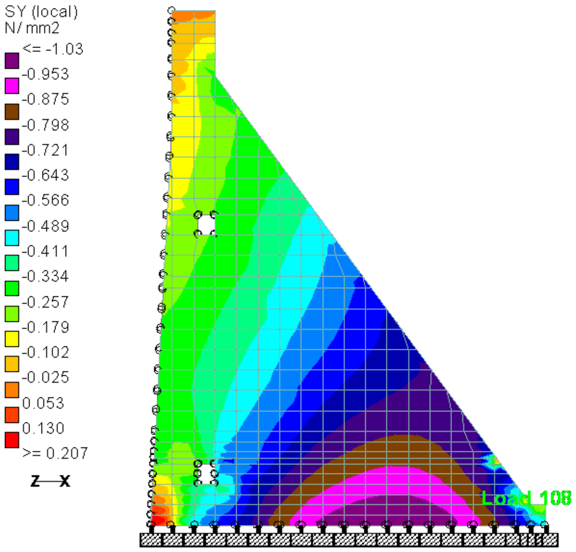

Figure 3.2 - *Case – E (B + EQ) - RSP (IS:1893-2002)*

4.1.2. Models 3 &4: Dam with Foundation (Stress diagrams):

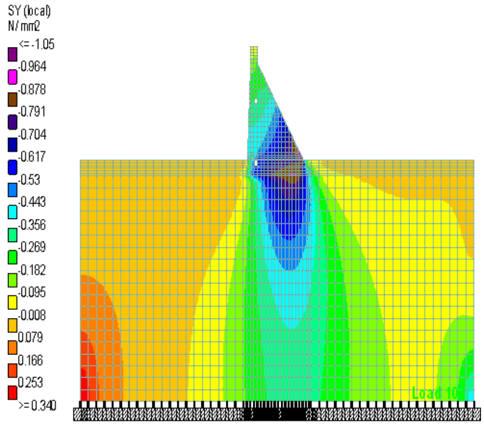

Figure 4.1 *Case – C (Flood Discharge Condition)*

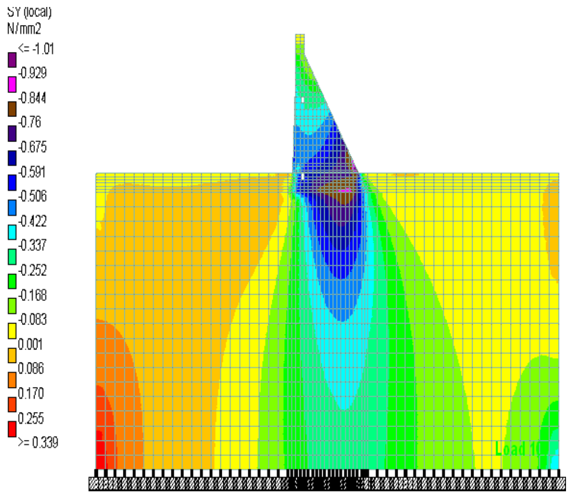

Figure 4.2 - *Case - E (B + Eq) - RSP (IS: 1893-2002)*

Dam Crest Displacements

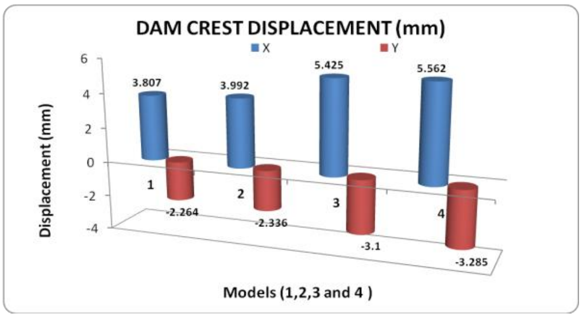

Figure5. *Comparison of Max. Dam crest displacement for models 1, 2, 3 and 4.*

Mode Shapes

Dam with Fixed base (Models 1 &2)

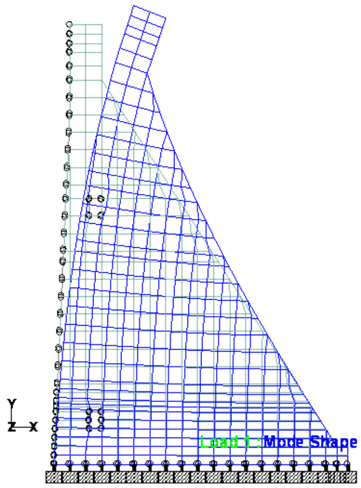

Figure 6. *Mode Shape -1 (T=0.17s)*

Dam with Foundation (Models 3 &4)

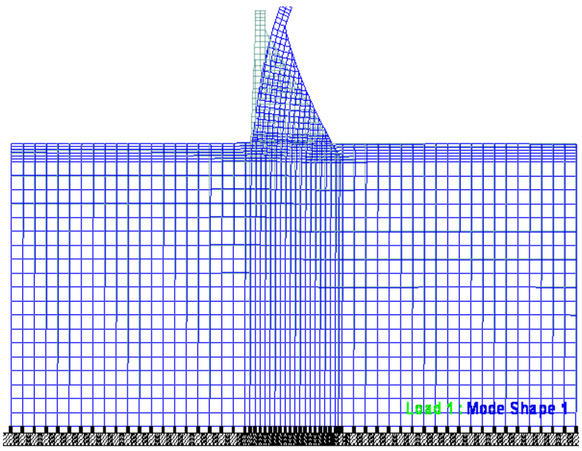

Figure 7. *Mode Shape -1 (T=0.192s)*

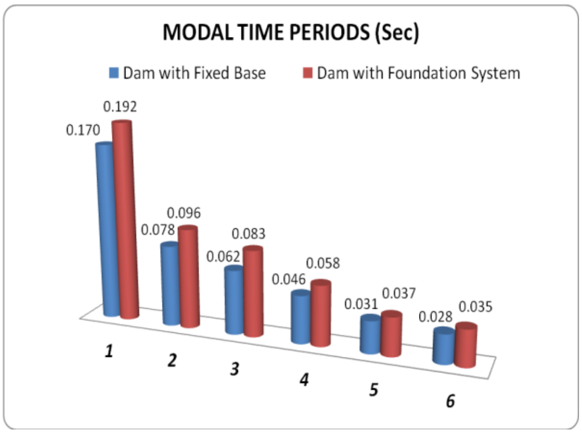

Figure 8. *Modal Time periods for first 6 Modes (Dam base fixed Vs foundation system)*

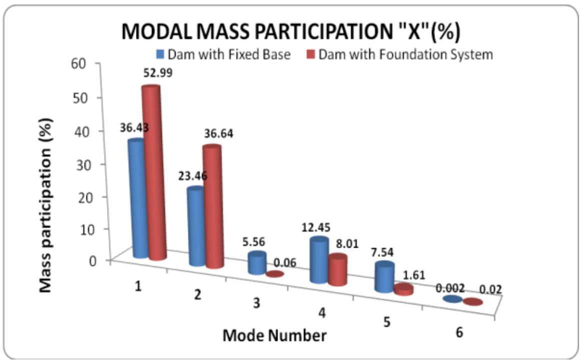

Figure 9. *Modal Mass Participation (X-direction) (Dam base fixed Vs foundation system)*

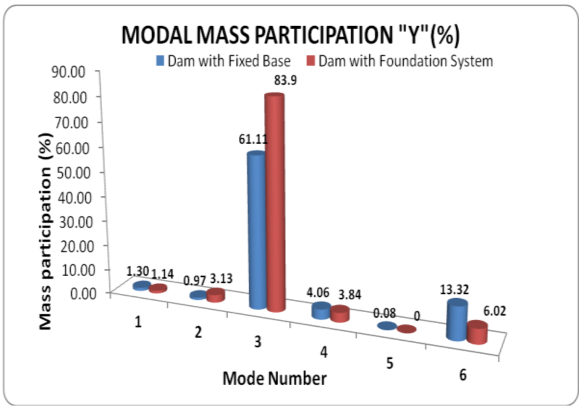

Figure 10. *Modal Mass Participation (Y-direction) (Dam base fixed Vs foundation system)*

5. CONCLUSIONS

The conclusions drawn from the above study are as follows

a. The Finite Element modelling of the 'Dam with Foundation System' plays a vital role in the design of concrete gravity dams, and is witnessed through the distribution of stresses (Compressive/Tensile) to the foundations.

b. Equating the design base shear (V_B = 0.6 W αh) from RSP Method of IS: 1893-1984 to base shear ($\tilde{V}_B$) calculated as per IS: 1893-2002, keeping the parameters like Z, I, Sa/g values constant, The R Value (Response Reduction Factor) for dam in the present case is worked out to 2.4.

c. It is observed that even under Normal Loading conditions, the stresses at Heel of dam are compressive in nature for 'Dam with Foundation System' where as the stresses at Heel of dam are Tensile in nature for 'Dam with Fixed base'.

d. Under Seismic Loading conditions for 'Dam with Fixed base' models, It is observed that a Narrow range of tensile stresses (15.80 – 18.10 t/Sqm)at Heel of dam as per Seismic Coefficient Method (SCM) where as a Marginal change in the range of tensile stresses (13.80 – 20.70 t/Sqm)at Heel of dam as per Response Spectrum (RSP) Method.

e. It is observed that 'Maximum Crest displacements' for 'Dam with Foundation System' (5.562 mm) are higher than for 'Dam with Fixed base' (3.992 mm).

f. It is noticed that a Response Spectrum modal parameter, 'Fundamental Frequency under 1st mode' for 'Dam with Foundation System' (5.21 Hz) is less when compared to 'Dam with Fixed base' (5.89 Hz).

g. It is witnessed that 'Total % of Mass Participation' for 'Dam with Foundation System' (99.3%) are higher than for 'Dam with Fixed base' (85.4%).

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AUTHORS' BIOGRAPHY

Dr. K. Rama Mohan Rao, an Eminent Professor & Director of BICS, Civil Engineering, JNTUH College of Engineering (Autonomous), Hyderabad. Apart from teaching various Engineering subjects and guiding no. of students at the Under graduate, Post graduate and Phd. levels with vast experience in the field of Structural Engineering, he is also rendering his valuable services in the capacity of Director to the Bureau of Industrial Consultancy Services (BICS).

Mr. Nagul Nanne Shaik, a Post Graduate Student of Structural Engineering at JNTUH College of Engineering (Autonomous), Hyderabad. He is having around 12 years experience in the field of Civil/Structural design engineering and working as Sr. Manager (Designs) with GKC Projects Limited, Hyderabad.