Evaluation of Seismic Design of Concrete Gravity Dams – Various Guidelines

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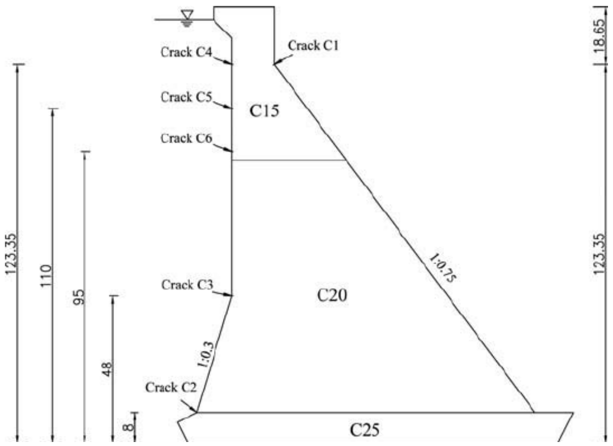
Tamghar dam, Maharashtra
Seepage Hazard

Karam dam, Madhya Pradesh
Flood Hazard



Koyna dam, Maharashtra;
Earthquake cracks

Earthquake loading may lead to several damaging circumstances in the performance of a dam. *Liquefaction*, where an embankment or *foundation* loses shear strength when undergoing shaking, may cause sliding, block, or rotational failures leading to excessive *settlement* and loss of freeboard and resulting in an overtopping failure. Overtopping may also be caused by slope failures or rock falls that enter the reservoir basin, displacing a large volume of water. A *seiche*, or earthquake induced wave, may also overtop and damage the structure. Fault rupture may lead to differential settlement and cracking of a dam leading to *internal erosion* and enlargement of cracks until failure ultimately results. During earthquake shaking *abutments* and foundations may shift and move allowing the dam to tilt, rotate, or slide and lose structural integrity. Slope failures on or near the dam may allow the reservoir to overtop the dam or failure material to block *spillways* and outlets. Often the failure of a dam under seismic loading is attributed to a combination or sequence of the above circumstances.

Shih-Kang Dam , Tiwan, Chi-Chi 7.7 MEQ, 2 bays damaged

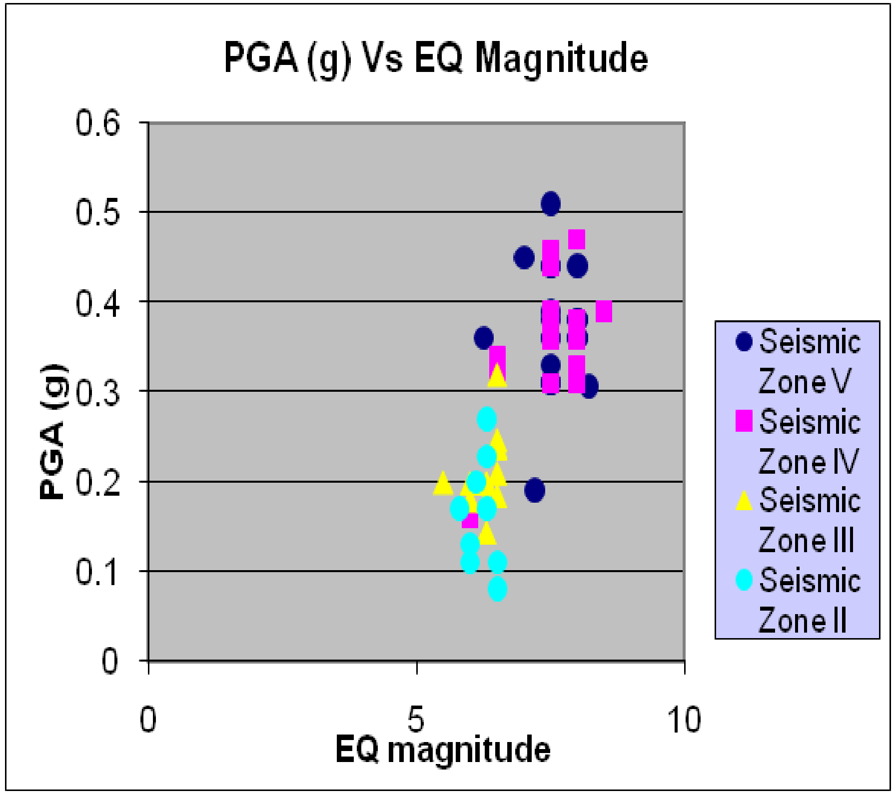
Bhuj, 2001, 7.7 M, dam in Kutchh, Crest settlement

Fujinuma dam, 19 m high (Japan, Tokohu, 2011 9.0 M EQ) failure. Peak Acceleration 0.45g. EQ duration about 100 seconds. Water waves overtopping resulted in failure.

The Zipingpu dam (China) is a concrete faced rockfill dam with the height of 156 m.The Dam suffered major cracking, settlement and slide due to 7.9 magnitude EQ May 2008. The peak value of settlement of the dam crest reached 744.3 mm, and the peak value of horizontal displacement toward the right and left abutment are 226.1 mm and 106.8 mm. The peak Hoz EQ acceleration at top was 20 m/s^2 and the bed rock acceleration was 5 m/s^2. Designed acc =0.26g. No catastrophic Failure

Earthquake Hazard

- Recently, the earthquake hazard has gained much importance in the dam industry on account of widespread human and economic loss.
- In India, major dam building activity is taking place in Himalayas which are more prone major seismic activity



DESIGN AND EVALUATION CRITERIA

The overall process of seismic design and evaluation of concrete dams consist of the following steps:

- Selection of design earthquakes and associated ground motions,
- Establishment of performance levels and performance goals,
- Analysis methodology for computation of seismic response, and
- Interpretation and evaluation of results to assess dam safety.

DESIGN EARTHQUAKES

	UNUSAL LOADIND	EXTREME LOADING
USACE	Operating Basis Earthquake	Maximum Design Earthquake
ICOLD	Operating Basis Earthquake	Safety Evaluation Earthquake/Maximum Credible Earthquake
INDIAN PRACTICE	Design Basis Earthquake	Maximum Credible Earthquake

(i) Operating Basis Earthquake (OBE): The OBE design is used to limit the earthquake damage to a dam project and, therefore, is mainly a concern of the dam owner. An average return period of 145 years (50% probability of exceedance in 100 years). **The dam shall remain operable after the OBE and only minor easily repairable damage is accepted.**

(ii) Design Basis Earthquake (DBE), as practiced in India is corresponding to 475 years return period.

(iii) Maximum Credible Earthquake: The MCE is a deterministic event, and is the largest reasonably conceivable earthquake that appears possible along a recognized fault or within a geographically defined tectonic province, under the presently known or presumed tectonic framework. The MCE is defined as the largest earthquake that can reasonably be expected to occur on a specific source, based on seismological and geological evidence.

1. Safety Evaluation Earthquake (SEE): The ICOLD Bulletin 148 (2016) has used this terminology. It is the worst possible ground motions at the dam site under which stability of the dam must be ensured and no uncontrolled release of water from the reservoir shall take place, **although significant structural damage is accepted**.
2. Further, the usage of SEE has been characteristically different than MCE on account of application of a probabilistic approach wherein the choice of return period of event is linked with hazard potential categorization of a dam. As per ANCOLD, return period are considered as 1000, 3000 and 10000 years for the SEE.
3. NCSDP guidelines consider the SEE as a probabilistic event of 2475 years return period considering the high seismicity in India. SEE is considered as equivalent of the deterministic MCE.

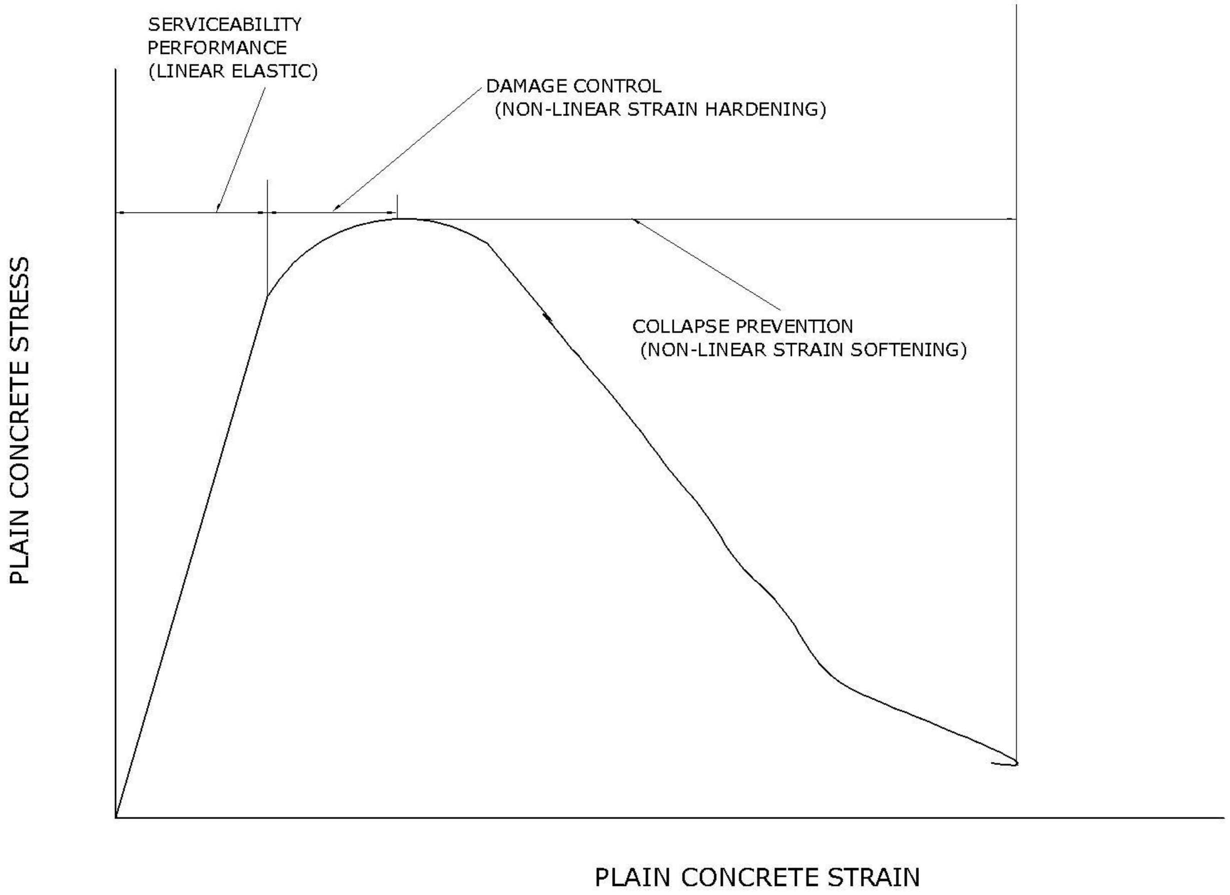
Performance Level	Criteria
• Serviceability	The dam is expected to be serviceable and operable
• Damage Control	Certain parts of the dam can deform beyond their elastic limits (non-linear behavior) if non-linear displacement demands are low. Damage may be significant, but it is generally concentrated in discrete the damaged structure is capable of resisting static loads and can be repaired to stop further damage by non- earthquake loads. Except for unlikely MCE events, it is desirable to prevent damage from occurring in substructure elements, such as foundation, and other inaccessible structural elements.

Performance Level

- Collapse Control

Criteria

Collapse prevention performance requires that the dam does not collapse regardless of the level of damage. The dam may suffer unrepairable damage with nonlinear deformation greater than those associated with the damage control performance but should not result in uncontrolled release of water. If the dam does not collapse when subjected to extreme earthquake events, its resistance can be expected to decrease with increasing displacements. This can affect the post-earthquake stability condition and should be checked. Collapse prevention performance should only be permitted for unlikely MCE events. Collapse prevention analysis should be evaluated using nonlinear dynamic procedures.

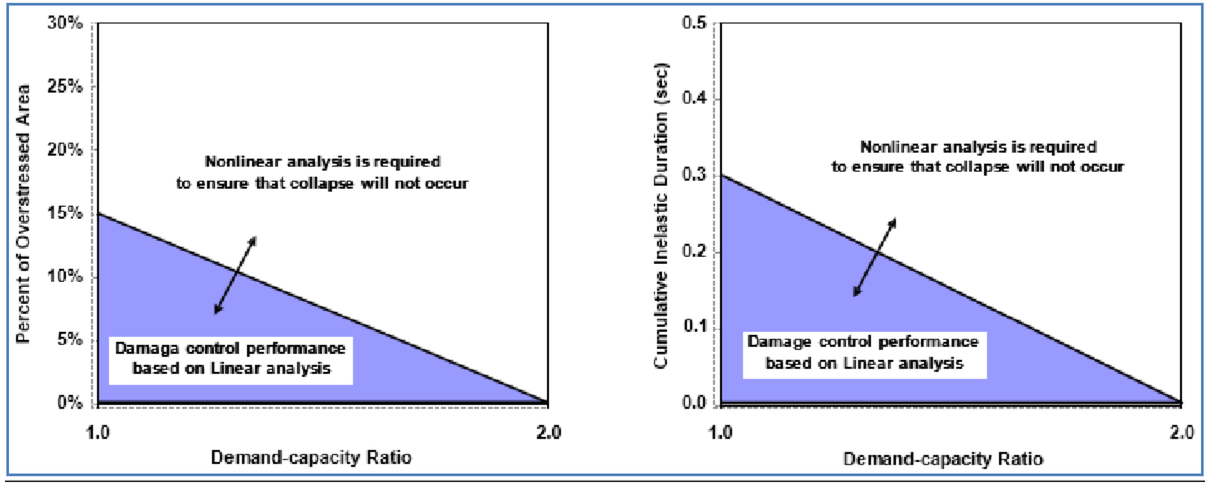

SERVICEABILITY
PERFORMANCE
(LINEAR ELASTIC)
DAMAGE CONTROL
(NON-LINEAR STRAIN HARDENING)
COLLAPSE PREVENTION
(NON-LINEAR STRAIN SOFTENING)
PLAIN CONCRETE STRESS
PLAIN CONCRETE STRAIN

Acceptance Criteria

- Response Spectrum Method

OBJECTIVE	PERFORMANCE LEVEL	
	DAMAGE CONTROL	SERVICEABILITY (OBE)
TENSION DUE TO FLEXURE	1.5	1.0
TENSION DUE TO SHEAR	0.9	0.8
SHEAR DUE TO SLIDING	1.0	0.8

- Time History Analysis



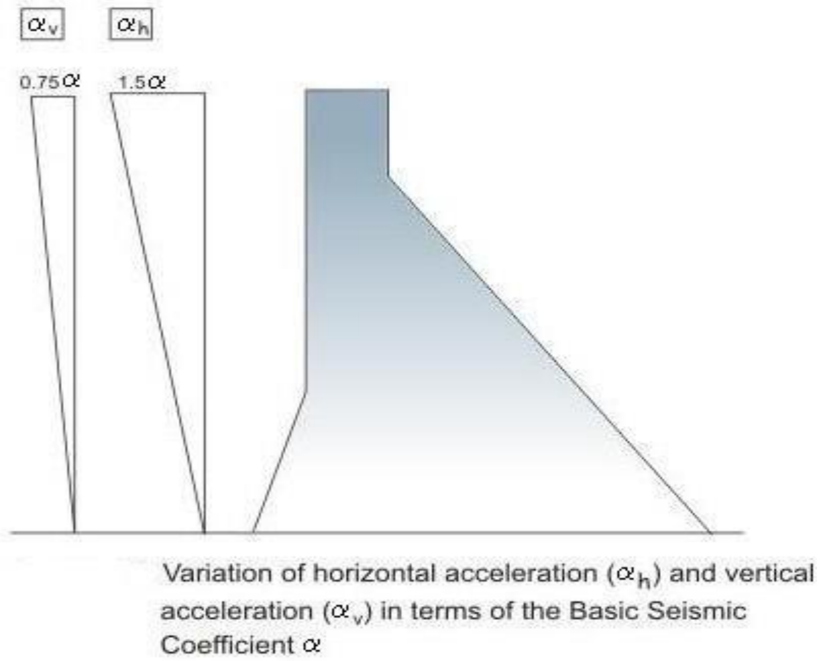
Sl.no	Performance level	USACE	ICOLD	NCSDP (India)
1	Serviceability	OBE (1 in 145 year return period)	OBE (1 in 145 year return period)	DBE (1 in 450 year return period) as per building code.
2	Damage Control (safety)	MDE (return period 1000, 3000 or 10000 depending on the hazard level)	SEE (return period based on the hazards potential) usually taken as 1000, 3000 and 10000.	MCE (based on DSHA or 2475 year return period). Restricted to 2475 year return period in view of large PGA envelope of higher return period earthquakes.

Sl.no	Performance level	USACE	ICOLD	NCSDP (India)
1	Serviceability	Linear Elastic Response Spectrum by FEM	Linear Elastic Response Spectrum by FEM	Pseudo-static analysis based on site specific seismic study with triangular distribution of seismic coefficients
2	Damage Control (safety)	Linear Elastic Response Spectrum based on DCR/Time History analysis based on DCR (if required). If DCR criteria not met. Non-linear time History analysis for Damage estimation.	Linear Elastic Response Spectrum based on DCR/Time History analysis based on DCR (if required). If DCR criteria not met. Non-linear time History analysis for Damage estimation.	Linear Elastic Time History analysis based on DCR. If DCR criteria not met, review the dam cross section.
3	Collapse prevention	Dynamic stability of concrete blocks detached by cracks	Dynamic stability of concrete blocks detached by cracks	

Example problem

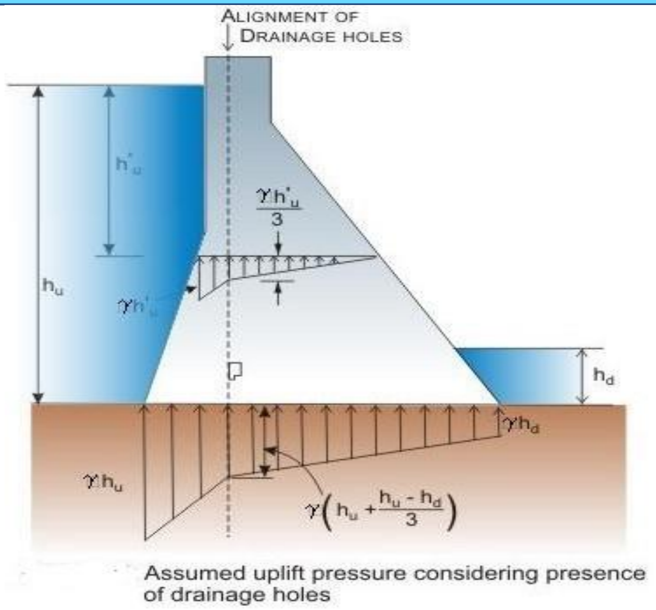
It is a 100 m high non- overflow gravity dam with crest thickness of 8 m and a base thickness of 91.25 m. On the lower two-third, the dam is sloped at 1(V):0.3 (H) on the upstream and at 1(V):0.75 (H) on the downstream face. The dam is first analyzed using Pseudo-static method which should be compliant to IS: 6512 (restricting plain concrete tensile strength to 4% of the compressive strength). The designed section is than analysed by Response spectrum and linear time-history method to check the section is compliant to the acceptance criteria

PSEUDO-STATIC ANALYSIS

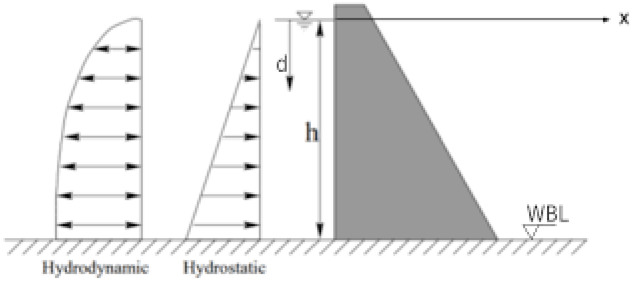


EQ distribution-triangular

horizontal and vertical seismic coefficients are 0.19 and 0.133 respectively



Uplift Pressure Distribution



Hydro-dynamic distribution-parabolic

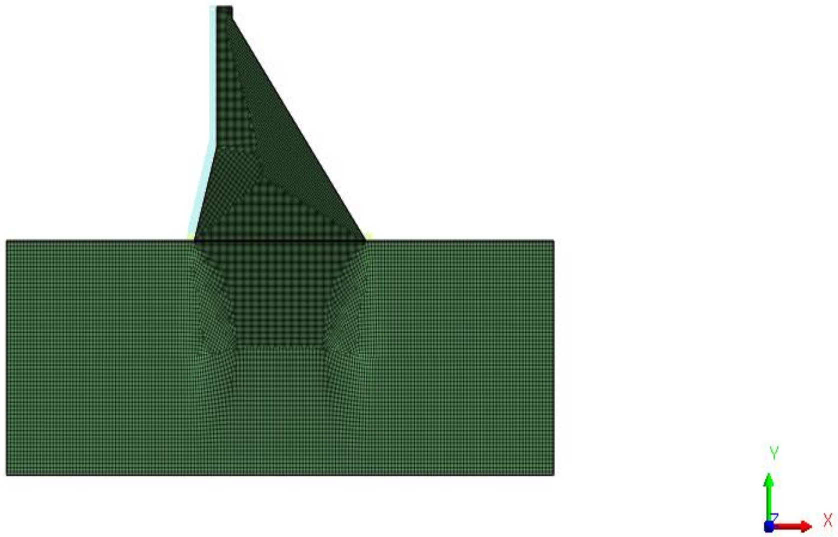
Result of Pseudo-Static analysis.

Load combination	Stress U/s (t/m²)	Stress D/s (t/m²)	Factor of safety (>1 for safe)	Allowable Tensile Stress (t/m²)
A (Construction)	192.749	41.03		-
B (usual)	64.779	141.08	1.32	No Tension
C(Flood or unsual)	51.712	121.80	1.23	1% of Fc
D (A+ DBE)	246.815	2.88	9.51	
E (B+DBE)	-16.031	205.97	1.15	2% of Fc
F(C in Drain chocked)	20.618	115.89	1.94	2% of Fc
G(E in Drain Chocked)	-57.773	198.03	1.32	4% of Fc

Fc = Compressive strength of concrete, (-ve = Tensile stress))

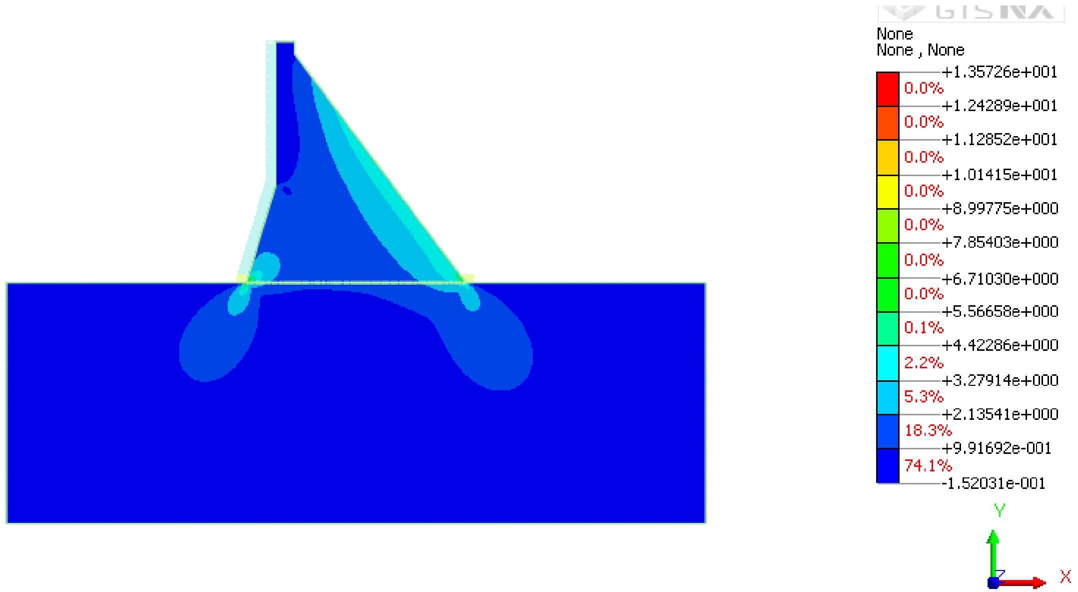
FEM ANALYSIS

The FEM analysis of the example gravity dam was carried out using a 2D model of the dam and foundation rock with a concrete (M25 grade) modulus of elasticity of 25000 MPa, a Poisson’s ratio of 0.19, and a unit weight of 24 KPa. The foundation rock was assumed massless but its modulus and Poisson’s ratio were assumed to be respectively 21230 MPa and 0.22. The inertia forces of the impounded water were represented by added hydrodynamic mass values in accordance with the generalized Westergaard method. The finite- element model is shown in Figure.



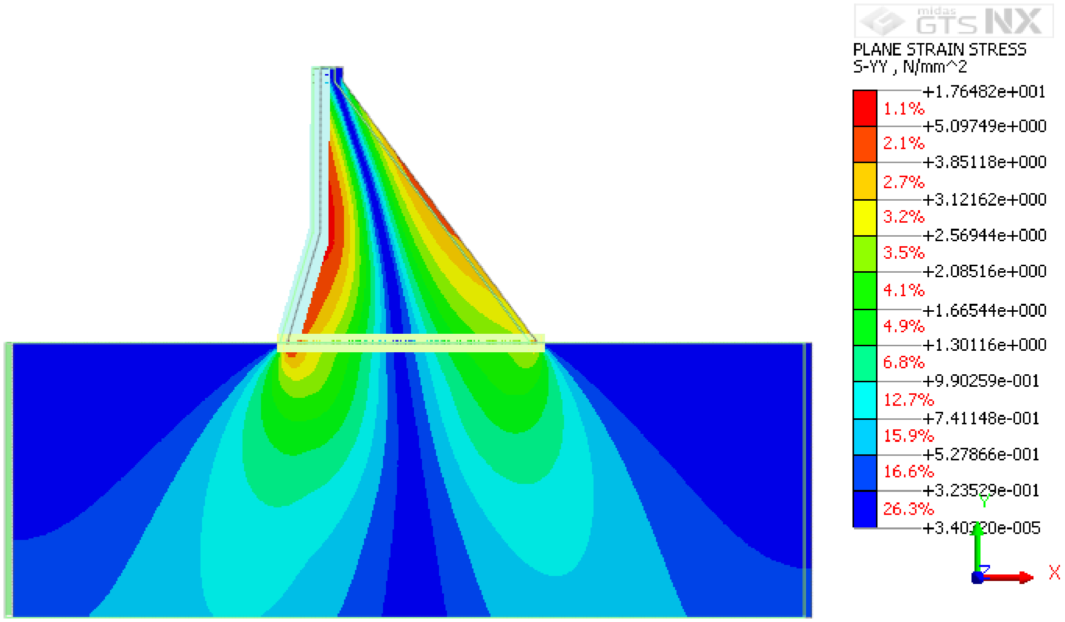
Midas-GTS-NX software

RESPONSE SPECTRUM ANALYSIS



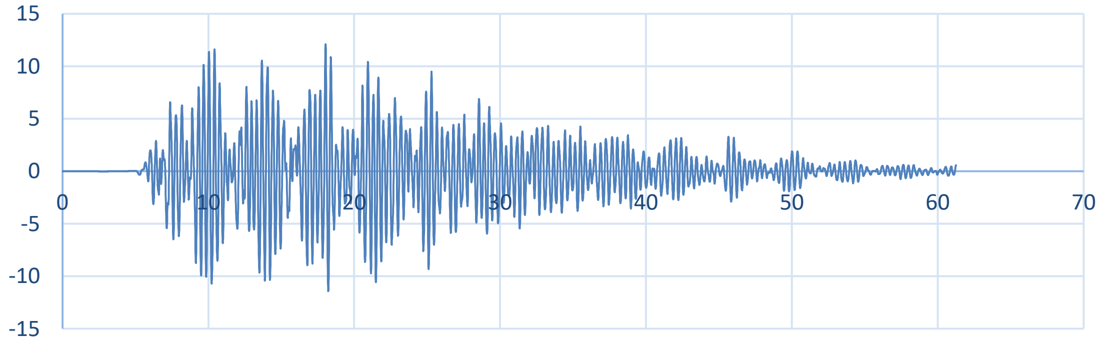
Maximum tensile stress as 5.6 MPa at the heel and toe region as shown in the figure 7. The DCR for M25 concrete for 5,6 MPa tensile stress is less than 1.5 which satisfy the acceptance criteria as stipulated in table-1 earlier. Hence, the gravity dam section as per IS 1893 and IS 6512 guidelines is safe as per Response Spectrum analysis for the MCE condition.

TIME HISTORY ANALYSIS



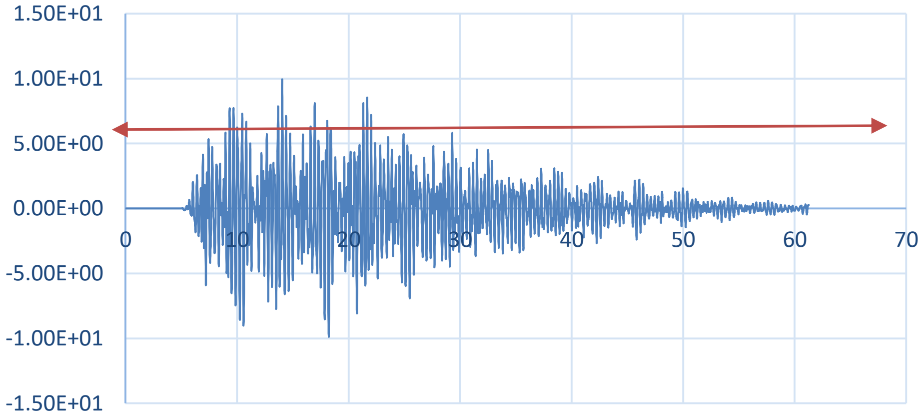
It can be estimated from the legend that area stressed above 5.1 MPa (tensile stress) is approximately 1.1%. The apparent tensile capacity of M25 grade concrete is 5.46 MPa (after Raphel). DCR is within the limit

At Heel
S-YY
(N/mm²)



The stress excursion duration for DCR>1 at heel and kink is 2.77 second and 1.16 second which are more than the acceptable limit of 0.3 seconds. The stress excursion at the toe is not exceeded the acceptable value of 0.3 seconds.

VERTICAL STRESS(MPa) AT U/S KINK V/S TIME



CONCLUSION

The 100 m high fravity dam have been analysed following the NCSDP guidelines. The solved example demonstates that the pseudo-static method, in which seismic parameters are consideered to vary triangularly, could estimate the 100m high dam cross section which fulfilled the acceptance criteria for MCE (1 in 2475 year return period) condition (barring the high tensile stresses which mighe have generated due to singularity in FEM analysis). In this example, foundation modulus is equivalenet to concrete moduls. However, for the foundation with low modulus (a usual scenarion in himalayan region) the psuedo-ststic method may not estimate the dam cross section which could withstand the Damage Control performance criteria.

RECOMMENDATIONS

1. The pseudo-static method is suitable for preliminary estimations and works well with the foundation having elsatic modulus as close to the dam material.
2. The Time History analyis is required to assess the performance for damage control level where limited cracking is allowed and have well defined performance crireria in
3. The NCSDP-2014 guidelines does not discuss the Safety Evaution Earthquake (SEE) as in ICOLD guidelines. NCSDP guidelines only discusses MCE (by detrministic approach) ot 1 in 2475 year earthquake for the Damage Control performance level.
4. The NCDP-2014 gudelines also do not discuss non linear analysis to assess the extent of cracking in case acceptance level do not match the Damage Control performance level.
5. There is need to classify the hazard level, in order to define the SEE for different hazard levels.