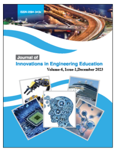

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Structural stability analysis of proposed Budhi Gandaki dam and optimization

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Abstract

High-rise arch dams are frequently employed in the construction of large storage-type hydropower projects due to their cost-effectiveness. This study presents the comparison in stress and deformation behavior of concrete dam and concrete face rock-fill dam under worst combination of loads. For illustrative purpose, the proposed double curvature arch dam of Budhigandaki Hydroelectric Project is chosen with some modifications. This study proposed the 3-D finite element method (FEM) for stress and deformation analysis of dam considering material non-linearity between concrete and rock-fill material following Drucker-Prager yield criteria. The proposed methodology is implemented through ANSYS 2021. The hydrodynamic pressure of reservoir water is modeled as added mass using Westergaard approach. The compressive and tensile stress developed in both types of dams are investigated and analyzed for different load combinations. The force acting at base of dam and deformation at crest level is also investigated. The results for both types of dam are found to be comparable which suggests that the wasteful volume of concrete can be replaced by consolidated soil (rock-fill) to decrease the overall construction cost of project.

1. Introduction

Nepal is a land limited but water rich country with potentiality of generating 83,000 MW of electricity but still the country is facing a high firm energy deficit [1]. This firm energy capacity can be increased by developing high storage dam hydropower projects. Because of its cost-effectiveness, high-rise arch dams are commonly used in the development of storage-type hydropower projects. Arch dams are economic and have a larger height-to-base-thickness ratio than other types of dams, despite some complexity in analysis and construction [2].

Prior to October 2000 perhaps hundreds or more concrete dams had been shaken by earthquakes felt at or near the dam site, but only about 20 had experienced recorded or estimated peak ground accelerations (PGA)s of 0.2g or higher. Up to 2013, there are about 20 dams that have experienced PGAs over 0.3g [3]. Concrete dams are designed to withstand a higher degree of seismic shaking than buildings and have performed well in the past and the overall performance of concrete dams during earthquakes has been satisfactory [4]. But due to poor tensile resistance of concrete material, strong ground vibrations during seismic activities may induce cracks in concrete dams and hence the potential dam failure could result in heavy loss in human life and damage in property because of incoming flood due to sudden burst of water. As a result, the structural stability analysis of concrete gravity dam is of great importance.

Among different methods for the analysis of dam, finite element method (FEM) has advantages in handling material non-homogeneity and non-linearity [5] so it is adopted for structural stability analysis in double curvature arch dam proposed for Budhi Gandaki Hydropower Project.

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2. Project description and considerations

The Budhi Gandaki Hydropower Project is located on the Budhi Gandaki River, approximately 2km from its confluence with Trishuli River at Benighat with estimated power generation capacity of 1200 MW. The double curvature arch dam has total height of 263 m, base width 80m and crest length 760 m [6].

The Budhi Gandaki dam project falls in active seismic region of possible future great earthquakes. A large amount of residual stress has to be released by an earthquake of magnitude, possibly not less than 8.5, with a rupture likely located along the Main Himalayan Thrust at 16 km depth, 20km to the north of the dam [7]. So the dam should be designed for relatively higher PGA. According to the bulletin N072 of the International Commission on Large Dams (ICOLD), two definitions of earthquake for which the dam should be designed or evaluated are recommended [8]:

- The Safety Evaluation Earthquake (SEE) – is the maximum level of ground motion for which a dam should be designed or analyzed. Damage to the dam, even extensive, may be acceptable, as long as no catastrophic flooding occurs. This corresponds to a very long return period, for example, 10,000 years.
- The Operating Basis Earthquake (OBE) – is the level of ground motion at the dam for which only minor damage is acceptable. The dam, appurtenant structures, and equipment should remain functional, and damage should be easily repairable. In many cases, OBE earthquakes are chosen with a minimum return period of 145 years (i.e., corresponds to a 50% probability of not being exceeded in 100 years).

From Deterministic Seismic Hazard Assessment the corresponding horizontal accelerations to be taken into account in the design of the project structures is []:

Operating Basis Earthquake (OBE): 0.6g
Safety Evaluation Earthquake (SEE): 1.2g

3. Objectives

- To investigate the behavior of a concrete dam in earthquake excitation using non-linear dynamic analysis.
- To find out optimized rock-fill core and concrete cover.

4. Finite Element Modelling of dam and material properties

4.1. Numerical modelling

This study is based on numerical model analysis of Budhigandaki dam using three dimensional Finite Element method. The finite element model is generated in ANSYS 2021 R2 for concrete dam and concrete face rock-fill dam considering material non-linearity. The concrete dam has been modeled with 23733 nodes forming 4160 isoparametric quadrilateral elements. Boundary conditions: All the nodes at contact of rock are fixed. All other nodes are free.

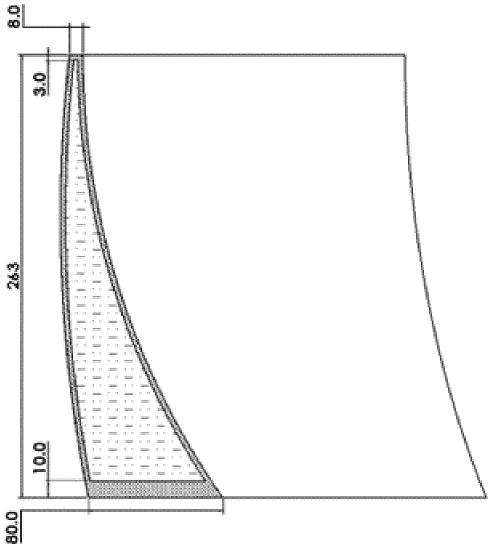

Figure 1: Schematic Diagram of Concrete face rock-fill dam

4.2. Material properties

As a dam body concrete of M25 grade is considered and consolidated soil is used as rock-fill material.

The Fluid-Structure Interaction (FSI) has been modelled according to the Westergaard (1933) [9];

$\mathrm{m}_{Ai} = \frac{7}{8}\rho\sqrt{H(H-z_i)}\,A_i$
where, H is water depth,
ρ is density of water,
z_i is height above base of dam, and
A_i is tributary surface area at point i/Nodal Surface area

A water mass has to be allocated to each node, in upstream face of the dam, to take into account the water effect during the earthquake

4.3. Failure criteria

Failure/Yield criterions are the assumptions on elastic material about how to determine the plastic deformation and define the elastic limit of material under combined

Table 1: Physical Properties of concrete and rock-fill material

Material	Modulus (MPa)	Density (kg/m^3)	Poisson's Ratio
Concrete	30000 (Elastic Modulus)	2300	0.18
Rock-fill material	58589	2899	0.28

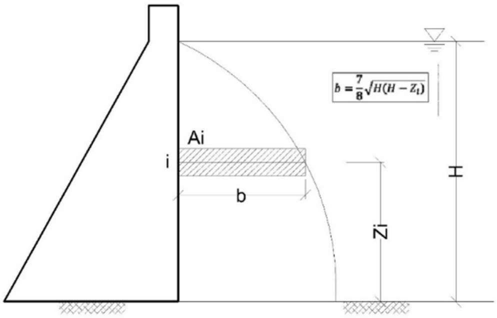

Figure 2: Westergaard added-mass representation (Source: EM-1110-2-6051)

state of stresses. The objective of mathematical theory of plasticity is to provide theoretical description of the relationship between stress and strain for a material which exhibits elasto-plastic response [10].

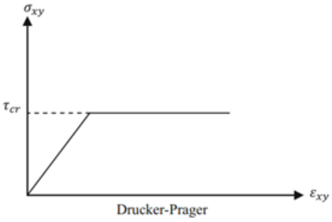

Figure 3: Stress-Strain Behavior in Plastic Case

Drucker-Prager Failure Criteria and uniaxial tension and compression damage variables are employed in non-linear analysis for concrete and rock-fill material in dam.

Table 2: Yield Surface Characteristics for Rock Fill Material [11]

Property	Value
Initial Inner Friction Angle	0.6°
Initial Cohesion	110 MPa
Dilatancy Angle	0.6°
Residual Inner Friction Angle	0.3°
Residual Cohesion	50 MPa

4.4. Loads

The dams have been analyzed for five different combinations of static and dynamic loads. The water levels considered for static analysis are the followings:

- Empty Reservoir
- Full Supply Level (540 masl)
- Minimum Operational Level (467 masl)

Seismic loads corresponding to OBE and SEE along with hydrodynamic load is considered for dynamic load combinations.

The load combinations studied for static and dynamic analyses are summarized in Table 3.

5. Results and discussions

The results of the dam calculations are presented in terms of deformation and stresses for static and dynamic calculations.

Table 4 and Table 5 presents maximum deformation in dam, maximum and minimum compressive stress in dam for five different combinations of load for concrete dam and concrete face rock-fill dam respectively. The maximum deformation in concrete dam is 308.92 mm for load combination – V (when reservoir is reaching FSL El. 540 under SEE) and to that of concrete face rock-fill dam is 408.5 mm under load combination – V. For static load combination (I, II and III), the higher deformation and stresses are observed when reservoir level is reaching FSL.

Dam behavior during OBE:

The dynamic behavior during OBE shows that:

- Compressive Stress: Up to 24.582 MPa (for concrete dam) and 28.74 MPa (for concrete face rock-fill dam) at FSL 540
- Tensile Stress: Up to 15.443 MPa (for concrete dam) and 19.322 MPa (for concrete face rock-fill dam) at FSL 540

Feasibility Study and Detailed Design of BudhiGandaki HPP (Phase 3: Final Detailed Design Report VOL 1 Main Report, 2015) [6] suggests maximum compressive stress up to 26.7 MPa with a full reservoir supply and tensile stress up to 13.8 MPa during OBE. The results obtained during the analysis are comparable to the result obtained from Detail Design Report of Budhigandaki

Table 3: Load Combinations

	Case	Self-weight	Empty	FSL 540	MOL 467	OBE	SEE
Combination-I	Static-Empty	*x*	*x*				
Combination-II	Static-FSL 540	*x*		*x*			
Combination-III	Static-MOL 467	*x*			*x*		
Combination-IV	Dynamic-FSL 540-OBE	*x*		*x*		*x*	
Combination-V	Dynamic FSL 540-SEE	*x*		*x*			*x*

Table 4: Maximum deformation of dam, maximum compressive and tensile stress in concrete dam without rock-fill material for static and dynamic load combinations

Results	Load Combinations				
	Static			Dynamic	
	I	II	III	IV	V
	Empty Reservoir	FSL 540 masl	MOL 467 masl	FSL 540-OBE	FSL 540-SEE
Maximum deformation (mm)	40.773	261.71	36.1	200.77	308.92
Maximum Compressive Stress (MPa)	15.204	19.639	6.145	24.582	34.532
Maximum Tensile Stress (Mpa)	1.904	4.112	1.311	15.443	19.232

HPP for concrete dam without rock-fill. But for concrete face rock-fill dam, the stresses (especially tensile stress) seems to be higher than compared to design report. To be noted that the high level of stress observed will occur during a very short time. Moreover, non-linear effects (tensions, joints openings) are not represented in this model, and must reduce the level of stress calculated. Therefore, the dam behavior in response to OBE is satisfactory.

Dam behavior during SEE:

Compared to OBE, the dynamic response to SEE increases in term of extreme values of stress (compression and tensile):

- Compressive Stress: Up to 34.532 MPa (for concrete dam) and 33.593 MPa (for concrete face rock-fill dam) at FSL 540
- Tensile Stress: Up to 19.232 MPa (for concrete dam) and 21.15 MPa (for concrete face rock-fill dam) at FSL 540

Feasibility Study and Detailed Design of BudhiGandaki HPP (Phase 3: Final Detailed Design Report VOL 1 Main Report, 2015)[6] suggests maximum compressive stress up to 36 MPa with a full reservoir supply and tensile stress up to 20.3 MPa during SEE. The results obtained during the analysis are comparable to the result obtained from Detail Design Report of Budhigandaki HPP for concrete dam with and without rock-fill.

The higher value of tensile stress for concrete dam with rock-fill gives evidence of non-linear effects in concrete and rock-fill material and their joint. But these stress levels will occur only during very short times. Still special attention should be given at the contact between two materials during construction.

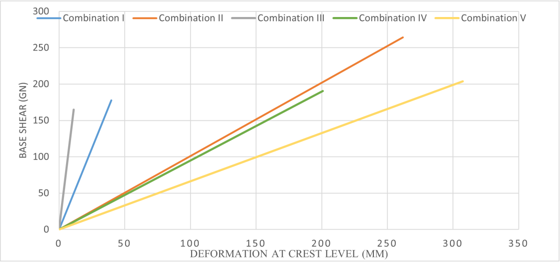

Figure 4: Plot of Base shear vs deformation at crest level for different load combination (concrete dam)

The plot of force reaction at base of the dam versus deformation at crest level for both concrete dam and concrete face rock-fill dam is presented in Figure 4 and Figure 5 respectively. The force-deformation curve for concrete dam is linear for all combination of loads which illustrates the linear analysis for concrete dam. But the force-deformation relation for concrete face rock-fill dam is found to be non-linear which illustrates non-linearity effect in dam due to composite material properties (i.e. concrete and rock-fill material). In both cases the deformation is maximum for load combination V (dynamic loading considering SEE). Figure 6 and Figure 7 presents the variation of horizontal displacement of dam obtained from linear and non-linear analysis of both concrete dam and concrete face rock-fill dam respectively. Figure 6 indicates that for concrete dam the extent of deformation increases with dam elevation and

Table 5: Maximum deformation of dam, maximum compressive and tensile stress in concrete face rock-fill dam for static and dynamic load combinations

Results	**Load Combinations**				
	Static			**Dynamic**	
	I	II	III	IV	V
	Empty Reservoir	FSL 540 masl	MOL 467 masl	FSL 540-OBE	FSL 540-SEE
Maximum deformation (mm)	79.836	361.47	106.75	210.41	408.5
Maximum Compressive Stress (MPa)	31.641	33.712	32.423	28.74	33.593
Maximum Tensile Stress (Mpa)	3.147	8.24	5.113	19.322	21.15

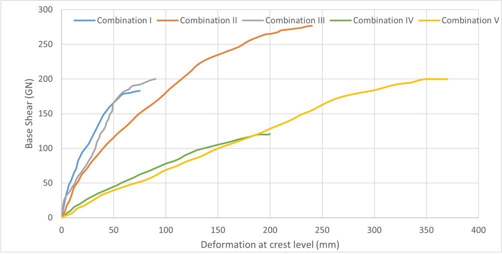

Figure 5: Plot of Base shear vs deformation at crest level for different load combination (concrete face rock-fill dam)

maximum deformation is observed at crest level for all load combinations. The deformation of dam is maximum for load combination V (dynamic loading considering SEE- PGA 1.2 g). Considering only static load combinations (combination I, II and III), the maximum deformation is for load combination II (FSL 540masl). Vertical displacement in dam increases upon increasing the load. But due to curved shape of the dam, the deformation for empty reservoir condition is more than MOL 467 masl since the hydrostatic force reduces the vertical displacement due to gravitational load. With further increase in reservoir level, displacement at crest level increases.

For concrete face rock-fill dam, the vertical displacement is proportional to elevation of dam but contradictory to previous case, for concrete face rock-fill dam the maximum deformation is observed below the crest level (possibly just below the contact between concrete and rock-fill material) for all load combinations as seen in Figure 7. This might be due to poor contact between concrete and rock-fill material. So special attention must be given during construction at the contact portion between concrete and rock-fill material.

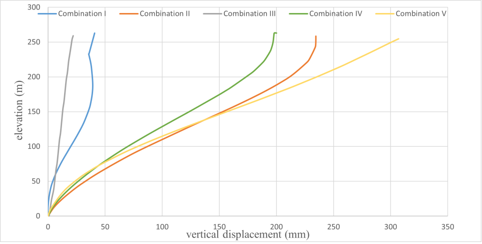

Figure 6: vertical displacement of dam with respect to elevation of dam for different load combinations (concrete dam)

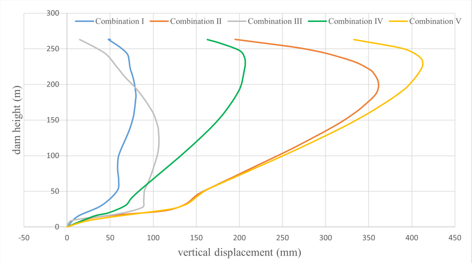

Figure 7: Vertical displacement of dam with respect to elevation of dam for different load combinations (concrete face rock-fill dam)

6. Economical Analysis

The economic analysis is based on district rate of Dhading district for Fiscal Year 2078/2079 for both concrete dam and concrete face rock-fill dam. This cost estimate includes only concreting works and rock-fill material for dam body.

Table 6 and Table 7 shows the approximate cost estimate for basic civil materials used in concrete dam and concrete face rock-fill dam. The total cost of civil material works for concrete dam is calculated 1514.89 Million USD and to that of concrete face rock-fill dam is 441.94 Million USD which is almost 3.4 times lesser than concrete dam.

Table 6: Cost Estimate for concreting works in concrete dam body

SN	Description	Rate (Rs.)	Quantity	Amount (Rs.)
1	Plain Cement Concrete (PCC) for RCC works M25 (1:1:2) for slab/lintels/columns/beams with approved quality of cement, sand and machine crushed stone aggregate including supply of materials, mixing, laying, curing the work at least 7 days etc all complete as per approved drawing specification and instruction of site engineer.	18,250.59	7,877,600.00 m^3	143,770,825,195.97
2	TMT steel reinforcement bar of Fe 500 grade including supplying, straightening, cleaning, cutting, binding and fixing in position with annealed tying binding wire all complete as per approved drawing specification and instruction of site engineer	126,247.00	393,880.00 Metric tons	49,726,168,360.00
	Estimated cost for concreting in concrete dam		Rs.	193,496,993,555.97
			MUSD	1,514.89

Table 7: Cost Estimate for materials in concrete face rock-fill dam body

SN	Description	Rate (Rs.)	Quantity	Amount (Rs.)
1	Plain Cement Concrete (PCC) for RCC works M25 (1:1:2) for slab/lintels/columns/beams with approved quality of cement, sand and machine crushed stone aggregate including supply of materials, mixing, laying, curing the work at least 7 days etc all complete as per approved drawing specification and instruction of site engineer.	18,250.59	1,954,700.00	35,674,422,668.14
2	TMT steel reinforcement bar of Fe 500 grade including supplying, straightening, cleaning, cutting, binding and fixing in position with annealed tying binding wire all complete as per approved drawing specification and instruction of site engineer	126,247.00	136,829.00	17,274,250,763.00
3	Earth filling in dam with watering, ramming including supply of filling materials within 50m distance all complete as per approved drawing, specification and instruction of site engineer.	591.00	5,922,800.00	3,500,374,800.00
	Estimated cost for concreting in concrete dam		Rs.	56,449,048,231.14
			MUSD	441.94

7. Conclusions

Based on the results presented in this study, the following conclusions can be drawn.

a. The vertical displacement of the dam increases with an increase in dam elevation, and the maximum deformation is observed at the crest level for the worst combination of load (Combination-

V) in a concrete dam. However, for a concrete face rock-fill dam, the maximum deformation is observed just below the contact between concrete and rock-fill material for all load combinations. Therefore, special attention should be given to the contact region during the construction of a concrete face rock-fill dam.

b. The compressive and tensile stresses in a concrete face rock-fill dam are found to be slightly higher (but comparable with the design report) than in a concrete dam. However, this higher tensile stress will occur during a very short time. Moreover, nonlinear effects such as joints, joint openings, drainage gallery, etc., must reduce the level of stress calculated, which has not been represented in the model.

c. Contrary to the slightly higher stresses in a concrete face rock-fill dam (which can be minimized by providing tension joints, joint openings), the economic analysis shows that the overall cost of the project can significantly be reduced by replacing a wasteful amount of concrete with consolidated soil material as rock-fill.

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