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Research Paper

Stress and Deformation Analysis of Powerhouse Cavern of Rasuwagadhi Hydroelectric Project, Rasuwa, Central Nepal

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A B S T R A C T

An underground powerhouse cavern of Rasuwagadhi Hydroelectric project lies in Bhotekoshi River, northern part of Rasuwa, Central Nepal. Letter box shaped cavern of maximum dimension 76.6 m in length, 15.3 m in width and 39.65 m in height is situated at the depth of 320 m with its longitudinal axis of east to west. Geologically, the area belongs to the rock of the quartzite with intercalation of dark grey schist of Higher Himalayan succession. To determine different properties unit weight, point load strengths of rock samples were done for the model analysis. The rock mass properties based on GSI were recorded in different chainage of cavern. By using various geotechnical property, and numerical methods deformation analysis of cavern was done. The analyses were carried by using 3-Dimensional and 2-Dimensional numerical modeling from Examine^{3D} and Phase^{2} softwares and then the modeling result were compared with the instrumented data from multi-point borehole extensometers. The deformation from both numerical model and instrumental data showed similar results.

1. Introduction

Himalaya – the young and restless giant (Valdiya, 1998) is characterized by fragile nature of terrain and rugged topography, complex geological structures, active tectonic process and seismic activity. These phenomena affect the construction and stability of large underground structures. To decrease these adverse condition and their negative impact, there are several considerations that need to be taken into account which includes local geology, earthquake forces, caverns (depth, location, and geometry), deformation and rock stress conditions, excavation sequence, techniques and influence of excavation methods on rock mass characteristics.

Variety of engineering activities requires underground excavation. Because of dimensions and lack of surface the requirements of high volume underground structures are increasing. A large underground structure cavern that has an increasing use in hydropower, oil storage and underground facilities. The larger size of these structures amplifies the instability compared to other underground openings. The ground in its natural state is in equilibrium stress state which is disturbed once the excavation is done. Such changes in stress conditions could compromise the stability of the structure, hence, the analysis of deformation and rock properties is necessary. This study is intended to carry out the deformation analysis three dimensionally and two dimensionally by Boundary Element Method and Finite Element Methods.

This research work presents the deformation analysis of Rasuwagadhi Hydeoelectric Project. Which is situated in Thuman and Timure village of Rasuwa district, Central Nepal. The project is run-of-river with design flow capacity of 80 m^3/s, total water head of 168 m, three

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counter type units with the total installed capacity of 111 MW. The project consists of underground powerhouse system situated on right bank of the Bhotekoshi River. The maximum dimension of powerhouse in this project is 76.6 m in length, 15.3 m in width and 39.65 m in height situated at the depth of 320m with its longitudinal axis of east to west. Three penstocks in upstream and three bus bar tunnel and three tailrace tunnel in downstream are connected with powerhouse. Geologically, the area belongs to the rock of grey colored medium grained medium to thinly foliated quartzite with intercalation of dark grey thinly foliated schist at places. This research work help to analyze stability condition and deformation analysis of powerhouse cavern. The analyses were carried by using 3-Dimensional and 2-Dimensional numerical modeling from examine^{3D} and Phase^{2} software's and then the modeling result were compared with the instrumented data from multi-point borehole extensometers.

Several conditions and parameters are responsible for tunnel deformation behavior. Schubert and Schubert (1993), Schubert (1996), and Steindorfer (1998) have studied the effect of geological structure on deformational behavior of rocks surrounding tunnel. Tsesarsky and Hatzor (2006) and Panthee et al. (2016) showed that the joint parameters are responsible for tunnel deformation. Deformability of any rock mass has significant influence in underground deformation. Panthee et al. (2018) revealed that the deformability of rock mass varies with rock mass classification.

The primary objective of the study is to analyze deformation behavior of powerhouse cavern of Rasuwagadhi Hydroelectric Project and the result obtained from numerical model is compared with instrumented data.

2. Methodology

Laboratory work and field work was done to study the geotechnical properties of rock mass of powerhouse cavern. For the laboratory analysis, rock samples were collected from different chainage of cavern and unit weight and point load test were done in laboratory. The point load strength tests of lump samples were calculated from suggested method of ISRM 1985. Bieniawski 1975 suggested relationship between UCS and point load strength which is used to calculate UCS of rock sample of powerhouse cavern. In field studies the rock mass classification was done in 5 m chainage interval of Powerhouse Cavern. Bieniawski's Geomechanical Classification System (Bieniawski 1989) was used to calculate RMR. Deformation Modulus was calculated based on RMR (Bieniawski 1978). Geological Strength Index (GSI) was calculated based on Sonmez and Ulusay (1999) by using different parameters and ratings such as surface condition rating (SCR) and structure rating (SR). This method of GSI calculation uses volumetric joint count (Jv) and RMR scheme (eg: roughness, weathering and infilling). The SR and SCR can be calculated by following equations [1] and [2].

$$SR = -17.5\ln(J_v) + 79.8 \qquad [1]$$

$$SCR = Rr + Rw + Rf \qquad [2]$$

Rock mass properties characterized by the biaxial failure criteria after Hoek and Brown (1980) presented the following empirical rock failure criterion for jointed rock masses.

$$\sigma_1' = \sigma_3' + UCS\left(\frac{m\sigma_3'}{UCS} + S\right)^a \qquad [3]$$

For intact rock that makes up the rock mass, equation [3] simplifies to

$$\sigma_1' = \sigma_3' + UCS\left(\frac{m\sigma_3'}{UCS} + S\right)^a \qquad [4]$$

The constant a, s and m can be expressed as follows:

$$a = \frac{1}{2} + \frac{1}{6}(e^{-GSI/15} - e^{-20/3} \qquad [5]$$

$$m = m_i \exp\left(\frac{GSI - 100}{28 - 14D}\right) \qquad [6]$$

$$s = exp\left(\frac{GSI - 100}{9 - 3D}\right) \qquad [7]$$

Where σ_1 is maximum effective principal stress, σ_2 is minimum effective principal stresses, σ_3 is uniaxial compressive strength of the intact rock material, m and s are the material constant for the intact rock; GSI is the Geological strength index. mi is the frictional characteristics of the component minerals in rock elements; D is the disturbance factor depending upon the degree of disturbance to which the rock mass has been subjected by blast damage and stress relaxation. It varies from 0 for undisturbed in-situ rock masses to 1 for very disturbed rock masses.

2.1 Analysis tools: Examine^{3D} and Phase^{2}

For deformation analysis different geotechnical and geo-mechanical data taken from field work and laboratory work were used in software like examinee^{3D} 4.0 and phase^2 8.0 software. For 3D geometrical modeling Examine^{3D}, for boundary element analysis COMPUTE^{3D-BEM} and for 2D modeling Phase^2 software were used.

Examine^{3D}; a 3D stress analysis for underground excavation is a computer-aided engineering analysis program for underground excavation structures in rock. This program is used for a general purpose for the modeling and visualization of three dimensional geometry, finite element data and micro seismic monitoring data for mines. In this program most of its functionalities are generated towards the generation of input data for, and the visualization of analysis results from, a companion program COMPUTE^{3D-BEM} (a three dimensional boundary element stress analysis program), which is supplied with Examine^{3D}.

Phase^2 is a two dimensional finite element program for calculating stress and displacements in underground or surface excavations. This program can be used for wide range of engineering works, including complex tunneling problems in weak rock, underground powerhouse, caverns, surface excavations such as open pit mines, and slopes in rock or soil. It can be used for both elastic and plastic analysis of excavations.

3. Results

3.1 Data collections

For the deformation analysis different geotechnical and geo mechanical data were taken in field and laboratory. Some data were obtained from Rasuwagadhi Hydroelectric Project. The data used for numerical modelling is given on **Table 1**.

3.2 Boundary Element Method result

The deformation analyses were performed in many section by Examine^{3D} software. The vertical section perpendicular to cavern axis cuts into two locations one at chainage (0+016.95) m and another is at (0+047.95) m. The horizontal cut section is at the elevation of 1635.05 m and another vertical cut section is axis of cavern. Theses cut section are same as the location of multipoint borehole extensometer inside the powerhouse cavern. In the model diagram, the northern part wall is upstream wall and the southern part wall represents the downstream wall. The chainage is start from the western face wall of the cavern.

At chainage 0+16.95 m the displacement of the outer part at 2 m, 5 m and 15 m from the excavation boundary point were analyzed from **Fig. 1**. These points refer the point where extensometer were installed. At the upstream wall the displacement magnitude of (20-30) mm is at 2 m, (20-30) mm at 5 m and (10-20) mm at 15 m from the excavation boundary of cavern, similarly the value of displacement magnitude (30-40) mm at 2 m, (20-30) mm at 5 m and 15 m from the downstream wall. In the crown part the magnitude of (10 to 20) mm displacement is

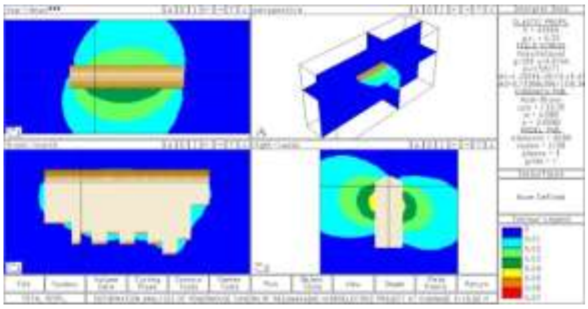

Fig. 1. Total displacement distribution at chainage 0+16.95 m

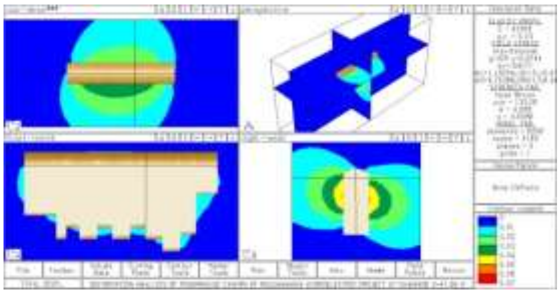

Fig. 2. Total displacement distribution at chainage 0+47.95 m

Table 1. Geotechnical and geomechanical parameters used in numerical model

Parameters	Values
Geological Strength Index	57
Unit weight	24.40 KN/M^3
UCS	133.26 MPa
Young's Modulus	10000 MPa
Poisson Ratio	0.23
Surface Elevation	320 m
m	4.966
m_i	23
D	0
s	0.0086
Tensile strength	0.08
Friction angle	50^0
Cohesion	1.7
σ_1	10.47 MPa
σ_2	9.01 MPa
σ_3	6.34 MPa

analyze at 2 m, (0-10) mm displacement is at 5 m and at 15 m from the excavation boundary from the crown part of the cavern were analyze.

At chainage 0+47.95 m, the displacement of the outer part at 2 m, 5 m and 15 m from the excavation boundary point were analyzed from **Fig. 2**. These points refer the point where extensometer was installed. At the upstream wall the displacement magnitude of (20 -30) mm is at 2 m and 5 m and (10-20) mm at 15 m from the excavation boundary of cavern, similarly the value of displacement magnitude (30-40) mm at 2 m, (20-30) mm at 5 m and 15 m from the downstream wall. In the crown part the magnitude of (10-20) mm displacement is analyzed at 2 m, (0-10) mm displacement is at 5 m and 15 m from the excavation boundary from the crown part of the cavern.

3.3 Finite Element Method result

Total displacement of the cavern outside the excavation is shown in **Fig. 3** at chainage 0+16.95 m maximum displacement distribution is centered at both the walls i.e. 37.5 mm. The displacement distribution shows butterfly type two lobes on each wall where maximum displacement is observed near the wall and gradually decreases as the area gets distal from the wall.

The magnitude of total displacement distribution at 2 m, 5 m and 15 m from boundary at upstream wall is (32.5-35) mm, (27.5-32.5) mm and (17.5-22.5) mm at the downstream wall the total displacement at 2 m, 5 m and 15 m is (35-37.5) mm, (30-35) mm and (17.5 - 22.5) mm. At the crown part the maximum value of displacement at 2 m is (0- 5) mm, at 5 m is (5-7.5) mm and at 15 m the value is (0-3.5mm).

In **Fig. 4** at chainage 47.95 m maximum displacement distribution is centered at both the walls i.e. 50 mm. The displacement distribution shows butterfly type two lobes on each wall where maximum displacement is observed near the wall and gradually decreases as the area gets distal from the wall. The magnitude of total displacement distribution at 2 m, 5 m and 15 m from boundary at upstream wall is (33-36) mm, (33-50) mm and (21-27) mm at the downstream wall the total displacement at 2 m, 5 m and 15 m is (36-42) mm, (30-36) mm and (21-27) mm at the crown part the maximum value of displacement at 2 m is (0-3) mm, at 5 m is (6-9) mm and at 15 m the value is (0-3 mm).

3.4 Distribution of Displacements after installation of support

Distribution of displacements after the installation of support was analyzed. The supports have been designed based on the Q-system. The details of support system provided by the project are presented in **Table 2**, The support provided by the shotcrete was not included

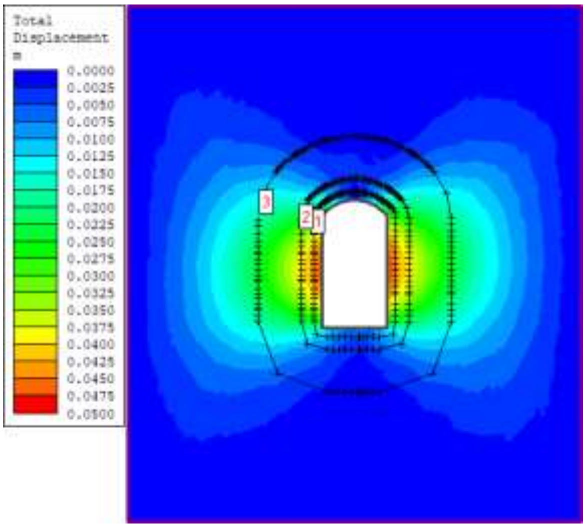

Fig. 3. Total displacement distribution at chainage 0+16.95 m

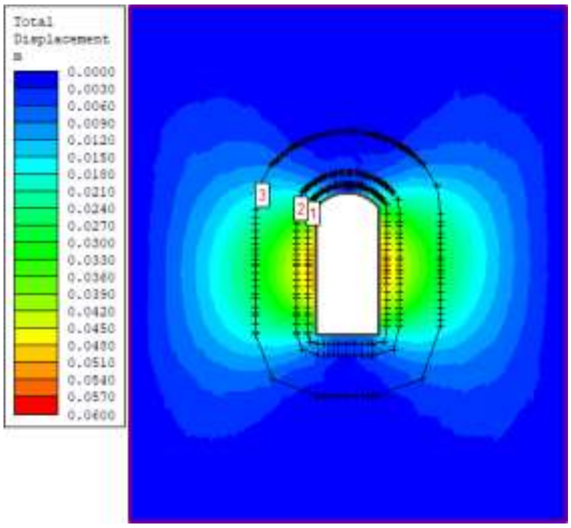

Fig. 4. Displacement at 2 m, 5 m and 15 m from outside the boundary of cavern at chainage 0+47.95 m

during numerical modelling.

In **Fig. 5** at chainage 16.95 m. The displacement distribution shows butterfly type two lobes on each wall where maximum displacement is observed near the wall and gradually decreases as the area gets distal from the wall. The magnitude of total displacement distribution at 2 m, 5 m and 15 m from boundary at upstream wall is (6.5-7.2) mm, (5.2-6.5) mm and (4.6-5.9) mm at the downstream wall the total displacement at 2 m, 5 m and 15 m is (6.5-7.2) mm, (5.2-6.5) mm and (3.3 to 4.6) mm at the crown part the maximum value of displacement at 2 m, 5 m and 15 m is (0-0.7) mm.

In **Fig. 6** at chainage 0+47.95 m. The displacement distribution shows butterfly type two lobes on each wallwhere maximum displacement is observed near the wall and gradually decreases as the area gets distal from the retaining wall encouraged the slupture.

Table 2. Geotechnical and geomechanical parameters used in numerical model

Structure	Roof		Wall	
	Grouted rock bolt	Shotcrete	Grouted Bar	Shotcrete
Powerhouse	8 m@1.5*1.3 m	150 mm	6 m@2.3 m	100 mm
Material properties				
Diameter 25 mm	Modulus 200000 MPa	Tensile capacity 0.21 MN	Residual tensile capacity 0.021	

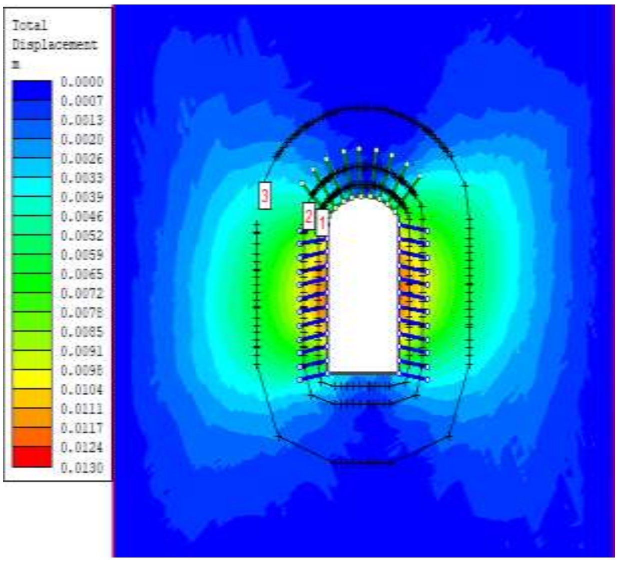

Fig. 5. Displacement at 2 m, 5 m and 15 m from outside the of cavern at chainage 0+16.95 m after support installation

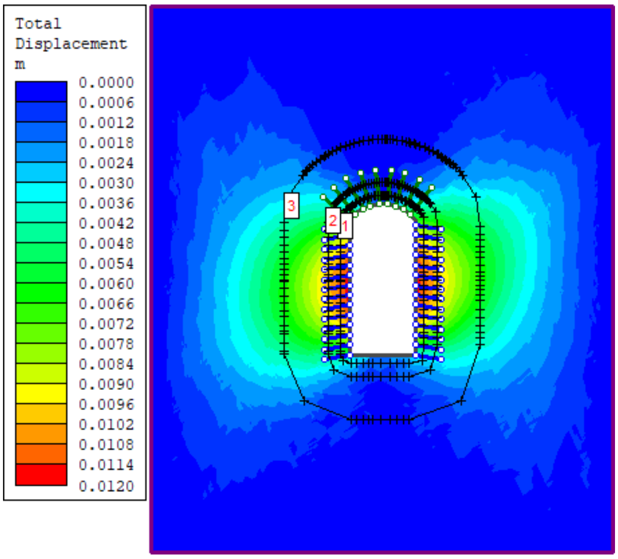

Fig. 6. Displacement at 2 m, 5 m and 15 m from outside the boundary of cavern at chainage 0+47.95 m after support installation

The magnitude of total displacement distribution at 2 m, 5 m and 15 m from boundary at upstream wall is (7.2- 7.8) mm, (6.6-7.8) mm and (4.8-6) mm. At the downstream wall the total displacement at 2 m, 5 m and 15 m is (7.2-7.8) mm, (6.6-7.8) mm and (3.6 to 4.8) mm. At the crown part the maximum value of displacement at 2 m, 5 m and 15 m is (0-0.6).

3.5 Deformation monitoring analysis from multipoint extensometer

In the powerhouse cavern of Rasuwagadhi hydroelectric project six multipoint extensometer were installed at two chainage: 0+16.95 m and 0+47.95 m. In each chainage, depth of anchor are 2 m, 5 m and 15 m which were installed at the elevation 1640.65 m of crown central line, 1635.05 m of D/S wall (left site) and at elevation of 1635.05 m of U/S wall right side. The modulus value was read in the multipoint extensometer then by analyzing this value deformation values were determined. At Chainage 0 + 16.95 m, the corresponding maximum deformation is -0.736 mm, -0.533 mm, 0.972 mm for the multipoint extensometer of 2 m, 5 m, and 15 m on a crown of elevation 1640.65 m. At downstream wall of elevation 1635.05 m, the maximum deformation is 6.5 mm, 14.5 mm and 15.2 mm of extensometer 2 m, 5 m and 15 m, for the multipoint extensometer of depth 2 m 5 m and 15 m on upstream at elevation 1635.05 m, the maximum deformation is 7.9 mm, 9.7 mm and 10.1 mm.

At chainage 0+47.95 m, the corresponding deformation is -0.4 mm, 0.6 mm, 0.4 for the multipoint extensometer of 2 m, 5 m and 15 m at crown of elevation 1640.65 m. The corresponding deformation of multipoint extensometer 2 m, 5 m and 15 m at downstream of elevation 1640.65 m is 2.5 mm, 9.6 mm, 17.4 mm. At the upstream wall of chainage 1640.65 m, the corresponding maximum deformation is 3.4 mm, 4.9 mm 4.3 mm for the multipoint extensometer of 2 m, 5 m and 15 m.

3.6 Comparison of displacement result from various model and condition with extensometer data

The maximum displacement yielded in the roof (crown) and sidewalls were (10-20) mm and (30-40) mm by Examine^{3D}, (6-9) mm and (33-50) mm in Phase^2. Likewise, the maximum displacement shown by extensometer was (17.4) mm in the wall and 0.6 mm in the crown. The deformation values are decreases in sidewall and crown after the support installation. The maximum displacement in roof and side wall after the support installation was (0-0.7) and (7.2-7.8) by Phase^2. The detailed comparison between different results is shown in **Table 3**, in which the deformation value by examine^{3D} Phase^2 and extensometer data were analysis, it showed similar result, but in some cases, variation of data may be due to influence of excavated transformer carven which gives reaction to power house carven.

Table 3. Comparison of displacement result from various model and condition with extensometer data

Depth of anchor	analysis from	Chainage 0+16.95 m			Chainage 0+47.95 m		
		Upstream	Down stream	Crown	Upstream	Down stream	Crown
2 m	EXAMINE^{3D}	20-30	30-40	10-20	20-30	30-40	10-20
5 m		20-30	20-30	0-10	20-30	20-30	0-10
15 m		10-20	20-30	0-10	10-20	20-30	0-10
2 m	Phase^2	32.5-35	35-37.5	0-5	33-36	36-42	0-3
5 m		27.5-32.5	30-35	5-7.5	33-50	30-36	6-9
15 m		17.5-22.5	17.5-22.5	0-3.5	21-27	21-27	0-3
2 m	Phase^2 with support installation	6.5-7.2	6.5-7.2	0-0.7	7.2-7.8	7.2-7.8	0-0.6
5 m		5.2-6.5	5.2-6.5	0-0.7	6.6-7.8	6.6-7.8	0-0.6
15 m		4.6-5.9	3.3-4.6	0-0.7	4.8-6	3.6-4.8	0-0.6
2 m	Ext measure data	7.9	6.5	-0.736	3.4	2.5	-0.4
5 m		9.7	14.5	-0.533	4.9	9.6	0.6
15 m		10.1	15.2	0.972	4.3	17.4	0.4

4. Conclusions

The numerical modeling was performed in FEM and BEM by phase^2 and examine^{3D}. These were compared with the data from extensometer. Basically, the displacement is the parameter that was analyzed by all these. Analysis was carried out by comparing different methods and their compatibility in data was finally studied. At first, analysis on examine^{3D} was done. Here, data were computed from the point (2 m, 5 m and 15 m): these point refers the point where extensometer were installed. Likewise, phase^2 was used for similar data computations with same reference points. Comparing the data obtained from examine^{3D} and phase^{2D}, we get the analogous output: the condition here is without support installation. Then, support data was analyzed in phase^{2D}: support data is based on the project support data installed in the field. The result was compared with the extensometer data and it showed similar results thus, verifying the analysis done based on these numerical models.

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