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Understanding the Structural Stability of the Tehri Dam: A Comprehensive Analysis

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Abstract

The Tehri dam is the highest dam in India. The height of dam is 260 m. It is situated on the Himalayan region which is in earthquake prone region. A Sengupta in 2006 found that the predicted deformation due to an M=7.0 earthquake are not large enough to compromise the safety of the dam. However the deformation predicted by Seed and Makdisi's method, and Bureau's method for an M=8.5 earthquake are large enough to compromise the safety of dam. The Seed and Makdisi's procedure predicted the maximum deformations, while the minimum deformations are computed by Jansen's method. In the present work, the stability analysis four type of analysis such as structural stability analysis, Centre of slip circle by genetic algorithm, stability of dam under sudden draw down condition and dynamic analysis are considered. Structural stability analysis have done by Fellenius method and radial slice method. In Fellenius method three number of slip circles are taken which cuts the slope at two third distances from top of slope. By finding the resisting moment and driving moment the factor of safety is found that for first slip circle, second slip circle and third slip circle are 1.997,2.103 and 2.045 respectively. In the radial slice method the failure wages are divided into number of slice radially by joining the line from the center of slip circle to the arch. The factor of safety is found as 1.15. The coordinate of Centre of slip circle has been found by genetic algorithm. In order to validate the genetic algorithm method, the input data has been imported from the results of graphical method. The centre coordinate of slip circle is obtained as (210,485) which was found to be very close to the value of Centre of slip circle by graphical method. Numerical analysis has been made by using commercially available software PLAXIS under sudden draw down condition. The deformation in X-direction was 16.99 m. Dynamic analysis has been used by PLAXIS software and the total deformation is obtained as 0.4150 m. The total displacement is found to be very much closed to the published result by A. Sengupta, (2006).

Keywords: word; Slope stability Analysis, Dynamic Analysis, Factor of Safety, Tehri Dam

INTRODUCTION

Tehri Dam was selected for this investigation because of its location on a mountain range in an earthquake-prone area. On the Bhagirathi stream in Tehri in Uttarakhand, India, there may be a multi-purpose dam called Tehri Dam made of rock and earth fill. The Tehri Dam is located in the Uttaranchal state, 200 kilometres northeast of Old Delhi. The dam is India's highest dam and ranks seventh in the world in terms of height at 260 metres (855 feet). A reservoir for agriculture, city water use, and the production of 1300,000 horsepower of electricity is kept in place by the Tehri Dam. The dam's construction began in 1997; portion one was finished in 2006. In 1996, the chamber was completed. The cost of construction was $1 billion [1–12].

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THDC Republic of India Ltd. owns the dam. The Tehri Hydro Development Corporation (THDC) may be a joint venture between the Uttaranchal and Republic of India governments. Soviet expertise and funding of about $416 million were supplied to the project in 1986 via an Indo-Soviet agreement. In addition, the Tehri Development Project comprises the 97-meter-tall Koteshwar Dam, which is being built 14 kilometres downstream of Tehri Dam. The 400 Megawatt Koteshwar Dam could entirely or partially submerge sixteen villages. It supplies Old Delhi, the province of Uttaranchal, and 270 million gallons of daily drinking water. Also, it provides stabilization for the 600,000 hectares of land's current irrigation system [12–17].

Technical Details

Type of Dam: Embankment, earth and rock-fill

- River: Bhagirathi River
- Height: 260.5 m (855 ft)
- Length: 575 m (1,886 ft)
- Width (Crest): 20 m (66 ft)
- Width (Base): 1,128 m (3,701 ft)

Objective

The objective of the present work is to study the static and dynamic stability of the Tehri dam

Scope of the studies

- Determination of structural stability by radial slice method and Fellinious method
- Determination of the Centre of the slip circle by a genetic algorithm through MATLAB programming
- Stability of the Tehri dam under sudden draw down condition by PLAXIS software
- Dynamic analysis: Determination of deformation by Finite element method through commercially available software PLAXIS

SITE CONDITION AND DAM DESIGN

Rocks and External Materials Used–Consequences

Since they are 65% clayey, the Tehri dam rocks are fractured and rife with earthquake fault lines. The sheer Weight of the water might reactivate these fault lines. There are indications of a sharp rise in earthquake frequency close to and far from the dam. Instead, the rock layers will be under strain from the expanding soil layer, which will eventually cause them to crack. The moist soil layers also contract as they dry. This cycle of expanding and drying could cause the rock layer to break even more and intensify the mechanisms that cause sand to be crushed [18]. The Bhagirathi river and the Bhilangana watercourse converge 1.5 kilometres downstream, where the Tehri dam was built. The Chandpur phyllite type of rock predominates around the stream gorge. In all likelihood, Chandpur's phyllite has collapsed and is of a greyish, inexperienced tint. The degree of tectonic deformation in the rocks here varies. Grade I Phyllites are overwhelmingly sandy and have a significant character (describing rocks or deposits composed of sand grains or sandy texture). Phyllites of Grade II are mostly clayey and are typically weather-beaten, thinly foliated, sheared, and broken. Phyllites of Grade III are primarily clayey and are typically weather-beaten, thinly foliated, cropped, and fractured. The weakest bedrock in the gorge is sheared phyllites. There was little to no real in-tunnel engineering experience available anywhere once the Tehri dam tunnelling project got underway, let an alone range of mountains [19].

Filling the Earth-Rock-fill Tehri Dam

Before building a dam, it is crucial to consider the rock's porousness (hydraulic conductivity). Dependence on a median price won't work when there is a significant variance in porousness, as there is for the Tehri rocks, especially if one is aware that collapse occurs at the weakest link. The primary prerequisite for the hydraulic physical phenomenon of rocks is the separation apertures inside the rocks. The hydraulic physical phenomena may be significantly affected by changes in apertures caused by stress, necessitating tests like the so-called Lugeon tests. One of the main disadvantages of the Lugeon check is that each review is limited to a space of only 100 m^2 and a height of 10 m. In other words, it was impossible to anticipate the findings of Lugeon experiments on the Phyllite rocks near the dam site to provide accurate engineering information. The Tehri dam's cross-section measures 575 metres across the natural depression at the crest while measuring 1,000 metres at the bottom and over 20 metres at the crest in the upstream-downstream direction. The design calls for a flat-topped shell of graded gravel with blasted rock that must be massive and mostly quartz, surrounded by a mothproof core made of clayey elements. The stability of the dam to earthquakes, the stability of the surrounding slopes to mudslides and collapse similarly on settlement, however, lacks certified experience. The delicate nature of the rock fills in comparison to the requirement for rocks with surfaces between 25 and 600 metric linear units or between 1" and 2 feet in size. The boulders utilized for the rock fills came from the new Dobata area, located about five kilometres upstream from the dam's location on the right bank of the Bhagirathi. The new Dobata borrows from the Tehri Garhwal district. These rocks were metamorphosed from rock arenaceous rock and are classified technically as tabular grains, equigranular, granoblastic (fragments are uneven) in texture, and rocks. The main difference between the New Dobata Borrow and the Recent Dobata Borrow is that the former had approximately 98% white quartz.

In comparison, the latter had 96% quartz with many transparent gems and many minerals. This suggests that the recent Dobata borrow's rocks were primarily clayish [20]. The topmost cowl must not be made of the most recent Dobata borrow rocks.

Material properties of Tehri dam

Material properties of Tehri dam are shown in Table 1.

Table 1. Materials physical and strength parameters (A.Sengupta-2006)

Zones of dam	Densities in t/m^3		Cohesion C(t/m^2)	Friction Angle Φ(in degrees)
	moist	*saturated*		
U/S Rock fill	1.92	2.16	0	40
D/S Rock fill	2.08	2.24	0	35
Core	1.86	2	0	30
Rock & Weathered Rock		2.30	0	45

Graphical Analysis

Analysis of slope stability has been carried out by structural stability analysis of the entire structure. Structural stability analysis considers several factors such as Angle of slope, unit weight of soil, cohesion, friction angle etc.

Discretization Of The Slopes And Boundary Condition

- The Tehri dam profile is obtained from “A Case study on Tehri dam” by S.Sandipa, S.Pandey (2013)
- The coordinates of different profile points along the X-axis and Y-axis are digitalized using the “*Digitizeit*” software.
- “Digitizeit”, an image decoding software, has been used to construct the dam profile. This software has unique ability to digitize a scanned graph or chart and recognizes solid lines, so the coordinates have been easily extracted. The obtained coordinates are used to plot the profile on a graph sheet. The profile graph sheets are used in structural stability analysis by the radial and Fellinius methods.

Structural Stability Analysis by Fellenius Method

Assumptions in Graphical Analysis:

- The average slope of the dam is considered by joining a line between the toe and the intersecting point of the reservoir's u/s face and FBL (free board level).
- (This assumption has been taken, as the Fellenius line cannot be obtained from two u/s slopes as provided in the Teton profile)
- The line of action of Weight is strictly at the Centre of the slice and taken as five units of a vertical line drawn from the arc.
- Efforts have been made to maintain the uniform thickness of slices.

Procedure

(a) The profile obtained from the “Digitizeit” is drawn on a graph sheet using a suitable scale, i.e. 1 cm = 25 m, both in X and Y directions.

(b) Construction of Fellenius line;

  a. Fellenius line is drawn by plotting its one end at a depth of H in the negative Y-axis and at a distance of 4.5 H along the X-axis from the toe of the slope, where H is the height of the crest. Its other endpoint is located by intersecting two lines, where one line makes angle α with the average u/s slope line, and the other makes β with the horizontal at the crest.
  b. Trial circles of different radii are drawn using a common centre on the Fellenius line.
  c. The trial failure wedge above the slip surface is divided into vertical slices. This trail failure wedge is usually of equal width.
  d. The angle θ subtended by the arc is measured, and arc length L is calculated by simple geometry.
  e. Three no. of factor of safety (FOS) values for three trial failure wedges are determined using programmed excel sheets. Above mentioned four trial failure wedges are shown in graph sheets.

Note: All the dimensions extracted from the graph sheet are modified as per suitable scale, i.e. 1 cm = 25 m

Data Extraction Techniques: (As per Table 2, Table 3 and Table 4)

Coloumn 2

Width of slice: Efforts have been made to maintain the uniform width of slices.

Coloumn 3

Near Side Height: The numbering of slices is done by taking the crest of the dam as a reference, so the slices are numbered starting from the crest, proceeding in a left direction. As per this fashion the right hand side of every slice is the near side height.

Coloumn 4

Far Side Height: In the same manner mentioned above the left hand side dimension of every slice is the far side height.

Coloumn 5

Slope Angle: Common slope of the Tehri dam profile taken to satisfy the Fellenius method's assumptions.

Coloumn 6

Failure Surface Angle: Measured geometrically from the triangles beneath the slices.

Coloumn7: Total Unit Weight:
Coloumn 8: Friction Angle: from Table 2
Coloumn 9: Cohesion:
Coloumn 10

Table 2. Results obtained from sheet no 1 by Fellenius method

Slice number	Width Of Slice(m)	Near Side Height(m)	Far Side Height (m)	Slope Angle (degrees)	Failure Surface Angle (degrees)	total unit weight (k/m^3)	Friction Angle φ (degrees)	Cohesion (k/m^2)	Weight of each slice	Normal component (N)	Tangential component (T)	N*TANφ
1	25	0	17.5	30	5	1.9	40	0	420	418.40	36.6	351.0
2	25	17.5	22.5	30	2	1.9	40	0	960	959.41	33.5	804.9
3	25	22.5	47.5	30	2	1.9	40	0	1680	1678.9	58.6	1408.6
4	25	47.5	60.0	30	5	1.9	40	0	2580	2570.1	225	2156.4
5	25	60	62.5	30	9	1.9	40	0	2940	2903.8	460	2436.3
6	25	62.5	60	30	13	1.9	40	0	2940	2864.6	661.30	2403.4
7	25	60	65	30	16	1.9	40	0	3000	2883.8	826.85	2419.5
8	25	65	70	30	20	1.9	40	0	3240	3044.6	1108.0	2554.4
9	25	70	70	30	23	1.9	40	0	3360	3092.9	1312.7	2595.0
10	25	70	67.5	30	26	1.9	40	0	3300	2966.0	1446.5	2488.5
11	25	67.5	66.2	30	31	1.9	40	0	3210	2751.5	1653.1	2308.6
12	25	66.2	58.7	30	35	1.9	40	0	3000	2457.5	1720.6	2061.9
13	25	58.7	50	30	40	1.9	40	0	2610	1999.4	1677.5	1677.5
14	25	50	37.5	30	45	1.9	40	0	2100	1485.0	1484.8	1245.9
15	25	37.5	17.5	30	50	1.9	40	0	1320	848.54	1011.1	711.93
16	12.5	17.5	0	30	53	1.9	40	0	210	126.39	167.70	106.04

Table 3. Results from sheet no 2 by Fellenius method

Slice Number	Width Of Slice (m)	Near Side Height(m)	Far Side Height (m)	Slope Angle (degrees)	Failure Surface Angle (degrees)	total unit weight(k/m^3)	Friction Angle φ (degrees)	Cohesion (k/m^2)	Weight of each slice	Normal Component(N)	Tangential Component (T)	N*TAN φ
1	25	0	12.5	30	4	1.920	40	0.000	300	299.269	20.925	251.091
2	25	12.5	32.5	30	1	1.920	40	0.000	1080	1079.836	18.847	905.995
3	25	32.5	42.5	30	3	1.920	40	0.000	1800	1797.534	94.198	1508.152
4	25	42.5	52.5	30	5	1.920	40	0.000	2280	2271.325	198.700	1905.669
5	25	52.5	57.5	30	10	1.920	40	0.000	2640	2599.898	458.398	2181.346
6	25	57.5	52.5	30	12	1.920	40	0.000	2640	2582.318	548.847	2166.596
7	25	52.5	57.5	30	15	1.920	40	0.000	2640	2550.057	683.233	2139.529
8	25	57.5	60	30	20	1.920	40	0.000	2820	2649.958	964.429	2223.347
9	25	60	60	30	23	1.920	40	0.000	2880	2651.087	1125.227	2224.294
10	25	60.	60	30	27	1.920	40	0.000	2880	2566.144	1307.404	2153.026
11	25	60	57.5	30	30	1.920	40	0.000	2820	2442.246	1409.906	2049.074
12	25	57.5	52.500	30	35	1.920	40	0.000	2640	2162.630	1514.144	1814.472
13	25	52.5	30	30	40	1.920	40	0.000	1980	1516.833	1272.641	1272.641
14	25	30	30	30	45	1.920	40	0.000	1440	1018.293	1018.175	854.360
15	25	30	10	30	50	1.920	40.000	0.000	960	617.123	735.363	517.774
16	25	10	0	30	50	1.920	40	0.000	240	154.281	183.841	129.443

Table 4. Results from sheet no 3 by Fellinius method.

Slice Number	Width Of Slice (m)	NearSide Height(m)	FarSideHeight (m)	SlopeAngle (degrees)	FailureSurfaceAngle(degrees)	TotalUnitWeight (k/m^3)	FrictionAngleφ (degrees)	Cohesion (k/m^2)	Weight ofeach slice	Normal component (N)	Tangentialcomponent (T)	N*TAN φ
1	25	0	15	30	2	1.9	40	0	360	359.78	12.56	301.86
2	25	15	30	30	5	1.9	40	0	1080	1075.8	94.12	902.68
3	25	30	30	30	8	1.9	40	0	1440	1425.9	200.3	1196.4
4	25	30	52.5	30	10	1.9	40	0	1980	1949.9	343.7	1636.0
5	25	52.5	50	30	15	1.9	40	0	2460	2376.1	636.6	1993.6
6	25	50	42.5	30	17	1.9	40	0	2220	2123.0	649.0	1781.2
7	25	42.5	45	30	20	1.9	40	0	2100	1973.3	718.1	1655.6
8	25	45	45	30	25	1.9	40	0	2160	1957.6	912.7	1642.4
9	25	45	42.5	30	25	1.9	40	0	2100	1903.2	887.4	1596.8
10	25	42.5	42.5	30	30	1.9	40	0	2040	1766.731	1020	1482.3
11	25	42.5	35	30	35	1.9	40	0	1860	1523.671	1066	1278.3
12	25	35	27.5	30	40	1.9	40	0	1500	1149.1	964.1	964.12
13	25	27.5	17.5	30	40	1.9	40	0	1080	827.36	694.	694.16
14	25	17.50	0	30	45	1.90	40.	0	420.00	297	296.	249.18

Total Weight of slice:

Weight of slice =

$$\frac{1}{2} \times \text{width of slices [Near side height+Far side height]} \times \text{Total unit weight}$$

The width of the slice, Near side height, and Far side height is taken from column no. 2, 3, and 4, respectively. For weight calculation, the unit length of the dam is taken into consideration

Coloumn 11

Normal component:

$$N = W \cos\theta \quad (1)$$

W is taken from column 10

Coloumn 12

Tangential component:

$$T = W \sin\theta \quad (2)$$

Column 13

A component

$$N \tan\varphi \quad (3)$$

Factor of safety:

$$F_S = \frac{cL + \sum N \tan\varphi}{\sum T} \quad (4)$$

Where,

c = Cohesion

L = Length of the trial slip circle

N = Normal component of Weight of slice

T = Tangential component of Weight of slice

φ = Angle of friction

Calculation

For sheet no 1 (As per Figure 1 and Table 2):

ΣT =13884

ΣN*TAN φ =27730.52

Factor of safety = (ΣN *TAN φ + cL) / ΣT =1.997

For sheet no 2 (As per Figure 2 and Table 3):

ΣT =11554.279

ΣN*TAN φ =24296.808

Factor of safety = (ΣN *TAN φ + cL) / ΣT =2.103

For sheet no 3 (As per Figure 3 and Table 4):

ΣT =8496.920

ΣN*TAN φ =17375.074

Factor of safety = (ΣN *TAN φ + cL) / ΣT =2.045

The Factor of Safety for all trials in Fellinous method are shown in Table 5.

Table 5. (Factor of safety by Fellenius method)

Sheet no	Radius of slip circle	Factor of safety
1	410	1.997
2	410	2.103
3	410	2.045

Structural Stability Analysis by Radial Slice Method

Procedure

- The cross-section of the Tehri dam is drawn on the graph sheet by taking the scale 1cm=50m on both X-axis and Y-axis.
- In this method, the Centre of the slip circle was found out by the Fellenius method
- The failure surface is taken, which passes in the slope at a two-thirds distance from the top.
- The failure wage is divided into a number of slices.
- The area of the slice was found out by the following:

Area of slice=area of sector-area of the triangle

Where the area of sector = 0.5*r*Φ

In which r =radius of the slip circle

Φ = Angle of the sector in radian

Area of triangle = 0.5*base of triangle*perpendicular x Distance to base

- By multiplying the unit weight by the area of the slice, the Weight of the slice is found.
- The Centre of gravity of each slice is found out by the following:

$$\text{Centre of gravity of each slice} = \frac{[\binom{Centreofgravityofsector*}{areaofsector}-\binom{Centreofgravityoftriangle*}{areaoftriangle}]}{Netareaofslice}$$

Where the Centre of gravity of sector = $\frac{4*r}{3*\Phi} * \sin\left(\frac{\Phi}{2}\right)$ (5)

Centre of gravity of triangle = $\frac{a+b}{3}$ (6)

In which a=distance to the point of perpendicular of the triangle

b= length of the base of triangle

- A line is drawn through the Centre of the slip circle O
- Drawing perpendicular distance from the C.G. of the slice to that line distance obtained d.
- The net sliding torque (Ts) (which is produced due to this Weight acting at the Centre of mass of the slope) = W*d

Where W= Total Weight of a slice

d=Distance of the Centre of gravity of the total Weight of the slice from the line which passes through point O

- The resisting torques produced are calculated as follows:

$$T_{r_n} = [(\mu \times w_n) + (C \times R \times \beta)] \times R \times sin\delta_n \quad (7)$$

Where

T_{rn} =Resisting torque due to n th slice

w_n = Weight of component

δ_n = Angle with the horizontal axis

β= Angle of the arc

Hence the net resisting torque (T_R)

$$T_R = \sum T_{r_n} \quad (8)$$

The factor of safety (F_{fos}) is calculated probabilistic slip surface as :

$$F_{fos}=\frac{T_R}{T_s} \quad (9)$$

Figure 1 shows the general configuration of radial slice method Table 6 shows the results obtained from the calculation of the driving moment. Table 7 shows results obtained from calculation of the resisting moment. So the factor of safety was found as 1.15 which is mentioned in Table 8.

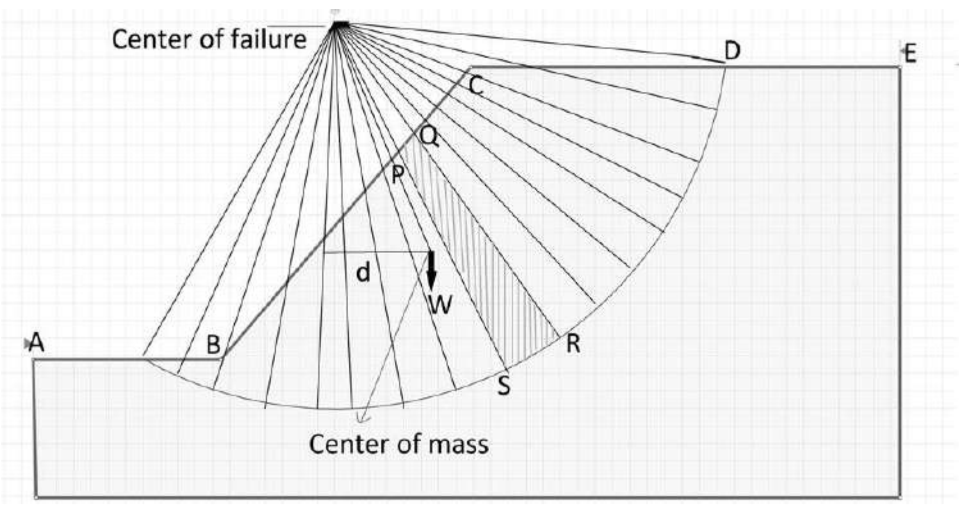

Figure 1. Diagram of radial slice method. (G P Kumar, 2015).

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Table 6. Results obtained from calculation of driving moment

Sector No	radius of slip circle r	Angle of archΦ in degree	Angle of archΦ in radian	length of arch	area of sector	base of triangle	Perpendicular distance	area of triangle	net area of slice	Unit weight	wt of slice	C.G of sector	a	b	(a+b)/3	c.g. of triangle	c.g. of slice	Angle of c.g	d	w*d	Σw*d
1	410	5	0.087222222	35.76111	7331.028	410	35	7175	156.0278	1.92	299.5733	273.39	380	410	263.33	262.32	782.4484	5	68.18986	20427.86	4393865
2	410	5	0.087222222	35.76111	7331.028	385	35	6737.5	593.5278	1.92	1139.573	273.39	358	380	245.8333	244.89	596.9111	1	10.41677	11870.67	
3	410	5	0.087222222	35.76111	7331.028	360	35	6300	1031.028	1.92	1979.573	273.39	343	358	233.6667	232.77	521.5948	5	45.45664	89984.75	
4	410	5	0.087222222	35.76111	7331.028	350	30	5250	2081.028	1.92	3995.573	273.39	340	345	228.3333	227.46	389.2618	10	67.58968	270059.5	
5	410	5	0.087222222	35.76111	7331.028	355	35	6212.5	1118.528	1.92	2147.573	273.39		340	226.66	226.45	534.103	15	138.2261	296850.7	
6	410	5	0.087222222	35.76111	7331.028	340	35	5950	1381.028	1.92	2651.573	273.39	335	340	225	224.14	485.578	22	181.888	482289.3	
7	410	5	0.087222222	35.76111	7331.028	340	32.5	5525	1806.028	1.92	3467.573	273.39		340	226.66	226.45	416.9888	28	195.7512	678781.5	
8	410	5	0.087222222	35.76111	7331.028	345	35	6037.5	1293.528	1.92	2483.573	273.39	350	360	236.6667	235.75	449.0735	33	244.567	607400	
9	410	5	0.087222222	35.76111	7331.028	355	35	6212.5	1118.528	1.92	2147.573	273.39	353	368	240.3333	239.41	462.1209	38	284.4922	610968	
10	410	5	0.087222222	35.76111	7331.028	370	32.5	6012.5	1318.528	1.92	2531.573	273.39	370	380	250	249	384.6086	43	262.2869	663998.6	
11	410	4	0.069777778	28.60889	5864.822	380	27.5	5225	639.8222	1.92	1228.459	273.39	370	380	250	249.39	469.3819	47	343.2649	421686.7	
12	410	5	0.087222222	35.76111	7331.028	400	35	7000	331.0278	1.92	635.5733	273.39	385	410	265	264	471.9534	53	376.8994	239547.2	

Table 7. Results obtained for calculation of resisting moment.

no of Slice	weight	cohesion	radius	angle of arch	angle with horizontal axis	coeff of friction	T	summation of T
1	299.57	0	410	0.087222	0.523598	1	61411.77	5065077
2	1139.57	0	410	0.087222	0.523598	1	233611.5	
3	1979.57	0	410	0.087222	0.523598	1	405811.3	
4	3995.57	0	410	0.087222	0.523598	1	819090.7	
5	2147.57	0	410	0.087222	0.523598	1	440251.3	
6	2651.57	0	410	0.087222	0.523598	1	543571.1	
7	3467.57	0	410	0.087222	0.523598	1	710850.9	
8	2483.57	0	410	0.087222	0.523598	1	509131.2	
9	2147.57	0	410	0.087222	0.523598	1	440251.3	
10	2531.57	0	410	0.087222	0.523598	1	518971.2	
11	1228.45	0	410	0.0697	0.523598	1	251831.9	
12	635.57	0	410	0.087222	0.523598	1	130291.7	

Table 8. Factor of safety by radial slice method

Radius of slip circle	factor of safety
410	1.15

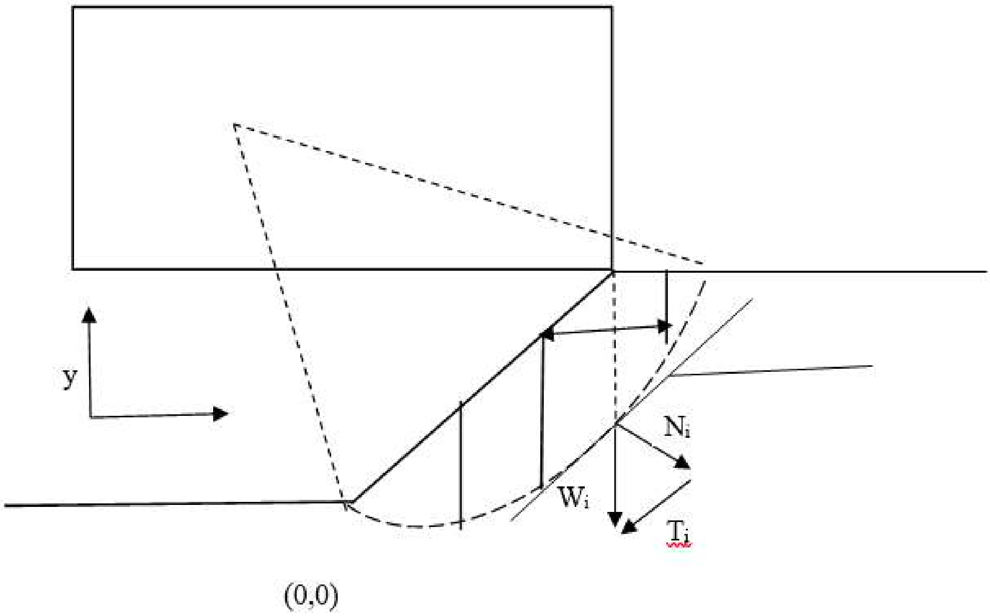

Figure 2. Model of a typical slope describing algorithmic method.

Model of a typical slope describing genetic algorithmic method to search the critical slip surface is shown in Figure 2.

Stability Analysis of Tehri Dam Under Sudden Draw-Down Condition

In this investigation, the dam's stability under conditions of abrupt drawdown was discovered. Because of the enormous pore water pressures inside the dam, a rapid drop in reservoir level could cause the dam to become unstable. A transient groundwater flow calculation is needed to analyze such a situation using the finite element method. The deformation analysis programme transfers the pore pressures obtained from the groundwater flow analysis, which are then employed in the stability study. This analysis exhibits the interaction performance of deformation analysis, transient groundwater flow, and stability analysis in PLAXIS 2D. The dam is 260 m high, 1128 m wide at the base, and 20 m wide at the top. A clay core and rock fill are used to build the dam. Beyond the dam, the typical water level is 223 metres high. The case where the water level lowers by 150 m is considered. The meshing under sudden draw down condition mentioned in Figure 3. After the calculation process, the results were obtained such are:

- From Figure 4, the maximum value of total displacement in X-direction at element 5 of node 2065(selected at crest) was 16.99 m, and at element 23 of node 1173 (selected at the toe) was -540.8 m.
- From the above Figure 5, the maximum value of incremental displacement in the X-direction at element 5 of node 2065 (selected at crest) was found as 0.3730 m and at element 23 of node 1173(selected at the toe), was found as -14.75 m.

- From Figure 6, the maximum value of total displacement in the Y-direction at element 5 of node 2065(selected at crest) was found as zero, and at element 23 of node 1173(chosen at the toe) was seen as -1484 m.
- From Figure 7, the maximum value of steady state pore pressure at element 5 of node 2065(selected at crest) was found as zero, and at element 23 of node 1173(chosen at the toe) was found to be 4760 kN/m^2
- From Figure 8, the maximum value of active pore pressure at element 5 of node 2065(selected at crest) was found as NIL and at element 23 of node 1173(selected at the toe) was seen as -4760 kN/m^2

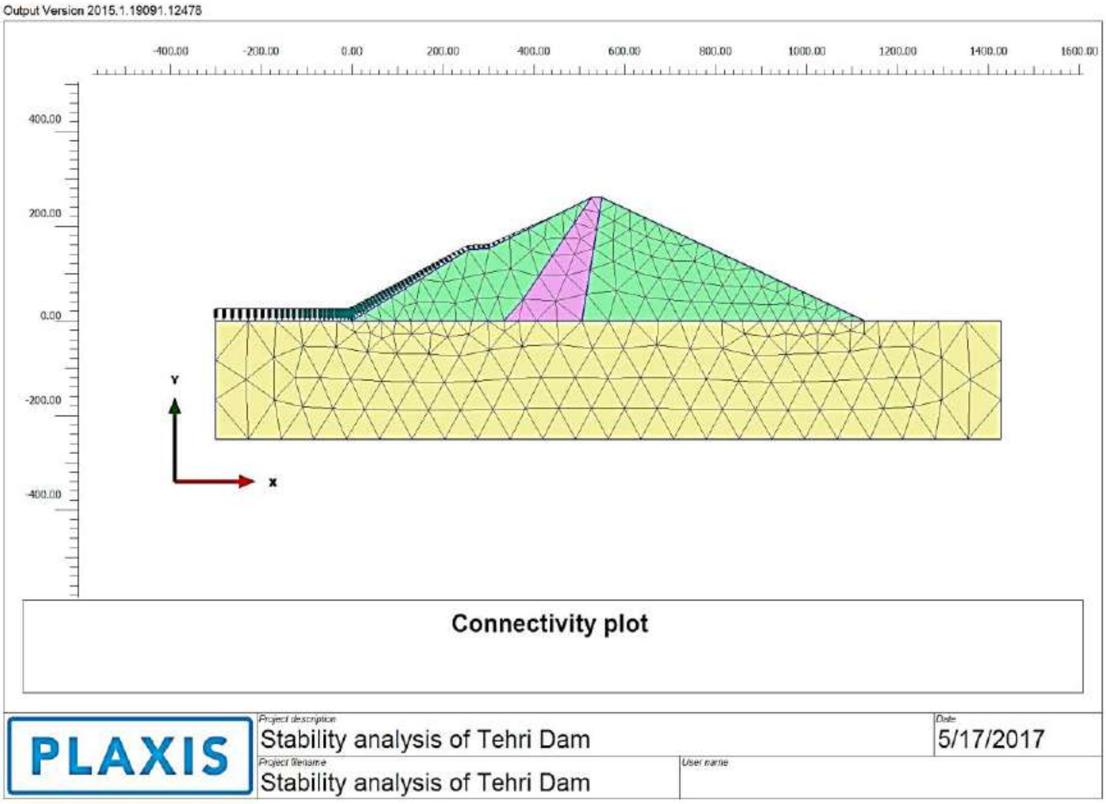

Figure 3. Mesh generation of sudden draw down condition.

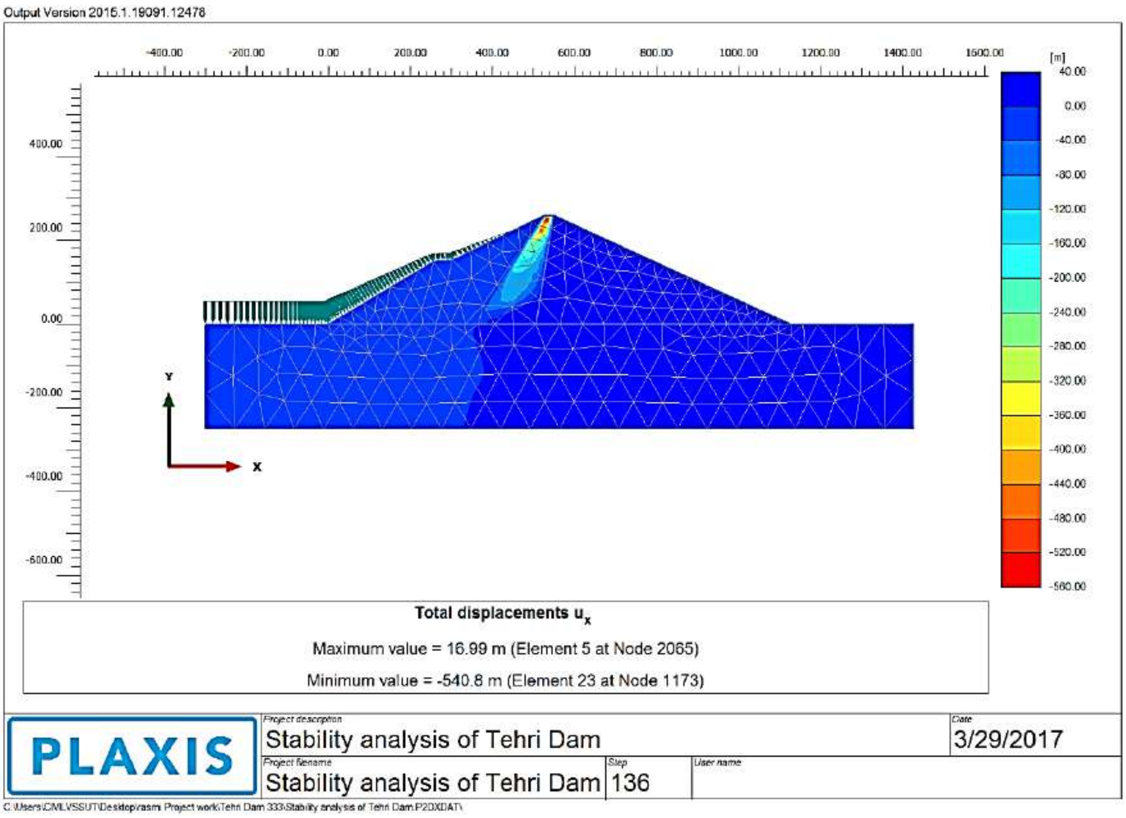

Figure 4. Total displacements after sudden drawdown.

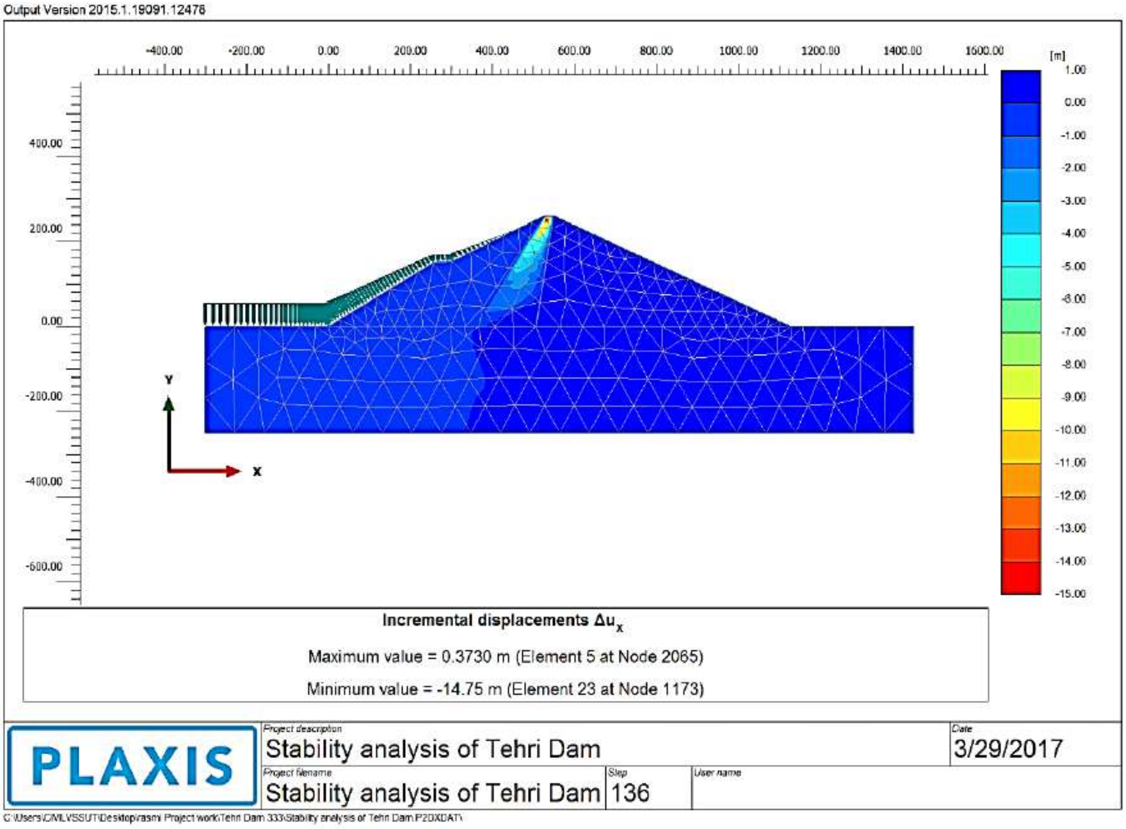

Figure 5. Incremental displacement.

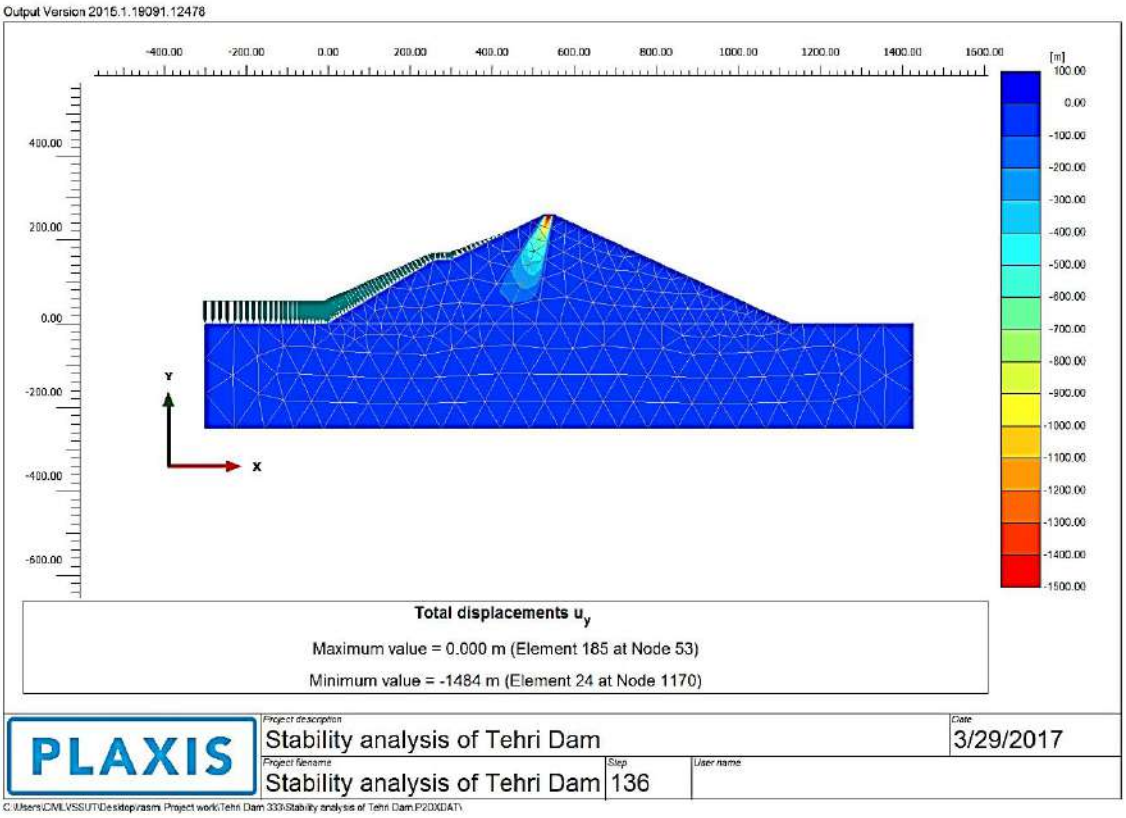

Figure 6. Total displacement in Y-direction.

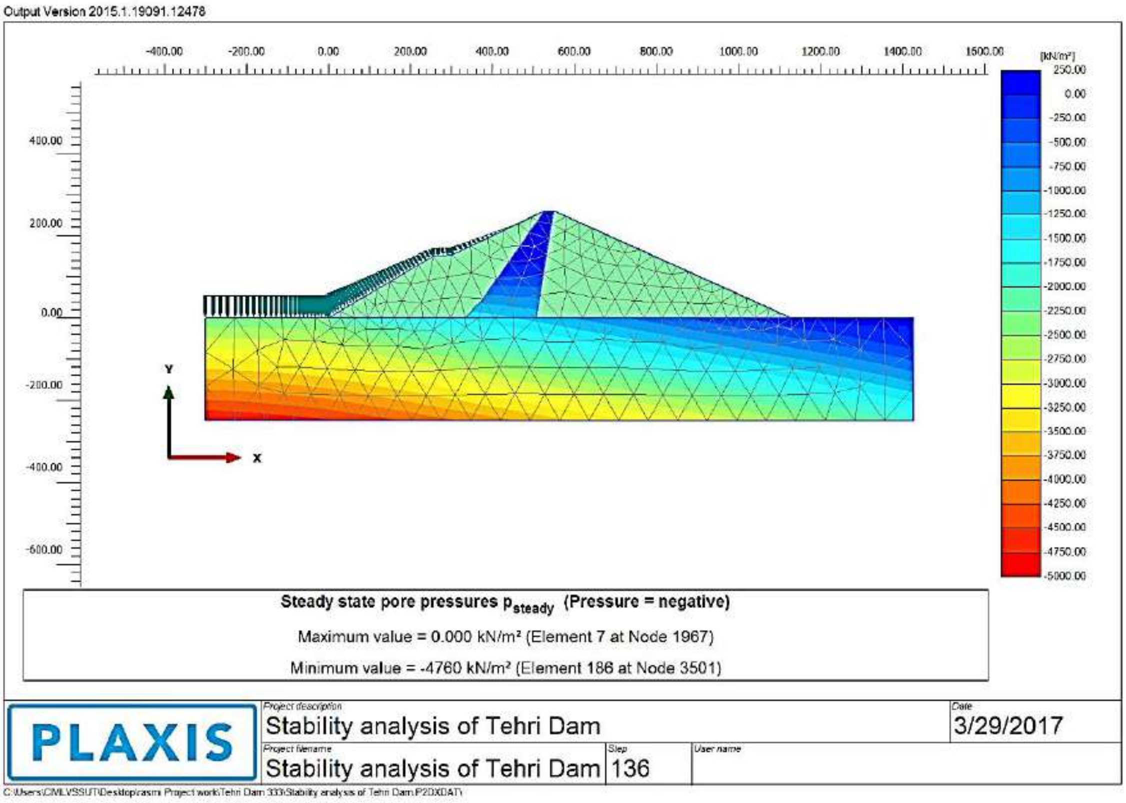

Figure 7. Variation of steady state pore pressure.

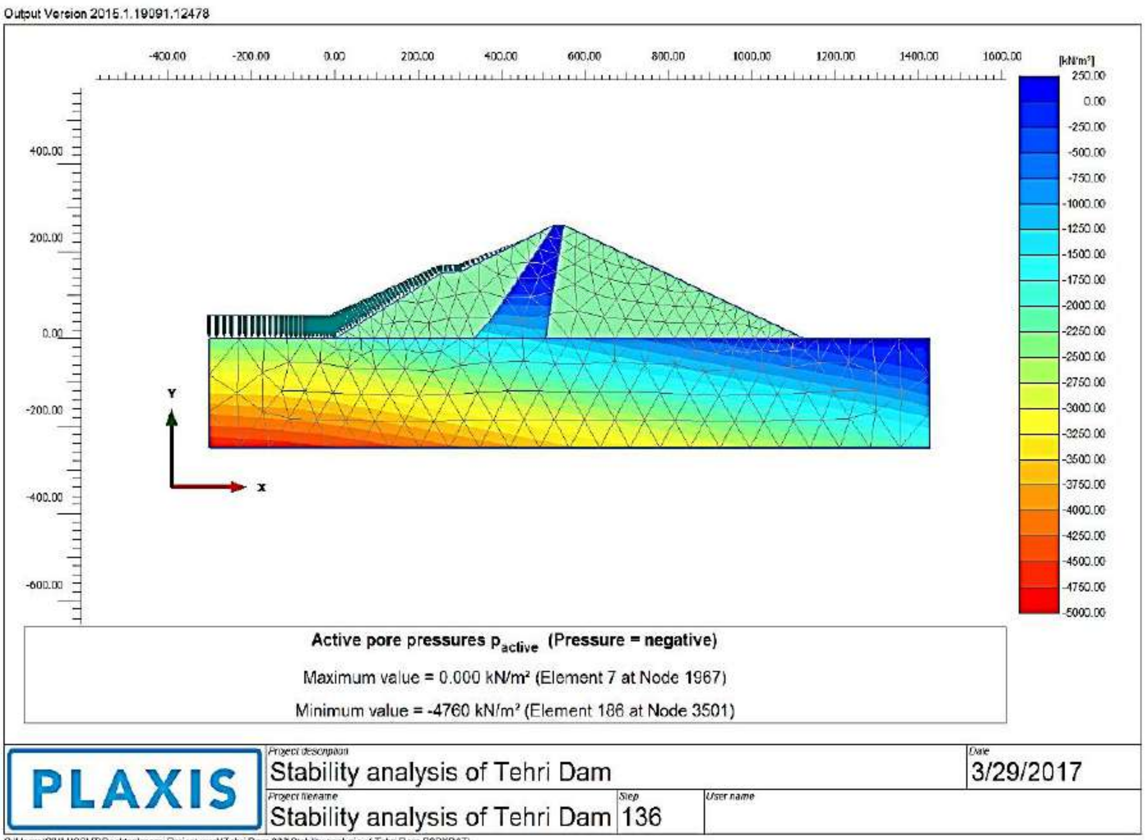

Figure 8. Variation of active pore pressure.

Dynamic Analysis of Tehri Dam

One of the most flexible tools available for the dynamic study of an embankment dam is the finite element approach. However, the accuracy of the outcome is strongly influenced by the material model and related material parameters that were selected. For the dynamic assessments of the Tehri dam in this work, a finite element programme called PLAXIS (PLAXIS 2D, 2015) is used. Advanced features and material models are available in PLAXIS to address numerous facets of challenging geotechnical issues. The construction of the dam geometry, specification of material models for each zone of the dam, assignment of material parameters to the corresponding zones, mesh generation, application of boundary conditions, and definition of steady state phreatic surface are necessary for the dynamic analysis in Plaxis. Three steps are taken in the numerical analysis. The first stage involves activating the gravity force. This step ignores the soil's undrained behaviour. The static analysis is completed when the dam is constructed, and the reservoir is impounded in the following stage. The dynamic analysis is done in the third stage. The acceleration time history of the chosen earthquake is specified during the dynamic analysis stage. To calculate the deformations of the dam during the earthquake analysis, the ground motion in this study was scaled to 05g and applied at the dam's base. The Tehri dam is located in an earthquake-prone zone IV. Hence a ground motion of 0.5 g was used. The peak acceleration was also found to be 5 m^2/s.The output in terms of acceleration, deformation, pore pressures and stresses is viewed at the end of each analysis stage. Mesh generated model of Terhri dam for dynamic analysis is mentioned in Figure 9. After calculation, the following results were obtained.

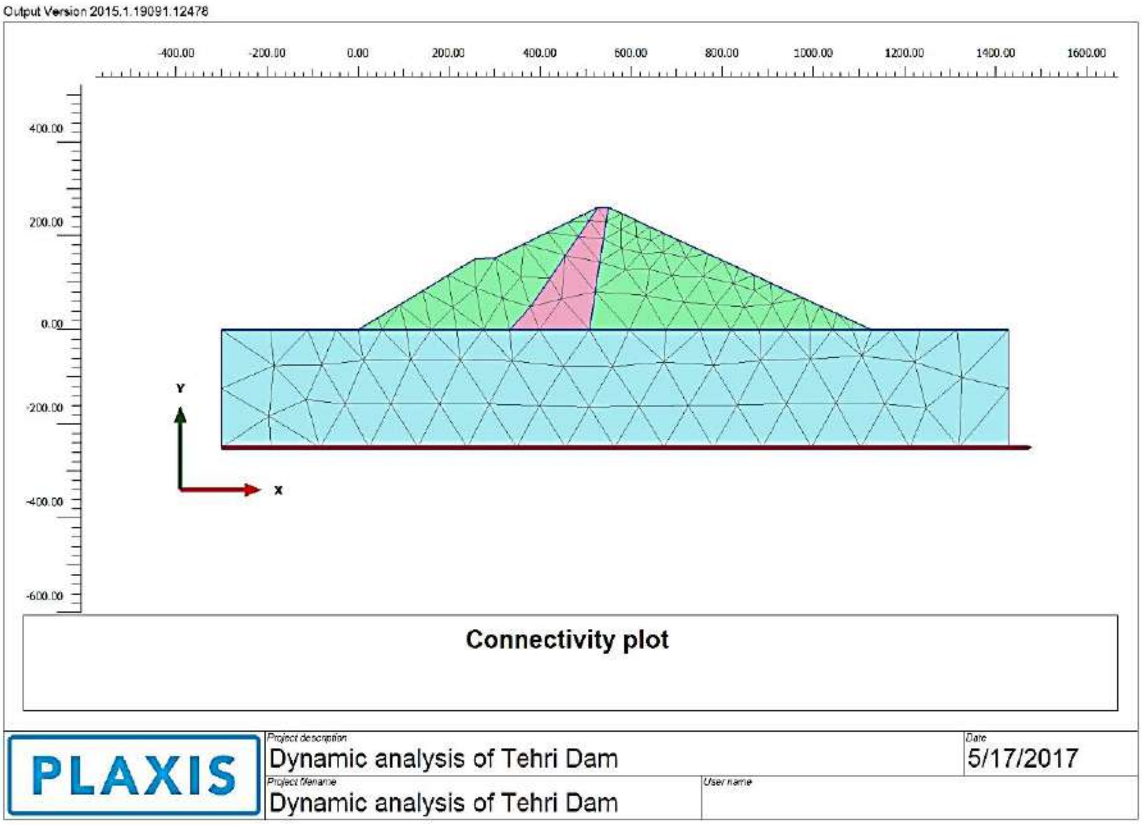

Figure 9. Mesh generated model of Terhri dam for dynamic analysis.

- Model showing total displacement in Figure 10 and Figure 11 shows a deformed mesh where the maximum deformation value was found as 0.4150 at element 3 of node 1281.
- From Figure 12, the maximum value of total displacement in the X-direction at element 2 of node 1140 (selected at crest) was found as 0.3545 m and at element 3 of node 1281(set at the toe) was seen as -0.3883 m.

- From Figure 13, the maximum value of total displacement in the Y-direction at element 1 of node 1239(selected at crest) was found as 0.1442 m and at element 3 of node 1281(set at the toe) was seen as -0.1465 m

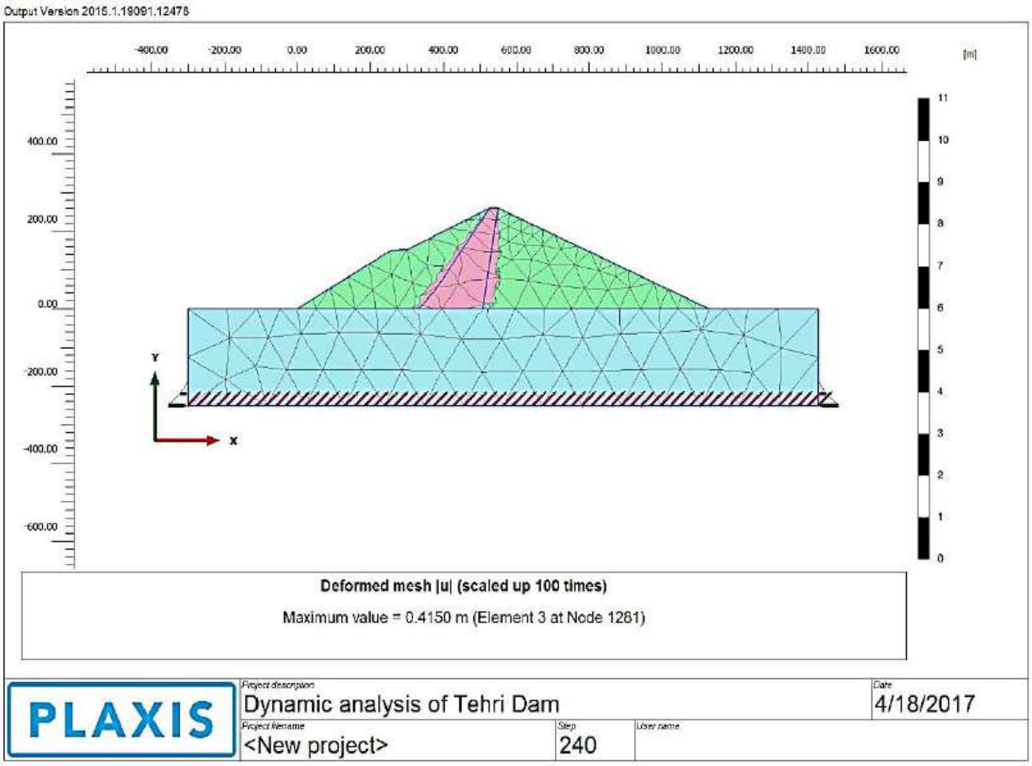

Figure 10. Model showing deformed mesh.

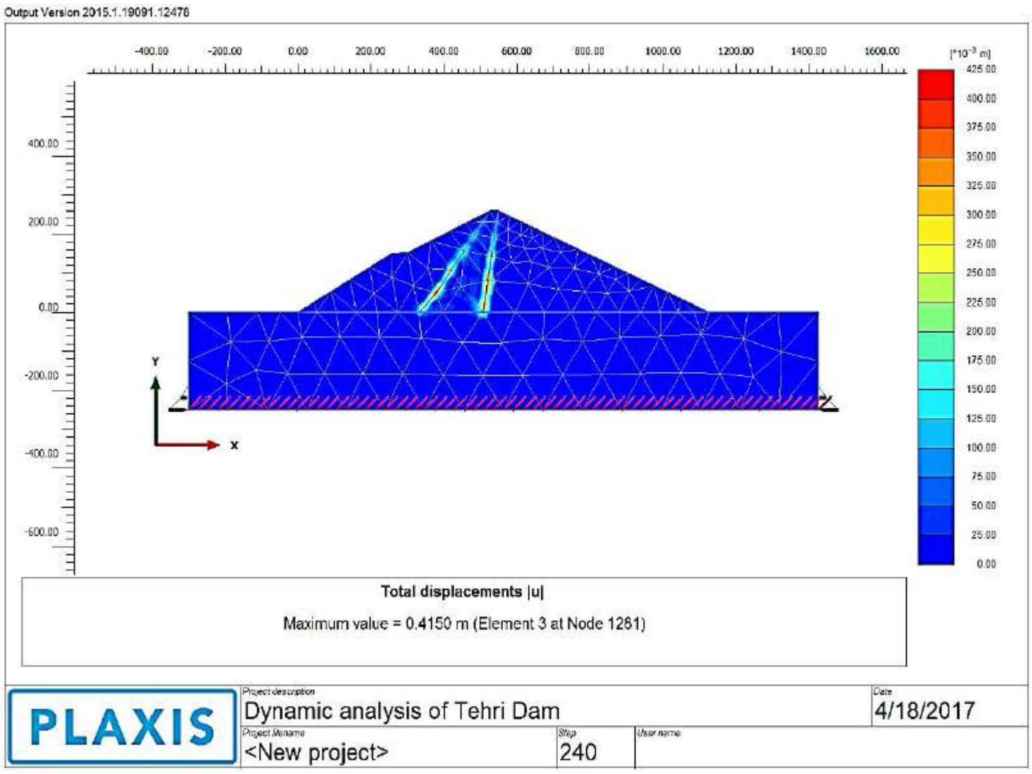

Figure 11. Model showing total displacement.

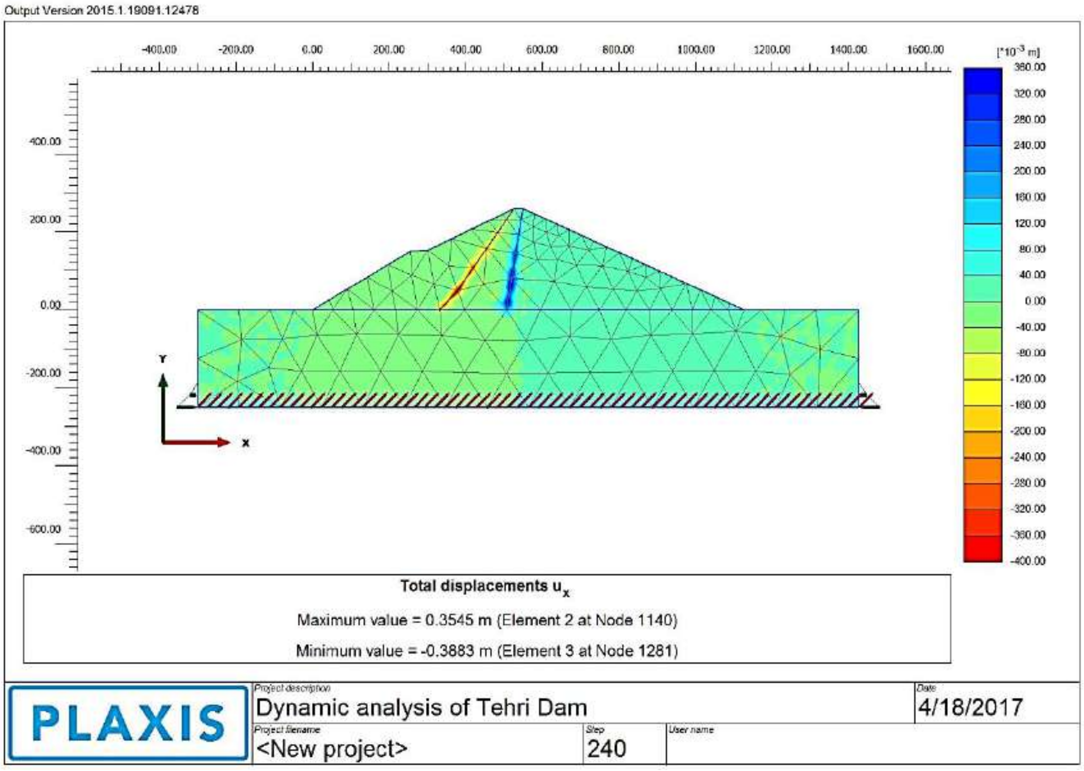

Figure 12. Model showing the total displacement in X-direction.

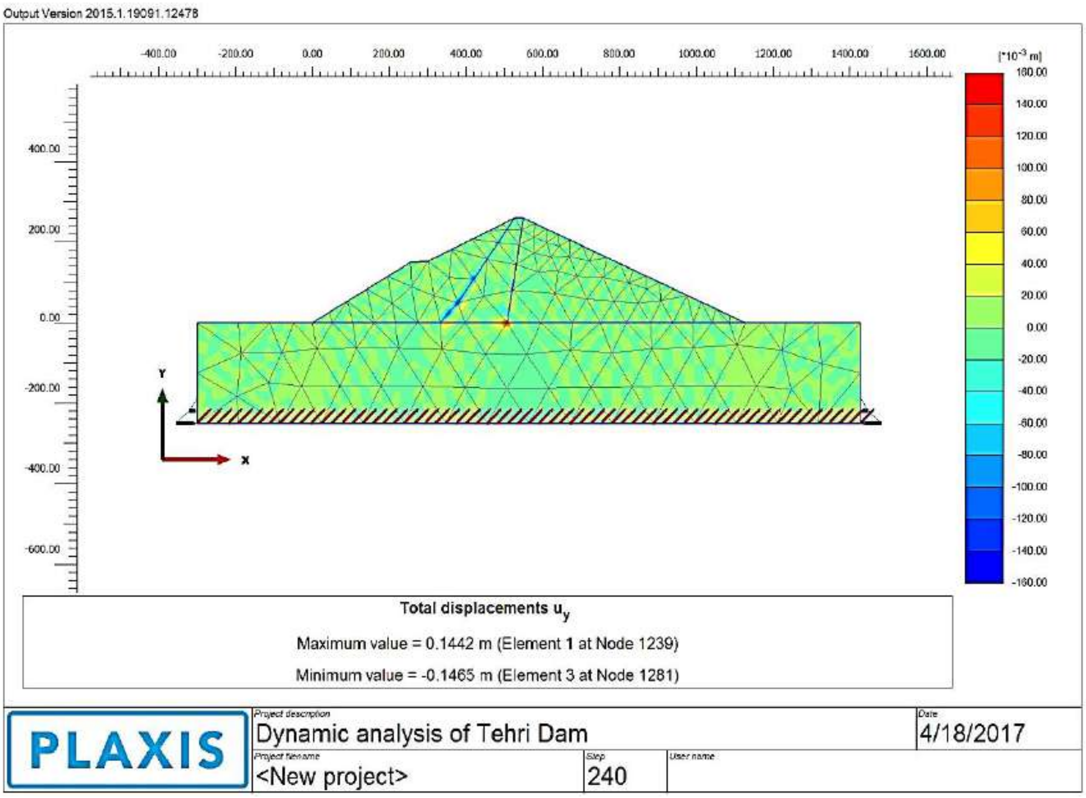

Figure 13. Model Showing the total displacement in Y-direction.

- From Figure 14, the maximum value of phase displacement at element 3 of node 1281(selected at the toe) was found as 0.4150 m.

- From Figure 15, the maximum value of sum phase displacement in element 3 of node 1281 was found as 0.4150 m and at element 113 of node 1809 was seen as 5.236 $*10^{-9}$
- From Figure 16, the maximum value of the velocity vector at element 3 of node 1281 was 6.977 m/s.

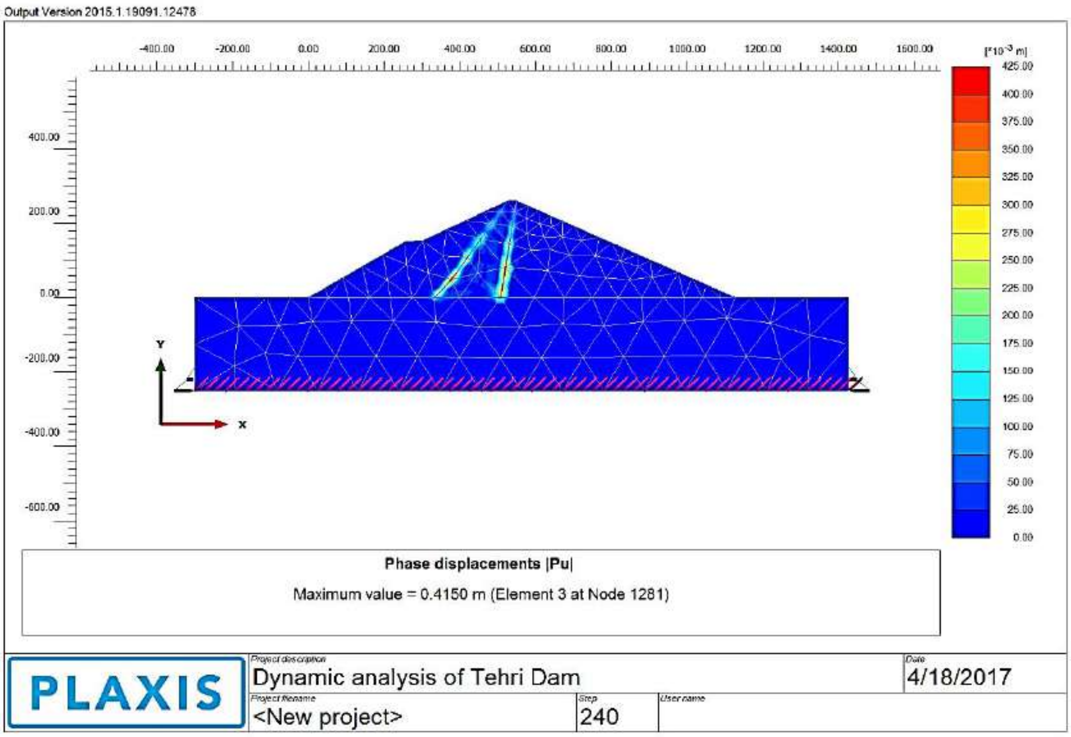

Figure 14. Phase displacement.

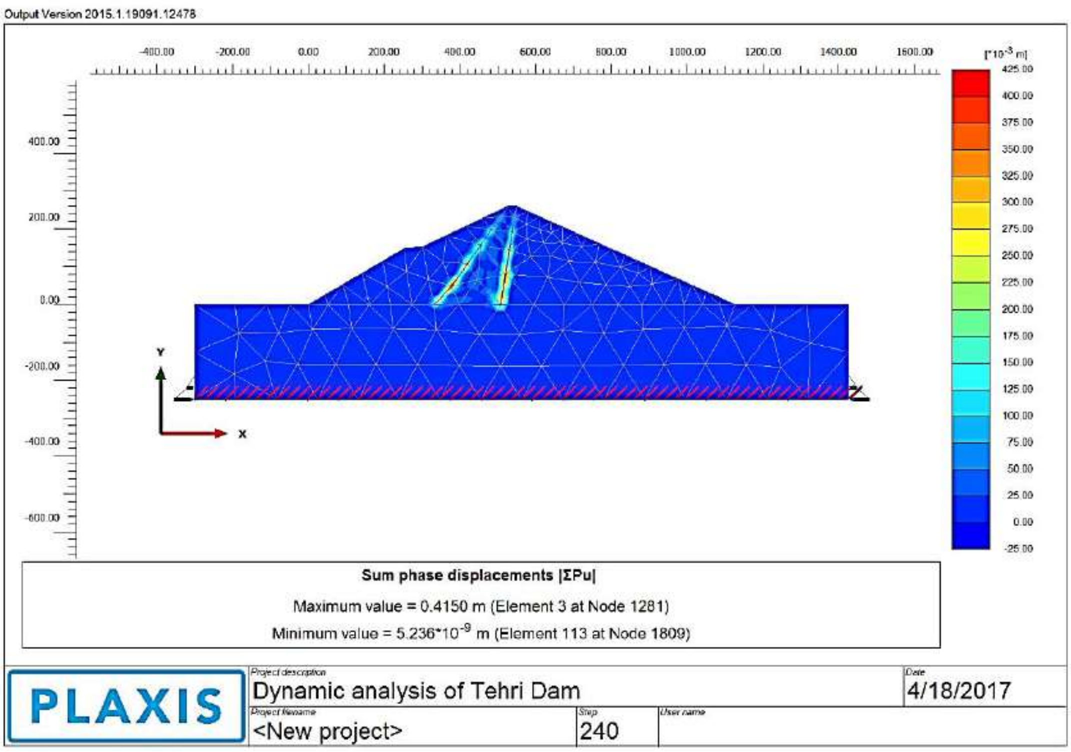

Figure 15. Model showing the Sum phase displacement.

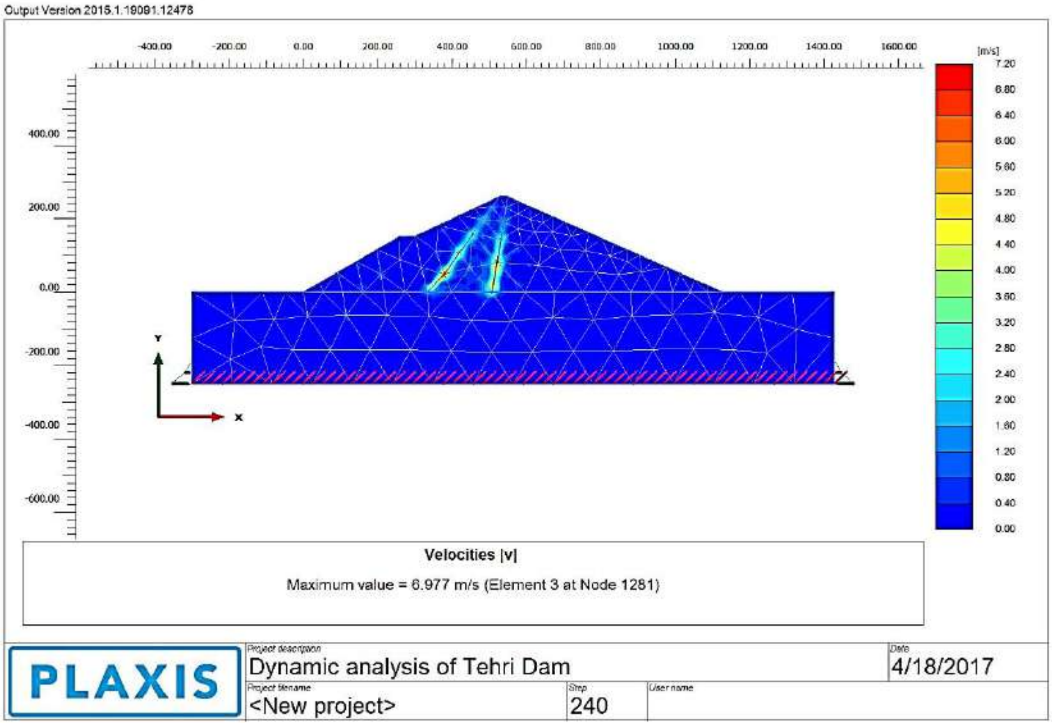

Figure 16. Model showing the velocity vector history.

Model showing the crest acceleration is on Figure 17. Dynamic displacement Histories is shown in Figure 18. Detail results of dynamic analysis are shown in Tables 9, 10. Dynamic analysis of the Terhi dam was conducted by A. Sengupta, (2006) using Seed and Makdisi's method, Double integration method, Jansen's method, and Swaisgood's method and the total displacement was found as 42 cm. So the numerical result of the present study is in good agreement with the published result.

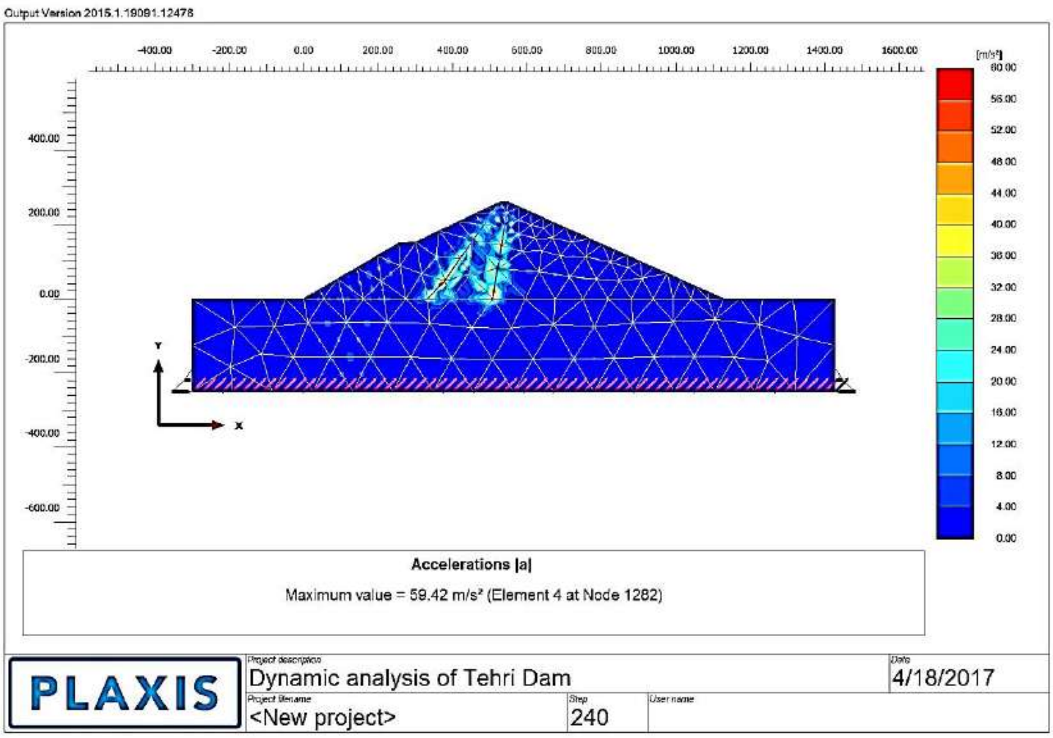

Figure 17. Model showing the crest acceleration.

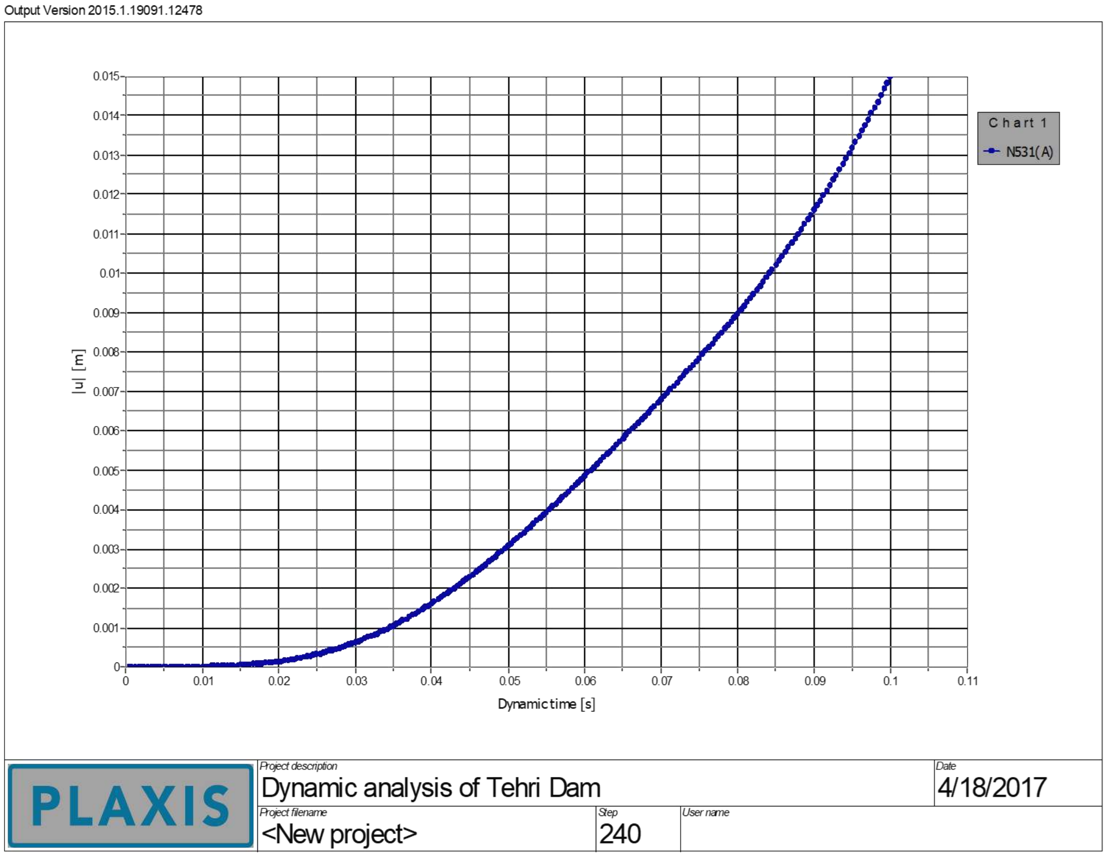

Figure 18. Dynamic displacement Histories.

Table 9. Results of sudden draw down condition

Parameters	**value**
Total displacement in X-direction (U_x)	16.99 m
Incremental displacement in X-direction (ΔU_x)	0.3730 m
Total displacement in Y-direction (U_y)	NIL
Steady state pore pressure (P_{steady})	NIL
Active pore pressure (P_{active})	NIL

Table 10. Results of Dynamic Analysis

Parameters	**Values**
Total displacement (u)	0.4150 m
Displacement in X-direction (u_x)	0.3545 m
Displacement in Y-direction (u_y)	0.1442 m
Phase displacement(p_u)	0.4150 m
Sum phase displacement (Σp_u)	0.4150 m
Velocity (v)	6.977 m/s
Crest acceleration (a)	59.42 m^2/s

CONCLUSION

Static analysis of the Tehri dam has been made by graphical methods such as Fellinious method and radial slice method to find out the safety factor. The factor of safety by the Felliniousmethod has been found as 1.997, 2.103, 2.045 by considering three slip circles of constant radius of 410 m. The safety factor by radial slice method for the same radius of the slip circle has been obtained as 1.15.

The coordinate of the Centre of the slip circle has been found by genetic algorithm. The input data has been imported from the results of the graphical method to validate the graphical method. The centre coordinate of the slip circle is obtained as (210,485), which was found to be very close to the value of the Centre of the slip circle by the graphical method.

Numerical analysis has been made using commercially available software PLAXIS under a sudden draw-down condition. The deformation in the X-direction was 16.99 m.

Dynamic analysis has been used by PLAXIS software to find out the total deformation as 0.4150 m and the deformation history. The total displacement was very close to the published result (A. Sengupta, 2006).

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