Static and pseudo-static stability analysis of right earthen embankment of nagarjuna sagar dam by geostudio

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Abstract: To ensure the safety of the dam, stability assessment of the dam is necessary. The objective is to perform slope stability analysis for upstream, downstream and seepage analysis during steady state, transient seepage conditions and to know about the displacement occurred at history nodes by the application of pseudo-static ground motion. The present work deals with the behavior of the Right earthen embankment of Nagarjuna Sagar which is in earthquake prone area of Zone-II (as per IS 1893-2002). Stability parameters slope, seepage and earthquake analyzed by SLOPE/W, SEEP/W, QUAKE/W tools in GeoStudio 2022 (finite element modeling based software). The model with full reservoir level is first analyzed by SEEP/W to find piezometric line which is basis to perform SLOPE/W for finding slope stability. Later an earthquake motion of 0.1 peak ground acceleration is subjected to it by using QUAKE/W. It is concluded from results, that obtained factor of safety lie within safety limits and seepage loss observed during the design life of 100 years is 562290 m^3, 3431117 m^3 for steady state and rapid drawdown.

Keywords: Pseudo-Static analysis, SEEP/W, SLOPE/W, earthen embankment, seepage loss.

1. INTRODUCTION

An Earthen embankment Dam is one of the structures used to store water in large quantities, it may fail due to seepage as well as erosion, structural instability, piping, internal crack, and rainfall. Therefore, dam must be protected to withstand driving forces which causes failure. During adverse conditions like drought, stored water is used for irrigation which prevents death of living beings. So the failure of dam stability will result in loss of property & lives of living beings. Therefore slope stability of the dam is important for its longevity to serve many generations. Porous material embankment dams are vulnerable to seepage-related issues. So it is essential for the safety of these earthen constructions to estimate seepage through embankment dams properly. If the dam is present in the earthquake zone then seismic analysis is performed. Slope failures arise when driving forces overcome resisting forces. The driving force is typically gravity, and the resisting force is the slope material's shear strength.

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Forces which cause slope failure are gravitational forces, seepage forces, earthquake forces, construction equipment loads. There are a number of different causes for failure of dams. Natural causes like floods, landslides, earthquakes etc. and other factors such as seepage, foundation failure, structural failure etc. can cause dam failures. Slope stability analysis is performed to find the FOS. The analysis is done by using the Mohr-Coulomb model.

2. LITERATURE REVIEW AND OBJECTIVE

Slope stability methods are Limit equilibrium method (LEM), Finite Element Modeling method, Numerical modeling method. The Limit Equilibrium method is most widely used as it involves all the interslice forces in calculation of factor of safety. Limit Equilibrium Method has different methods based on the forces acting on the slices of critical slip surface. All methods are based on comparison of forces or moments resisting instability of mass and those causing instability. Swedish method of Slices is the first LEM introduced by Fellenius [1], further it is developed by Bishop [2], Janbu [3]. As the emergence of electronic computers, iterative procedures & complex mathematical expressions are involved in Morgenstern-Price (MP) method [4]. Spencer method [5], Corps of Engineers [6] in which horizontal force equilibrium is satisfied, Lowe-Karafiath [7] where moment equilibrium is not satisfied, Sarma [8] in which moment and horizontal force equilibrium are satisfied, which are used for determination of slope stability.

[9] studied static and seismic stability performance of the left embankment of Nagarjuna Sagar dam. Static study involves slope and seepage stability behavior of earthen embankment at normal water level. Dynamic analysis is done by subjecting an earthquake acceleration of 0.2g and displacements of the structure at crest and base (history nodes) are calculated for 5 and 7 seconds of seismic motion besides to post earthquake stability on up and down streams. [10] observed the slope stability (D/S) and transient seepage (U/S) of earthen dam model by Entry & Exit, Grid & Radius method in four different cases involving berm on the D/S of dam with the help of SLOPE/W and SEEP/W tools in Geostudio. The four cases are without berm & without drain, with berm without drain, without berm with drain, with berm with drain. [11] studied slope stability of five dams at different locations with five water levels starts with empty reservoir on the upstream by 5 LEM (MP method) [4], Spencer's method [5], Bishop Simplified method [2], Janbu method [4], ordinary method or method of slices). The variation in FOS of all the methods used is doesn't exceed 6% in comparison. [12] presented the model of earthen dam checked under safety by using SLOPE/W and SEEP/W using Geostudio. Steady state analysis is done to know pore water pressures inside the dam, transient analysis is performed in 5 days. Using SLOPE/W safety factor is determined which is 1.958. [13] observed the slope and seepage stability analysis of Haditha dam, Iraq at three different water levels (maximum, normal, minimum operational levels) with 6 methods available (MP, Corps of engineers #1 , #2, Bishop, Janbu, Ordinary) in Limit Equilibrium with Geostudio 2007. Using SEEP/W pore water pressure distribution and water flux through the toe drain are determined. Through SLOPE/W, stability factor is obtained and compared with BDS – 1994 [14], USACE – 2003 [6]. Based on materials in the dam, phreatic line is lowered which prevents sloughing. Hence it is safe against seepage and slope failure under different levels of water. [15] studied the failure analysis of Homogeneous Earthen dam model by placing berm, vertical filter, and horizontal filter, rock toe in individual case to a model dam by using SEEP/W and SLOPE/W in Geostudio. After analyzing the cases the best remediated dam is made by providing berm and external filters. Pipes through the embankment should be avoided as it leads to different failure modes of earthen dam. However, in case the pipe is

provided in the dam then it should be provided with horizontal filter or vertical filter diaphragm to prevent the washing of fines during leakage.[16] studied the static and dynamic analysis of Grindeho dam in Ethiopia. Seepage rate is observed in reservoir full, empty reservoir level, and drawdown conditions. Seepage loss per year through the dam during rapid drawdown and steady state with full reservoir and seepage loss for full reservoir in 50 year design period is calculated. Slope stability is found through Morgenstern Price [4] , Bishop [2] , Janbu [3], Spencer method [5] and compared with Benchmark safety and legislation.[17] investigated the post quake (with 0.134g, 0.161g, 0.375g) slope stability analysis of Haditha dam at maximum, normal, minimum operational water level on upstream and downstream with all available LEM (Morgenstern Price [4], Spencer [5], Corps of Engineers #1, #2 [6], Bishop [2], Janbu [3], Ordinary and QUAKE/W Stress method) in Geo-slope and compared with USACE-2003 [6] and BDS-1994 [11] limitation standards. They concluded that dam is safe against the highest pg which has recorded in current years. The objective of paper is to inspect the behavior of Right Earthen embankment of Nagarjuna Sagar against slope, seepage, earthquake stability by using finite element modeling based software Geostudio.

3. STUDY AREA

Nagarjuna Sagar dam (NSD) is built of rubble masonry shares the border with Nalgonda district in TN state (seismic zone-III with zone factor of 0.16g as per IS 1893- 2002) and Palnadu district in AP state (lies in the seismic zone –II with zone factor of 0.1g as per IS 1893- 2002) constructed over the river Krishna. It has Left earthen embankment in Telangana state has length of 2560.32m and Right earthen embankment in Andhra Pradesh with a top width of 9.14m, length of 853.44m. Besides to embankments, the dam has right & left canals in which two Kaplan turbines are there for electricity generation. Dam has a FRL of 179.83m with a catchment area of 215000 sq.km, total and active capacities are 405 TMC ft, 244.41 TMC ft. The location of Nagarjuna Sagar dam shown in Fig. 1.

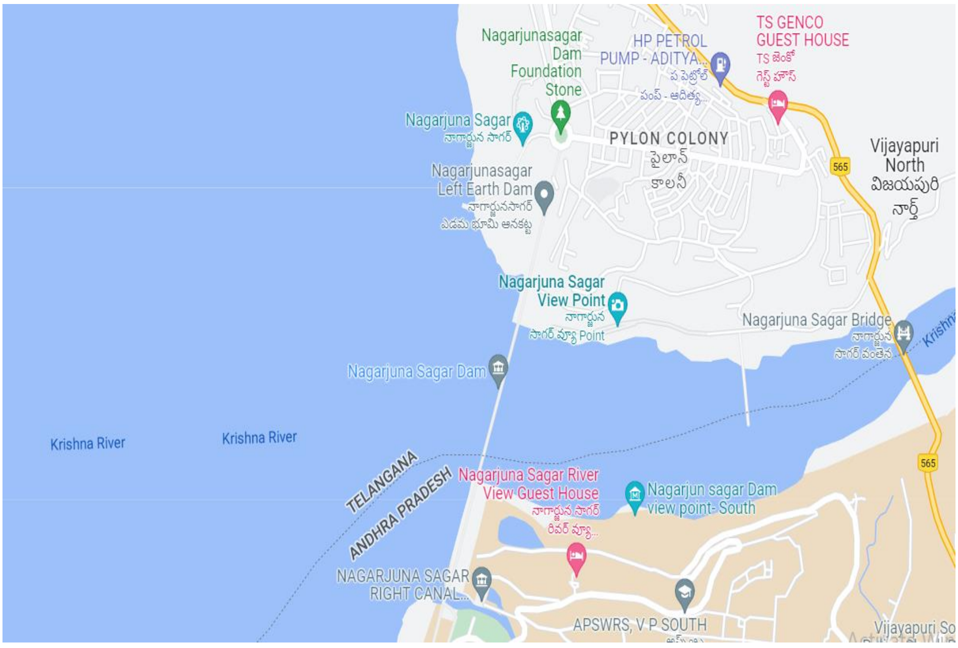

Fig. 1: Location of Nagarjuna Sagar dam, India

4. METHODOLOGY

Available tools in Geostudio are SLOPE/W for slope stability, SEEP/W for steady state seepage analysis and transient seepage analysis, SIGMA/W for stress and deformation, QUAKE/W for calculation of excess pore water pressures and displacement due to earthquake motion, TEMP/W for freezing effect, CTRAN/W for analyzing contaminant migration, AIR/W for air transfer in mine dump and other porous medium. Limit equilibrium method, finite element modeling, and numerical modeling are three methods available in determination of slope stability. In this research, Morgenstern Price method 1965, which is under limit equilibrium method is adopted and performed by using SLOPE/W command in Geostudio. Besides to the Seepage rate and its stability, seepage loss per design life of the structure is found by using SEEP/W command. Displacements at history nodes and its stability in response to earthquake (EQ) motion are estimated by using QUAKE/W for different exposures of time with respect to 0.1g, 0.16g which means k_h of 0.1, 0.16.

4.1 LIMIT EQUILIBRIUM METHOD

From the past decennaries, stability of earth slopes was analyzed by various limit equilibrium methods in geotechnical engineering. The earliest numerical analysis method is the splitting of sliding mass (which is likely to fail) into vertical slices, which was proposed early in the 20th century. Based on Forces acting a slice, limit equilibrium methods are classified into ten methods. The figure 2 describes how the forces acting on the interslice.

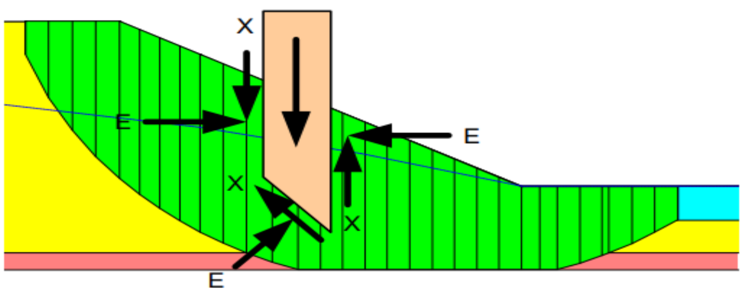

Fig. 2: Forces acting on inter-slice in critical slip surface
Where X - interslice shear force acts tangential to plane, E - interslice Normal force

4.1.1 *SLOPE ANALYSIS USING MORGENSTERN PRICE METHOD*

Geostudio offers a several user specified inter slice force functions in SLOPE/W under MP method which are Data point specify, trapezoidal, clipped- sine, Half- sine, constant. Two factor of safety equations were developed with respect to force and moment equilibrium. A constant relationship is maintained between interslice shear and normal forces. Trial & error process is done to maintain a constant shear- normal ratio which gives identical FOS for both the equations shown in figure 3. Therefore both moment and force equilibrium equations are satisfied.

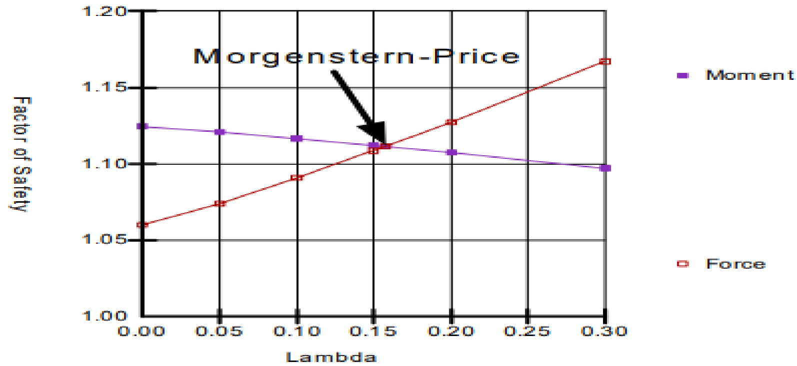

Fig. 3: MP safety factor for half-sine function

Inter relation between interslice shear and normal force is

$X = E \lambda f(x)$ (1)

Where λ is constant obtained from the intersection of moment and force equilibrium, f(x) is specified function value for interslice force, X is interslice shear, E is interslice normal. This method gives lower FOS compared to rest of methods in limit equilibrium as they do not involve the inter slice forces in determining the safety factor. Spencer method is quite similar to this method except various inter slice force functions availability. If "constant" inter slice force function is used in MP method then it would result in same FOS for both Spencer and MP methods.

4.2 SEEPAGE ANALYSIS

Piezometric line is established using SEEP/W analysis which is used as base for SLOPE/W analysis in determining the FOS at D/S and U/S. SEEP/W tool is used for calculation of seepage rate at any point in the cross- section of the structure.

To resemble the field conditions of water level, there are two types of seepage analyses. They are steady state seepage shows the constant storage of water level and transient seepage describes the sudden depletion of water level which occurs during floods. The following equations are derived on the basis of Darcy's law.

Mathematically, steady state seepage is

$\partial/\partial x \, (k_x \, \partial H/\partial x) + \partial/\partial y \, (k_y \, \partial H/\partial y) + Q = 0$ (2)

Transient seepage equation is

$\partial/\partial x \, (k_x \, \partial H/\partial x) + \partial/\partial y \, (k_y \, \partial H/\partial y) + Q = m_w \, \gamma_w \, \partial H/\partial t$ (3)

Where H = total available hydraulic head difference, k_x = permeability in x-direction, t = time, Q = discharge, k_y = permeability in y-direction, m_w = slope of the storage, γ_w = the unit weight of water.

4.3 EARTHQUAKE ANALYSIS

QUAKE/W is a geotechnical finite element software product used for the seismic analysis of earth structures subjected to earthquake shaking and other sudden impact loading such as dynamiting or pile driving.

4.3.1 *PSEUDO-STATIC ANALYSIS*

Seismic stability of structure is checked by giving an earthquake motion in terms of constant vertical and/or horizontal acceleration. The inertial forces caused by pseudostatic accelerations acts at a centre of critical slip surface of slope are F_h and F_v which are also known as pseudostatic forces.

$$F_h = (a_h W) / g = k_h W \quad (4)$$

$$F_v = (a_v W) / g = - k_v W \quad (5)$$

Where k_h, k_v and a_h, a_v are horizontal and vertical (pseudostatic coefficients, pseudostatic accelerations), W is weight of failure mass, g is gravity acceleration.

$$FOS = \text{resisting force / driving force}$$

$$= c*l + ((W - F_v)\cos\beta - F_h \sin\beta)\tan\varphi / ((W - F_v)\sin\beta + F_h\cos\beta) \quad (6)$$

Where l is length of failure plane, β is angle of failure plane with the horizontal.

4.4 MODEL ANALYSIS: RIGHT EARTHEN EMBANKMENT OF NAGARJUNA SAGAR DAM

The conceptual model has an impervious core over spread by semi pervious material and the frontal, hindmost slopes are covered with excavated material. There are three filters such as coarse, transition, fine are placed on either side after excavated material which allows the water penetrated to the embankment will pass into it and later removed by pipes. Thereby reducing the risk and improving the life span of the structure. At the toe portion, rock fill toes are provided. The foundation has grout holes to fill the gaps in the rock.

The index properties of the soil material given in table 1. For analysis of model, Mohr coulomb material model is taken into consideration. The geometry consists of eight regions which resemble the foundation, rockfill toe, excavated material, coarse, transition and fine filters, semipervious material and impervious core. Model dam is displayed on Fig.4.

The analyses involve SEEP/W shows the long run steady state seepage & transient seepage, SLOPE/W gives the slope stability in terms of FOS, QUAKE/W is used to analyze the response to ground shaking due to earthquake motion and transient seepage representing sudden drawdown condition before earthquake. A granular toe drain is placed beneath the rockfill toe at the downstream side as the piezometric line fall into the toe drain from the filters. The finite element mesh of model case study has 221 nodes and 188 elements as shown in figure 14. The Shear Modulus parameter used in dynamic analysis is chosen based on type of soil in graphical form. Rest of the soil parameters which are used for analysis given in table 1.

Table 1: Soil properties in present study

Material	Specific weight (KN/m³)	Cohes-ion (KPa)	Perme-ability (m/s)	Internal friction (^{0})	Saturat-ed water content	Poiss-on ratio	Damp-ing ratio
Core	22	27	$1e^{-08}$	40	0.5	0.3	0.8
Semi pervious	19	10	$1e^{-06}$	33	0.46	0.3	0.3
Excavated fill	20.5	22	$1e^{-06}$	34	0.48	0.2	0.25
Transition zone	16	0	0.001	45	0.42	0.15	0.15
Filter 1	19	0	0.0001	44	0.42	0.2	0.18
Filter 2	17	0	$1e^{-05}$	40	0.42	0.25	0.2
Rockfill	26	0	0.01	34	0.4	0.4	0.05
Foundat-ion	21	5	$5.5e^{-07}$	36	0.48	0.27	0.4

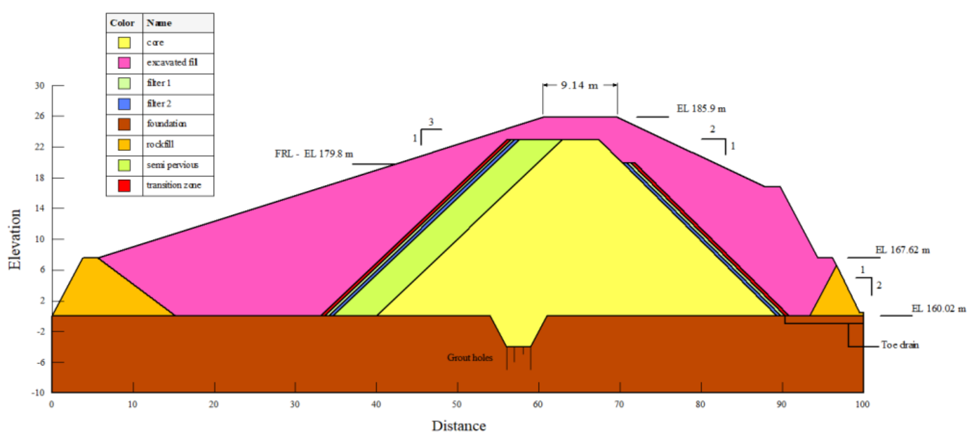

Fig. 4: Simulation of right earthen embankment

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5. RESULTS AND DISCUSSIONS:

5.1 STATIC ANALYSIS

The SEEP/W analysis is first performed to know the flow rate in the drain and to know the piezometric line which is the basis to perform SEEP/W analysis. To calculate the Seepage rate and factor of safety, volumetric water content, permeability, saturated water content, specific weight of soil, angle of internal friction, residual water content are necessary. Van Genuchten hydraulic conductivity function is used for seepage analysis. Steady State seepage analysis for long run upto FRL of Embankment is displayed on the figure 5. The seepage flow rate can be seen in Fig. 6.

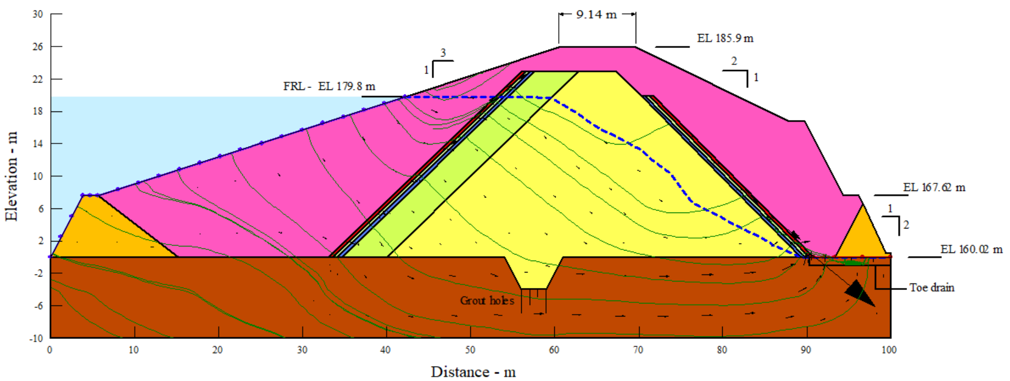

Fig. 5: Seepage flow with arbitrary flow paths and flux vectors

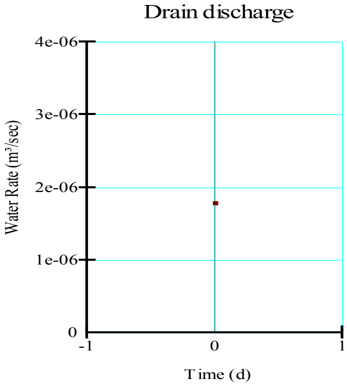

Fig. 6: Discharge Q ($1.783e^{-06}$ $m^3/s/m$) in the drain for Steady State seepage.

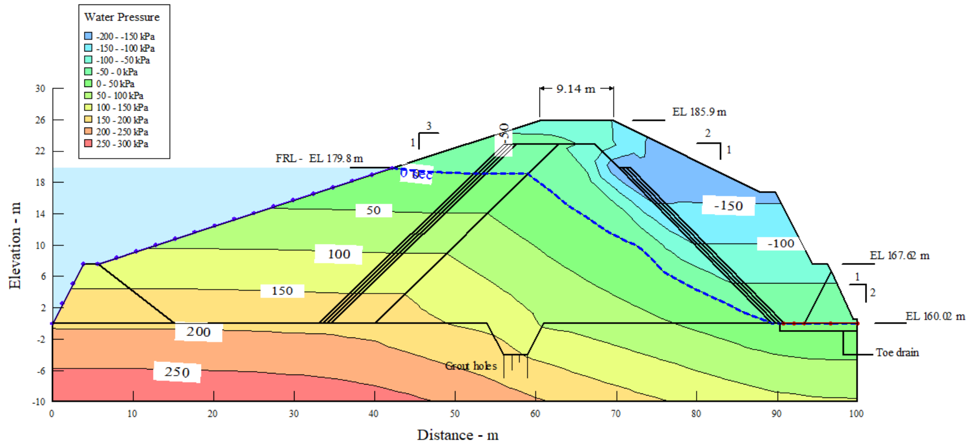

Fig. 7: Pore Water Pressure distribution in seepage flow

The pore water pressure inside the dam through steady state seepage is displayed on figure 7. Downstream and upstream slope stability analyzed by using SLOPE/W shown in Fig. 8 and Fig. 9 respectively.

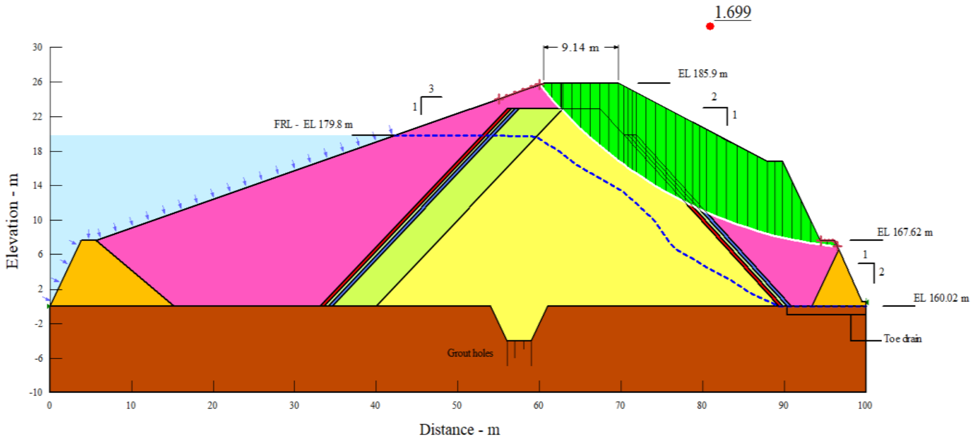

Fig. 8: Downstream FOS for slope stability analysis

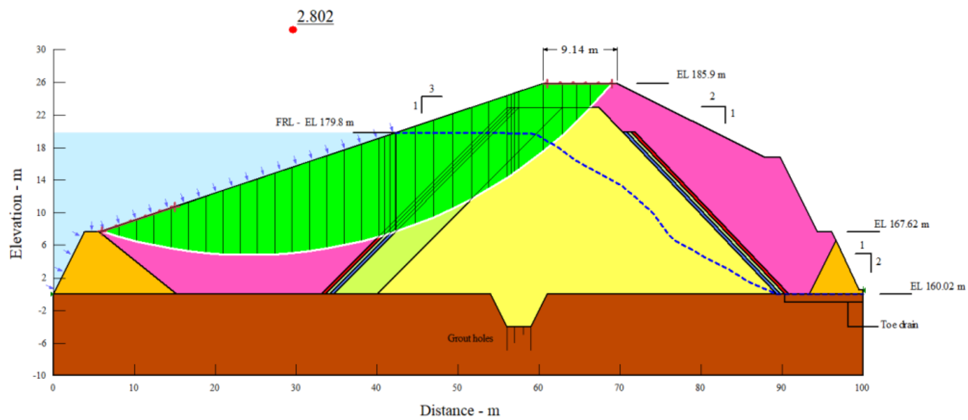

Fig. 9: Upstream FOS for slope stability analysis

In SEEP/W, transient seepage (or) instantaneous drawdown analysis is performed for 5days and the behavior of stability pattern is observed by drawdown analysis. For instantaneous seepage, the stability is dropped to certain level immediately and gradually rise. The reason behind the drop is due to sudden dissipation of pore water pressure and reduction in water level, leads to reduction in resultant forces. Rise of FOS is due to gradual increase of friction between the soil particles with release of pore water pressure thus increased the resisting forces. The transient seepage for 5 days and stability during transient seepage displayed in the Fig. 10 and Fig. 11 respectively.

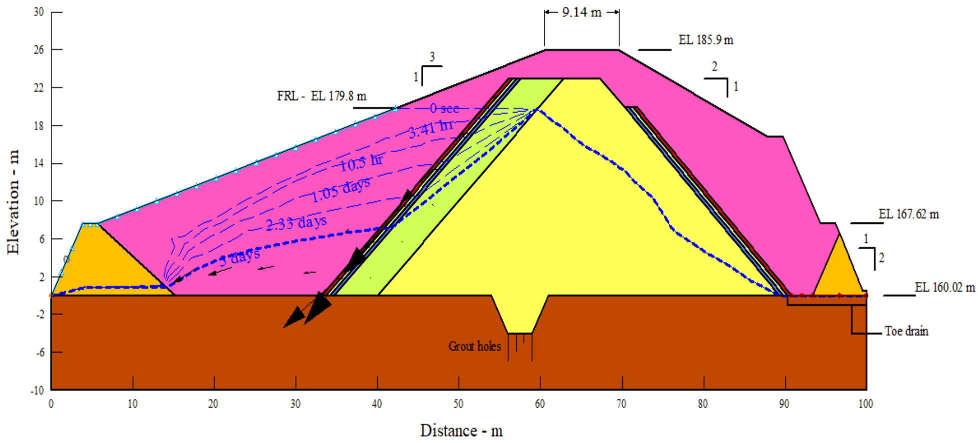

Fig. 10: Instantaneous drawdown for 5 days

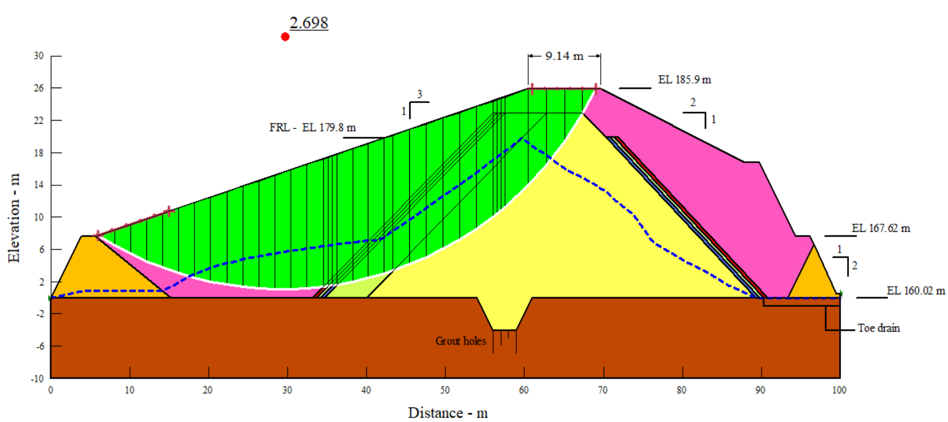

Fig. 11: Upstream Slope Stability after instantaneous drawdown for 5 days

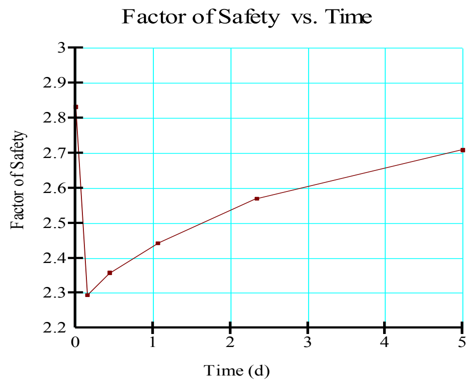

Fig. 12: FOS for Rapid drawdown for 5d

Due to sudden instantaneous or rapid drawdown FOS drops suddenly and regains up to a certain limit due to variation of head continuously in exponential manner. For 5d, FOS drops from 2.833 to 2.29 at 0.142d (1st step) and later along with time FOS regains to 2.698. The drawdown process is performed in exponential manner. In drawdown analysis, drawdown for 5 days is done in logarithmic steps. This pattern of reduction and increase up to a certain value follows the partial differential equation for instantaneous drawdown. The variation of FOS during rapid drawdown along with time displayed in figure 12. Stability of slope is proportional to number of days for drawdown.

5.1.1 *SEEPAGE LOSSES THROUGH DRAIN*

The water flow through drain is entered from filters and the foundation in the right embankment dam and is removed by pipes in the drain which is known as seepage loss (q). In steady state seepage, seepage loss is calculated by using the formula below.

$$q = Q \times B \tag{7}$$

$q = 1.783e^{-06}\ m^3/s/m \times 100 = 1.783e^{-04} m^3/s$

$= 5622.9\ m^3/$ year.

Where B is the width of the model dam.

This dam has been in practice since 1967 to serve its objective of utilizing reservoir water for irrigation to surrounding districts. For design span of 100 years, the estimated water loss is 562290 m^3. For rapid drawdown, seepage loss is

$$q = Q \times B \tag{8}$$

$q = 1.088e^{-05}\ m^3/s/m \times 100 = 1.088e^{-03}\ m^3/s$

$= 34{,}311.17\ m^3/$ year $= 34311.17 \times 100\ m^3$

Therefore, the seepage loss is 3431117 m^3 for 100 years design span.

5.2 PSEUDO-STATIC ANALYSIS

An earthquake motion of particular g (peak ground acceleration) is imposed on the right earthen embankment to observe the amount of displacement. As per 1893:2002, India is classified into five seismic zones. Least the number represents the safe zone. Andhra

Pradesh comes under Zone-II and Telangana is assigned as Zone-III. IS Code for Seismic Zone –II and III - 0.1, 0.16 respectively. Time history plot for dynamic analysis is displayed on figure 13. In Dynamic QUAKE/W, Equivalent Linear Dynamic analysis method is selected for an earthquake (horizontal g (a_h) of 0.1g or horizontal seismic coefficient k_h of 0.1) for 10 seconds is applied on the model. In SEEP/W, steady state seepage analysis acts as parent analysis for QUAKE/W. In this study, model embankment dam presents the results when it is subjected to both the horizontal EQ motions of 0.1g, 0.16g with various durations and not studied for further increase in g as the dam location lies on these two seismic zones.

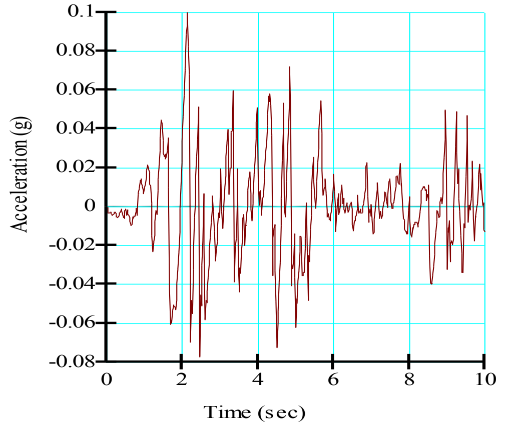

Fig. 13: EQ Time- history plot 0f 0.1g for 10 sec

Points can be tagged at anywhere on the embankment crossection to record displacement at that particular point are known as History Nodes. Using QUAKE/W analysis, deformation due to earthquake along with three History Nodes are marked as A,B,C as displayed in the figure 14 and X- Displacements Vs Time at A,B,C graphs displayed in Fig.15.

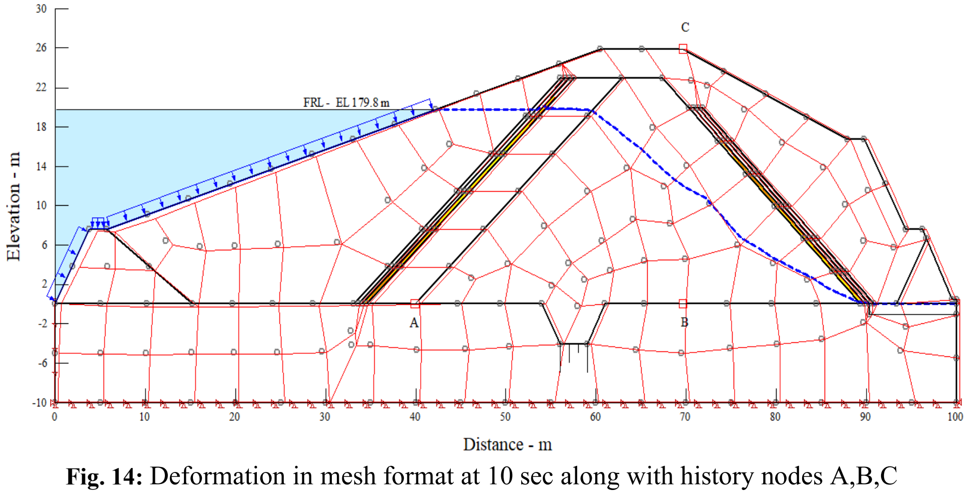

Fig. 14: Deformation in mesh format at 10 sec along with history nodes A,B,C

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Circles represents nodes, red lines between nodes are finite elements and whole network represents deformation pattern of finite element mesh. Liquefaction is observed in fine sands represented with yellow color in Fig. 14.

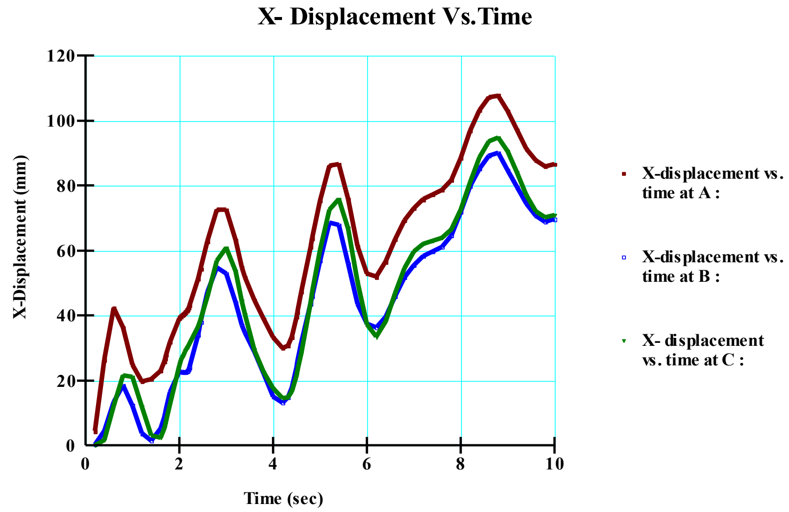

Fig. 15: Plot of time and X- displacement at History nodes

The maximum displacement at A is 0.107m, at B is 0.068m, and at C is 0.095m are caused by excess PWP formed due to liquefaction (due to earthquake shaking). Post Safety factor after earthquake is analyzed by QUAKE/W stress in SLOPE/W tool. Post FOS for upstream represented in the Fig.16 respectively.

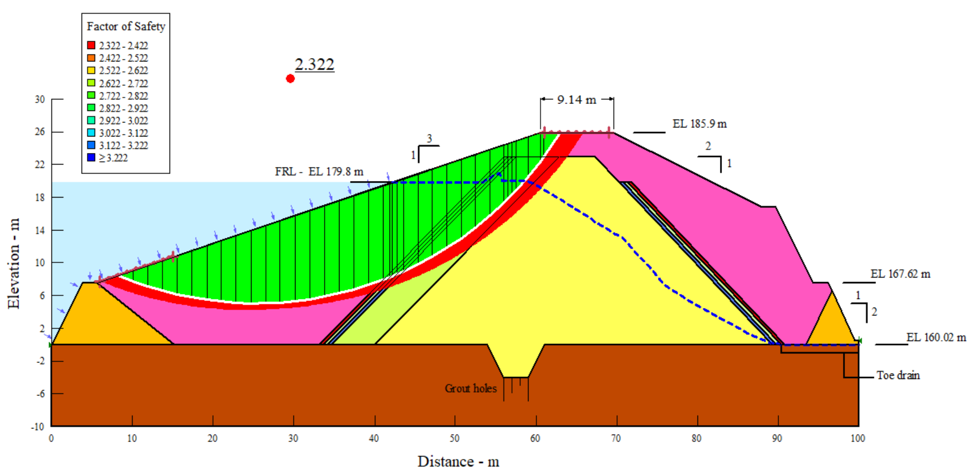

Fig. 16: Post EQ FOS at upstream

In the Post EQ analyses, red color along critical slip surface represents critical safety factor range obtained after performing analysis. As Liquefaction occurs in fine sands, piezometric line shifts upward at filter 2. The displacements in horizontal direction at history nodes which varies with different pga (g) and earthquake duration by using QUAKE/W displayed on table 2.

Table 2: Represents X- Displacements at History Nodes

EQ pga (g)	Duration of EQ motion (Sec)	Displacement (m) at A	Displacement (m) at B	Displacement (m) at C
0.1	5	0.053	0.034	0.039
0.16	5	0.645	0.045	0.050
0.1	7	0.070	0.052	0.057
0.16	7	0.095	0.075	0.080
0.1	10	0.107	0.068	0.095
0.16	10	0.157	0.081	0.143

6. CONCLUSIONS

The aim of paper is to investigate the stability of the right earthen embankment in terms of seepage, slope geometry, exposure to earthquake motion. Analyses performed in three stages of sequence.

1. Conducting SEEP/W (steady state) acts as parent analysis for SLOPE/W & QUAKE/W to know seepage losses for steady state and rapid drawdown are 5622.9 m^3/ year, 34,311.17 m^3/ year and for a design life of 100 years seepage loss will be 1135296 m^3, 3431117 m^3.
2. Performing SLOPE/W to determine the FOS value during static SLOPE/W at upstream is 2.802, downstream is 1.699 & FOS during rapid drawdown analysis at 5d is 2.698, first step is critical as FOS fall suddenly and 1st step FOS (2.29) is greater than 1.3.
3. QUAKE/W to find stability corresponding to imposed earthquake motion in horizontal direction of 0.1g according to IS code 1893-2002 [18] for ten seconds. Permanent displacements due to earthquake motion are found at history nodes (A,B,C) are 107, 68, 95mm along with post safety factor obtained at upstream , downstream were 2.322,1.39 respectively. Displacements at history nodes are found for different durations corresponding to 0.1g, 0.16g. The highest displacement is observed at history node A at 0.16g (peak horizontal acceleration) for 10 seconds.
4. The FOS values according to USACE (2003) for FRL in the upstream and downstream is 1.5. During rapid drawdown and empty reservoir is 1.3. According to IS 1893: 2002, seismic FOS for stable condition must be greater than one. The EQ (QUAKE/W) analysis is executed for 0.1g, even with higher peak horizontal acceleration the FOS will not fall below one due to stable flat slope on upstream side. On comparison to obtained results with permissible values, it is concluded that embankment is safe against possible failure modes studied in the research.

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