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Seepage Analysis of Earthen Dam using Geo-Studio Software - A Case Study

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***Abstract*: Earthen dams are mostly prone to failures. Seepage failure accounts for 40% of the total failures. So it is necessary to minimise the seepage within the embankment to increase the stability and thereby increasing the life of structure. This project focuses on calculating the amount of seepage for different reservoir heads on the upstream side of Kas dam, an earth-fill zoned dam in Satara district, Maharashtra using Geo studio software and comparing it with analytical results. Stability analysis of dam is also carried out on software and factor of safety is obtained from it. Variation in structural parameters like upstream and downstream slope, reservoir head at upstream, transition filters, type of rock toe drain, berm width and its effect on phreatic line and ultimately seepage through the dam body. Seepage analysis is done by using the Geo-studio software (V 9.1.1.16749). The outcome of this study shows that the dam is safe against seepage failure from the seepage analysis carried out in Geo studio software and SEEP/W can be efficiently used for seepage analysis**

***Keywords*: Seepage loss, Phreatic line, Geo studio software, Earthen dam.**

1. Introduction

India, as a subcontinent, since ancient times, has a diversity of natural assets. This is hugely due to the natural presence of huge water bodies that promotes the growth of life in the country across various landscapes. As the mankind evolved, water became an important asset to be used as not only for domestic utility, but also for energy production. Dams have been the earliest and most effective form of structures which can be used for storage of water and also a source of storage for potential energy which is later to be converted into power for the household and industrial purposes. Hence, dams are one of the most vital sources of water and energy even in the modern times. Dam construction is of national importance as it involves huge stakes of life and property. Hence, the construction of dams has to be secured using multiple measures and techniques to harness the maximum utility for the huge investment of the country and taxpayer’s money. As dams are mega structures, even relatively minimal losses result into huge loss in the long run which in turn brings down the effectiveness of the structures.

Out of the various types of dams, earthen dam embankment is a structure with complex Geometry and expected to remain stable under all conditions. In case of dam holding reservoir water, the knowledge of water flow inside embankment is extremely important to estimate the seepage loss inside the water storage dams.

One of the important points in the study stages and during construction of earth dams is seepage through the dam body. Seepage is the continuous movement of water from the upstream face of the dam toward its downstream face. The upper surface of this stream of percolating water is known as the phreatic surface. The phreatic surface should be kept at or below the downstream toe. The position of the phreatic surface influences the stability of the earth dam because of potential piping due to excessive exit gradient and sloughing due to the softening and weakening of the soil mass as if it touches the downstream slope or intersects it.

About 30% of earth dams have been failed due to the seepage failure like piping and sloughing. Recent studies show that internal erosion and piping are the main causes of failure and accidents affecting embankment dams; and the proportion of their failures by piping is increased. The sloughing of the downstream face of a homogeneous earth dam occurs under the steady-state seepage condition due to the softening and weakening of the soil mass when the top flow line or phreatic line intersects it.

Steady seepage develops after a reservoir pool has been maintained at a particular elevation for a sufficient length of time to establish a steady line of saturation through the embankment. The seepage forces which develop in the steady state condition act in the downstream direction. Another condition that may happen in earth dams is rapid draw down of reservoir water table. When the reservoir is emptied, a phreatic surface or water table is formed in the embankment. The free water surface in the embankment does not fall as rapidly as the reservoir level. A reverse hydraulic gradient is established which results in a flow in the embankment towards the emptied reservoir. The water table in the embankment gradually recedes as water flows out towards the toe. The hydro-static pressure in the embankment decreases as the water table falls, and the soil effective stresses increase. The period immediately after draw down of the reservoir level is a critical one with respect to the design of the embankment. The hydro-static pressure in the embankment causes an unstable situation as it acts towards the free face. The effective stresses in the soil are low therefore the full strength of the soil is not established and the frictional resistance is low. The proposed project work focuses on parameters of material obtain from Kas dam can be studied and the input of the parameter can be given to the software and by applying various permutations and combination of structural parameters of the dams in the simulations to controlling the seepage in embankment.

2. Objective

1. To study behavior of phreatic line within earthen embankment for different reservoir heads on upstream side.
2. To estimate the seepage in embankment using Geo-studio software.
3. To check the stability and estimate the seepage in the embankment by varying some structural parameters

3. Literature review

Following are the outcomes from the previous research papers
to complete literature review of the project.

- The failure of the dam due to seepage was calculated by analytical approach using Geo-studio software.
- The slope stability analysis was carried using SLOPE/W in Geo-studio approaches.
- The comparison was done between analytical and software results. The variations in the results is about 10-15%.
- Stability analysis were carried out by varying the structural parameters of the dam such as changing the position of filter drains and changing berm width.
- The results showed that by varying the structural parameters the stability of the earthen dam can be improved.
- Provision of drain increases the factor of safety on the downstream side.
- Provision of a drain on downstream side improves the factor of safety (FoS) on the upstream side.
- SLOPE/W software is used under different conditions to evaluate slope stability.
- Slope stability analysis of earth dams is very important to ascertain the stability of the structure.
- The failure of the dam due to seepage was calculated by analytical approach using Geo-studio software.
- The slope stability analysis was carried using SLOPE/W in Geo-studio approaches.
- The comparison was done between finite element analyses to the limit equilibrium method results.

Based on literature review it was concluded that Geo-Studio Software is better best option for seepage and stability analysis for earthen dam.

4. Study Area

Kas dam was constructed in 1885 for water supply for Satara city, Maharashtra. Kas dam belong to the Satara municipal council, Satara. In order to cater additional water requirement of Satara city, it was decided to raise the height of existing dam. As the work involved is of a local self-government hence taken up on consultancy basis.

Table 1
Kas dam details

Dam Name	Kas Dam
State Name	Maharashtra
Type of Dam	Earthen Dam
Owner	Government of Maharashtra
Nearest City	Satara
Impounds	Kas Lake
Catchment Area	7.123 Sq. km
Latitude/ Longitude	17 -42 0 N , 73 -49 -20 E
Total Storage Capacity	14.16 M cum
Type	Composite
Height	27.70 m
Length	590 m

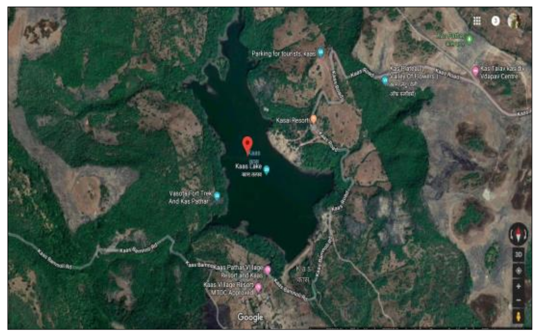

Fig. 1. Kas dam location (Google Maps)

Collection of Data:

All the data was collected from the, Water Resource Department Satara, Government of Maharashtra.

5. Introduction to Software

Geo-Studio is analysis based software in which we can perform various types of analysis related to Geotechnical studies, it is user friendly software which is available free for students. Geo-Studio is capable of solving complex problems using finite element method of analysis.

Flow quantity is a key parameter in quantifying seepage losses from a reservoir or identifying a potential water supply for domestic or industrial use. Pore-pressures associated with groundwater flow are of particular concern in Geotechnical engineering. The pore-water pressure, whether positive or negative, is an integral component of the stress state within the soil and consequently has a direct bearing on the shear strength and volume change behavior of soil. Flow quantity is a key parameter in quantifying seepage losses from a reservoir or identifying a potential water supply for domestic or industrial use. Pore-pressures associated with groundwater flow are of particular concern in Geotechnical engineering. The pore-water pressure, whether positive or negative, is an integral component of the stress state within the soil and consequently has a direct bearing on the shear strength and volume change behavior of soil. It is no longer acceptable to simply ignore the movement of water in unsaturated soils above the phreatic surface. Not only does it ignore an important component of moisture flow in soils, but it greatly limits the types of problems that can be analyzed. It is central to the analysis of problems involving infiltration and moisture redistribution in the vases zone. Transient flow problems such as the advance of a wetting front within an earth structure after rapid filling are typical examples of situations in which it is impossible to simulate field behavior without correctly considering the physics of flow through unsaturated soils. Fortunately, it is no longer necessary to ignore the unsaturated zone. With the help of this document and the associated software, flow through unsaturated soils can be incorporated into numerical models so that almost any kind of seepage problem can be analyzed.

In general, all water flow is driven by energy gradients associated with the total head of water as represented by the components of pressure head (or pore water pressure) and elevation. The term seepage often is used to describe flow problems in which the dominant driving energy is gravity, such as a case in which seepage losses occur from a reservoir to a downstream exit point. In other situations, such as consolidation, the primary driving energy may be associated with the creation of excess pore-water pressures as a result of external loading. However, both of these situations can all be described by a common set of mathematical equations describing the water movement. As a result, the formulation used to analyses seepage problems can also be used to analyses the dissipation of excess pore-water pressures resulting from changes in stress conditions. In the context of the discussions and examples in this document and in using the Geo-Studio software, the term seepage is used to describe all movement of water through soil regardless of the creation or source of the driving energy or whether the flow is through saturated or unsaturated soils.

6. Model Formation Using Geo-Studio SEEP/W

A. Creating problem workspace and analysis properties

Create a SEEP/W analysis and set up the problem workspace. Choose analysis type, including steady-state, transient or coupled analyses, and define initial pore-water pressure conditions, convergence criteria, time duration and increments, and advancement.

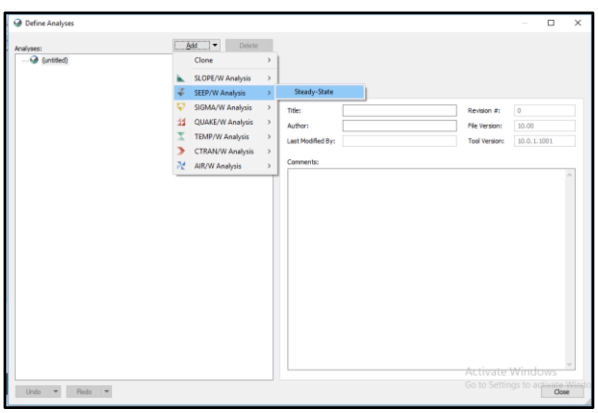

Fig. 2. Selection of Analysis

B. Drawing domain regions or import from a CAD program

Draw the regions in domain using CAD-like drawing tools, including drawing polygon and circular regions, coordinate import, copy-paste Geometric items, length and angle feedback, region splitting and merging, and direct keyboard entry of coordinates, lengths, and angles. Alternatively, import AutoCAD DWG or DXF files directly into Geo-Studio to create your domain Geometry.

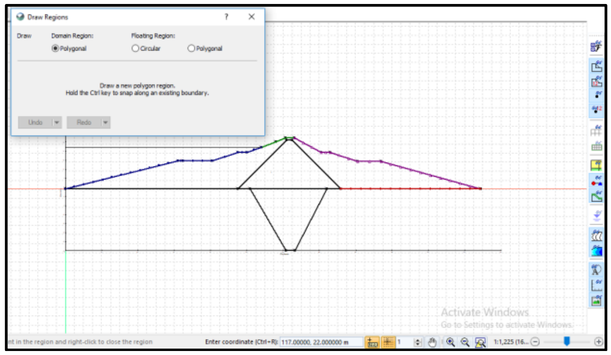

Fig. 3. Draw regions

C. Defining material properties and pore-water pressure

Define the material properties for analysis, assign them to regions on the domain, and then define your initial pore-water pressure conditions. Select from Saturated/Unsaturated, Saturated Only and Interface material models. Define hydraulic material functions using spline data point entry, Freedland-Xing or van Genuchten methods. Define the initial pore-water pressure conditions for transient scenarios using results from other SEEP/W analyses, defined spatial functions or draw an initial water table.

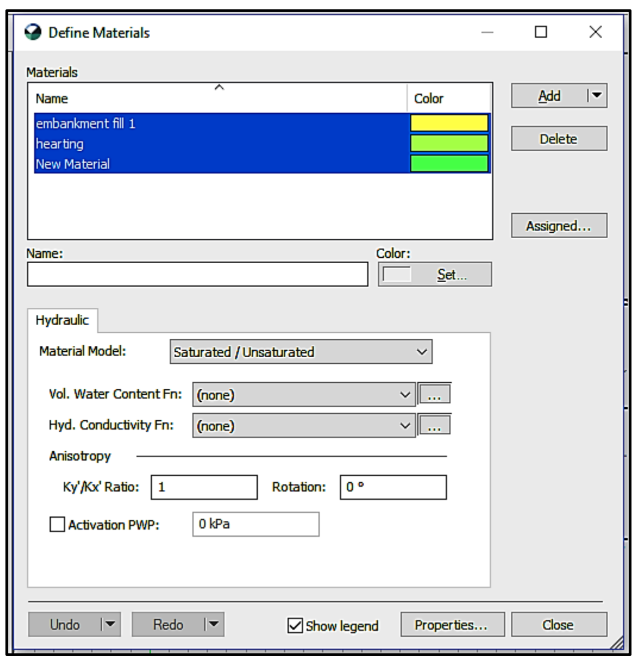

Fig. 4. Define material

D. *Defining hydraulic boundary conditions*

Define hydraulic boundary conditions to simulate total head, pressure head, pore-water pressure, unit flux (q) or total flux (Q) conditions. Time-varying conditions can also be modelled using total head, pressure head, unit flux (q) or total flux (Q) vs. time functions. The total head vs. volume function can also be used to simulate volume of water entering or exiting the domain via a specified boundary.

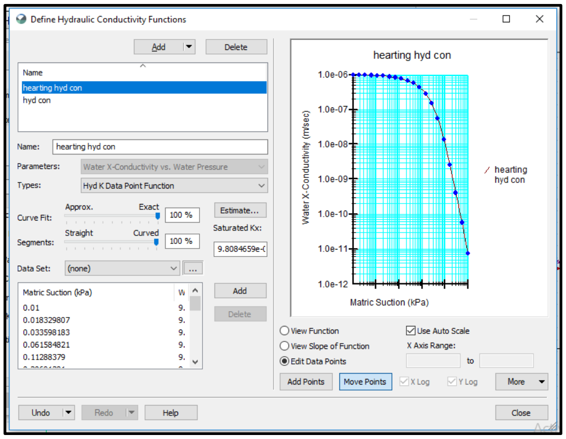

Fig. 5. Boundary conditions

E. *Drawing mesh properties*

Open Draw Mesh Properties to refine the mesh drawn on the entire domain, or along specific Geometric regions, lines or boundaries. Interface elements can also be created to simulate Geo-synthetic or other thin materials.

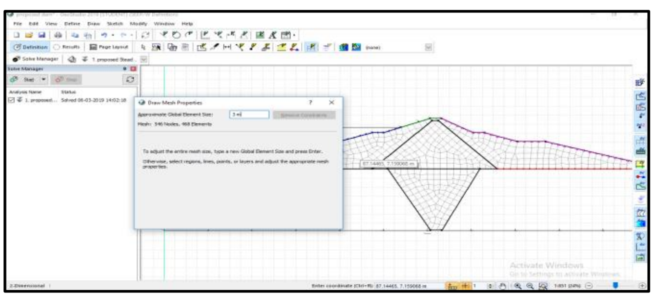

Fig. 6. Draw mesh properties

F. *Analysis of Results*

When the problem is completely defined, start the analysis process in the Solver Manager window. The Solver Manager displays the solution progress, allowing to cancel if necessary. While the solution is in progress, we can look at preliminary results in the Results window.

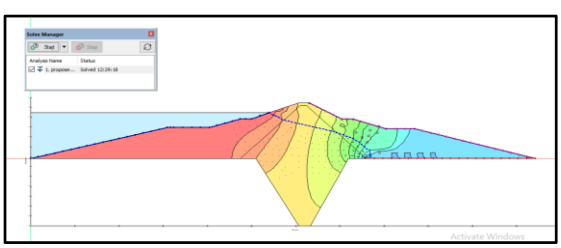

Fig. 7. Solve manager

G. *Seep/w problem result*

When the Solver is finished, the Total Head contours are displayed, along with the location of phreatic surface, or zero pressure isocline, and flux vectors. Contour legends and properties can also be modified. Labels can be added to contour lines for display in Results View. Flow paths can also be drawn in steady-state analyses. Using graph command section can be selected for graphical result as shown in fig. 8. After using graph command a graph is generated which shows flow rate in m^3/s on Y-axis and horizontal distance from u/s in m as shown in fig. 9. at selected location.

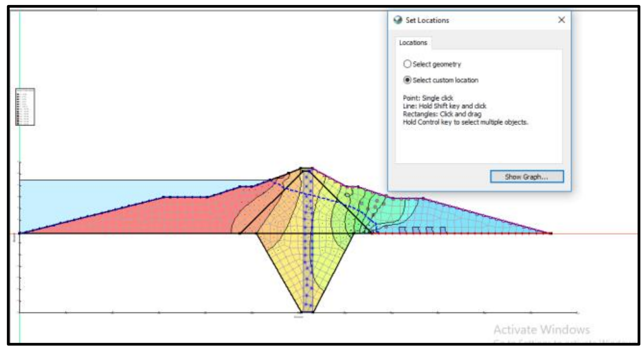

Fig. 8. Selection of location for result (screenshot)

Fig. 9. shows the results of water rate at 121.5m from upstream toe.

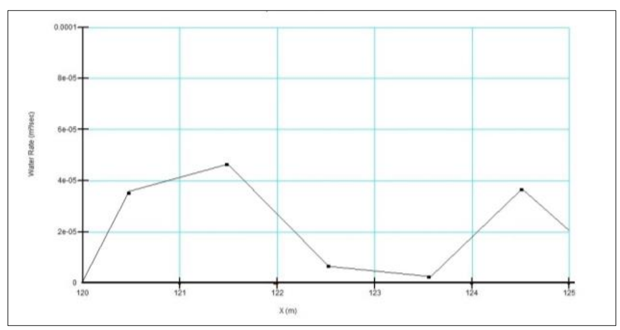

Fig. 9. SEEP/W results

H. *Existing profile of Kas dam*

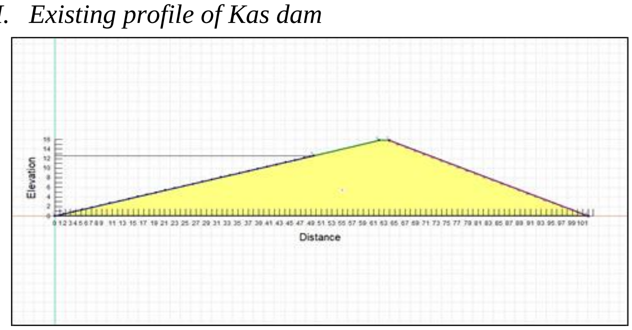

Fig. 10. Profile of Existing Kas dam in Geo-studio software

1) *Details of existing dam*

Type of earthen embankment: Homogenous
Width of dam: 102m
Height of the dam:15.2m
Water head up to full reservoir level(FSL):12.6m

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I. Proposed profile of Kas Dam

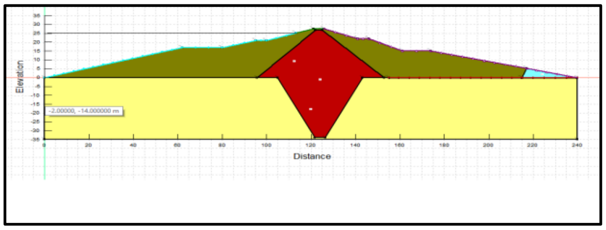

Fig. 11. Proposed Profile of Kas dam in Geo-studio software

1) Details of proposed dam

Type of earthen embankment: Zoned
Width of dam: 228.5m
Height of the dam:28.2m
Water head up to full reservoir level(FSL):24.2m

7. Result and Discussion

A. Behavior of phreatic line within earthen embankment for different reservoir heads on upstream side

1) Change reservoir head on upstream side and check results

Result of SEEP/W at TBL 28.2m as shown in fig. 12.

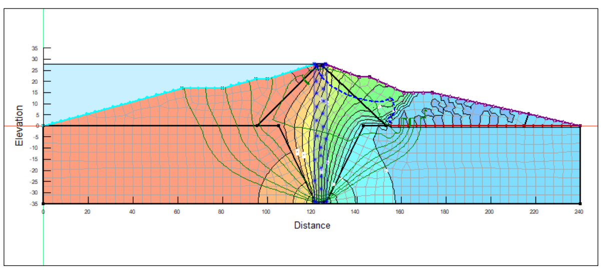

Fig. 12. Reservoir head at proposed TBL-28.2m

Graphical result at TBL 28.2m as shown in fig. 13.

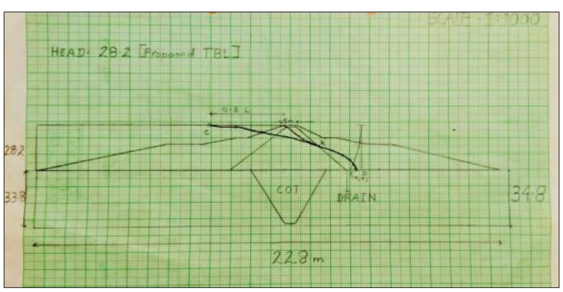

Fig. 13. Reservoir head at proposed TBL-28.2m

Result of SEEP/W at HFL 26.2m as shown in fig. 14.

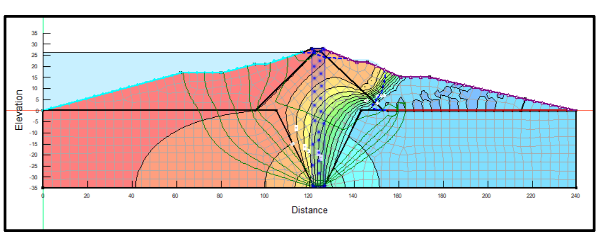

Fig. 14. Reservoir head at proposed HFL-26.2m

Graphical result at HFL 26.2m as shown in fig. 15.

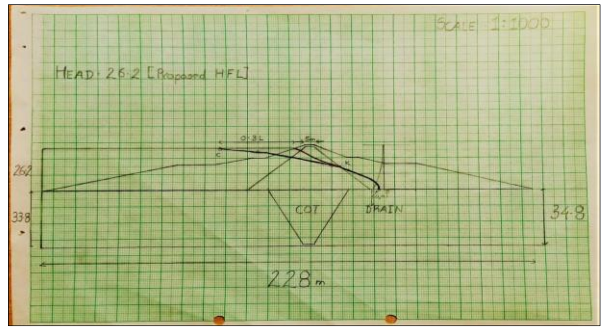

Fig. 15. Reservoir head at proposed HFL-26.2m

Result of SEEP/W at FSL 24.2m as shown in fig. 16.

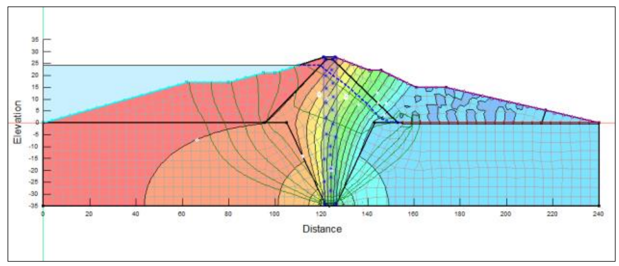

Fig. 16. Reservoir head at proposed FSL-24.2m

Graphical result at FSL 24.2m as shown in fig.17.

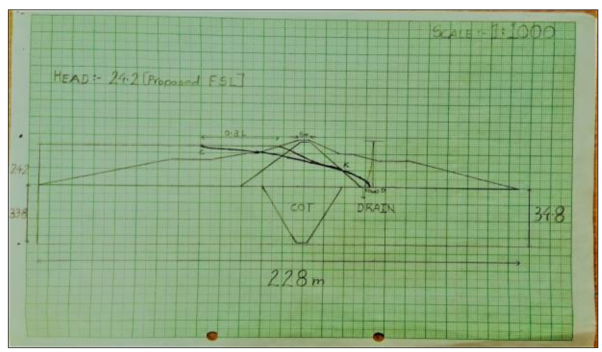

Fig. 17. Reservoir head at proposed FSL-24.2m

Result of SEEP/W at FSL 12.6m as shown in fig. 18.

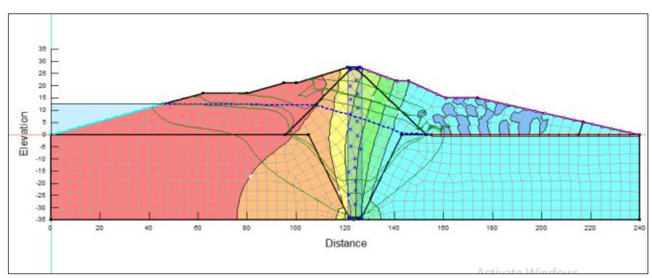

Fig. 18. Reservoir head at existing FSL-12.6m

Graphical result at existing FSL 12.6m as shown in fig. 19.

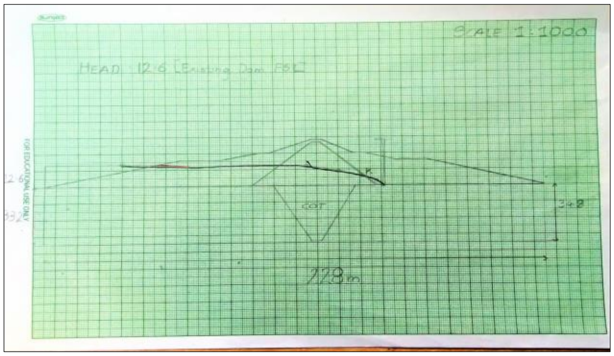

Fig. 19. Reservoir head at existing dam FSL-12.6m

2) Interpretation from phreatic line in embankment for different reservoir heads

For proposed TBL(28.2m)-Variation in actual and base parabola, the distance of point ‘K’ from the toe of hearting=22m, distance between focus and directrix ‘S’=0.6m

For proposed HFL (26.2m)-Variation in actual and base parabola, the distance of point ‘K’ from the toe of hearting=20m, distance between focus and directrix ‘S’=0.5m

For proposed FSL(24.2m)-Variation in actual and base parabola, the distance of point ‘K’ from the toe of hearting=16m, distance between focus and directrix ‘S’=0.4m

For existing FSL(12.6m)-Variation in actual and base parabola, the distance of point ‘K’ from the toe of hearting=9m, distance between focus and directrix ‘S’=0.2m

The results obtained show that for different reservoir heads at the upstream side of the dam the distance of point where the actual parabola ends in the hearting of the embankment i.e. point (k) decreases with decrease in the reservoir head. The distance from the focus and the directrix decreases with decrease in head. Also the saturated area below the phreatic line decreases with decrease in the reservoir head at upstream side.

B. Calculation of seepage in embankment at different reservoir head using Geo-studio software

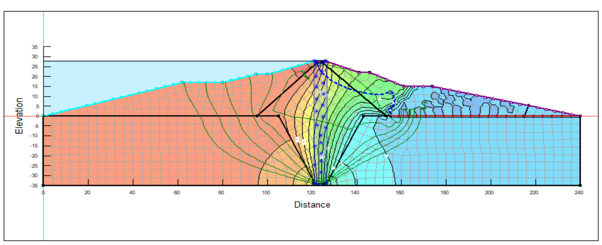

Fig. 20. Reservoir head at proposed TBL-28.2m

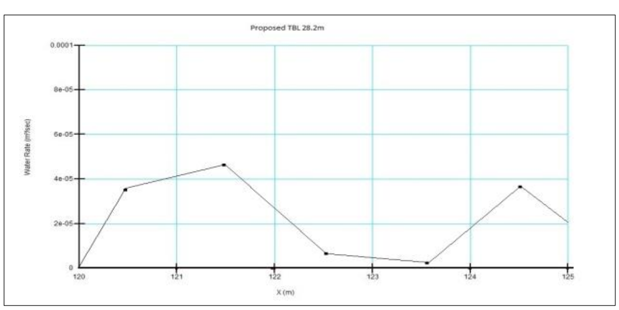

Fig. 21. Results at proposed TBL-28.2m

Water rate for section at hearting at 121.5 m from upstream toe and at TBL 28.2 m is shown in fig. 21.

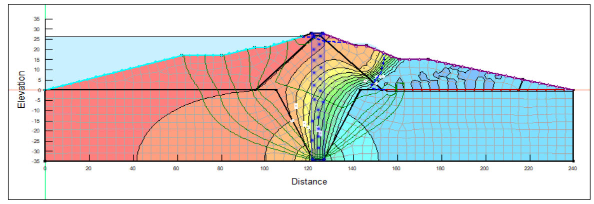

Fig. 22. Reservoir head at proposed HFL-26.2m

Water rate for section at hearting at 121.5 m from upstream toe and at HFL 26.2 m is shown in fig. 23.

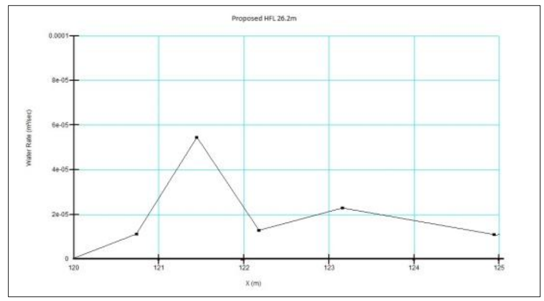

Fig. 23. Result at proposed HFL-26.2m

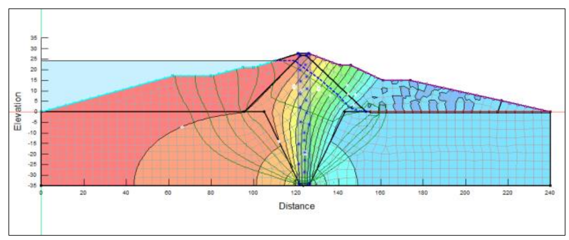

Fig. 24. Reservoir head at proposed FSL-24.2m

Water rate for section at hearting at 121.5 m from upstream toe and at FSL 24.2 m is shown in fig. 25.

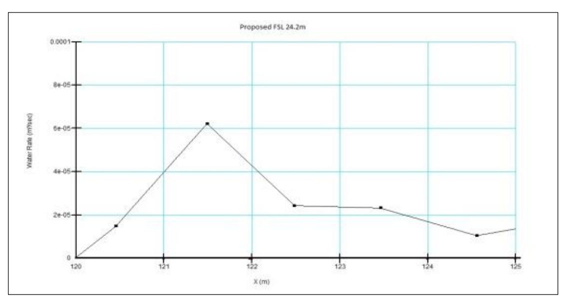

Fig. 25. Result at proposed FSL-24.2m

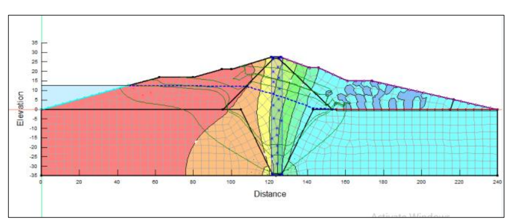

Fig. 26. Reservoir head at existing FSL-12.6m

Water rate for section at hearting at 121.5 m from upstream toe and at existing FSL 12.2 m is shown in fig. 27.

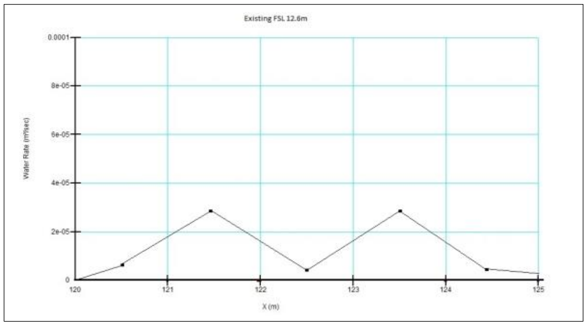

Fig. 27. Results at existing FSL-12.6m

Table 2
Software results

S. no.	Water head on U/S side	Water rate ($m^3/s/m$)
1.	Proposed T.B.L -28.2m	4.8×10^{-5}
2.	Proposed H.F.L -26.2m	5.5×10^{-5}
3.	F.S.L of proposed dam- 24.2m	6.1×10^{-5}
4.	F.S.L of existing dam- 12.6m	2.9×10^{-5}

1) Results of graphical method for seepage analysis of the study area

Graphical results using flownet method at TBL 28.2m is shown in fig. 28.

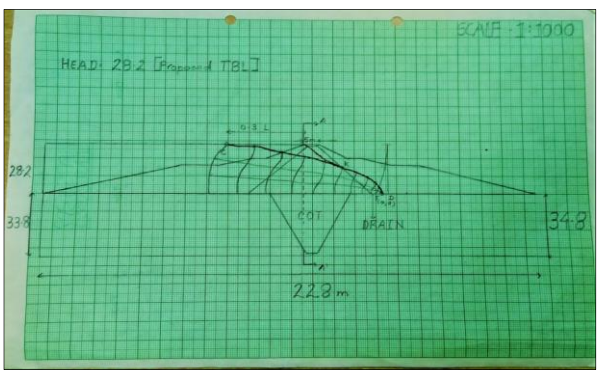

Fig. 28. Reservoir head at proposed TBL-28.2m

Graphical results using flownet method at HFL 26.2m is shown in fig. 29.

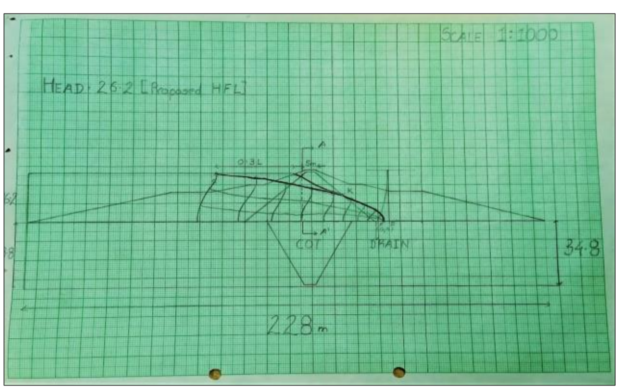

Fig. 29. Reservoir head at proposed HFL-26.2m

Graphical results using flownet method at FSL 24.2m is shown in fig. 30.

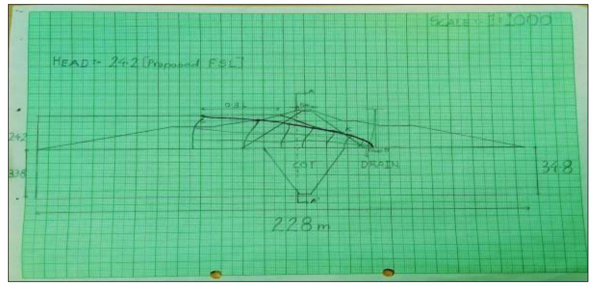

Fig. 30. Reservoir head at proposed FSL-24.2m

Graphical results using flownet method at existing FSL 12.6m is shown in fig. 31.

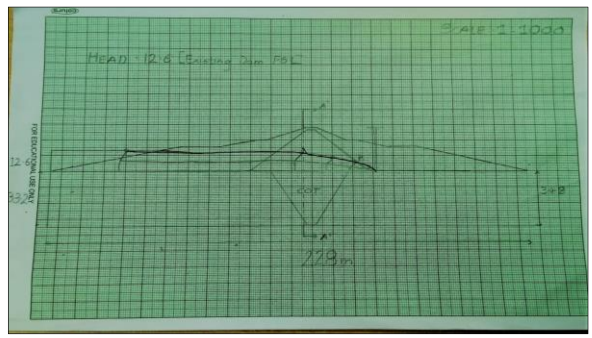

Fig. 31. Reservoir head at existing FSL-12.6m

2) Analytical calculations

The seepage rate (q) can be calculated from flownet, using Darcy's law,

Seepage /Discharge q= K ($H.N_f / N_d$)

Where, K –permeability in horizontal direction

H- Head of water

N_f- number of flow channels

N_d- number of potential drops

Calculations:

Table 3
Calculations of analytical result

S. no.	K(m/s)	H (m)	N_f	N_d	q ($m^3/s/m$)
1.	6.0968×10^{-6}	28.2	3	9	5.73×10^{-5}
2.	6.0968×10^{-6}	26.2	3	8	5.99×10^{-5}
3.	6.0968×10^{-6}	24.2	3	7	6.32×10^{-5}
4.	6.0968×10^{-6}	12.6	2	5	3.07×10^{-5}

3) To calibrate the results from software and analytical

Table 4
Comparison of results

Head of reservoir	Software result q ($m^3/s/m$)	Analytical result q ($m^3/s/m$)
Proposed T.B.L -28.2m	4.8×10^{-5}	5.73×10^{-5}
Proposed H.F.L -26.2m	5.5×10^{-5}	5.99×10^{-5}
F.S.L of proposed dam-24.2m	6.1×10^{-5}	6.32×10^{-5}
F.S.L of existing dam-12.6m	2.9×10^{-5}	3.07×10^{-5}

From table 4, it can be observed that the results from analytical and software have some variations. However, for HFL and FSL the results are almost similar. Therefore, SEEP/W can be efficiently used for seepage analysis.

C. Check the stability and estimate the seepage in the embankment by varying some structural parameters

1) Check the stability of the downstream in Geo-studio

Stability of downstream profile in SLOPE/W Geo-studio to calculate factor of safety against sliding is shown in fig. 32.

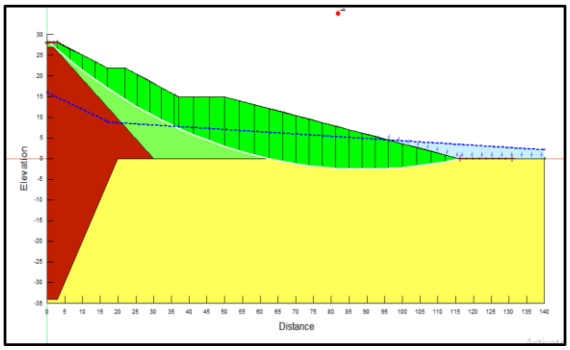

Fig. 32. Stability of downstream in SLOPE/W

Software results:

Factor of safety at sliding =1.562>1.5

Therefore, the dam is safe against sliding failure on downstream side for steady seepage condition.

2) Check the seepage by providing berms at the upstream side of the dam

Seepage in embankment with berms at the upstream side is shown in fig. 33.

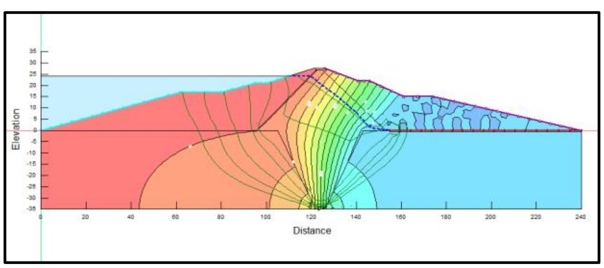

Fig. 33. Seepage in embankment with berms at upstream side

Seepage in embankment without berms at the upstream side is shown in fig. 34.

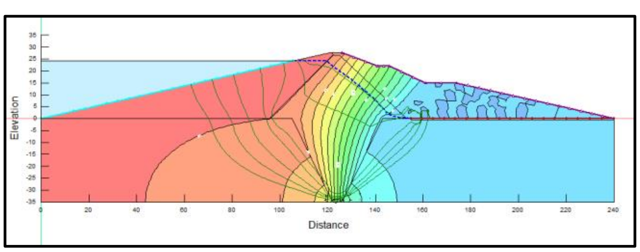

Fig. 34. Seepage in embankment without berms at upstream side

From figure 33 and 34 it was observed that no significant change in the extent of phreatic line in embankment with respect to variation in providing berms and without berms in upstream side.

3) Effect of rock toe and horizontal blanket on seepage through embankment

• *Rock toe/ Toe filter:*

The rock toe consists of stones of usually size varying 15-20 cm. It consists of three layers of sand, coarse sand and gravel as per filter criteria requirement. The height of rock toe is kept between 25 – 35 % of reservoir head.

Height of proposed dam structure -28.2 m

Height of rock toe provided -4.5m ,which is safe as per standard guidelines.

• *Horizontal blanket/ Horizontal filter:*

The horizontal extends from the toe of downstream end, up to a distance varying from 25 – 100 % of the distance of the toe from the center line of the dam. Horizontal filter length should be three times the height of the dam is sufficient.

Height of proposed dam structure -28.2 m

Length of horizontal filter-78m which is safe as per standard guidelines.

The provision of rock toe and horizontal filter reduces the pore pressure in the downstream portion of the dam and thus increases stability of dam, permitting steep slopes and thus effecting economy in construction.

8. Conclusion

The results obtained show that for different reservoir heads at the upstream side of the dam the distance of point where the actual parabola ends in the hearting of the embankment i.e. point (k) decreases with decrease in the reservoir head. The distance from the focus and the directrix decreases with decrease in head. It means the saturated area below the phreatic line decreases with decrease in the reservoir head at upstream side.

The results obtained theoretically and using software are approximately same. While working on large scale work theoretical method is more time consuming and tedious. Hence, SEEP/W can be efficiently used for seepage analysis. The seepage rate is maximum (4.8 x 10^{-5} m^3/s/m) for TBL and minimum (2.9 x 10^{-5} m^3/s/m) for FSL of existing dam.

It is observed that dam is safe against sliding failure at downstream side for steady seepage conditions. Hence there is no internal erosion due to seepage. The provision of rock toe and horizontal filter reduces the pore pressure in the downstream portion of the dam and thus increases stability of structure, permitting steep slopes and thus effecting economy in construction

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