Seepage and Stability Analysis of Earthen Dam in Slow and Rapid Drawdown Conditions

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Abstract

Embankment dams are large rock or earthen dam which withhold the water pressure of upstream reservoir by the shear strength of the compacted soil used in the construction of dam. Various materials like sand ,gravel, clay etc. are used along with semi-pervious waterproof natural covering for the construction of any earthen dam. Along with semi pervious materials , impervious materials are used for the construction of core in the center of dam. This act as a protection against problems like seepage erosion and piping. The friction and interaction of particles plays a vital role in binding the materials together and act as stable mass.
Slope stability during reservoir drawdown is the most important consideration for embankment dam design. Reservoir water pressure has a stabilizing effect on the upstream dam faces under operating condition . The stabilizing effect of the water is lost during rapid drawdown condition but the pore water pressures that remains within the embankment, may remain high. Due to which the dam stability along the upstream face of the dam, may decrease until the high pore water pressure within the dam dissipate. Dissipation of pore water pressure depends on the permeability and storage characteristics of the embankment materials. Highly permeable materials drain quickly but low permeable materials takes time to drain during rapid drawdown condition.

Keywords: *Slope stability; Seepage; Instantaneous drawdown; slow drawdown*

Introduction

Slope stability analysis is performed to find out the safest design of embankment, road cuts, open-pit mining, excavations ,landfills etc. under different conditions. In other words, it is the resistance of inclined surface to failure by collapsing and sliding.
Successful and safe design requires geological information and site characteristics such as soil mass, slope geometry, groundwater conditions etc. The presence of water has a detrimental effect on slope stability. Water pressure acting in pore spaces or other discontinuities in the materials that make up the pit slope will reduce the strength of those materials. Correct analysis techniques depends on both site conditions and the potential mode of failure.
Stability analysis was performed graphically or by using a hand-held calculator but today we use softwares like PLAXIS, GEOSLOPE etc. which uses limit equilibrium techniques through computational limit analysis approaches(FEM, Discontinuity layout optimization) to complex and sophisticated numerical solution.
Conventional methods of slope stability analysis can be divided into three groups: kinematic analysis, limit equilibrium analysis, and rock fall simulators. All the limit equilibrium methods assume that the shear strength of the materials along the potential failure surface are governed by linear (Mohr-Coulomb) or non-linear relationships between normal stress and the shear strength on the failure surface. The most commonly used variation is Terzaghi's theory of shear strength which states that
$s = c + \sigma. \tan \phi$
where $\tan \phi$ is the coefficient of plane sliding friction, which describes the packing, surface roughness, and hardness of the materials constituting the slope , s is the shear strength , c is the effective cohesion and σ is the effective shear strength.
Many slope stability analysis tools uses various methods of slices such as Ordinary method of slices (Swedish circle method/Petterson/Fellenius), Bishop ,Spencer, Sarma etc.
Stability of a slope depends on its soil properties, geometry and the forces to which it is subjected to internally and externally. The surface water pressure and pore water pressure are examples of such internal and external forces that may have consequences both from hydrostatic and hydrodynamic perspectives on the slope stability. Whether a slope is partially or totally submerged, the internal and external forces that affect the slope can change as the water level changes. As a result of the water level change, both seepage-induced pore pressures due to transient flow and stress-induced excess pore

pressures develop inside the slope. Excess pore water pressures dissipate over time and consolidation takes place. The rate of dissipation of excess pore pressures and decrease in seepage-induced pore pressures depend on the drawdown rate and the hydraulic conductivity and compressibility characteristics of the slope materials.
If change in external water level happens without allowing the time needed for the drainage of the slope soils, it is called sudden or rapid drawdown (RDD). Due to rapid drawdown , slope stability will decrease which may lead to slope failure.

The purpose of this paper is to investigate the slope stability during rapid and slow drawdown depanding on different rates of drawdown relative to hydraulic conductivity of slope materials using GEOStudio software.

Theoretical Background

Stability analysis of earthen embankment dam can be accomplished by different limit equilibrium methods for concluding the critical failure surface and, associated minimum values of Factor of safety.

Seepage Analysis
The seepage analysis has been performed to predict pore pressure distributions under full reservoir condition by steady-state seepage analysis and under drawdown condition by transient seepage analysis. The estimate of total quantity of seepage losses through an embankment slopes is based on the difference in elevation of water between the upstream and downstream side of the earthen dam along with the hydraulic conductivity of respective embankment material. According to the Darcy's law, the specific discharge through a saturated soil medium is given by;

$$q = k*i; \qquad (1)$$

where q = the specific discharge (i.e. discharge per unit area) through the soil medium, k = the hydraulic conductivity of soil material, i = slope of gross available hydraulic head. Darcy's law was initially derived to estimate the specific discharge for saturated soil. Later research shows that it can also be applied to estimate the flow of water through unsaturated soil media. The quantity of water flowing through a saturated soil mass as well as the distribution of water pressure can be estimated by the theory of flow of fluids through any porous medium. The general form of two-dimensional differential equation (Laplace equation) to estimate seepage is expressed as:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = \frac{\partial \theta_w}{\partial t}. \qquad (2)$$

There are two basic types of seepage analysis, steady-state seepage to simulate reservoir water under full storage conditions and transient-state seepage to simulate drawdown in the reservoir water. The related mathematical formulation associated with each type is expressed as:

Steady-State Seepage

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = 0. \qquad (3)$$

Transient-State Seepage

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = m_w \gamma_w \frac{\partial (H)}{\partial t} \qquad (4)$$

where H = total available hydraulic head difference,
K_x= the hydraulic conductivity in the horizontal x-direction,
h_w = volumetric water content of the soil,
t = time, Q = applied boundary flux i.e. discharge,
K_y = the hydraulic conductivity in the vertical y-direction,
m_w = the slope of the storage slope,
Y_w = the unit weight of water.

Limit Equilibrium Methods for Stability Analysis
Limit equilibrium analysis methods have been used in geotechnical engineering for many years to assess the stability of earthen slopes. An analysis of slope stability starts with supposition that the stability of the slope is governed by downward mobilized forces and upward resisting forces. The relative stability of slope is characterized by the term factor of safety (FOS), defined as the ratio of the summation of shear resistance and shear mobilized for individual slices:

$F.O.S = \sum S_{resistance} / \sum S_{mobilised}$

Shear strength (resistance):
$S_{resistance} = c + (N\text{-}\mu)*\tan\Phi$
Shear stress (mobilized)
$S_{mobilised} = W\sin\alpha$

Where c = effective cohesion ; Φ = effective frictional angle; N=Wcosα= base normal, W=the slice weight, μ = the pore-water pressure, α = base inclination.

Experimental setup

Seepage analysis

S.no	Components	Specifications
01	Type of dam	Zoned type dam
02	Dam height	10m
03	Freeboard	2m
04	U/s water level	8m
05	Type of materials	Core –clay , shell - silty clay, filter-Gravel
06	Slope of the dam	U/S 2:1 D/S 2:1
07	Thickness of filter	1m
08	Estimation methods of vol.water content	Sample functions
09	Saturated water content	0.5
10	Maximum suction	1000kpa
11	Estimation method of hydraulic conductivity	Van Genuchten
12	Saturated Kx Core shell filter	 0.001m/day 0.0864 m/day 100m/day
13	Ky/Kx ratio	1
14	Residual water content	0.005
15	Rotation	0^0

BOUNDARY CONDITIONS
For Instantaneous Drawdown

S.no	Boundary conditions	Kind	value
1	Upstream seepage face	Water flux	0 $m^3/d/m^2$
2	Toe drain	Water total head	0 m
3	Total head U/s	Water total head	8m
4	U/s Drawdown	Water total head	0m

For slow drawdown

S.no	Boundary conditions	Kind	value
1	Upstream head	Water total head	8m
2	Toe drain	Water total head	0m
3	U/s seepage condition	Water total head	Water total head Time 8m 0 days 0 5 days

Stability analysis

Instantaneous drawdown and slow drawdown Slope Stability analysis
Kind: SLOPE/W
Parent: instantaneous drawdown and slow drawdown steady state seepage analysis respectively
Method: Spencer
Settings

PWP Conditions from: *Parent Analysis*
Unit Weight of Water: *9.807 kN/m³*

Slip Surface

Direction of movement: *Right to Left*
Use Passive Mode: *No*
Slip Surface Option: *Entry and Exit*
Critical slip surfaces saved: *1*
Optimize Critical Slip Surface Location: *No*
Tension Crack Option: (none)

Distribution

F of S Calculation Option: *Constant*

Advanced

Geometry Settings
- Minimum Slip Surface Depth*: 0.03048 m*
- Number of Slices: *30*

Factor of Safety Convergence Settings
- Maximum Number of Iterations: *100*
- Tolerable difference in F of S: *0.001*

Solution Settings
- Search Method: *Root Finder*
- Tolerable difference between starting and converged F of S: *3*
- Maximum iterations to calculate converged lambda: *20*
- Max Absolute Lambda: *2*

Materials

Embankment shell

Model: Mohr-Coulomb
Unit Weight: 20 kN/m³
Cohesion': 5 kPa
Phi': 27 °
Phi-B: 0 °

Core

Model: Mohr-Coulomb
Unit Weight: 20 kN/m³
Cohesion': 10 kPa
Phi': 30 °
Phi-B: 0 °

Methodology

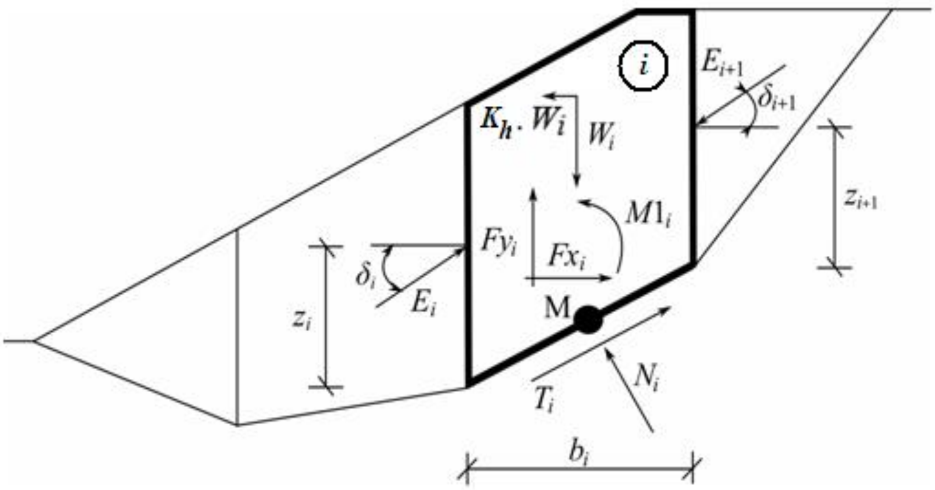
To develop a numerical model by using Geoslope software, a cross section of zoned earthen dam, with given dimensions , was constructed. After construction of dam, FEM mesh was developed and seepage and stability analysis was carried out

Initial steady state seepage analysis

In order to perform initial steady state seepage analysis, different components of dam like core, shell and filter were assigned with different materials. After assigning materials ,boundary conditions for upstream and downstream were assigned based on different drawdown conditions.
For instantaneous drawdown analysis , upstream seepage face was assigned with water flux of 0 m^3 /d/m^2 Upstream toe and toe drain were assigned with 0m of total water head value. For upstream water level total water head of 8m was assigned. Similarly for slow drawdown analysis, upstream seepage face was assigned with the help of spline data point function and water total head of 8m was drawdown in 5 days.

Stability analysis

For slope stability analysis in general, the **Spencer's method** has been found to provide a reasonably accurate result. This method satisfies both moment and force equilibrium of the sliding mass. However, a number of repetition are required to obtain an accurate value of factor of safety satisfying the complete equilibrium.
The Spencer method is a general method of slices developed on the basis of limit equilibrium. It requires a satisfying equilibrium of forces and moments acting on individual blocks. The blocks are created by dividing the soil above the slip surface by dividing planes. Forces acting on individual blocks are displayed in the following figure.



Stability analysis for Instantaneous drawdown conditions
For instantaneous drawdown stability analysis ,instantaneous drawdown steady state seepage analysis analysis was used as parent file and materials properties like Cohesion ,unit weight and phi were assigned for core and shell of the dam.

Stability analysis for slow drawdown conditions
For slow drawdown stability analysis , slow drawdown steady state seepage analysis was used as parent file and materials properties like cohesion, unit weight and phi were assigned for core and shell of the dam.

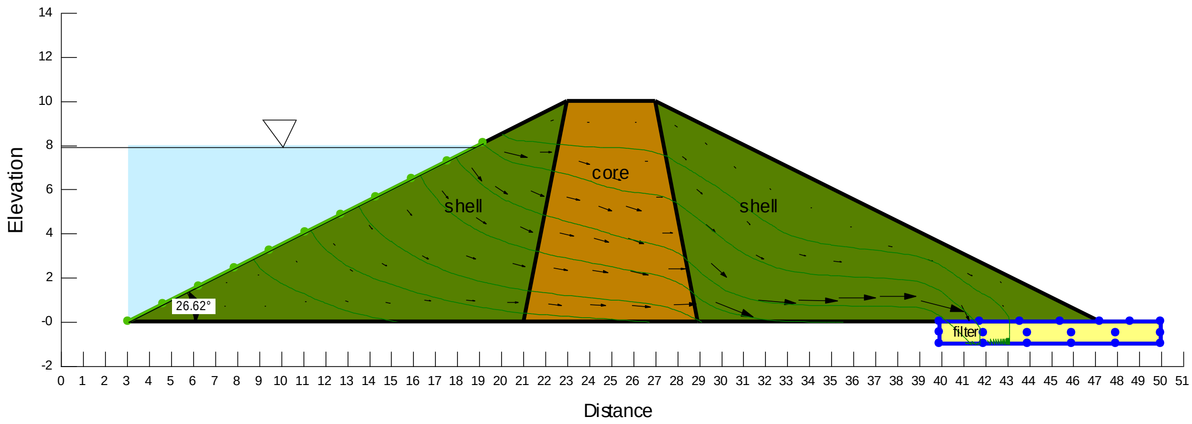
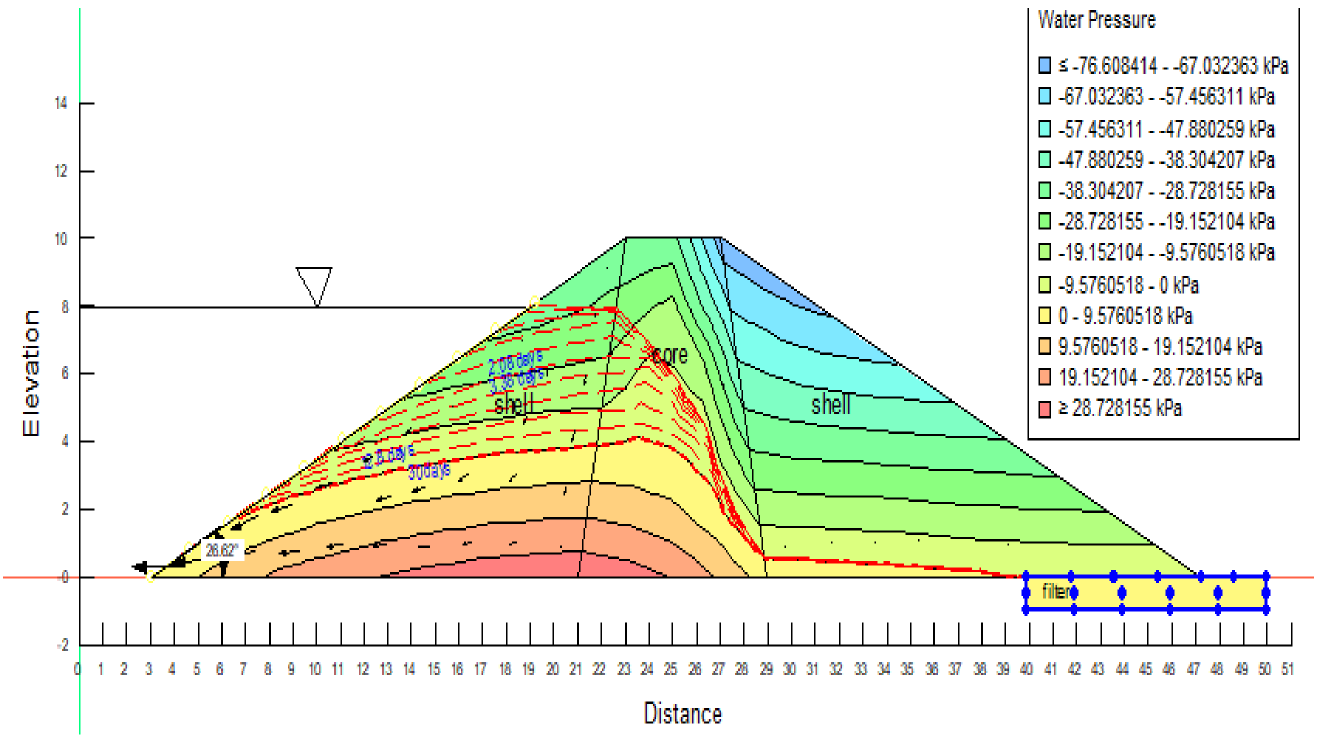


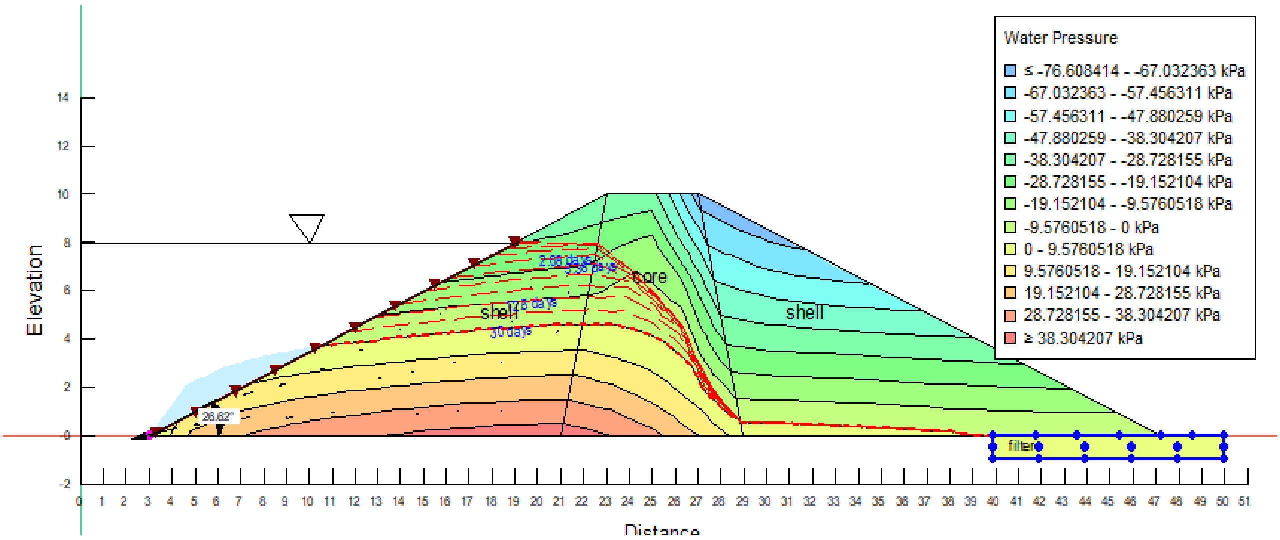
Fig 1. Steady state seepage analysis.

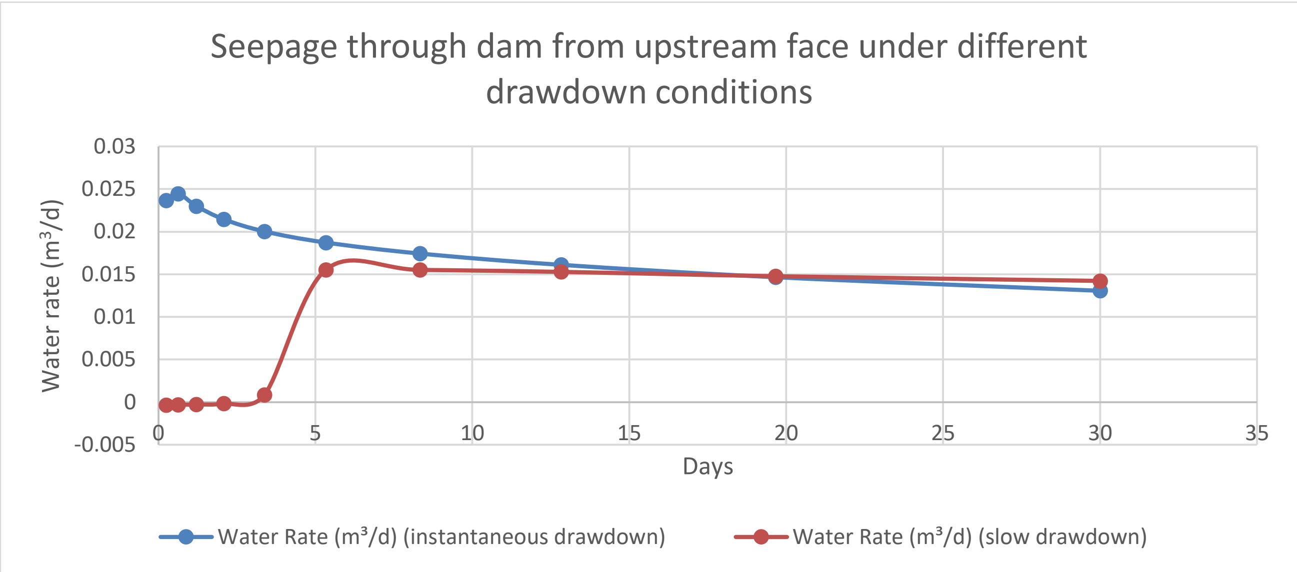
Results

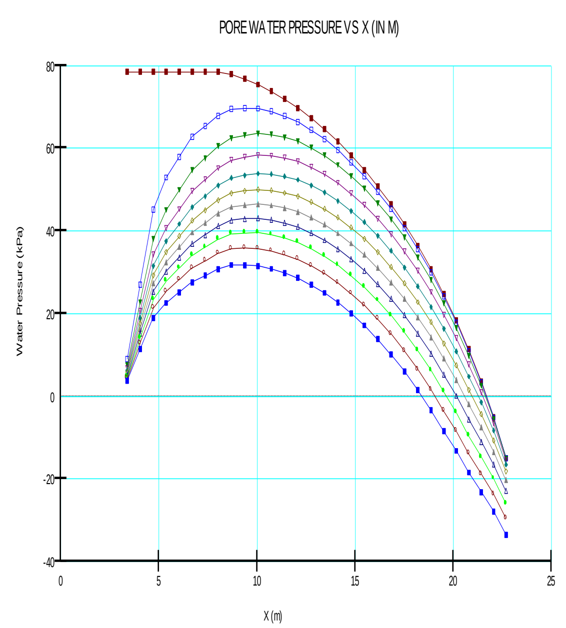
<u>Change in pore water pressure in 30 days during **slow drawdown conditions**</u>



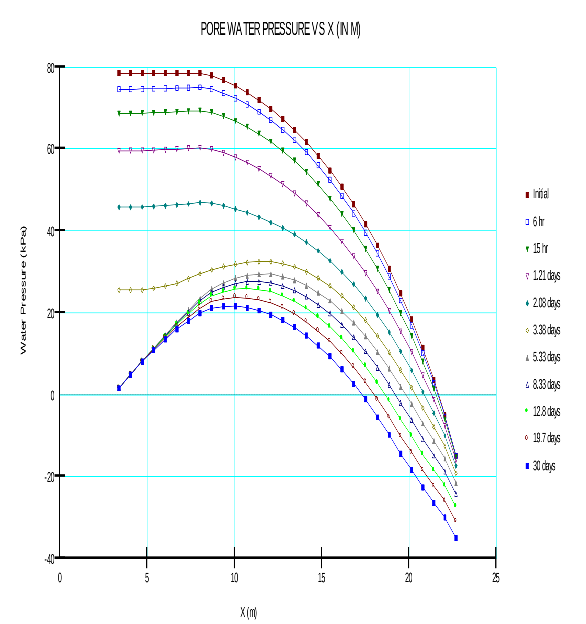
Change in pore water pressure in 30 days during **instantaneous drawdown conditions**







FOR INSTANTANEOUS DRAWDOWN CONDITION

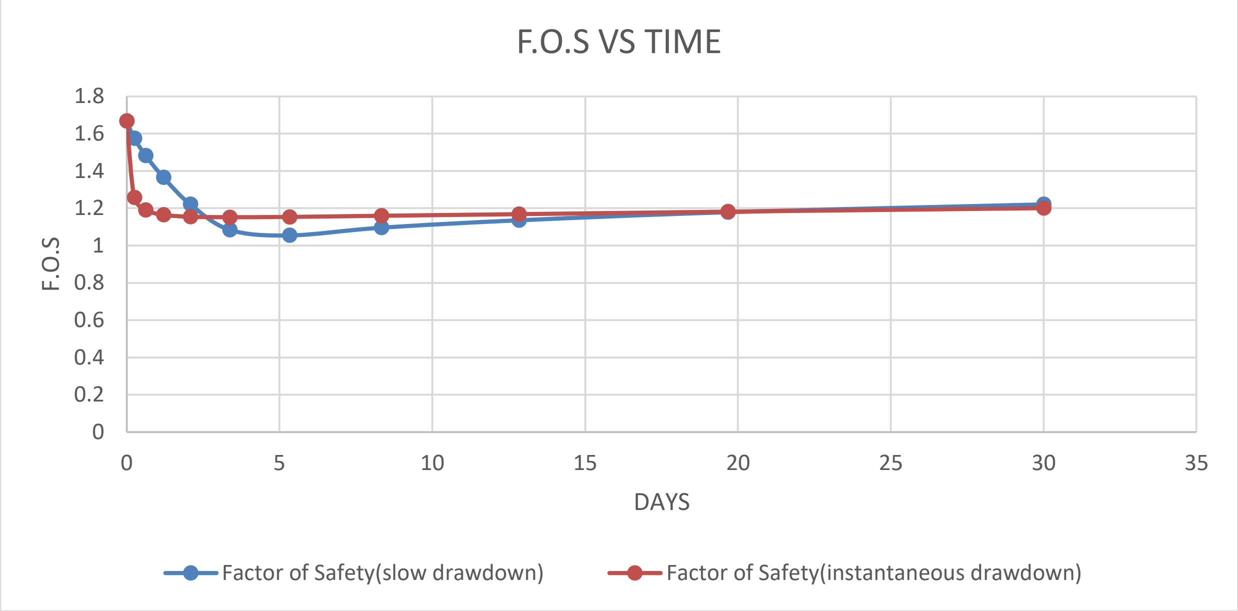


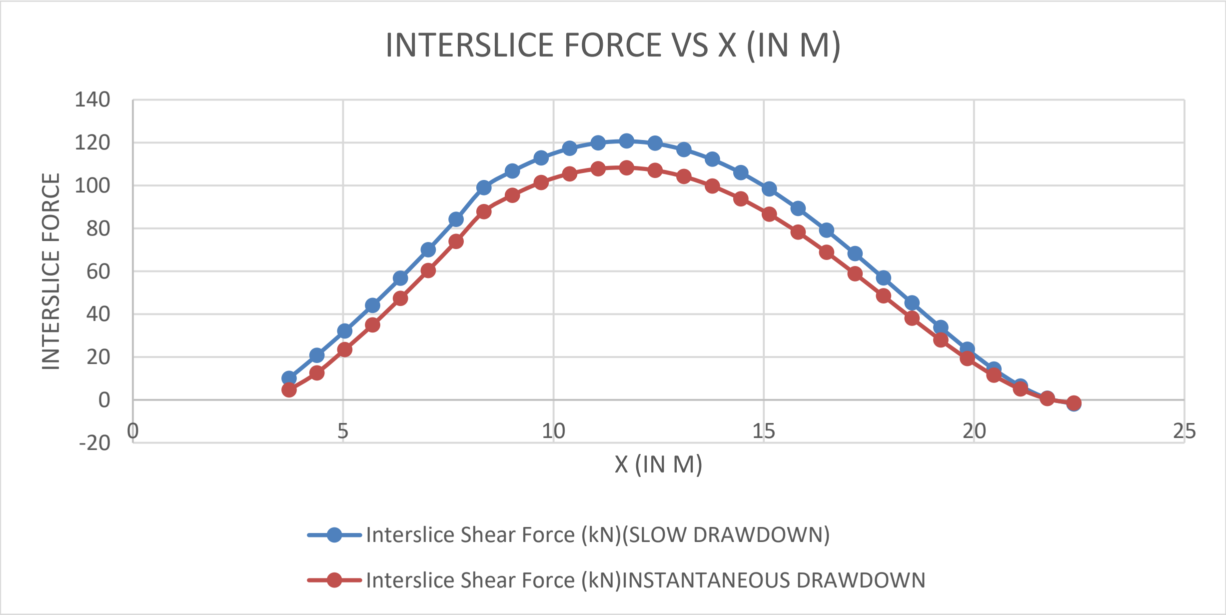
FOR SLOW DRAWDOWN CONDITION

Stability analysis

The change in factor of safety in different drawdown conditions is tabulated below

Time(days)	F.O.S (SLOW DRAWDOWN)	F.O.S(INSTANTANEOUS DRAWDOWN)
0	1.666	1.666
0.25	1.574	1.256
0.625	1.481	1.190
1.20833	1.364	1.164
2.08	1.220	1.153
3.375	1.084	1.151
5.333	1.054	1.152
8.333	1.095	1.159
12.83	1.135	1.167
19.66	1.178	1.181
30	1.220	1.200





CONCLUSION

After seepage and stability analysis of earthen dam under slow and rapid drawdown, following conclusions were proposed:

- Factor of safety drops in both the cases and in slow drawdown case it drops more than instantaneous case but the factor of safety recovers over the time as the excess pore-water pressure within the embankment dissipates. After 30 days the, factor of safety of slow drawdown case becomes more then the instantaneous drawdown case.
- Velocity vectors show that less water was leaving the domain via the upstream slope, and more of the water is flowing out of the drainage filter, due to the continued presence of water in the reservoir. As the reservoir level decreases over time, flow from the upstream face increases in both instantaneous and slow drawdown case.
- The stability of a slope during drawdown is greatly influenced by the how fast its pore water drains.
- Water rate or seepage through upstream face of dam decreases during instantaneous drawdown condition in 30 days period but in slow drawdown condition, it increases till 6th day then becomes constant.
- The pore water pressure during slow and instantaneous drawdown conditions remained higher at the upstream side of the dam and also at the central core but in slow drawdown condition , the pore water pressure in first 5-6 days is much higher than the instantaneous drawdown condition.
- Water pressure in the upstream side of dam, in both the conditions, decreases with time but at the end of 30th day , the water pressure is more in instantaneous drawdown case than the slow drawdown case.
- Water flux in both the cases first increases and then decreases with time but in instantaneous drawdown case ,water flux reaches its peak value in 1-2 days and in slow drawdown case ,the water flux reaches its peak value in 5-6 days and then decreases with time. At the end of 30days the flux value of slow drawdown case is bit higher than the instantaneous case.
- In slow drawdown case ,the exit gradient at the upstream increases slowly in first 2 days but in 3rd to 4th the value of exit gradient increases rapidly and then decreases with time. In instantaneous drawdown case the exit gradient increases in first 2 days then decreases passage of time.
- Base shear Res. Force in instantaneous drawdown case increases for first 12- 13 days then decreases with time. In slow drawdown case the base shear res. force increases in first 2 days then decreases for the 3rd day and after 3rd day,it increases with with time.

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