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Seepage and Slope Failure Study Using Finite Elements Analysis.

Abstract: - This research paper is all about performing intensive research on the aspects of seepage and slope failure that occur in earth dams, this survey work utilizes sophisticated Finite Element Analysis (FEA), particularly PLAXIS 3D. During this investigation which investigates the dynamics of the interactions between the soil and water, experimentation of various degrees of saturation is considered at one point or the other. Also, the effect of the physical properties of soil, specifically, Young's modulus and angle of internal friction revealed the hydraulic regime and the state of the river, including the conditions of sharp drawdown and low water, respectively. This is done to enable assessment of the impact of the said properties. The high importance of FEA is stated in its capacity to model shapes and materials that are non-linear. This is so because FEA can give insight into the behavior of earth dams as elaborated above in the literature review. Thus, the research is a noteworthy contribution to the field of geotechnical engineering because by providing modern suggestions for the design and maintenance of dams while improving the current knowledge regarding the stability of the objects in question, the notes included in the paper are practical. As can be seen, these recommendations are intended to secure the further performance and safety of dams throughout their utilization period.

Keywords: FEA, Seepage, Stability, Dams, PLAXIS, Modulus, Friction, Hydraulics, Safety, Stress, Deformation

INTRODUCTION

So, geotechnical engineering has dramatically benefited from the FEA, it is still very robust and ubiquitous at the moment to study the complicated processes developed in geotechnical systems with emphasis on the infiltration and incline durabilities. Owing to the unclear used mappings, this computational method gives a close view of how the individual factors influence the stability and solidity of subsurface structures like reservoirs, inclines, mounds, etc.

Understanding Complex Geotechnical Behaviors:

Seepage Analysis: Through F. E. It is viable to simulate the infiltration processes that occur in layers of the soil. Water's ability to work with the soil particles and the changes in its states like washed-dried affects leakage rate/structure strength; this knowledge is vital in making a prognosis. FEA simulations are particularly valuable because dispense with the complications of boundary conditions and most of the non-linear material properties and hence offer a valuable insight into seepage regime and possible failure mode under different loading and hydrant conditions Li&Desai, 1983, Fu&Jin, 2009.

Slope Stability: Slope failure is a phenomenon that is characterized by several factors that include; slope form and slope material. FEA assists in mimicking such circumstances and or making the engineers comprehend the stability of slopes under some circumstances including natural calamities such as earthquakes and man-made calamities such as excavation or loading. The finite element analysis has the ability to model strength – deformation character of soil assuming the given values of adhesion, angle of repose of the spill, and interstitial fluid pressure to estimate the failure of slope and has the prospect of charting the remedies (Duncan and Wright, 2005; Griffith and Lane, 1999).

Essentially, advancement has been made on incline steadiness and infiltration examination in the years over the headway of diverse methods and speculations. For many years, the only way to understand incline stability was through stories and incidents detected happiness and, at the same time, to perform simple calculations. Karl Terzaghi started geotechnical engineering in the first half of the twentieth century and helped to set the preconditions for the field, which also included incline stability analysis. Techniques like the efficacious pressure

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and the shear potency of the soil as pointed out by Terzaghi (Terzaghi, Peck, and Mesri 1996) offered a more scientific revelation concerning inclines. As for the seepage analysis, the first tries have been carried out according to Darcy's Principle, which gives an account of the movement of a liquid through porous material. This principle was important for explaining penetration through soils; this is important in grade stability as well as the dependability of earth-filled structures such as reservoirs (Chen, Lin, and Lee 2003).

However, mainly due to the restriction of computation facilities, with the increase of computers' capability and associated software, FEA gradually evolved as the most favored in geotechnical engineering. That is why it was useful to carry out a systematic examination of the stress distribution and stress stain in the soil mass for various loading conditions, including percolation. FEA was used because it covered complications in shape and shed light on the differences between several materials Therefore, FEA proved to be essential in the designs of earth embankments, slopes, and support systems under certain circumstances (Dumcan & right, 2005; Hammah, et al., 2004). Furthermore, due to FEA, there is also an option of carrying out the integrated analysis in which both mechanical and hydraulic interactions can be investigated at once.

This attitude was very important in determining the behavior of the soil formations that is when it is affected by water and moisture and times when it lacks it in infiltration and inclination stable analysis (Freeze, 1971; Thieu et al., 2001).

1. There is only one analysis carried out on earth dams namely seepage analysis.

The analyses of percolation within the terrestrial formations especially the terrestrial embankments have been the subject of most studies; this they say because percolation plays the most central role in determining the stability of these formations and structures. Consequently, there is inner corrosion of the particles comprising soil embankments, channeling and raise in the pressure of the pore fluid which poses a considerable danger to the solids of soil. The main research in this area is Freeze (1971), in which the author examines the concept of three-dimensional temporary soil-saturated and unsaturated movement in aquifer basins. Thus, owing to this study, the start of comprehending the flow irregularities of water and determining stability about the earthly frameworks of structures was made. For the same insights on how infiltration flow is influenced by water levels, for example during reservoir filling and drawing, Fu and Jin (2009) too took into consideration the diurnal variation of this process across dams.

The Finite Element Analysis or FEA popularised infiltration analysis with many significant advancements. I noted that FEA was appropriate to employ for modeling infiltration occurrence in terrestrial ramps since it offered an ability to take into consideration the different forms and alterations in the distribution of the introduction of penetrated materials. Of them, Thieu et al. (2001) used FEA to give information about seepage in soaked and dry soil systems; the application includes both steady state as well as transient conditions of the seepage. Their labor described how FEA could be utilized to predict the prospective regions where a dam structure might be vulnerable because of leakage.

PLAXIS which stands as one of the popular FEA software in geotechnical engineering has been particularly hailed for its application in infiltration study. In their paper, Zhou and Li realized that PLAXIS was acknowledged in studying the interaction between surface water – groundwater in earth dams, and its ability to simulate hydraulic mechanical behavior. It is such a strong connection is required for the understanding of the maximum consequences of the leakage impact in the aspect of the dam 's durability and also for the formation of pseudo pore aqua pressures and the corresponding strains in the body of the dam. Moreover, other researchers have also paid attention to the long-run repercussions such as off-bάking and its consequences for the stability of inclines. Li and Desai (1983) wrote about some of the strain and infiltration tests in the earthen embankments and possible continuing deterioration due to infiltration. Their labor underlines the necessity for being alert and looking into it from time to time to guarantee the proper strength and security of the constructions of the dams.

1. 2 WHAT CONTRIBUTES TO SLOPE FAILURE AND SEEPAGE REGARDING SOIL PROPERTIES

As for the steadiness of inclines and the infiltration attributes of formations on the land, the ground attributes including porosity, adhesion, and the inclination of inner resistance are pronouncedly influenced. Some of them have assessed the effects of the above characteristics on the behavior of soil embankments and slopes as indicated in the following works, which in most cases employ FEA in the analyses.

Infiltration studies pertain greatly to the concept of permeability because the latter is an element that defines the rate and pattern of water flow through the terrains. In their research carried out in 2003, Chen, Lin, and Lee concluded that porosity is the most relevant factor that should be used to regulate the pressures in infiltrating soil embankments and the steadiness of these pressures. Higher permeability was shown in the course of the research which means that seepage is likely to rise and as a result, erosion and damage of the structure of the dam is likely to occur.

Further, it is elaborated that slope stability analysis entails both the cohesiveness and the inclination to internal friction. Describing the results for the slope stability, Baker (2004) explained how these potency parameters of the soil influence the stability of the inclines; they postulated that the decline in the measure of adhesion and internal friction angles made the slopes vulnerable to slip-off. A finite element analysis was made to assess what this paper is about; to depict different scenarios of behavior of the material and show how with different values of these two factors the modes of failure differ from one another.

The effect of these shocked soil characteristics on earth dam security was also investigated by FEA in the subsequent study after the one conducted by Dawson et al. (1999). I learned that their investigation employed the potency reduction technique in FEA simply to assess the stability of inclines about various soil types, with useful understanding concerning how alterations in the characteristics of soils might provoke instability.

Another research featuring the use of FEA in this regard is established in the work done by Griffith and Lane (1999) who applied the technique to examine how changes in the nature of the soil can influence stability and percolation in earth dams. These FEA procedures were carried out by their research with emphasis on the functionality of FEA regarding relatively complex mechanical and hydraulic coupling within the soils; which greatly improves understanding of the processes of slope failure together with infiltration.

PLAXIS was identified earlier as one of the most used FEA software, and it was applied by Li and Desai (1983) to model the behavior of earth embankments with various sorts of soil. They also concentrated on variations of the parameters concerning the physical characteristics of the ground, adhesion as well as porosity, much as conducting the planning/assessment of the terrestrial formations.

1. METHODS AND MATERIALS

For the finite element analysis of the earth dam, detailed soil properties were defined to accurately simulate the behavior under various conditions. These properties are essential in understanding how different soil layers react to environmental and operational factors, influencing the overall stability of the dam. The properties are outlined in Table 1.

Table 1. Soil Properties

Parameters	**Shell**	**Subsoil**	**Core**
Model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
Type	Drained	Drained	Undrained (b)
γ (unsaturated and saturated)	16, 20	17, 22	16, 18
E' and μ	50E3, 0.33	200E3, 0.25	25E3, 0.3
c', S'u	5, -	1, -	-, 10
φ', ψ	30, 1	35, 5	-, -
k	0.2	0.01	1E-4

A parametric investigation was carried out by altering the parameters: E' (Young's elasticity) and φ' (angle of inner friction). The E' coefficients for the outer and inner layers were modified without altering the E' coefficient of the underlying soil. The φ' was changed from 30° to 35°. The examination took into account various stream operations for every one of the situations: Complete (elevated) repository height of the dam, Quick depletion in 5 and 10 days span, Gradual depletion in 50 days, and Diminished water level of the dam.

The spokesperson terrestrial embankment examined in this investigation was 35 meters in altitude, with a lateral inclination of 1 in 2.5 on both the upstream and downstream surfaces. The underlying soil depth was 30 meters. The elevated reservoir level was established at 30 meters with an extra 10 meters of subterranean water. Suitable hydraulic boundary circumstances were allocated to the upstream side, at the commencement of the upstream facade, and the final segment of the subterranean component.

2. RESULTS AND DISCUSSION

3.1 RESULTS

The results obtained from the finite element analyses are visually represented in a series of figures, specifically Figures 3 through 21. These illustrations are truly informative and a clear representation of the analysis's outcomes and findings. Thus, anyone will have an idea about the FINITE ELEMENT ANALYSES and the assessment of the data, and observations on these figures. In Figure 3, there is the portrayal of normal stress that acts on the body of an earth dam as well as on the subsoil. This drawing also contributes to unveiling the distinctions of stress, which is an important step in comprehending the forces availed within the spoil of the dam as well as the soil. The analysis of this figure will assist the engineers and researchers make right decisions wherein they can build stable earth dams that will suffice the requirements and stress on them. The normal stress is reflected in details and variations in figure 4 that depict an indication of the type of variation in the normal stress and information on the variation with different kinds of variation and other variations in this aspect distinctly. Nevertheless, this is advantageous in a way whereby one gets to have a rather broader perspective of what is actually happening and is able to analyze and contrast it in manners that would not have been possible usually. Similarly, Figure 5 provides a detailed description of the active pore pressure from which the following can explain the impact of several factors on this performance indicator. In any case, these figures provide for the smooth integrated holistic and useful vision of the normal strain characteristics and the active pore pressure magnitudes, as well as allowing the researchers and the practitioners make the proper decisions and draw proper conclusions.

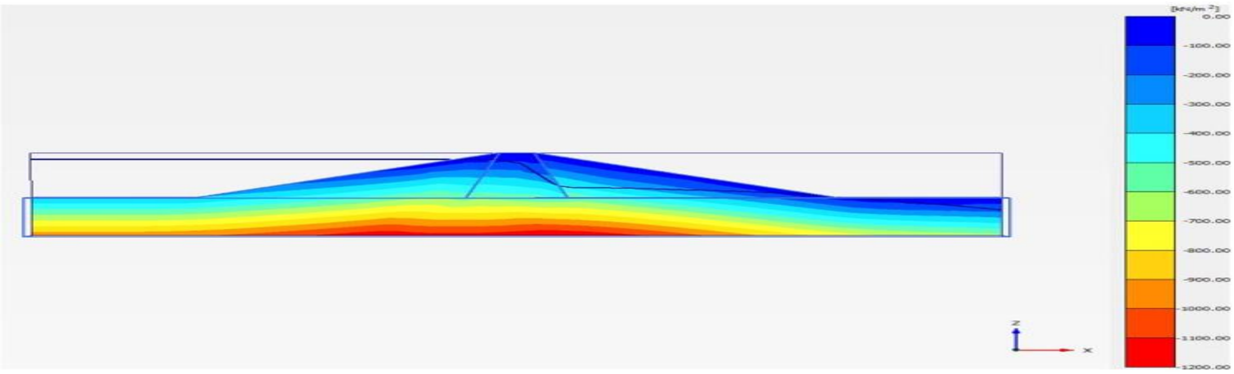

Fig. 3. Normal stresses

The plots indicated in Fig. 3 demonstrate changes of the normal stresses in the body of earth dam and subsoil. This figure is significant because the learned stress distribution in the structure defines in which layers of the dam it is most stressed. Greater normal stress values were measured in the pipe's core zones, quite expectedly because of its content weight and water pressure. The indicated scheme of these stresses is necessary for defining the zones in the construction of the dam which can influence the occurrence of failure when the level of stresses increases.

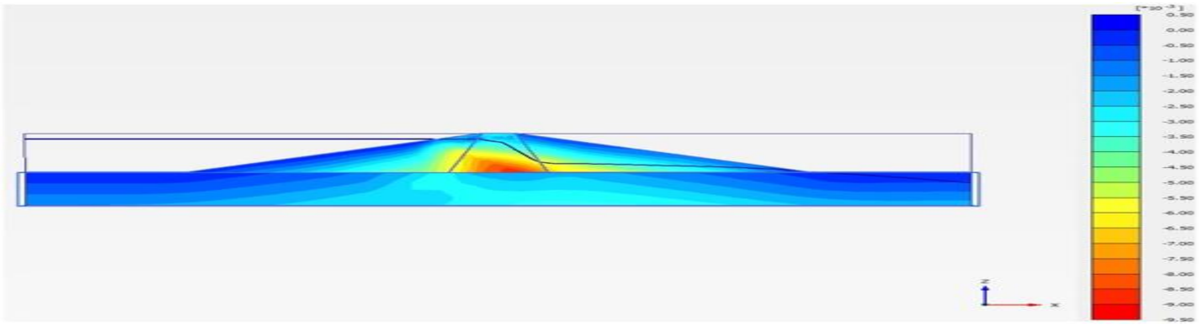

Fig. 4. Normal strains

Regarding the normal strain, it is evident from Fig. 4 how the normal strains increase progressively from one point to the other in both the dam and the subsoil. Stress gradient can be also included in the list of parameters that define how great amount of stress the material of the dam can undergo or whether the dam is going to crack. The figure provides a feel of how the structure of the dam bows when subjected to operational loads to reveal part of the dam that may raise some concern, at least due to excessive deformation that may cause some form of failure in its structure.

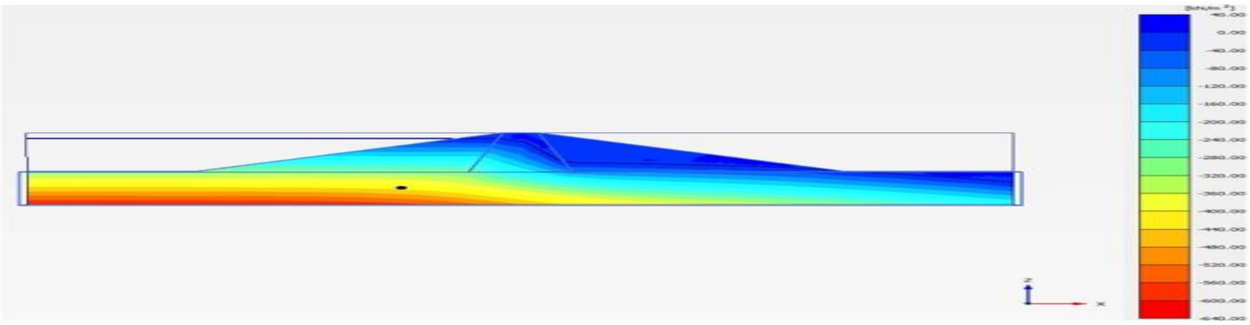

Fig. 5. Active pore water pressure

The changing pattern of the active pore water pressure for the given earth dam placement is shown in the following figure 5. Measurement of pore water pressure is significant in the stability of the dam because high pore pressures tend to decrease effective stress within the soil mass of the dam hence create instability to the slope or sliding. This figure is particularly helpful in illustrating how the dam responds with water of different levels as well as in identifying regions of the dam that high degrees of pore pressures might decrease the level of safety.

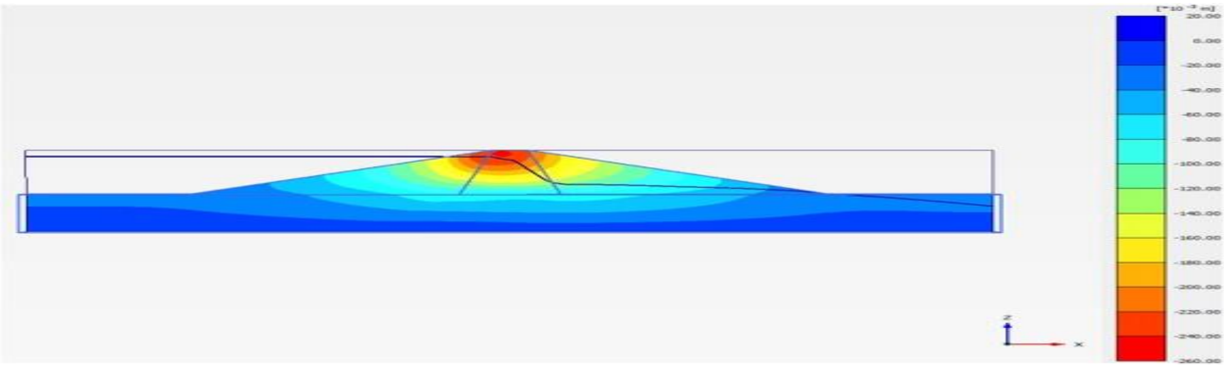

Fig. 6. Displacement contours

Figure 6 shows the displacement contours of the earth dam, highlighting the areas where the most significant movements occur under load. Displacement contours are critical in identifying potential zones of weakness and areas where material might be moving or settling more than expected. This information is essential for long-term monitoring and maintenance of the dam, ensuring that any unusual movements are detected and addressed promptly to prevent structural failures.

Stability outcomes are articulated in the configuration factor of security (FS) for all the instances (Figures 7 – 18). The FS values are displayed along the vertical axis. The displacement exhibited along the x-axis in all the aforementioned figures is the complete theoretical one, which lacks any tangible significance. In the illustrations, HR represents elevated reservoir level and LL represents diminished water level. The inclinations of internal friction of 30 and 35 □ are displayed in the illustrations.

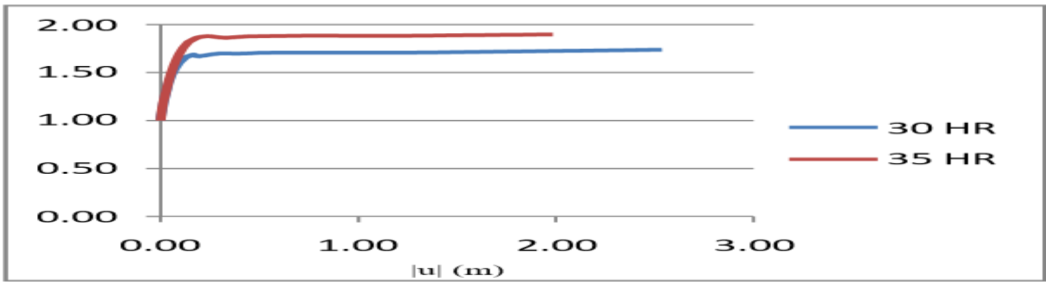

Fig. 7. Variation of FS for full reservoir condition: Ec = 102.4 MPa and Es = 195 MPa

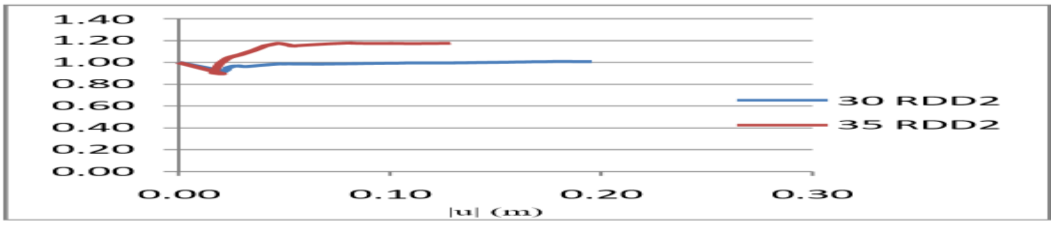

Fig. 8. Variation of FS for rapid drawdown (RDD2) condition: Ec = 102.4 MPa and Es = 195 MPa

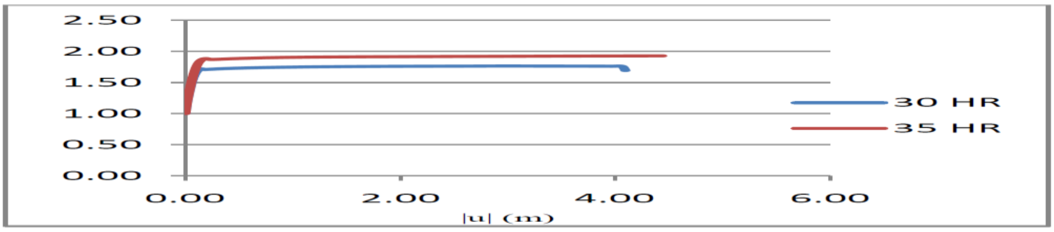

Fig. 9. Variation of FS for full reservoir condition: Ec = 64 MPa and Es = 128 MPa

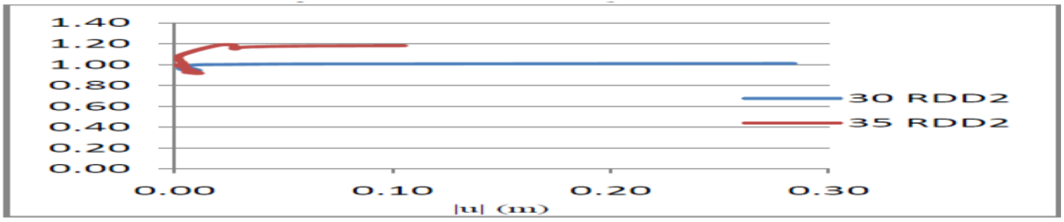

Fig. 10. Variation of FS for rapid drawdown (RDD2) condition: Ec = 64 MPa and Es = 128 MPa

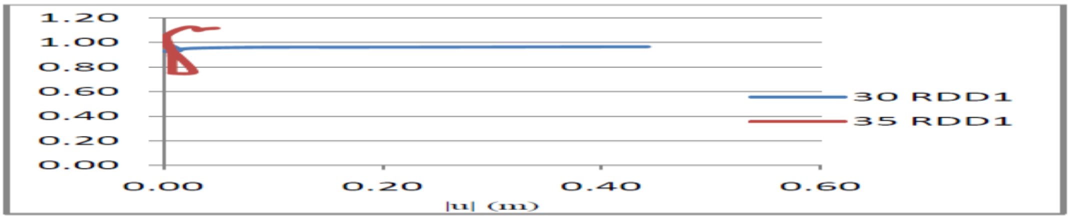

Fig. 11. Variation of FS for rapid drawdown (RDD1) condition: Ec = 40 MPa and Es = 80 MPa

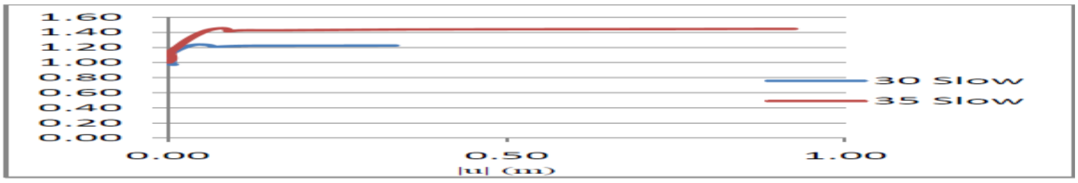

Fig. 12. Variation of FS for slow drawdown condition: Ec = 40 MPa and Es = 80 MPa

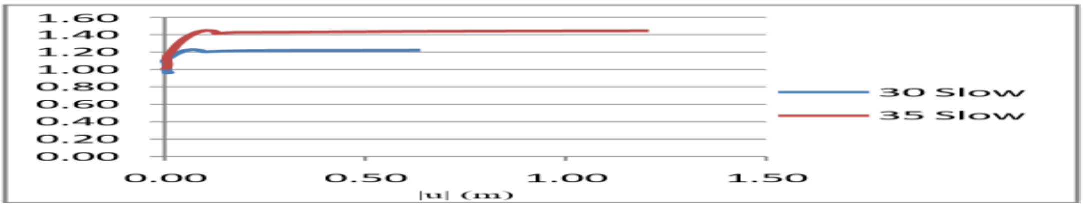

Fig. 13. Variation of FS for slow drawdown condition: Ec = 25 MPa and Es = 50 MPa

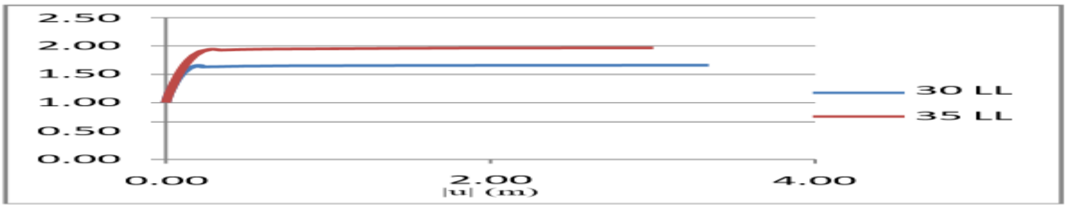

Fig. 14. Variation of FS for low reservoir condition: Ec = 25 MPa and Es = 50 MPa

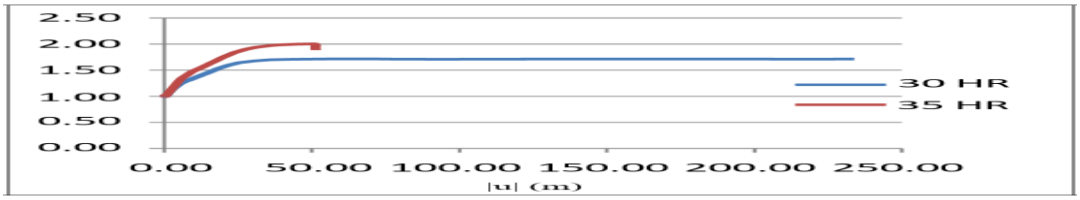

Fig. 15. Variation of FS for full reservoir condition: Ec = 102.4 MPa and Es = 204.8 MPa

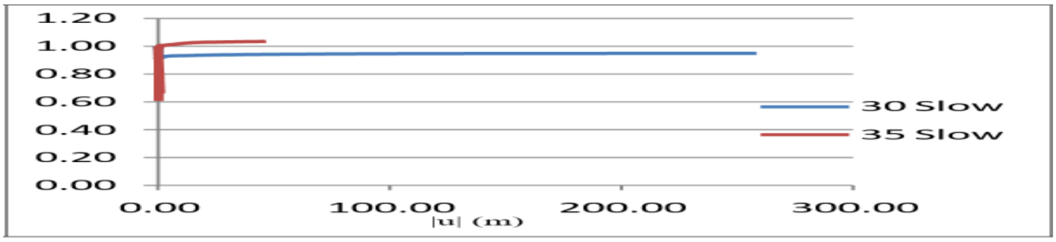

Fig. 16. Variation of FS for slow drawdown condition: Ec = 102.4 MPa and Es = 204.8 MPa

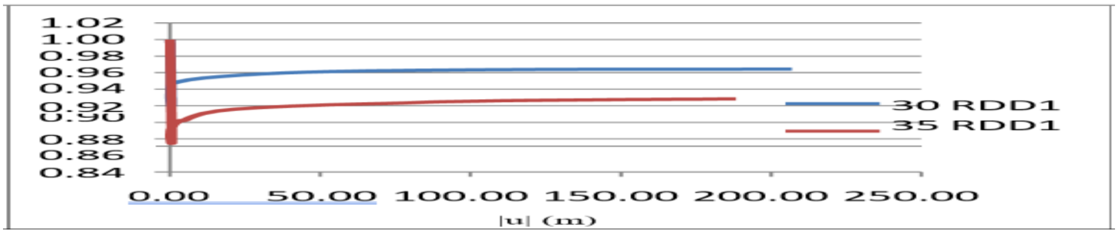

Fig. 17. Variation of FS for rapid drawdown (RDD1) condition: Ec = 102.4 MPa and Es = 204.8 MPa

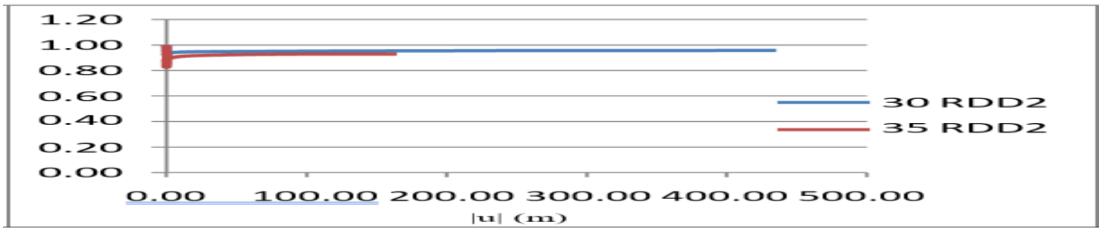

Fig. 18. Variation of FS for rapid drawdown (RDD2) condition: Ec = 102.4 MPa and Es = 204.8 MPa

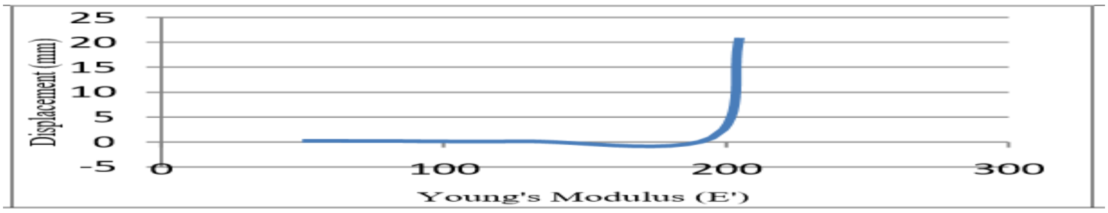

Fig. 19.(a) Displacement v/s E'

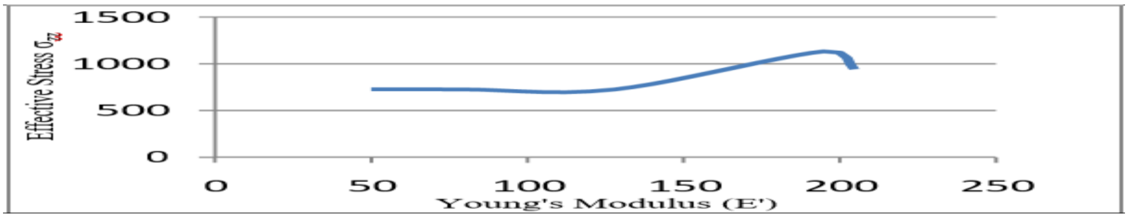

Fig. 19.(b) Effective stress v/s E'

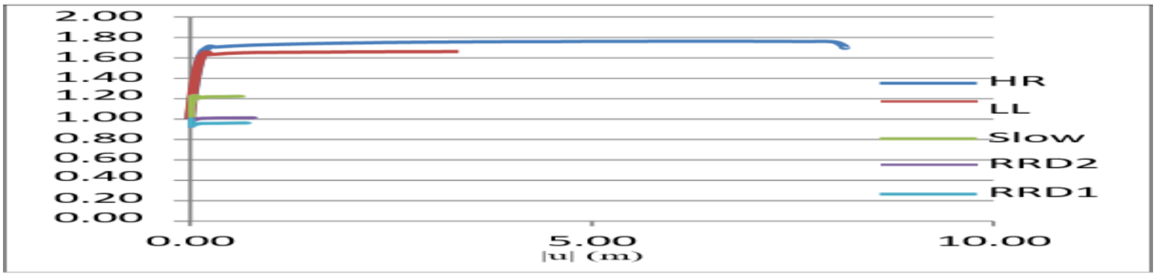

Fig. 20. FS for all conditions with φ' = 30□, Ec = 25 MPa and Es = 50 MPa

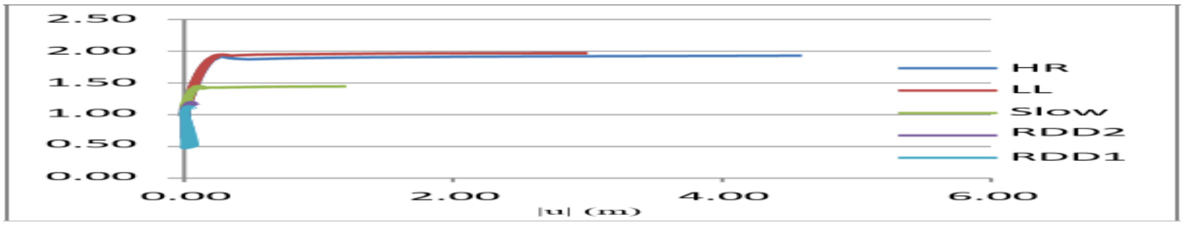

Fig. 21. FS for all conditions with φ' = 35□, Ec = 25 MPa and Es = 50 MPa

3.2 DISCUSSION

The outcomes and examination provided in the preceding sections offer valuable perspectives into the conduct and durability of earth dams under diverse circumstances (Fu and Jin, 2009). Here, we explore the primary discoveries and their consequences:

Stress Allocation: The fluctuation of customary pressures within the embankment and underlying ground, as illustrated in Figure 3, suggests elevated pressures in the nucleus areas owing to the mass of substances and hydraulic force. This wisdom is vital for recognizing regions susceptible to possible breakdown under intense pressure circumstances, directing fortification and upkeep endeavors (Morgenstern and Price, 1965).

Deformation Patterns: Figure 4 illustrates the fluctuation of perpendicular strains in the reservoir and underlying soil. Comprehending how the dam substance distorts under burden is crucial for evaluating potential regions of worry where excessive distortion may result in structural vulnerabilities. Surveillance and attending to these regions can avert disastrous breakdowns (Griffiths and Lane, 1999).

Pore Aquatic Pressure: Figure 5 showcases the dynamic pore aquatic pressure within the earth dam. Elevated pore water pressure has the potential to diminish the efficient stress within the ground, possibly resulting in slope instability or slippage. Recognizing areas with heightened pore pressure is essential for preserving dam integrity, particularly during swift reduction or elevated reservoir circumstances (Bishop, 1955).

Displacement Evaluation: Figure 6 exhibits the displacement outlines of the earth dam, emphasizing regions with noteworthy shifts under burden. Identifying uncommon motions is crucial for extended surveillance and upkeep to avert architectural malfunctions and guarantee the stability of the dam (Duncan and Wright, 2005).

Margin of Safety (MoS): Figures 7 - 18 present MoS values under different circumstances, such as complete reservoir, swift drawdown, gradual drawdown, and reduced water levels. These principles provide perspectives into the dam's durability under various circumstances, taking into account fluctuations in Young's modulus and inclination of internal friction (Thieu et al., 2001). Significantly, a rise in φ' resulted in a decline in FS values, specifically in fast drawdown situations, when Es surpassed the subsoil's Young modulus. This observation emphasizes the significance of material characteristics in dam stability evaluation.

Impact of Young's Elasticity (E'): Illustrations 19(a) and 19(b) unveil the correlation between displacement, efficient pressure, and Young's elasticity (E') of the ground. More rigid soil (elevated E') generally leads to reduced deformation and decreased effective stress. Nevertheless, a crucial aspect is noted when Es approaches the modulus of the underlying stratum, resulting in substantial distortion. This underscores the necessity to meticulously contemplate material rigidity in dam design and evaluation (Das, 2002).

Effect of Internal Friction (φ'): Illustrations 20 and 21 exhibit FS values under diverse circumstances for distinct φ' values. Elevated φ' values are correlated with elevated shear potency, resulting in amplified FS values. This emphasizes the importance of soil shear resistance in determining dam stability across operational scenarios (Chen et al., 2003).

Restrictions: The investigation recognizes constraints associated with model precision, the extent of material characteristics, and the generalization of findings (PLAXIS 3D-2013). These constraints ought to be taken into account when implementing the discoveries in practical dam engineering ventures (Holtz and Kovacs, 1981).

In summary, this investigation offers an all-encompassing examination of leakage and incline durability in soil embankments employing Finite Element Analysis (FEA). The outcomes provide precious perspectives into the conduct of terrestrial barriers under diverse circumstances, emphasizing the significance of substance characteristics, strain allocation, and distortion configurations in evaluating barrier steadiness. Engineers and geotechnical specialists can utilize these discoveries to advise dam design, upkeep, and safety precautions, ultimately contributing to the advancement of more resilient and dependable earth dams (Chen, 1995).

3. CONCLUSION

When compared to the reliability of the limit equilibrium method, the values of FS that are evaluated using PLAXIS are more reliable. When using PLAXIS, conducting parametric sensitivity studies is a simple process.

There was a significant decrease in the FS values during the quicker drawdown (also known as the rapid drawdown in five days duration, RDD1), which was then followed by the drawdown in ten days duration (RDD2). Analysis of the section for drawdown is always required because there is a possibility of the development of excessive pore water pressure due to the sudden change in the water level; however, the phreatic surface cannot change rapidly. This is the reason why it is always mandatory to analyze the section.

It has been determined that the FS is greater than 1.6 in both the full (high) reservoir condition and the low reservoir condition for the reservoir. It has been discovered that the FS values are lower than the values that have been stipulated for other conditions.

The decrease in the values of FS for both short-period drawdown conditions (i.e., RDD1 and RDD2) was a consequence of an increase in the values of φ' and Es, which were greater than the Young's modulus of the subsoil. Compared to the slow drawdown condition, this is a significant difference.

There was a sudden increase in the displacement for the same number of iterations, and the same was observed for the variation of effective stresses. This occurred as the Es approached the value of Young's modulus of subsoil. These two phenomena were observed simultaneously.

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