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SENSOR-BASED EXPERIMENTAL AND NUMERICAL APPROACH TO ENHANCE DAM SAFETY

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***Abstract**:* Dams play a critical role in water resource management, providing irrigation, flood control, and hydroelectric power generation. However, ensuring their safety remains a paramount concern owing to the potential risks associated with failure. This study presents a comprehensive approach for enhancing dam safety by integrating experimental, numerical, and sensor-based analyses. Physical experiments were conducted on a scaled model to simulate various scenarios including temperature, stress analysis, and slope stability deterioration. The sensors installed in the dam were digital temperature, piezoelectric sensor, accelerometer ADXL345, and ultrasonic sensors. The sensors were placed at intervals of 5 cm from the bottom to the free board. GeoStudio is a suite of software used to model geotechnical and geoenvironmental engineering problems. It includes various modules, such as SLOPE/W for slope stability analysis, SEEP/W for groundwater seepage analysis, and SIGMA/W for stress-deformation analysis. The results revealed that the comparison between the experimental and numerical results is valid, as in 5 cm, the stress value in the experimental is 8.35 kpa and in numerical is 10.5 kpa, as in 10 cm, the stress value in the experimental is 49.6 kpa and in numerical is 53.6 kpa and in15 cm, the stress value in the experimental is 112.8 kpa and in numerical is 118 kpa. With increasing water depth, the stress also increases. Integrating experimental and numerical approaches enhances the understanding of stress behavior and slope stability and facilitates the refinement of numerical models for more accuracy. Finally, this study presents the detailed evolution process of an earthen dam by preventing failure through early warning (pre-alarm) from sensors.

keywords **-** Dam Safety, Dam Instrumentation, Stress Analysis, Slope stability, Seepage, GeoStudio.

I. INTRODUCTION

Dams play a crucial role in water resource management; however, their construction and operation require careful planning to balance the benefits and potential environmental and social impacts. International standards and guidelines exist for ensuring the safe design and operation of dams. India has a total of 5, 334 dams, with approximately 447 large dams still in the construction process. Historically, dams have served as vital reservoirs for productive utilization of natural resources. These dams significantly contribute to India's water resource management, agricultural development, and power generation. However, they also raise environmental and social considerations and their operations are subject to careful monitoring and management.

Melih and Onur, (2010) introduce some case studies on dam instrumentation retrofitting practices. Based on detailed inspections, the deck is covered with a new concrete slab. New stress, strain, and joint movement monitoring equipment have been implemented and observed to have problems related to seepage and uplift-reducing facilities. To monitor possible deficiencies, the installation of a new pore water pressure monitoring system would be beneficial. Sun et al. (2012) introduced a tailings dam monitoring and pre-alarm system (TDM PAS) based on the Internet of Things (IoT) and cloud computing (CC) for mine safety monitoring. This study emphasizes the significance of TDMPAS in enhancing tailings dam safety and its potential for continued advancement in mine safety technology. TDMPAS has significantly improved the safety of tailings dams in the mining industry through several key advancements. First, it enables real-time monitoring of critical parameters such as the saturated line, impounded water level, and dam deformation, allowing for proactive risk management and timely intervention in the case of potential hazards. Towhata et al. (2015) proposed a simple monitoring method for early warning of rainfall-induced landslides.

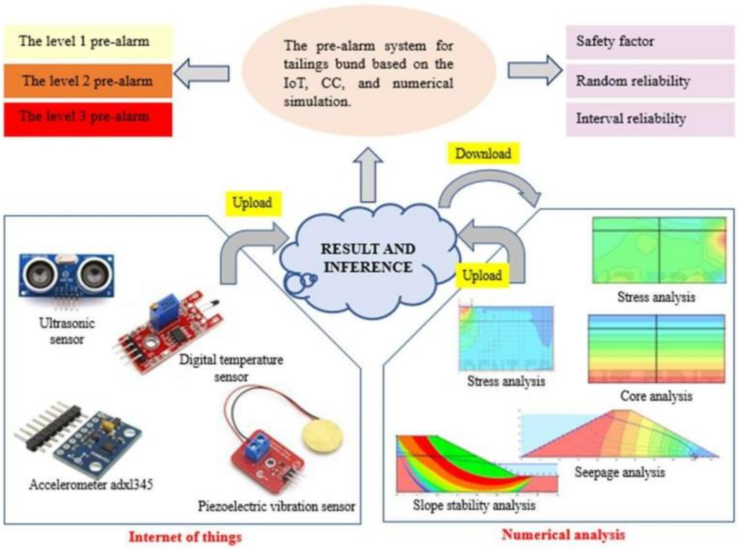
The wireless system was designed with a group of simple sensor units placed on a slope. Tilt sensors installed on slope surfaces can detect some pre-failure behaviors due to heavy rainfall. The observed tilt angles responded sensitively to heavy rainfall events, and continuous tilting was observed for several hours prior to failure. The data were analyzed by plotting graphs to show the observed pore water pressures in the instruments at similar RL with respect to the distance from the dam axis. This section also discusses the determination of the actual hydrostatic pressure at the piezometer tip level based on the water level of the reservoir at the time of monitoring, as well as the analysis of the difference between the actual and observed pressures.

Bhargavi et al. (2023) Dam monitoring is a multistep phenomenon that needs improvisation. The opening and shutting of dam entryways occur by checking the water level. The live surveillance framework screens adjacent dam regions and aids in saving lives. The signals from the sensors were passed through A Wi-Fi camera placed near the dams to demonstrate live surveillance in the dam area. Therefore, by using the aforementioned idea, automatic opening and closing of dam gates, proper routing of water according to the requirements, and live surveillance of dam areas can be easily achieved.

The imperative for studying and enhancing dam safety lies in the potentially catastrophic consequences of dam failures, which can result in the loss of life, property damage, and environmental devastation. Experimental analysis allows researchers to simulate real-world conditions and observe dam behavior, while numerical analysis provides the ability to model complex interactions and predict performance under various scenarios. The main objective of this project was to ensure dam safety by embedding sensors and numerical analysis techniques.

II. METHODOLOGY

The soil sample was collected from the Siddaganga Institute of Technology stadium, and surface debris or vegetation was removed from the sampling area. Various tests were carried out to determine the soil properties, namely, the particle size distribution (sieve analysis), Atterberg limits, compaction tests, and permeability tests, and the results are tabulated in Table 1.



Key factors of the methodology

1. Atterberg limits are used to classify fine-grained soils based on their plasticity, which affects the soil's engineering behaviour.
2. Appropriate compaction increases soil strength, reduces settlement, and improves stability, making it essential for foundations, roadbeds, and embankments.
3. Permeability is crucial in assessing drainage and groundwater flow, as well as in predicting the behaviour of soil under loads and in foundation designs.

Table 1: Parameters considered in the study

Parameters	Remarks
Type of Soil	Silty
Unit weight of Soil	20 kN/m^3
Density	18 kN/m^3
Permeability	0.000179cm/sec
OMC	11.5%
Poison's Ratio	0.35

2.1 Dam Dimension

In this study, an earth-fill dam with a modest height of 7.5 meters, a 2-meter freeboard, and a 2-meter crest width was subjected to both experimental and numerical analyses. Careful consideration was given to selecting these specific dimensions to align with the scale of the experimental setup, as detailed in the subsequent sections. The width of the crest and the minimum freeboard were chosen according to the recommendations outlined by the U.S.. Bureau of Reclamation and Strange for Low-height Earth Dams. The assumption is that the dam's base is impermeable, preventing any seepage beneath it. Moreover, this impermeable base possesses adequate strength to uphold the weight of an earth-fill dam. The embankment slopes must remain stable during both construction and reservoir operations. Consequently, the recommended slope ratios, as per Terzaghi and Strange, are 2.5:1 for the upstream side and 1.75:1 for the downstream side. The adopted strategy to build a reliable realistic model is based on two main techniques which are

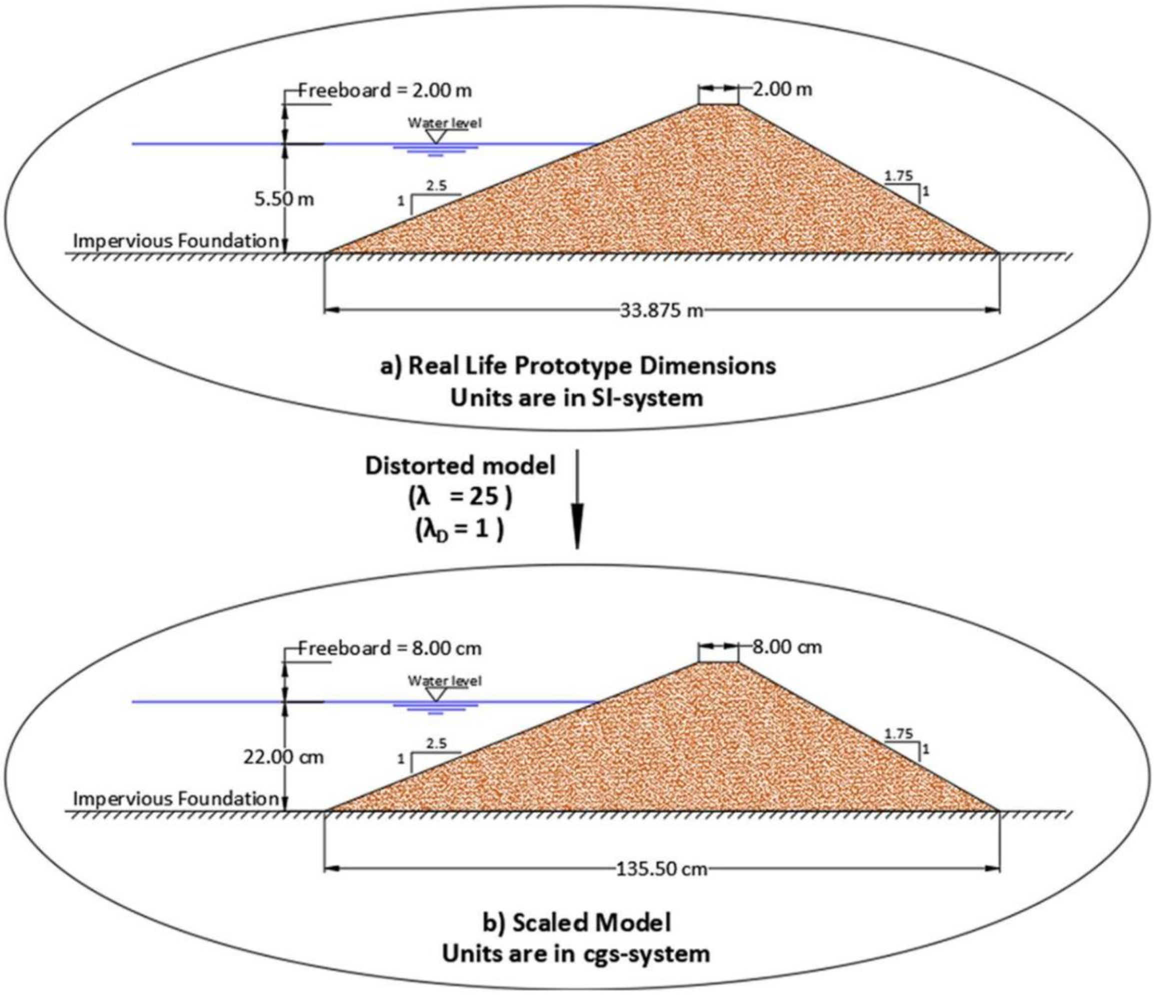


Figure 2.1: Real-life prototype versus scaled model.

1- Avoidance: This means to avoid the scaling effects as much as possible, taking into consideration both financial and scientific aspects. Based on previous research, the length transforming factor (ratio between corresponding lengths in the prototype and model) is selected as (λ=25) which provides a typical model scale that compromises between reasonable size and acceptable scale effects.

2- Compensation: This is achieved by giving up the exact geometric similarity of some parameters in favor of an improved model–prototype similarity. Hereby, the selected length transforming factor (λ=25) has been applied to all the dimensions except the grain size of the used porous material (). The transforming factor of the porous material's grain size is chosen to be equal to unity (λ_D=1) (i.e. the same porous material is used in the model and prototype).

It is a usual practice in permeability tank models to reduce the seepage model's geometry proportionally, but fill the seepage space with the same material as the prototype instead of applying full geometrical similarity. This is a special case of distorted models that prevents the development of micro-seepage instead of laminar flow.

2.2 List Of Sensors Used

Temperature sensor: The operating principle of a digital temperature sensor varies depending on its type. However, the fundamental concept involves sensing ambient temperatures and producing the corresponding output. The output is then converted into digital form through an Analog-to-Digital Converter (ADC), making it interpretable by a computer

Figure 2.2: Temperature sensor.

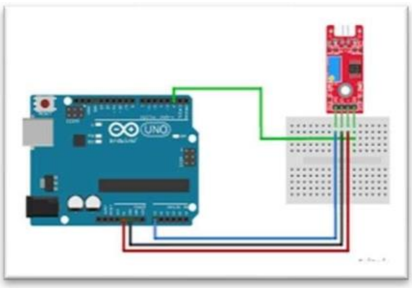


Figure 2.3: Connection of temperature sensor

Accelerometer ADXL335: ADXL335 is a 3-axis accelerometer measuring acceleration in terms of g-force. Placed on the dam, it can detect variations in tilt and slope. Arduino processes the acceleration data to determine the slope ofthe heel of the dam.

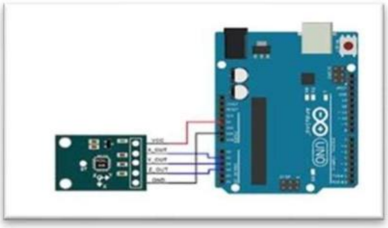


Figure 2.5: Connection of accelerometer sensor

Piezoelectric sensor: Piezoelectric pressure sensors are mainly based on the piezoelectric effect (Piezoelectric effect). Electrical components and other machinery are used to convert the pressure to electricity. Measurement precision instruments, such as pressure transmitters and pressure sensors, are then performed.

Figure 2.6: Piezoelectric

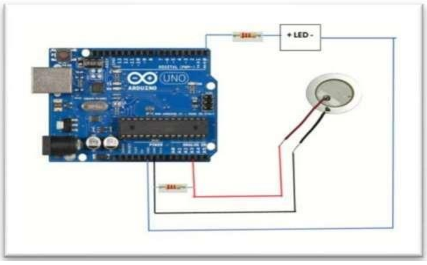


Figure 2.7: Connection of Piezoelectric sensor

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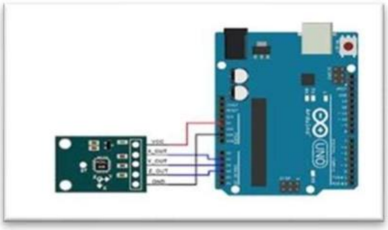

Figure 2.9: Connection of accelerometer sensor

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Figure 2.10: Piezoelectric sensor

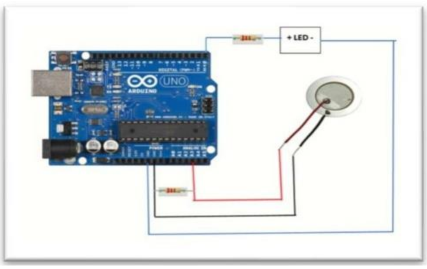


Figure 2.11: Connection of Piezoelectric sensor

Ultrasonic sensor: Ultrasonic sensors emit short, high-frequency sound pulses at regular intervals. These propagate in air at the velocity of sound. If they strike an object, they reflect back as an echo signal to the sensor, which computes the distance to the target based on the time span between emitting the signal and receiving the echo.

Figure 2.12: Ultrasonic sensor

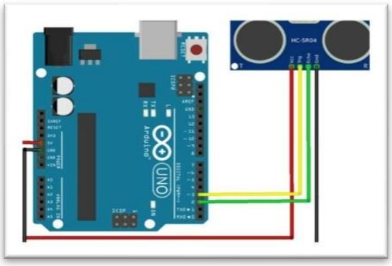
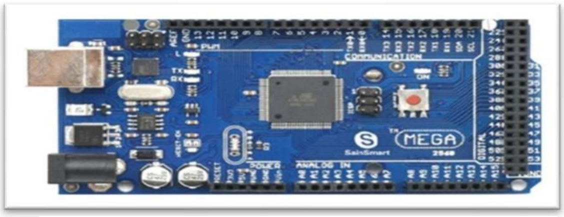


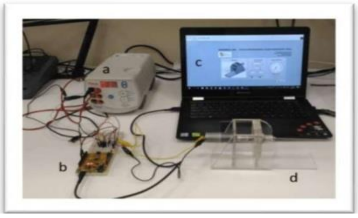
Figure 2.13: Connection of Ultrasonic sensor

2.3 Design Of Arduino

The Arduino Mega is a microcontroller board based on ATmega2560. It has 54 digital input/output pins, 16 analog inputs, four (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. The large number of pins and features makes it suitable for complex projects, including water dam monitoring systems.

The above sensors are connected to the Arduino mega via a laptop, and the results are shown in the Arduino IDE software when the code is uploaded.





2.4 Experimental Setup

According to the laboratory conditions, the experimental setup was based on the dimensions mentioned in the figure.

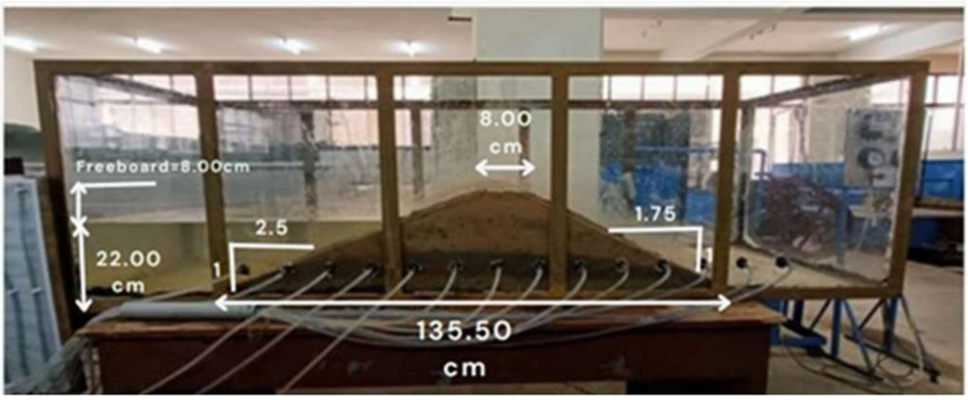


Figure 2.16: Experimental Setup

The sensors are placed in the core as per IS7436 Portion 1 (1993) and embedded temperature, accelerometer, and piezoelectric sensors and embedded at an interim of 5 cm from the bottom up to the freeboard.

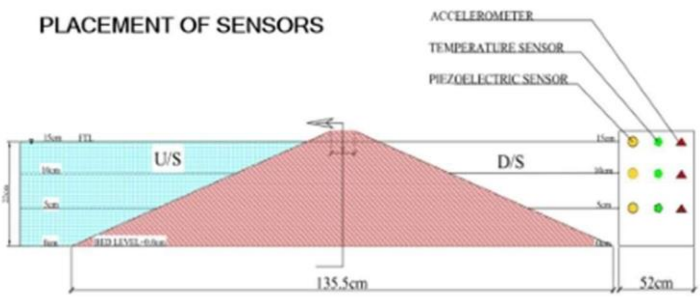
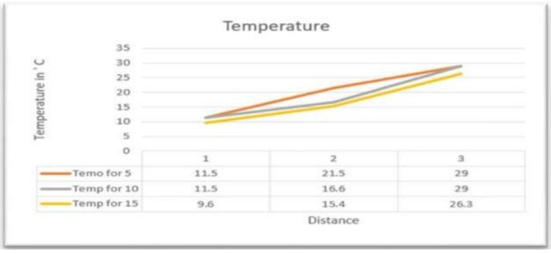


Figure 2.17: Placement of sensors.

III. Experimental Analysis

The Figures 3.1 and 3.2 provides a clear and concise depiction of temperature variations over a specific period. With accurate and detailed measurements, this product is ideal for scientific research, data analysis, and temperature monitoring applications. The x-axis represents the distance, and the y-axis represents the temperature values. The line or bars in the graph show the temperature fluctuations, allowing users to easily interpret and analyze the data.The temperature was lower at 5 cm from the base. At the topmost layer (15 cm), the temperature increased and fluctuated. This stress vs distance graph is a powerful tool for analyzing and understanding the relationship between stress levels and the distance traveled. With a clear and concise design, it provides a visual representation of how stresslevels fluctuate as the distance increases or decreases. The graph is divided into two axes, with the stress levels plotted onthe vertical axis and the distance on the horizontal axis. The graph was color-coded to easily distinguish between different stress levels, allowing users to quickly identify patterns and trends. As the water level increased, stress also increased.



IV. Numerical Analysis

The obtained numerical results were compared with the experimental results, as shown in Table 2. It is clear that, the stress values obtained at different locations in the experimental study are very close to numerical values. After validating the numerical model, the seepage and slope stability were analyzed.

Table 2: Numerical results

Experimental Analysis	Numerical Analysis
At 5cm, Temperature: 8.8 °C Stress: 8.35 kPa Slope: 1:7	At 5cm, Stress: 10.5 kPa Slope: 1:8.2
At 10cm, Temperature: 15 °C Stress: 49.6 kPa Slope: 1:8.5	At 10cm, Stress: 53.6 kPa Slope: 1:9.3
At 15cm, Temperature: 28.4 °C Stress: 112.8 kPa Slope: 1:10.1	At 15cm, Stress: 118 kPa Slope: 1:12

4.1 Seepage Analysis*:*

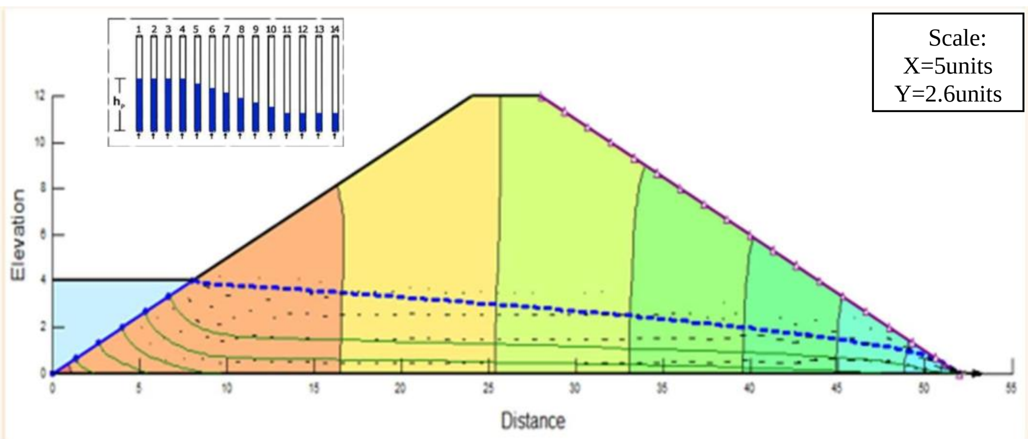


Figure 4.1: The PWP Distribution by SEEP/W

The figure above shows the seepage at 10 cm. Under the defined boundary conditions, two boundary conditions are automatically generated. One is zero pressure, and the other is drainage. Now, we have created a boundary condition called Reservoir, which is to be plotted on the upstream side, set to a water table depth of 10 cm. Finally, for mesh properties, we created a final discretization for the global mesh by changing this value to 1m.The output is then shown.

IV.2 Stress Analysis:

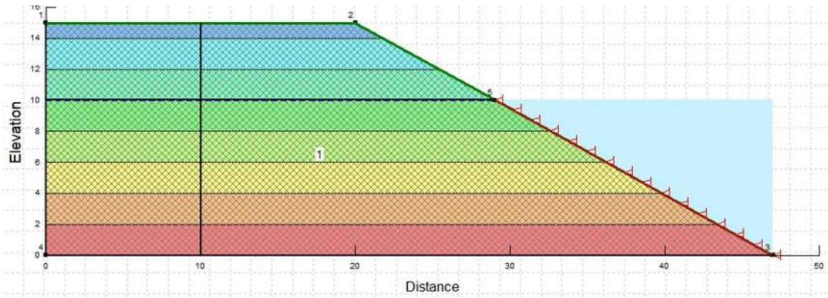


Figure 4.2: The total stress by SIGMA/W

According to the filter form, there was variance in the maximum stress values. Increasing the permeability coefficient from 1 to 1.5 at upstream slope (1:2.5) increases the amount of stress by (0.05%), (0.1%), and (0.03%) for each state (no horizontal filter, horizontal filter, and core) respectively. The value at 10 cm depth was 53.6 kPa. As observed, as the water level increases, the pressure at the bottom level also increases.

IV.3 Slope Analysis:

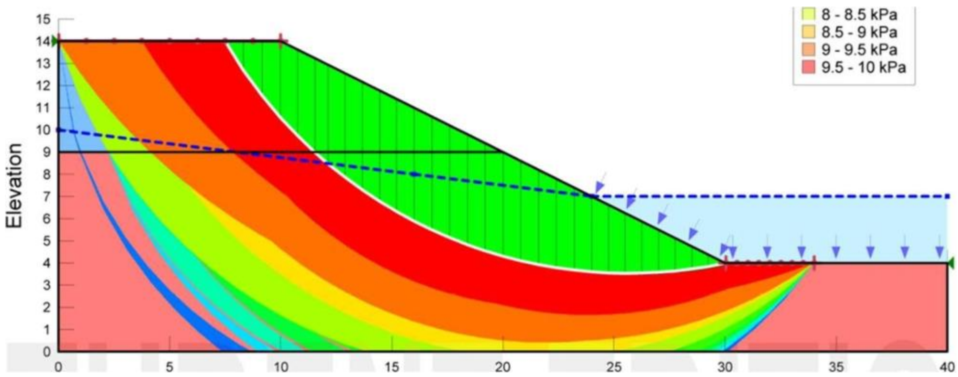


Figure 4.3: F.S for upstream side by entry exit method for maximum water level

The initiation of slip circles was induced by defining the entry point at the toe and the exit at the highest point of the embankment. The identified critical slip circle corresponds to the respective factor of safety, as illustrated in Figure (SLOPE/W with critical slip surface), which is 1.64. (SEEP/W critical slip surface) shows the magnitude contours of pore water pressures that are negative above the phreatic line owing to suction, and positive below the phreatic line. Water flows from the upstream slope to the downstream slope of the earthen dam.

V. CONCLUSION:

- Numerical analysis offers detailed insights into seepage patterns and potential flow paths within the earthen bund, whereas experimental methods provide empirical validation of seepage behaviour under real-world conditions.
- Integrating numerical and experimental approaches enhances the understanding of stress behaviour and facilitates the refinement of numerical models for more accurate predictions.
- With the increase in the water depth, the stress also increases
- Finally, this study reveals the detailed evolution process of earthen bund by protecting it from failure with an early warning (pre-alarm) from the sensors.

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