



## Alternative Main Dam Design Based on Seepage and Stability Analyses of Jlantah Dam, Karanganyar, Indonesia

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### Abstract

Earthfill dams are widely used because they can be constructed under diverse geological and geographical conditions and can utilize locally available materials. However, seepage and slope instability remain critical safety concerns in dam design. The configuration and thickness of the zones within the dam body, particularly the core, can significantly affect seepage control and slope stability. This study evaluates three alternative zoned earthfill dam configurations for Jlantah Dam, Indonesia: the existing vertical-core design (Alternative 1), an inclined-core design (Alternative 2), and a diaphragm-type design (Alternative 3). Seepage and slope stability analyses were performed using GeoStudio SEEP/W and SLOPE/W under maximum flood level (MFL), minimum water level (MWL), and rapid drawdown (RD) conditions, considering non-seismic, Operating Basis Earthquake (OBE), and Maximum Design Earthquake (MDE) loading. The allowable seepage discharge was set at 0.0617 m<sup>3</sup>/s, corresponding to 1% of the average river discharge. The calculated seepage discharges for Alternatives 1–3 ranged from 0.00906 to 0.0197 m<sup>3</sup>/s, with Alternative 3 producing the lowest values of 0.0179, 0.00906, and 0.0169 m<sup>3</sup>/s under MFL, MWL, and RD conditions, respectively. Under non-seismic loading, the calculated Factor of Safety (FS) values ranged from 1.912 to 2.877, exceeding the minimum requirement of 1.3 for all alternatives. Under OBE loading, the FS values ranged from 1.277 to 1.683, satisfying the minimum requirement of 1.2. However, under MDE loading, the FS values ranged from 0.523 to 0.742, which are below the minimum requirement of 1.0 for all alternatives. Overall, Alternative 3 provides the most effective seepage control, whereas Alternative 1 provides the highest slope stability. The results demonstrate that dam-body configuration significantly influences the balance between seepage control and slope stability and should therefore be carefully considered in the design and evaluation of zoned earthfill dams.

**Keywords:** Embankment dam, dam type, stability, seepage stability, slope stability

### 1. Introduction

Embankment dams are among the most commonly used types of dams. Their construction involves the placement and compaction of soil, sand, gravel, and rock using appropriate methods to form a water-retaining barrier. One of the main advantages of embankment dams is their applicability to a wide range of geological and geographical conditions. In addition, the materials used for the dam body can generally be obtained from sources available in the vicinity of the dam site <sup>[1]</sup>. Despite these advantages, embankment dams are associated with several potential hazards. The most common hazards include seepage through the dam body and slope failures occurring within the embankment. Recent dam-safety guidance emphasizes that seepage and slope stability analyses are essential components of the assessment and design of embankment

dams <sup>[5]</sup>.

Seepage is the flow of water through the pores of the materials comprising the dam. Excessive seepage may cause internal erosion and the development of concentrated flow paths within the dam body (*pipng*), which can ultimately lead to structural failure. Recent numerical studies have demonstrated that seepage can be closely associated with internal erosion, changes in soil permeability, and progressive instability of embankment slopes <sup>[6]</sup>. Slope failures may occur on either the upstream or downstream slopes of the dam. Various factors can trigger such failures, including earthquakes, heavy rainfall, and water levels exceeding the design capacity. The stability of an embankment dam is influenced by several factors, including the dam type, material properties, dam geometry, and construction methods. Therefore, dam design must carefully

consider several important aspects, including safety factors, material availability, construction costs, and operation and maintenance requirements.

Jlntah Dam is located at the confluence of the Jlntah and Puru Rivers, within Tlobo and Karangari Villages, Jatiyoso District, Karanganyar Regency, Central Java Province, Indonesia. With a total reservoir storage capacity of approximately 10.97 million m<sup>3</sup>, the primary functions of Jlntah Dam are irrigation and raw water supply [2]. In addition, the dam is intended to support a micro-hydropower plant, as well as water conservation and tourism development in Karanganyar Regency.

In the existing design, Jlntah Dam is a zoned embankment dam with an impervious central core consisting of compacted clay material positioned vertically within the dam body. One of the critical considerations in dam design is the selection of an appropriate dam-body configuration that meets the specific site conditions and functional requirements. The dam body is the principal component responsible for retaining the reservoir and controlling seepage through the embankment. Therefore, the design of the individual zones comprising a zoned embankment dam requires careful analysis. Recent research has demonstrated that the thickness and geometry of the zones in zoned earth dams can significantly influence seepage characteristics and hydraulic performance [3, 7]. The configuration of internal drainage and seepage-control elements can also affect both seepage discharge and slope stability [8].

Therefore, further analysis of the zones comprising the dam body is required, particularly to evaluate alternative dam-body configurations. Recent experimental and numerical research has also shown that the configuration and condition of internal diaphragm systems can influence seepage behavior and slope stability, highlighting the importance of evaluating alternative seepage-control configurations in earth dams [9]. In this study, two alternative dam-body designs with different configurations, namely an inclined-core design and a diaphragm-type design, were developed and compared with the existing vertical-core design. Seepage analyses were then conducted to determine the seepage discharge and hydraulic performance of each dam configuration. Slope stability analyses were also performed to compare the Factor of Safety (FS) of the dam slopes for

each design using both manual calculations and GeoStudio 2018 R2. The use of numerical modeling for coupled seepage and slope-stability assessment has been demonstrated in recent studies using SEEP/W and SLOPE/W [8].

The objective of this study is to analyze seepage and slope stability for different dam-body configurations and to identify an effective and safe dam design that satisfies the applicable dam safety standards.

## 2. Methods

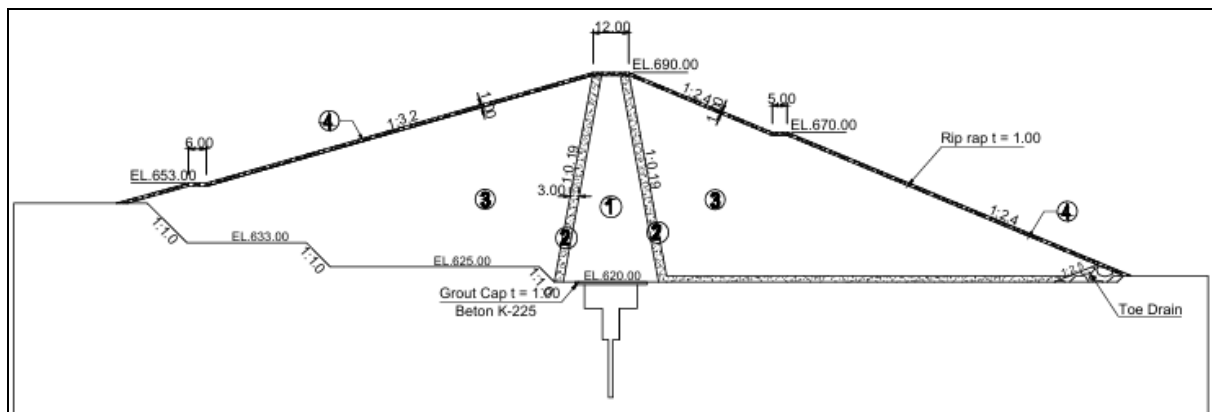
The analyses were conducted using GeoStudio 2018 R2 SEEP/W and SLOPE/W software. The safety and stability of the dam were evaluated with respect to seepage and slope failure. The required data included the Detailed Engineering Design (DED) of the Jlntah Dam body, material parameters, and other relevant technical data. The material parameters used in the analyses were obtained from laboratory testing. The parameters for the dam embankment materials and foundation soils included unit weight, friction angle ( $\phi$ ), cohesion ( $c$ ), water content, and hydraulic conductivity ( $k$ ). These geotechnical parameters are essential input variables for numerical seepage and slope stability analyses of earth and embankment dams [15].

The use of integrated seepage and slope stability modeling is widely applied in the assessment of embankment dams. Recent studies have demonstrated the application of SEEP/W for evaluating seepage behavior and pore-water pressure distributions, followed by SLOPE/W for assessing dam slope stability under different hydraulic conditions [15, 16]. In addition, recent research has shown that changes in reservoir water levels and seepage conditions can significantly affect pore-water pressures and the resulting Factor of Safety of dam slopes [16]. Numerical modeling using SEEP/W and SLOPE/W has also been combined with laboratory-based material characterization to evaluate seepage control measures and their influence on overall dam stability [17].

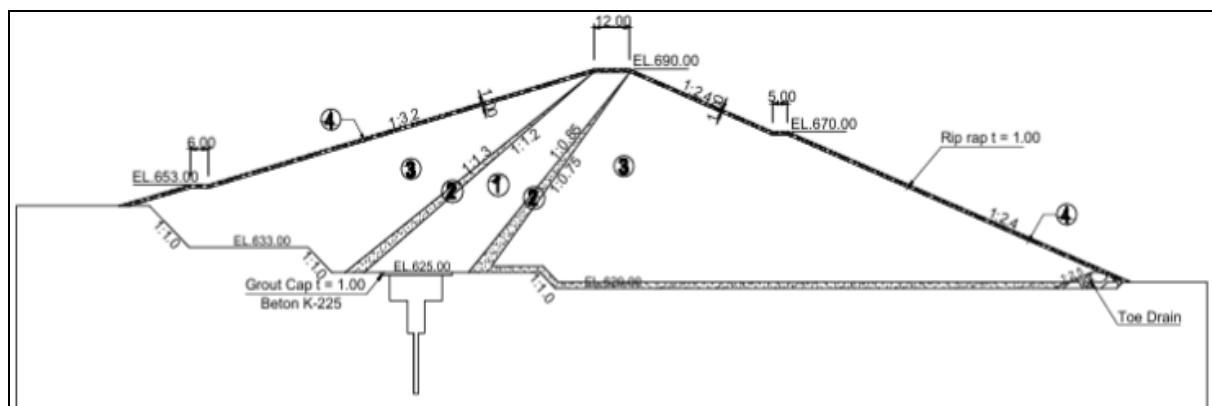
In this study, three dam configurations were considered in the analyses: a vertical-core design, an inclined-core design, and a diaphragm-type design, as illustrated in Figures 1–3, respectively

**Table 1:** Material Parameters

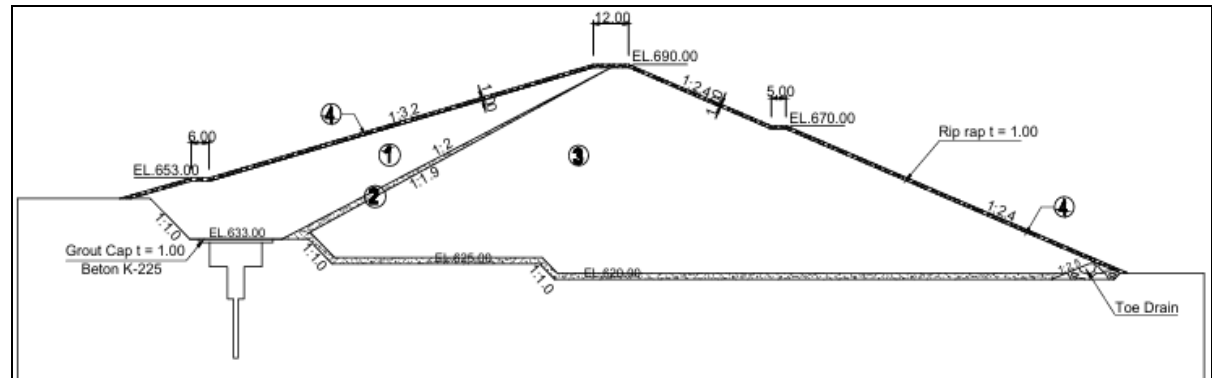
| Zone                          | $\gamma$ (kN/m <sup>3</sup> ) | $\phi$ (°) | $c$ (kN/m <sup>2</sup> ) | WC   | $k$ (m/s) |
|-------------------------------|-------------------------------|------------|--------------------------|------|-----------|
| Core Zone                     | 17.46                         | 17.32      | 22.56                    | 0.57 | 1.10E-08  |
| Filter Zone                   | 19.61                         | 29         | 0                        | 0.30 | 4.60E-06  |
| Random Zone                   | 19.91                         | 38         | 0                        | 0.30 | 9.42E-05  |
| Rip-Rap Zone                  | 21.57                         | 42         | 0                        | 0.20 | 1.00E-03  |
| Rock Toe                      | 22.56                         | 42         | 0                        | 0.20 | 1.00E-03  |
| Foundation (Volcanic Breccia) | 20.59                         | 45         | 98.07                    | 0.35 | 2.70E-06  |
| Grout Cap                     | 21.58                         | —          | —                        | 0.05 | 1.00E-12  |
| Grouting                      | 20.59                         | 45         | 98.07                    | 0.35 | 6.00E-07  |



**Fig 1:** Alternative Design 1 (Existing Design, Vertical Core)



**Fig 2:** Alternative Design 2 (Inclined Core)



**Fig 3:** Alternative Design 3 (Diaphragm)

Three dam-body configurations were considered in the analyses: vertical-core, inclined-core, and diaphragm-type configurations. The selection of alternative core configurations is consistent with recent studies demonstrating that the geometry and dimensions of internal zones and cores can significantly influence seepage behavior and slope stability in zoned earth dams [10, 11]. Seepage and slope stability analyses of the dam body were performed under maximum flood water level, minimum water level, and rapid drawdown conditions. These reservoir operating conditions are important for evaluating the hydraulic and mechanical response of embankment dams, particularly because rapid drawdown can generate critical pore-water-pressure conditions and reduce upstream slope stability [12]. Recent numerical studies have also demonstrated the importance of considering reservoir water-

level fluctuations when evaluating seepage and slope stability [13].

Earthquake-induced slope stability was evaluated using the Operating Basis Earthquake (OBE) and Maximum Design Earthquake (MDE) criteria, corresponding to return periods of 100 years and 10,000 years, respectively.

The seepage discharge obtained from the SEEP/W simulations was compared with the allowable seepage discharge. The slope stability safety factors were determined using SLOPE/W based on the results of soil investigations and laboratory testing. The application of SEEP/W and SLOPE/W for evaluating seepage discharge, pore-water pressure, and slope stability of embankment dams has been demonstrated in recent numerical studies [5, 8, 9]. In particular, SEEP/W-based numerical modeling has been applied to evaluate seepage through zoned earth dams with

different zone geometries and hydraulic properties<sup>[14]</sup>. The allowable seepage discharge was specified as less than 1% of the average river discharge. The slope stability of the dam was considered acceptable when the calculated Factor of Safety (FS) satisfied the applicable criteria for each loading condition<sup>[4]</sup>. Under non-seismic conditions, the minimum required FS was 1.3 for the maximum flood water level, minimum water level, and rapid drawdown conditions. Under Operating Basis Earthquake (OBE) loading, the minimum required FS was 1.2 for the same three water-level conditions. Meanwhile, under Maximum Design Earthquake (MDE) loading, the minimum required

FS was 1.0 for the maximum flood water level, minimum water level, and rapid drawdown conditions. Accordingly, the slope stability criteria adopted in this study were  $FS > 1.3$  for non-seismic conditions,  $FS > 1.2$  for OBE loading, and  $FS > 1.0$  for MDE loading.

### 3. Results and Discussion

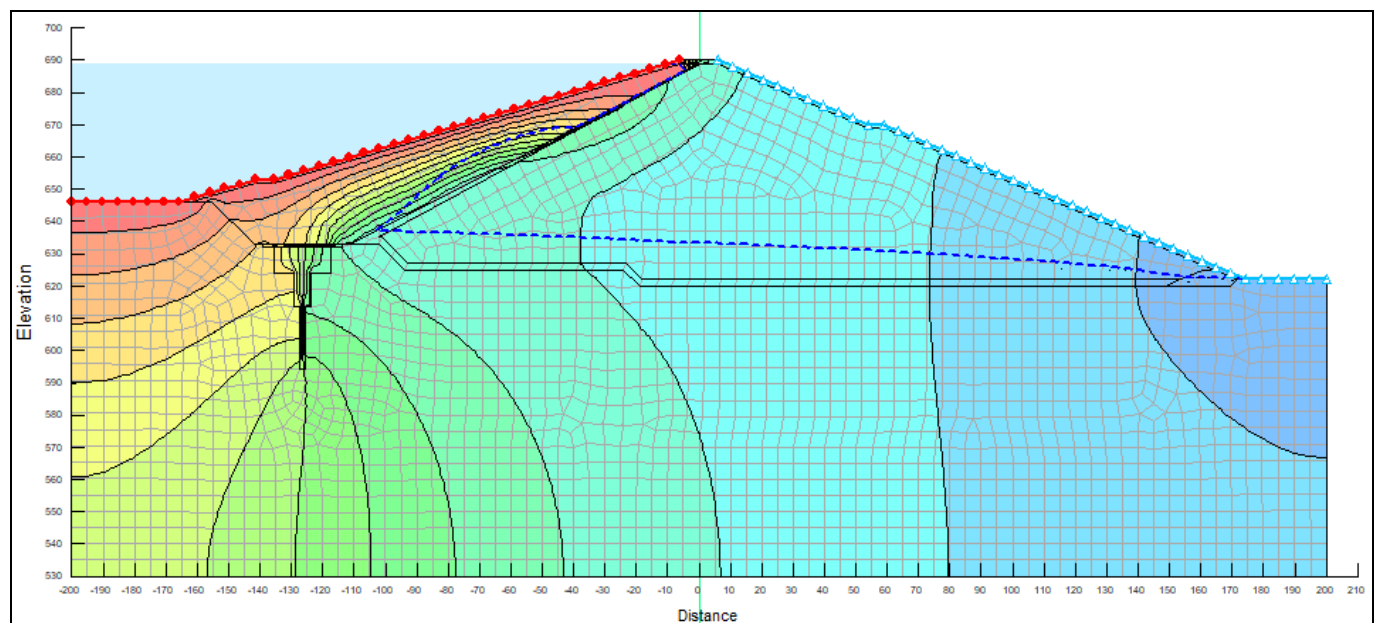
**3.1 Seepage Analysis:** Seepage analysis was conducted for the three dam configurations to determine the seepage discharge generated by each design. The SEEP/W simulations in GeoStudio produced seepage flow profiles for each reservoir water-level condition.

**Table 2:** Summary of Seepage Discharge

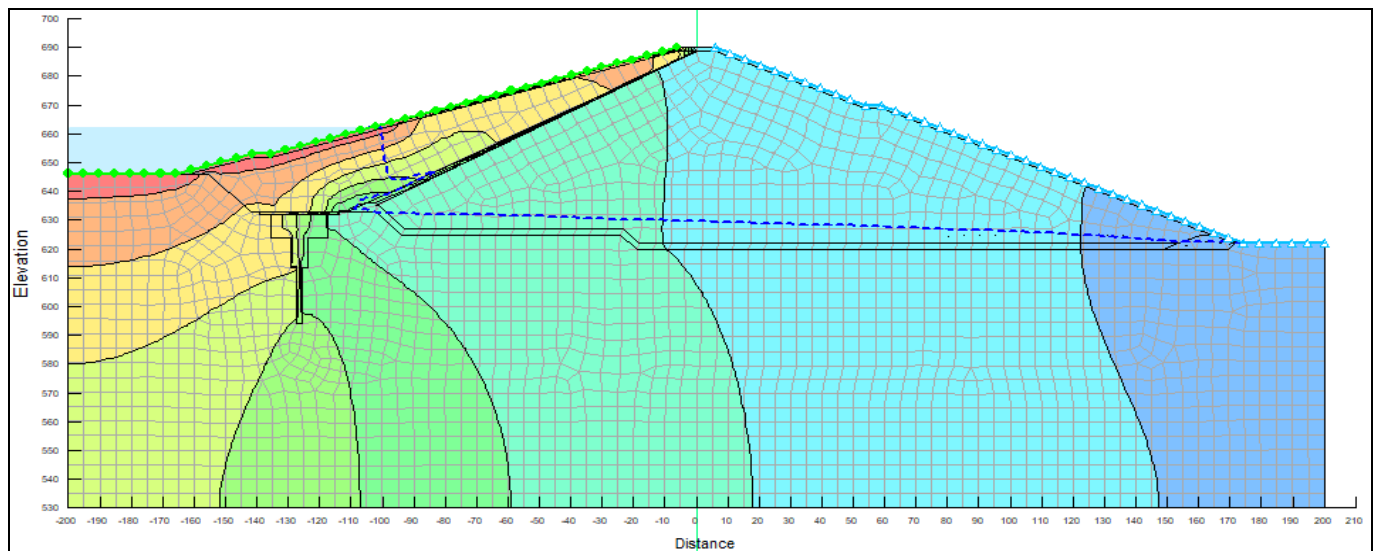
| Design        | Condition | Allowable Seepage, $Q_{allow}$ (m <sup>3</sup> /s) | Seepage Discharge, $Q$ (m <sup>3</sup> /s) | Check                  |
|---------------|-----------|----------------------------------------------------|--------------------------------------------|------------------------|
| Alternative 1 | MFL       | 6.17E-02                                           | 1.89E-02                                   | $Q < Q_{allow}$ (SAFE) |
|               | MWL       |                                                    | 1.25E-02                                   | $Q < Q_{allow}$ (SAFE) |
|               | RD        |                                                    | 1.85E-02                                   | $Q < Q_{allow}$ (SAFE) |
| Alternative 2 | MFL       |                                                    | 1.97E-02                                   | $Q < Q_{allow}$ (SAFE) |
|               | MWL       |                                                    | 1.21E-02                                   | $Q < Q_{allow}$ (SAFE) |
|               | RD        |                                                    | 1.86E-02                                   | $Q < Q_{allow}$ (SAFE) |
| Alternative 3 | MFL       |                                                    | 1.79E-02                                   | $Q < Q_{allow}$ (SAFE) |
|               | MWL       |                                                    | 9.06E-03                                   | $Q < Q_{allow}$ (SAFE) |
|               | RD        |                                                    | 1.69E-02                                   | $Q < Q_{allow}$ (SAFE) |

The allowable seepage discharge was specified as less than 1% of the average river discharge. The average discharge of the Jlantah River is 6.167 m<sup>3</sup>/s; therefore, the allowable seepage discharge was calculated as 0.062 m<sup>3</sup>/s. As presented in Table 2 and Figures 4–6, the seepage discharge obtained from all three dam configurations was below the allowable limit under all analyzed water-level conditions. Thus, all three designs satisfy the seepage safety criterion. Among the three alternative dam configurations, Alternative 3 (diaphragm-type design) produced the lowest seepage

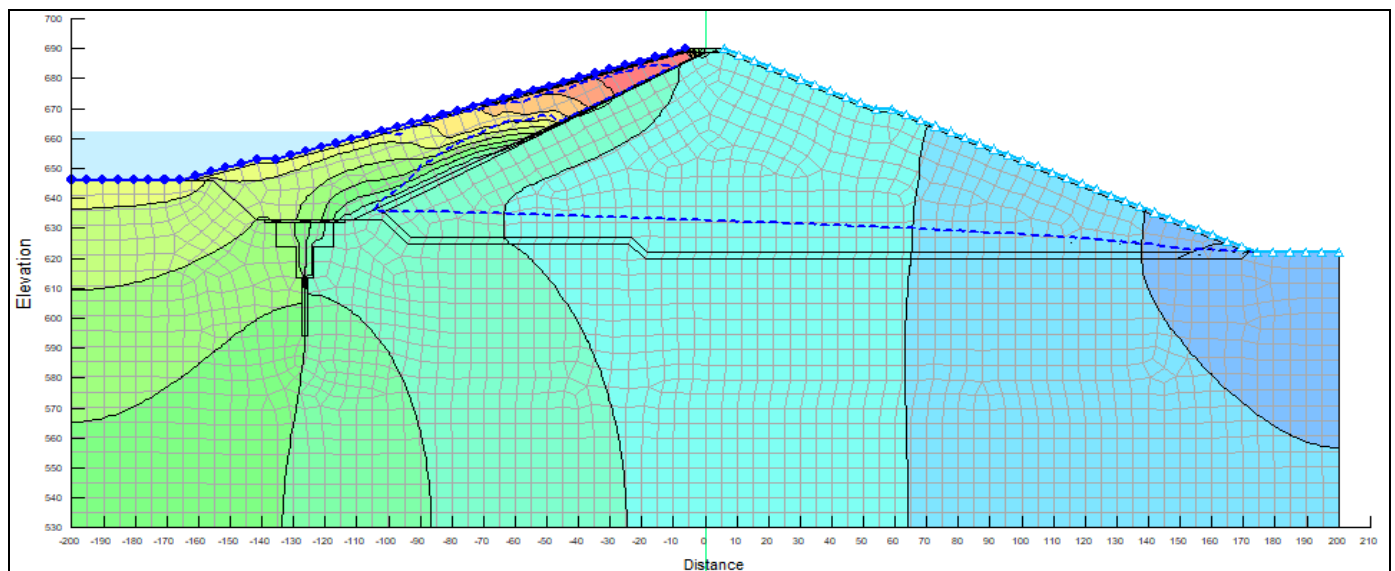
discharge under all water-level conditions. Under the maximum flood level, minimum water level, and rapid drawdown conditions, the calculated seepage discharges for Alternative 3 were  $1.79 \times 10^{-2}$ ,  $9.06 \times 10^{-3}$ , and  $1.69 \times 10^{-2}$  m<sup>3</sup>/s, respectively. These values correspond to approximately 29.0%, 14.7%, and 27.4% of the allowable seepage discharge, respectively. The results indicate that the diaphragm-type configuration provides the most effective seepage control among the three alternatives.



**Fig 4:** Seepage Analysis of Alternative Design 3 under Maximum Flood Level Conditions



**Fig 5:** Seepage Analysis of Alternative Design 3 under Minimum Water Level Conditions



**Fig 6:** Seepage Analysis of Alternative Design 3 under Rapid Drawdown Conditions

### 3.2 Slope Stability Analysis

Slope stability analyses were performed under maximum flood level, minimum water level, and rapid drawdown

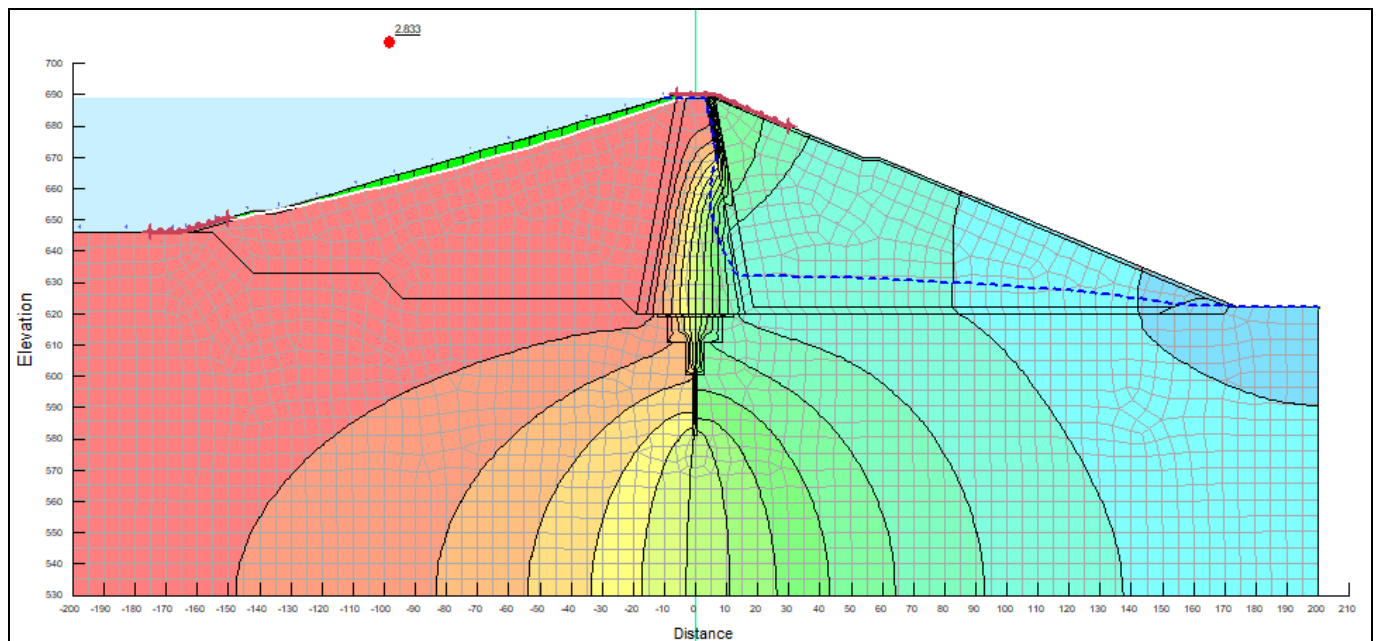
conditions. Table 3 presents the calculated safety factors (SFs) for the upstream and downstream slopes of the dam under conditions without seismic loading.

**Table 3:** Safety Factors under Non-Seismic Conditions

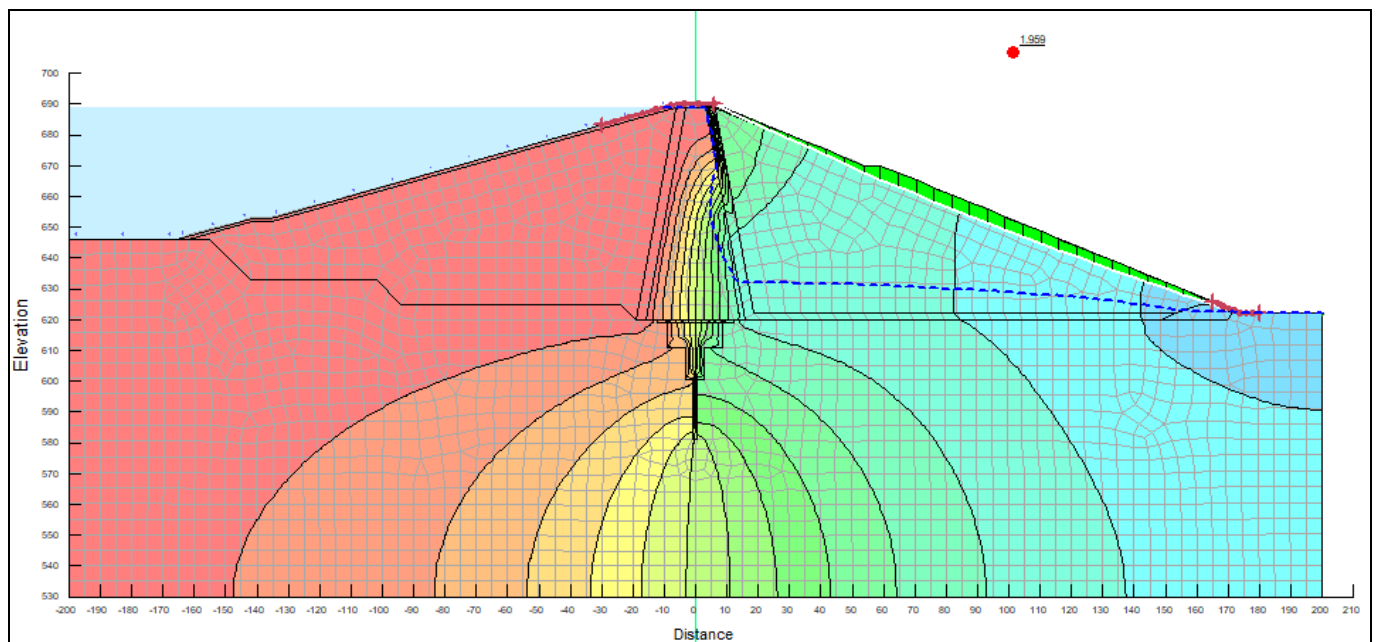
| Design        | Condition | Allowable SF | Upstream SF | Downstream SF | Check                    |
|---------------|-----------|--------------|-------------|---------------|--------------------------|
| Alternative 1 | MFL       | 1.3          | 2.833       | 1.959         | FS > Allowable FS (SAFE) |
|               | MWL       |              | 2.544       | 1.961         | FS > Allowable FS (SAFE) |
|               | RD        |              | 2.337       | 1.960         | FS > Allowable FS (SAFE) |
| Alternative 2 | MFL       | 1.3          | 2.877       | 1.959         | FS > Allowable FS (SAFE) |
|               | MWL       |              | 2.055       | 1.963         | FS > Allowable FS (SAFE) |
|               | RD        |              | 1.986       | 1.960         | FS > Allowable FS (SAFE) |
| Alternative 3 | MFL       | 1.3          | 2.823       | 1.959         | FS > Allowable FS (SAFE) |
|               | MWL       |              | 1.912       | 1.963         | FS > Allowable FS (SAFE) |
|               | RD        |              | 1.931       | 1.962         | FS > Allowable FS (SAFE) |

The results indicate that all three dam configurations satisfy the required slope stability criterion under all non-seismic loading conditions. The calculated safety factors for both the upstream and downstream slopes are consistently higher

than the allowable value of 1.3, indicating that the three alternative designs provide adequate slope stability under maximum flood level, minimum water level, and rapid drawdown conditions.



**Fig 7:** Slope Stability of Alternative Design 1 under Maximum Flood Level Conditions without Seismic Loading (Upstream)



**Fig 8:** Slope Stability of Alternative Design 1 under Maximum Flood Level Conditions without Seismic Loading (Downstream)

The results of the analyses under non-seismic loading conditions indicate that the calculated safety factors for all alternative dam configurations satisfy the specified allowable safety criteria.

Based on the seismic regional risk factor of 32 for Jlantah Dam, the dam site is classified as Seismic Risk Class IV (Extreme). Therefore, seismic slope stability analyses were performed considering two earthquake hazard levels. The Operating Basis Earthquake (OBE), for which no significant damage is permitted, was considered with a 100-year return period, while the Maximum Design Earthquake (MDE), under which some damage may occur but structural collapse must be prevented, was considered with a 10,000-year return period.

**Table 4:** Earthquake Return Period Parameters

| Y/H  | Earthquake Return Period |                    |
|------|--------------------------|--------------------|
|      | OBE (100 years)          | MDE (10,000 years) |
| 0.25 | 0.156                    | 0.675              |
| 0.50 | 0.130                    | 0.563              |
| 0.75 | 0.119                    | 0.514              |
| 1.00 | 0.107                    | 0.464              |

The coefficient values used in the OBE and MDE seismic loading models in GeoStudio were determined based on the Y/H ratio, with the maximum coefficient value of 0.464.

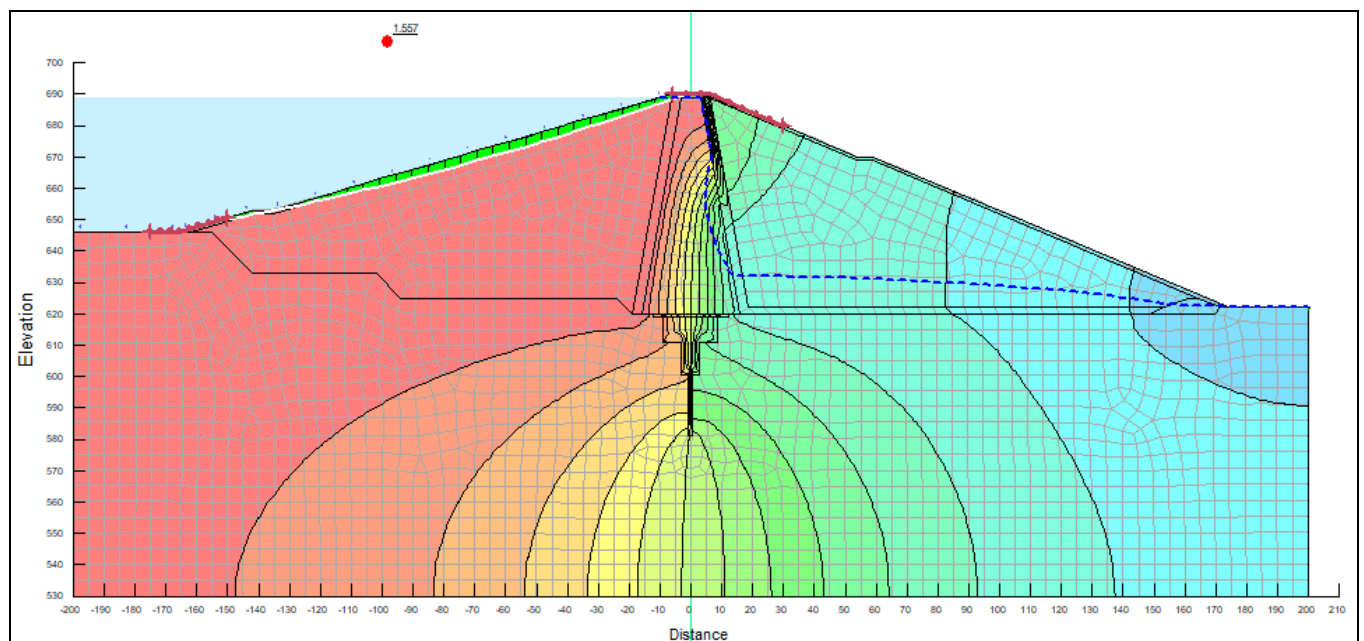
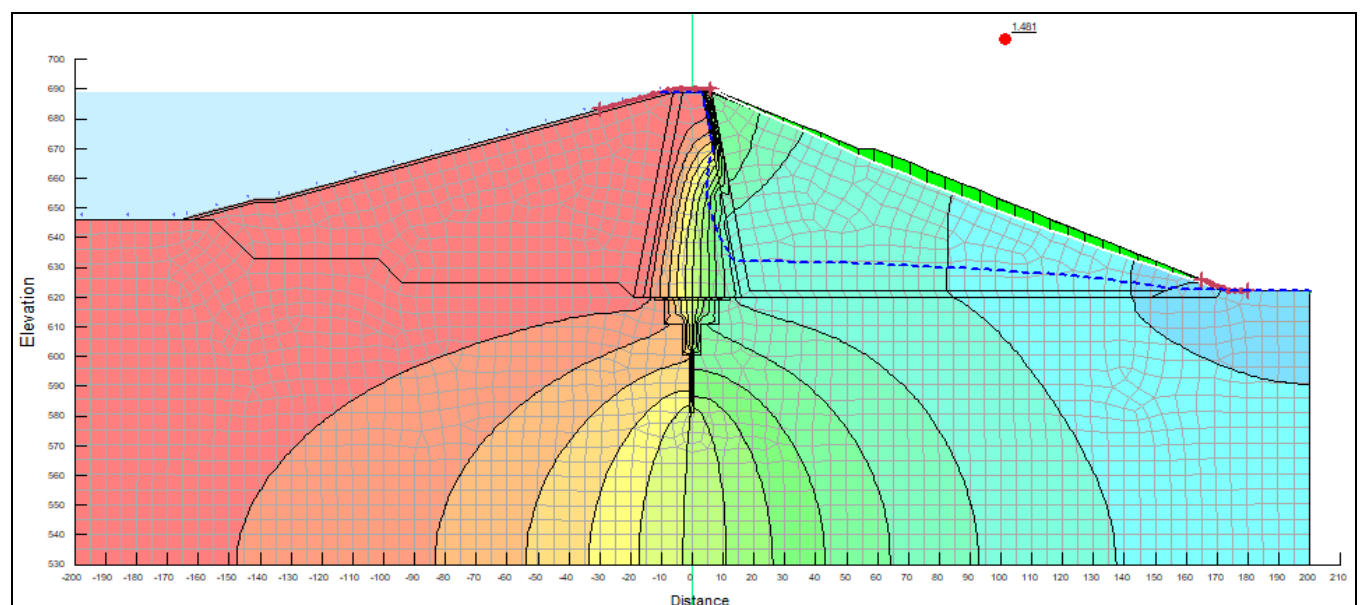
The results of the slope stability analysis under OBE seismic loading conditions are presented in Table 5. The calculated Factor of Safety (FS) for each alternative dam design under OBE conditions satisfies the specified acceptance criterion, with FS values greater than 1.2.

**Table 5:** Factor of Safety under OBE Seismic Loading

| Design        | Condition | Allowable FS | Upstream FS | Downstream FS | Check                           |
|---------------|-----------|--------------|-------------|---------------|---------------------------------|
| Alternative 1 | MFL       | 1.2          | 1.557       | 1.481         | FS > FS <sub>allow</sub> (SAFE) |
|               | MWL       |              | 1.683       | 1.482         | FS > FS <sub>allow</sub> (SAFE) |
|               | RD        |              | 1.539       | 1.481         | FS > FS <sub>allow</sub> (SAFE) |
| Alternative 2 | MFL       | 1.2          | 1.581       | 1.481         | FS > FS <sub>allow</sub> (SAFE) |
|               | MWL       |              | 1.414       | 1.483         | FS > FS <sub>allow</sub> (SAFE) |
|               | RD        |              | 1.349       | 1.481         | FS > FS <sub>allow</sub> (SAFE) |
| Alternative 3 | MFL       | 1.2          | 1.589       | 1.481         | FS > FS <sub>allow</sub> (SAFE) |
|               | MWL       |              | 1.324       | 1.483         | FS > FS <sub>allow</sub> (SAFE) |
|               | RD        |              | 1.277       | 1.483         | FS > FS <sub>allow</sub> (SAFE) |

The results of the slope stability analysis under OBE seismic loading are presented in Table 5. All three alternative dam designs satisfy the allowable Factor of Safety (FS) criterion of 1.2 under maximum flood level (MFL), minimum water level (MWL), and rapid drawdown (RD) conditions. The

calculated FS values for the upstream slope range from 1.277 to 1.683, while those for the downstream slope range from 1.481 to 1.483. Therefore, all alternative designs meet the required slope stability criterion under OBE seismic loading conditions.

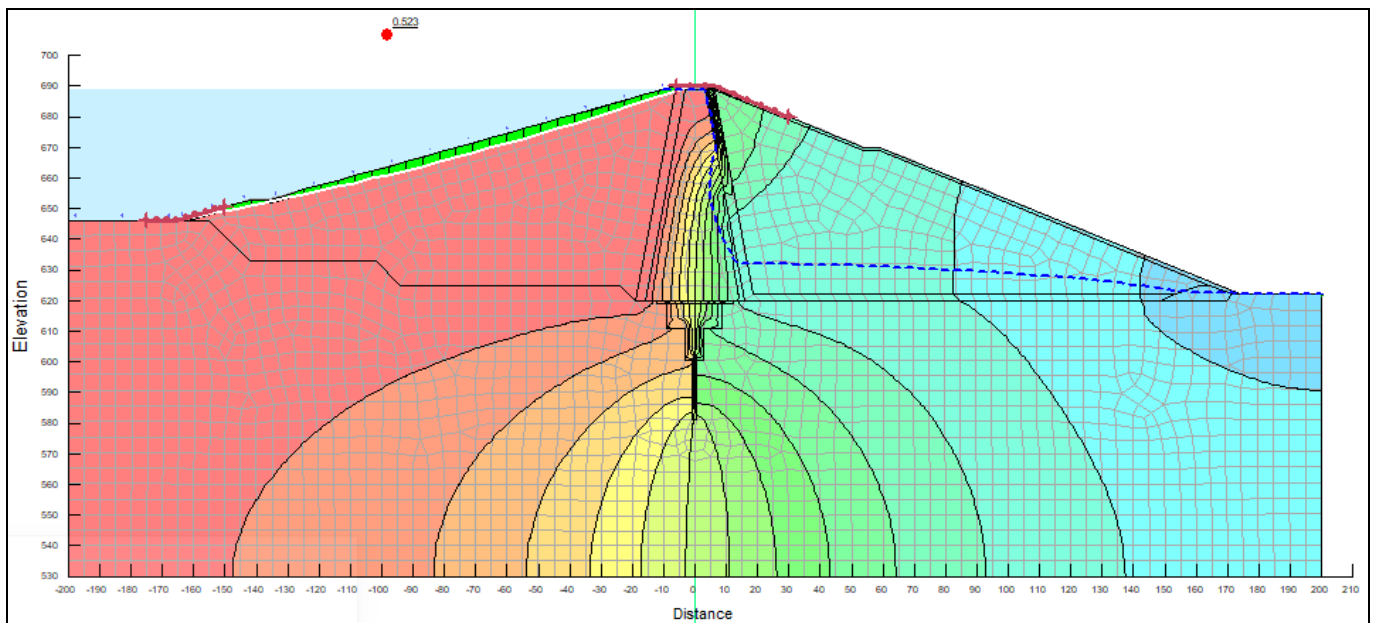
**Fig 9:** Slope Stability of Alternative Design 1 under MFL Conditions with OBE Seismic Loading (Upstream)**Fig 10:** Slope Stability of Alternative Design 1 under MFL Conditions with OBE Seismic Loading (Downstream)

The results of the slope stability analysis under MDE seismic loading conditions are presented in Table 6. The analysis indicates that the Factor of Safety (FS) of the dam

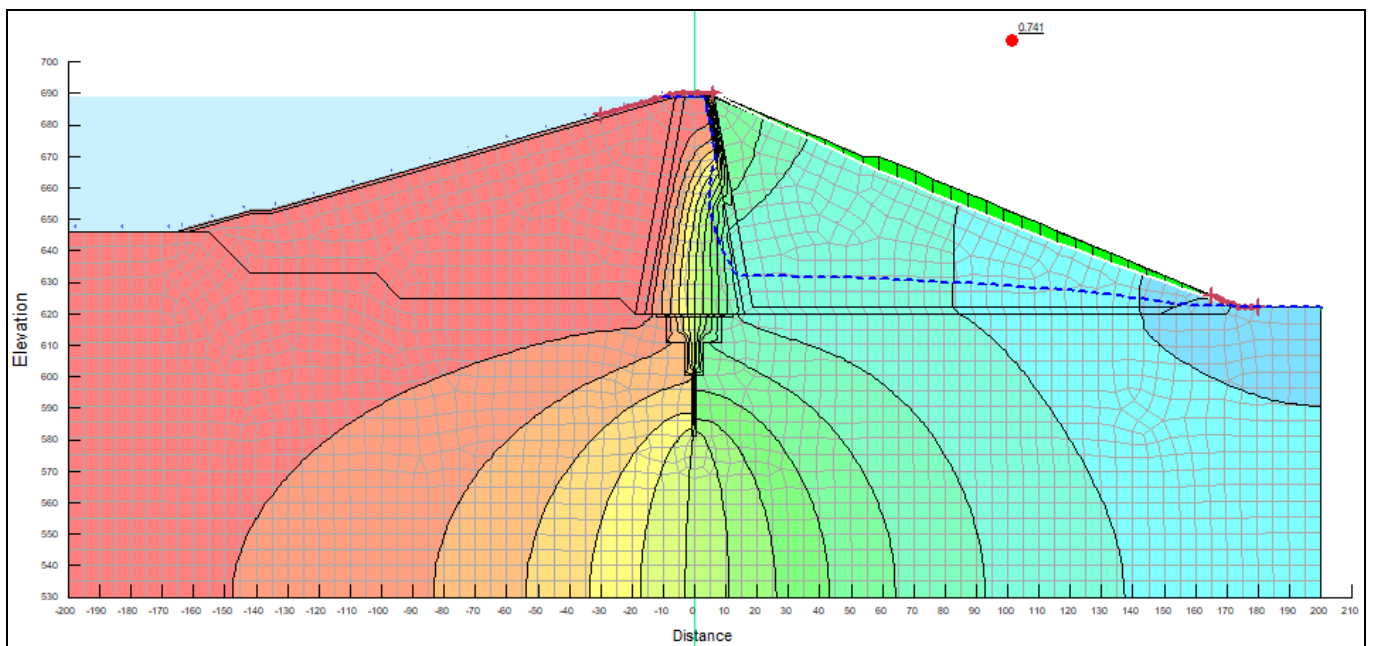
slopes under MDE seismic loading does not satisfy the required criterion, as the calculated FS values are below 1.0.

**Table 6:** Factor of Safety under MDE Seismic Loading

| Design        | Condition | Allowable FS | Upstream FS | Downstream FS | Check                  |
|---------------|-----------|--------------|-------------|---------------|------------------------|
| Alternative 1 | MFL       | 1.0          | 0.523       | 0.741         | FS < FS_allow (UNSAFE) |
|               | MWL       |              | 0.712       | 0.741         | FS < FS_allow (UNSAFE) |
|               | RD        |              | 0.643       | 0.740         | FS < FS_allow (UNSAFE) |
| Alternative 2 | MFL       | 1.0          | 0.530       | 0.741         | FS < FS_allow (UNSAFE) |
|               | MWL       |              | 0.633       | 0.742         | FS < FS_allow (UNSAFE) |
|               | RD        |              | 0.592       | 0.741         | FS < FS_allow (UNSAFE) |
| Alternative 3 | MFL       | 1.0          | 0.598       | 0.741         | FS < FS_allow (UNSAFE) |
|               | MWL       |              | 0.618       | 0.742         | FS < FS_allow (UNSAFE) |
|               | RD        |              | 0.596       | 0.741         | FS < FS_allow (UNSAFE) |



**Fig 11:** Slope Stability of Alternative Design 1 under MFL Conditions with MDE Seismic Loading (Upstream)



**Fig 12:** Slope Stability of Alternative Design 1 under MFL Conditions with MDE Seismic Loading (Downstream)

Based on the slope stability analyses conducted under both non-seismic and seismic loading conditions, Alternative Design 1 exhibits the highest Factor of Safety (FS) among the three alternative designs.

#### 4. Conclusion

The seepage analysis results for Alternative Design 1 (existing design, vertical core), Alternative Design 2 (inclined core), and Alternative Design 3 (diaphragm-type design) indicate that all three configurations satisfy the allowable seepage criterion under maximum flood level, minimum water level, and rapid drawdown conditions. The calculated seepage discharges are less than 1% of the average river discharge, corresponding to the allowable limit of 0.0617 m<sup>3</sup>/s.

The slope stability analysis results show that all three alternative designs satisfy the required Factor of Safety (FS) criteria under non-seismic and OBE seismic loading conditions. Under non-seismic loading, the calculated FS values exceed 1.3, while under OBE seismic loading, the FS values exceed 1.2 for maximum flood level, minimum water level, and rapid drawdown conditions. However, under MDE seismic loading, none of the three alternative designs satisfies the required minimum FS criterion of 1.0. The calculated FS values are below 1.0 under maximum flood level, minimum water level, and rapid drawdown conditions.

Based on the seepage analysis, Alternative Design 3 (diaphragm-type design) is the most effective configuration for controlling seepage because it produces the lowest seepage discharge under all analyzed water-level conditions. In contrast, Alternative Design 1 (existing design, vertical core) provides the highest slope stability among the three alternatives, as indicated by its generally higher Factor of Safety values. Therefore, Alternative Design 3 is the most effective for seepage control, whereas Alternative Design 1 provides the greatest resistance to slope failure.

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