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Integrated Numerical Assessment of Rapid Drawdown Stability of Kulekhani Rockfill Dam, Makawanpur Nepal Using GeoStudio Software

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Abstract

The Kulekhani Rockfill Dam at Makawanpur District in Bagmati Province is the Nepal's one and only large storage hydropower reservoir project that plays a critical role in country's peak energy generation. The long-term safety assessment of such dam is very crucial because seepage conditions, reservoir operation and rapid drawdown may significantly influence its embankment stability and deformation behavior over time and continuous operations. This study presents an integrated numerical investigation of seepage, slope stability and deformation characteristics of the Rockfill Dam using the GeoStudio software where SEEP/W was used to evaluate seepage behavior and transient pore-water pressure response while SLOPE/W to assess its either slopes' stability under steady-state and rapid drawdown conditions and SIGMA/W to investigate the deformation characteristics.

The results from the analyses indicate that the embankment dam remains stable under normal operating conditions with factors of safety (FOS) of 2.006 and 1.627 for the upstream and downstream slopes respectively. Under rapid drawdown conditions, the factor of safety progressively decreased and reached a minimum value of 1.793 which indicates that rapid drawdown represents the governing loading condition for the safety of dam. The sensitivity analyses over different parameters showed that the friction angle of the rockfill shell is the most influential parameter controlling the slope stability of the dam. Introduction of an upstream stabilizing berm showed improvement in the factor of safety from 1.750 to 1.930, an increase of approximately by 10.3%. The model validation has demonstrated satisfactory agreement between numerical predictions and available design values of the Project.

The study confirms that integrated numerical modelling provides an effective framework for evaluating the hydraulic characteristics, stability and deformation performance of rockfill dams. The findings highlight the importance of reservoir operation control and provide practical recommendations for future safety management of Kulekhani Dam and similar type of embankment dams in Nepal or elsewhere.

Keywords: *Rapid drawdown, Rockfill dam, Slope stability, GeoStudio, SEEP/W, SLOPE/W, SIGMA/W.*

1. Introduction

Construction of embankment dams, particularly rockfill dams, play a significant role in hydropower generation, water supply, flood control and irrigation projects worldwide. Due to economic feasibility, flexibility and adaptability of embankment dams to complex geological terrain and seismic conditions, rockfill dams have been widely adopted in mountainous regions. Unlike rigid concrete dams, rockfill dams possess favorable deformation characteristics and can accommodate foundation movements and seismic loading without catastrophic failure. The safety of any embankment dam depends on the interaction between seepage behavior, slope stability and deformation characteristics. Among various loading conditions upon such dam, rapid drawdown is widely recognized as one of the most critical conditions because reservoir water levels decrease more rapidly than the dissipation of pore water pressures within the embankment body and during such rapid drawdown conditions, the stabilizing hydrostatic pressure acting on the upstream face is removed while elevated pore-water pressure remains within the dam body and effective stress decreases and slope stability may be significantly reduced. Previous studies by (Seed & Makdisi, 1978; Fell, MacGregor, Stapledon, Bell, & Foster, 2015; Casagrande, 1965) identified rapid drawdown as a governing design and operational condition for embankment type of dams. (Pandey, Knoblauch, & Zenz, 2023) also evaluated slope stability during reservoir drawdown using both limit equilibrium and finite element approaches and demonstrated that rapid drawdown significantly reduces the factor of safety. In addition to rapid drawdown effects, the long-term performance of rockfill dams is influenced by seepage characteristics, material degradation, settlement behavior and seismic loading. Seepage through embankment dams directly affects pore-water pressure distribution and effective stress conditions, thereby influencing overall stability and deformation characteristics. (Wu, et al., 2024) investigated seepage failure probability in high core rockfill dams and highlighted the importance of transient pore-water pressure dissipation during reservoir water level lowering. (Aniskin, Stupivtsev, Sergeev, & Bokov, 2024) reported that reservoir drawdown strongly influences seepage conditions and overall dam stability. The stress redistribution caused by reservoir operation, self-weight compression, particle rearrangement and cyclic loading may induce significant deformation and crest settlement during the service life of the dam. These coupled hydraulic and mechanical processes necessitate integrated numerical assessment methods capable of simultaneously evaluating seepage, stability and deformation behavior. (Liu, Zhou, Zhang, Jiang, & Mi, 2024) conducted coupled seepage-deformation analyses and emphasized the importance of integrated numerical modelling for evaluating the response of rockfill dams under fluctuating reservoir levels. These studies have demonstrated the effectiveness of numerical approaches in design of dams along with dam safety assessment. Although considerable research has been undertaken internationally, comprehensive investigations of rockfill dams in Nepal remain limited. Existing studies have generally focused on individual aspects of dam behavior such as seepage analysis, stability assessment or deformation analysis rather than adopting an integrated approach that considers the interaction among hydraulic, geotechnical, and operational factors. Nepal possesses numerous hydropower projects located within highly seismic and geologically complex mountainous regions. Among these, the Kulekhani Hydropower Project occupies a unique position as the country's first and only large storage-type hydropower reservoir project and as the Kulekhani Rockfill Dam is Nepal's only large storage reservoir representing a strategically important hydraulic structure, a comprehensive assessment of seepage, stability, and deformation behavior remains necessary to ensure long-term operational safety despite the satisfactory historical performance of the Project. Therefore, the present study tries to address this research gap by employing the GeoStudio software package including SEEP/W, SLOPE/W and SIGMA/W modules to investigate the seepage behavior, slope stability and deformation characteristics of Kulekhani Rockfill Dam under steady-state and rapid drawdown conditions.

Thus, the objective of this study is to evaluate seepage characteristics, slope stability, deformation behavior, parameter sensitivity, and strengthening measures for Kulekhani Rockfill Dam using integrated numerical modelling approach. The findings of this study are expected to contribute to the long-term safety assessment and management of Kulekhani Rockfill Dam and provide a practical framework for the evaluation of similar rockfill dams operating under complex hydraulic and seismic conditions in Nepal and elsewhere.

Figure 1: Location map of Kulekhani Dam

2. Study Area

The Kulekhani Rockfill Dam is located in Indrasarowar Rural Municipality of Makawanpur District, Bagmati Province, Nepal at approximate latitude of 27°35′25″N and longitude of 85°09′21″E situated along the Kulekhani River approximately 10 KM downstream of Palung along the Highway connecting Kathmandu and Hetauda. The project area lies within the Lesser Himalayan geological zone and is characterized by rugged mountainous topography with complex geological formations and high seismic activity which make dam safety assessment particularly crucial. The Kulekhani Hydropower Project is the first and only large storage type hydropower project in Nepal which consists of the Kulekhani-I, Kulekhani-II, and Kulekhani-III hydropower schemes with a combined installed capacity of approximately 114 MW. Unlike run-of-river (ROR) hydropower projects, the Kulekhani hydropower project's system operates using seasonal reservoir storage and plays a vital role in meeting peak electricity demand in Nepal. Consequently, the reservoir experiences significant seasonal and operational fluctuations making the evaluation of rapid drawdown effects essential for ensuring long-term safety of dam.

The Kulekhani Dam is a zoned rockfill embankment dam with a maximum height of 114 m above foundation level and a crest length of 397 m; its typical cross section is shown in Figure 2. The dam consists of a central impervious core supported by upstream and downstream rockfill shells, filter zones, transition layers and foundation treatment measures. The impervious central core acts as the principal seepage barrier while the rockfill shells provide structural stability and facilitate drainage. Its internal filter and transition zones are designed to prevent migration of fine particles and maintain the integrity of the embankment under various loading conditions. The principal geometric characteristics of the Kulekhani Rockfill Dam are summarized in the Table 1.

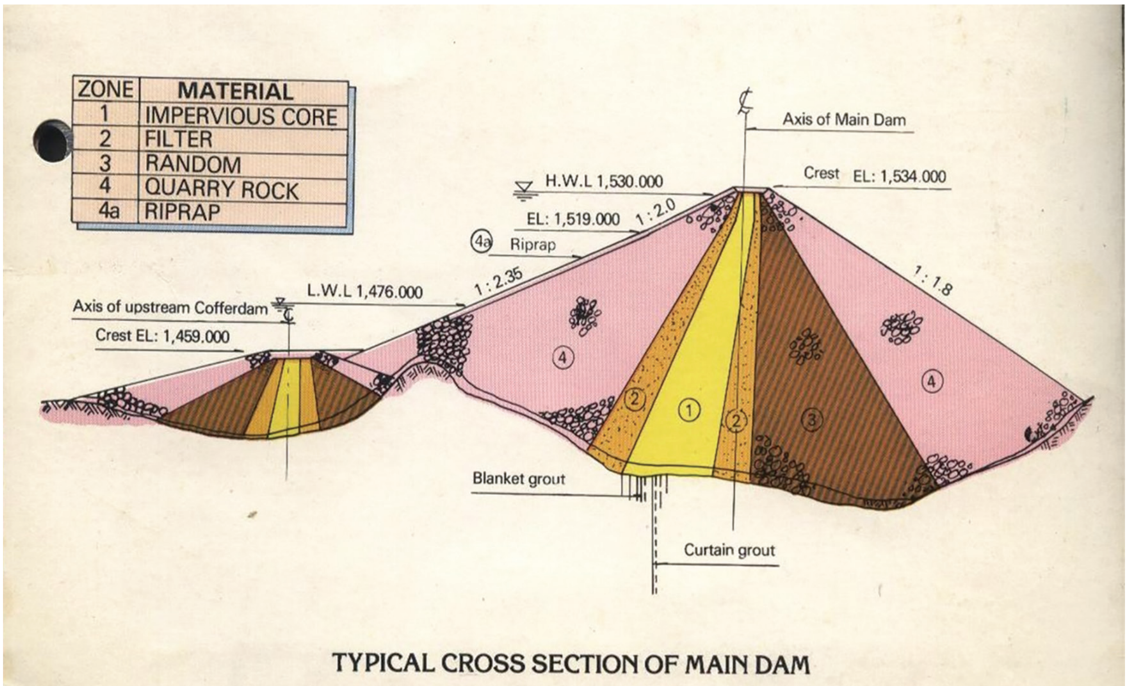

Figure 2: Cross section of Kulekhani Rockfill Dam (Source: (Kulekhani Hydroelectric Development Board, 1983))

Table 1: Engineering Characteristics of Kulekhani Dam

DamType :	**Zoned rockfill dam**
Reservoir:	Kulekhani Reservoir
Crest Elevation:	EL. 1,534 m
Maximum Water Level in the spillway:	EL. 1,530 m
Dam Height:	114 m
Crest Length:	397 m
Upstream Slope:	1:2.0 above EL. 1,519 m 1:2.35 below EL. 1,519 m
Downstream Slope:	1:1.8
Embankment Volume:	4,416,000 m^3

3. Methodology

3.1 Research Methodology

The study has adopted an integrated numerical modelling approach using GeoStudio Software where SEEP/W was used to evaluate steady-state and transient seepage conditions and SLOPE/W to calculate factors of safety using the Morgenstern-Price method while SIGMA/W was used to evaluate deformation and crest settlement characteristics. Hydraulic conductivity, shear strength, and elastic parameters were adopted from project reports (Kulekhani Hydroelectric Development Board, 1983) and published literature. The ratio of vertical to horizontal hydraulic conductivity (ky/kx) was assumed as 1.0 for all materials due to lack of anisotropy data.

3.2 Numerical Model Development

A two-dimensional representative cross-section of Kulekhani Rockfill Dam was developed based on available design drawings and construction reports of the Hydropower Project. The embankment was divided into several material zones consisting of the impervious core, transition zones, upstream and downstream rockfill shells, drainage zones and foundation materials. The geometry was digitized and imported into GeoStudio for subsequent analyses.

The finite element mesh was generated using triangular elements of varying density to adequately capture the geometry and hydraulic gradients within the critical zones. Then mesh refinement was applied near the core-shell interfaces, drainage zones and expected critical slip surfaces

3.3 Seepage Analysis using SEEP/W

Seepage analyses were performed in the software using the SEEP/W module of Geostudio to evaluate pore-water pressure distribution, seepage behavior and phreatic surface variation of the dam body. In this analysis, both steady state conditions to establish long term seepage conditions and transient conditions to simulate rapid drawdown cases were considered. The seepage behavior in the SEEP/W analyses was governed by using Darcy's law and finite element formulation for saturated and unsaturated flow analysis.

The software enables users to analyze complicated seepage problems by using Darcy's law:

$$q=k.i \qquad 1$$

Where q is the volumetric flow rate of water, k is hydraulic conductivity and i is the hydraulic gradient. For the analysis of two-dimensional seepage problems, Equation 1 is modified and the differential equation is as below:

$$\partial/\partial x(kx\,\partial H/\partial x) + \partial/\partial y(ky\,\partial H/\partial y) + Q = \partial\theta/\partial t \qquad 2$$

In Equation 2, H is total head, kx and ky are hydraulic conductivities in horizontal and vertical directions respectively, t is time, θ is the volumetric water content and Q is flux value at applied boundary. In this equation, the difference between the flux incoming and outgoing at a point, is equal to the difference in volumetric water content. SEEP/W conducts analyses as if there is no loading or unloading on the soil body and it assumes constant stress. The finite element method is one of the robust techniques used for this purpose. This method splits the shape of the problem into small cells, and it establishes the location of failure surface without making assumptions. Besides it can show deformations under the stresses.

By using SEEP/W program seepage rates, flow velocity, pore pressures in the embankment, total head and the saturated-unsaturated hydraulic conductivity of soil can be obtained. In order to conduct seepage analysis, saturated water content, hydraulic conductivity and residual water content for each material type are needed. From this way, volumetric water content and hydraulic conductivity functions for different soil types can be obtained. Hydraulic boundary conditions corresponding to reservoir water levels were applied along upstream face of the dam and atmospheric boundary conditions were assigned at the downstream toe to permit the discharge of the seepage. The SEEP/W results obtained from the analyses were subsequently coupled with SLOPE/W and SIGMA/W analyses results.

3.4 Stability Analysis using SLOPE/W

Then slope stability analyses of either slope were carried out using the limit equilibrium method implemented in SLOPE/W module of GeoStudio under steady state seepage and rapid drawdown conditions. To obtain the factor of safety for the upstream and downstream slopes with limit equilibrium method, SLOPE/W program was used. Basically, there are two types of factor of safety; moment equilibrium factor of safety and force equilibrium factor of safety.

Moment equilibrium factor of safety is the ratio of the summation of resisting moments throughout the critical slip surface to the summation of the mobilized moments throughout the critical slip surface. It is given as:

$$Fm = \frac{\Sigma\,(c'\beta R + (N-u\beta)\,R\tan\phi')}{\Sigma Wx - \Sigma Nf + \Sigma kWe \pm \Sigma Dd \pm \Sigma Aa} \quad \text{..............3}$$

Force equilibrium factor of safety is the ratio of the summation of resisting forces throughout the critical slip surface to the summation of the mobilized forces throughout the critical slip surface. It is shown as:

$$Ff = \frac{\Sigma\,(c'\beta\cos\alpha + (N-u\beta)\tan\phi'\cos\alpha)}{\Sigma N\sin\alpha + \Sigma kW - \Sigma D\cos\omega \pm \Sigma A} \quad \text{..............4}$$

In above equations, c' is cohesion, ϕ' is internal friction angle, u is pore water pressure, W is weight of slice, N is normal force on the slice, D is point load, kW is seismic load on slice, R is moment arm, X is the horizontal distance from slice, e is vertical distance from slice, d is perpendicular distance from point load, α is perpendicular distance from resultant, ω is angle of the point load from the horizontal and A is resultant external water forces.

The steady-state stability analyses were conducted under full reservoir and normal operating conditions where both the upstream and downstream slopes were investigated to identify potential critical slip surfaces and determine overall safety margins. The analyses were performed using the Morgenstern-Price method of slope stability analysis since it satisfies both force and moment equilibrium conditions and provides reliable results for embankment dam stability analyses. The rapid drawdown analyses were performed by simulating reservoir level reductions over various drawdown periods ranging from several hours to several weeks. The reduction of hydrostatic support combined with retained pore-water pressures was considered explicitly through transient seepage analyses. The factor of safety was evaluated at each drawdown stage to determine the most critical operating condition. The pseudo-static seismic analyses were conducted to assess the effects of earthquake loading. Horizontal seismic coefficients representing historical seismic conditions in Nepal were applied to the numerical model to evaluate dam stability under earthquake loading.

3.5 Stress Deformation Analysis using SIGMA/W

The finite element stress deformation analyses were carried out using SIGMA/W module of the software to evaluate deformation behavior and crest settlement characteristics of the dam. Its detailed formulation enables us to figure out too complex problems in stress- deformation issues. This SIGMA/W utilizes the following the finite element equation.

$\int[B]T[C][B]dv\{a\}=vb\int<N>Tdv+pv\int<N>TdA+\{Fn\}$……...5

In above Equation 5, it is matrix of strain-displacement, C is constitutive matrix, $\{a\}$ is column vector of horizontal and vertical deformations, $<N>$ is row vector of interpolating functions, A is area throughout the boundary, v is element volume, b is intensity of body force, p is incremental surface pressure and $\{Fn\}$ is incremental force. SIGMA/W calculates stress and strain values for each step by solving above equation.

The pore water pressure obtained from SEEP/W were coupled with SIGMA/W to obtain deformation analysis. The finite element analysis was then interpreted based on the total deformation, displacement contours, stress distribution and crest settlement response under different loading scenarios. To check the seismic deformation analysis, the acceleration time- history record of the 2015 Gorkha earthquake was applied in SIGMA/W. A 40 second strong motion segment of the earthquake accelerograph was selected to simulate earthquake induced dynamic loading conditions and evaluate the crest settlement and deformation behavior.

3.6 Materials Properties

The geotechnical parameters adopted in the analysis were obtained from original design reports of the Kulekhani Hydropower Project, previous investigations on the dam and published literature. The representative values were selected for each material zone based on available information and engineering judgment as presented in Table 2 to Table 5.

Table 2: Hydraulic conductivity value used in SEEP/W

Material	Hydraulic Conductivity (m/s)	Reference
Impervious core	1×10^{-8} - 1×10^{-9}	(Fell, MacGregor, Stapledon, Bell, & Foster, 2015)
Filter	1×10^{-4} - 1×10^{-5}	(Cedergren, 1997)
Quarry rock (Rockfill)	1×10^{-3} - 1×10^{-2}	(Sherard, Dunnigan, & Talbot, 1984)
Foundation (Bedrock)	1×10^{-7} - 1×10^{-8}	(Hoek & Bray, 1981)

Table 3: Volumetric Water Function Values

Material	θ_s	θ_r	Reference
Impervious core	0.45	0.1	(Fredlund & Xing, 1994)
Filter	0.35	0.05	(Seequent, 2024)
Quarry rock (Rockfill)	0.25	0.02	(Fell, MacGregor, Stapledon, Bell, & Foster, 2015)
Foundation bedrock	0.03	0.005	(Van Genuchten, 1980)

Table 4: Shear Strength parameters (Source: (Kulekhani Hydroelectric Development Board, 1983)

Material	Unit Weight γ (kN/m³)	Cohesion c (kPa)	Friction Angle φ (°)
Impervious Core	20	15	30
Filter Material	19	0	33
Random (Excavated Material)	18	0	35
Quarry Rock (Rockfill)	20	0	41
Foundation Soil/Rock	22	300	40

Table 5: Elastic properties of rockfill dam

Material	Elastic Modulus E (MPa)	Poisson's ratio(ν)	Reference
Impervious core	20–40	0.35	(Duncan & Chang, 1970)
Quarry rock (Rockfill)	100–300	0.3	(Sherard, Dunnigan, & Talbot, 1984)
Filter Zone	80–150	0.3	(Fell, MacGregor, Stapledon, Bell, & Foster, 2015)

3.7 Sensitivity Analysis

Sensitivity analyses were performed to evaluate the influence of uncertainties in material properties and operational conditions on overall safety of the dam. The parameters varied were Drawdown duration, Core friction angle, Shell friction angle, Cohesion values, Unit weight and Reservoir operating conditions. The sensitivity study provided insight into the parameters governing the stability performance of Kulekhani Dam.

3.8 Model Validation and Verification

The reliability of the numerical model was assessed through comparison with published design data, historical performance records, empirical relationships and previously published studies. The validation process ensured that the numerical predictions were consistent with accepted engineering practice and observed dam behaviour.

4. Results And Discussion

4.1 Seepage Behaviour

The seepage analysis demonstrated that the central impervious core effectively controls seepage through the embankment and the majority of hydraulic head loss occurs across the core region while the filter and shell zones provide safe drainage of the seepage. The phreatic surface remained within the embankment and did not intersect the downstream face, indicating satisfactory seepage performance.

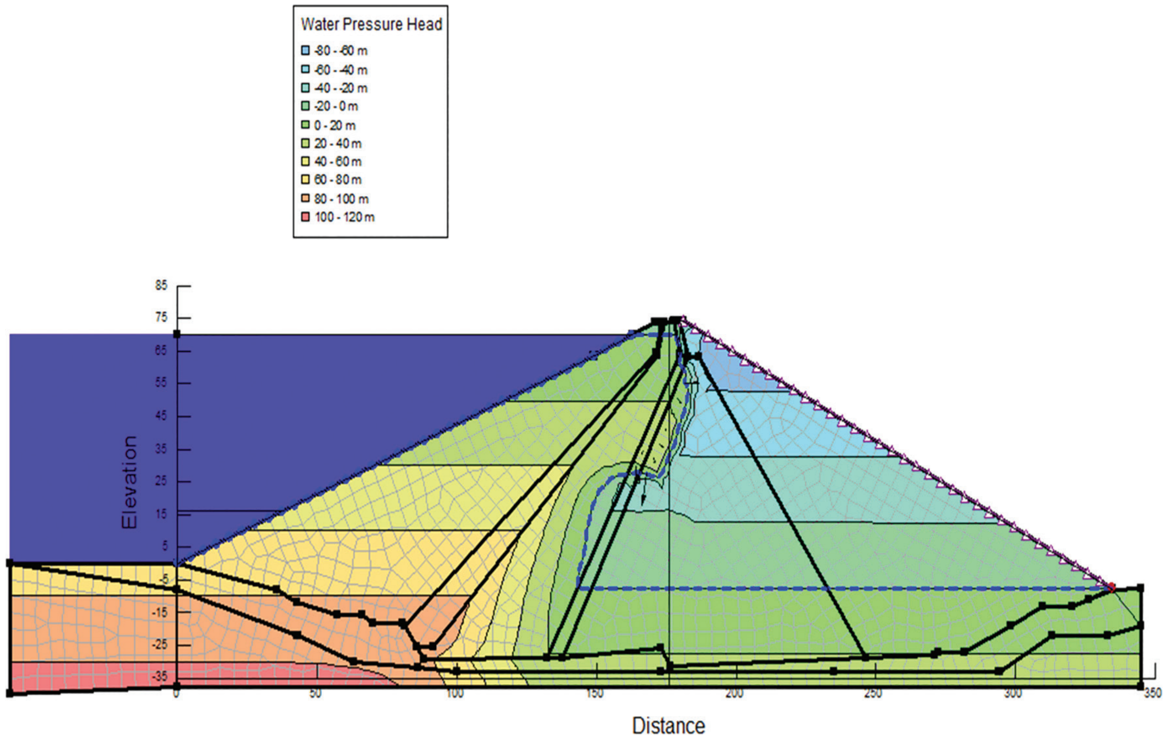

Figure 3: Seepage contours and flow net

4.2 Stability under Steady-State Conditions

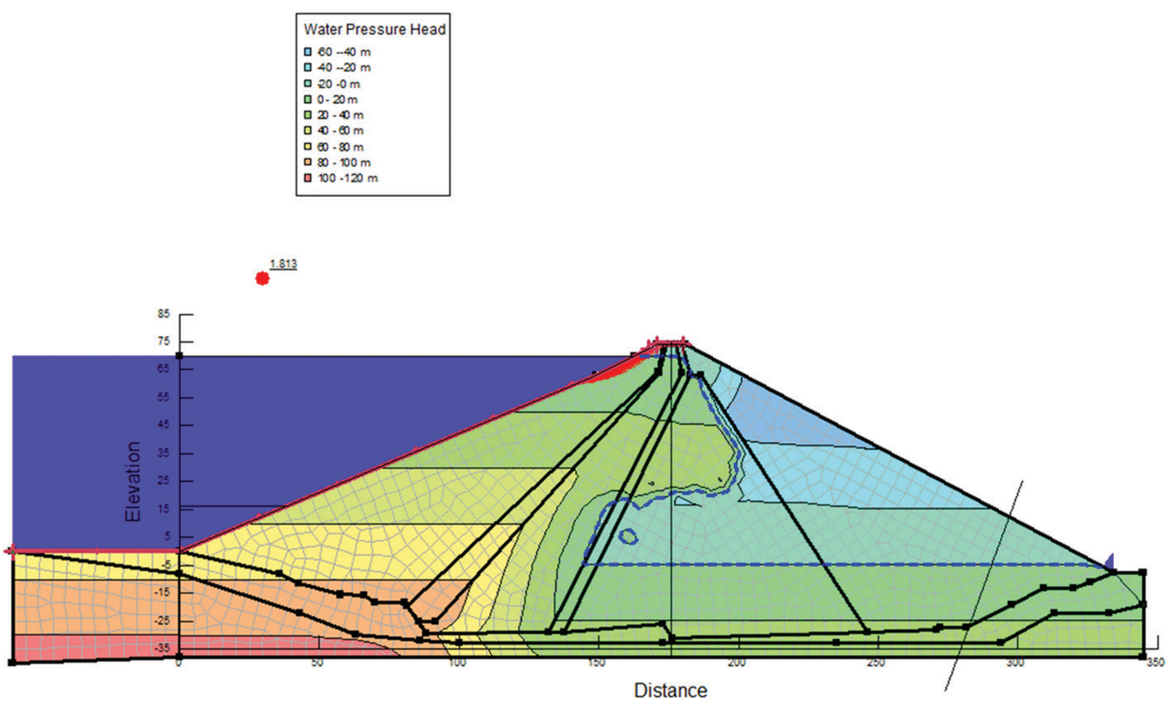

Figure 4: Upstream slope FOS and critical slip surface

Table 6: Factors of Safety under Steady-State Conditions

Condition	FOS
Upstream	2.006
Downstream	1.627

The factor of safety values obtained under steady-state conditions exceeded the minimum requirements specified by international dam safety guidelines. The upstream slope exhibited factor of safety values greater than 1.5, while the downstream slope showed even higher safety margins. These results indicate satisfactory performance of the embankment under normal operating conditions. The comparison among Morgenstern-Price, Bishop, Janbu and Ordinary methods demonstrated relatively small differences in predicted factors of safety, confirming the robustness of the analyses.

4.3 Stability under Rapid Drawdown Conditions

The rapid drawdown was identified as the most critical loading condition affecting the upstream slope. The reservoir water head is about 70 m which is analyzed under rapid drawdown scenario that 70 m water drops zero in 65 days. The slope stability under different time is analyzed and Factor of Safety is calculated as below:

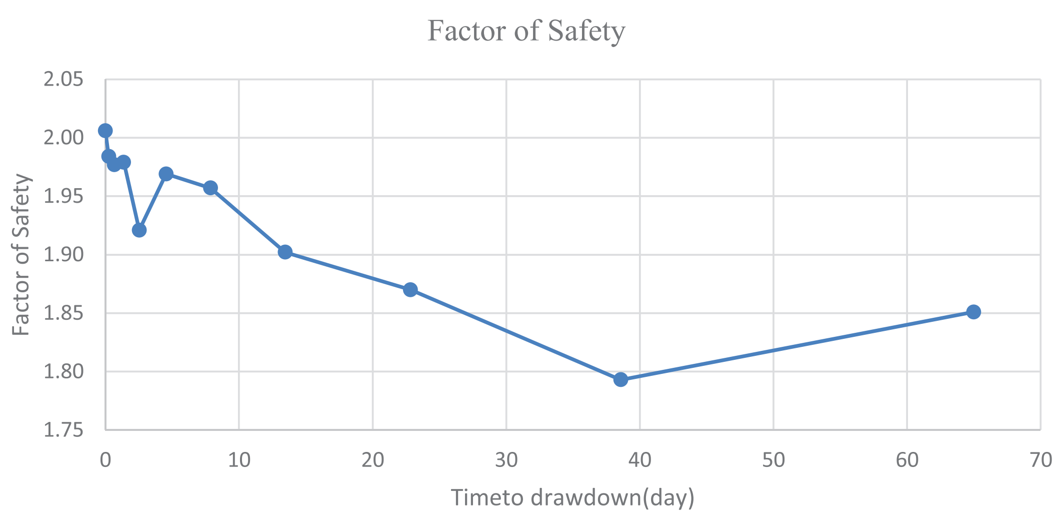

Figure 5: FOS versus Drawdown Duration

The results here demonstrate progressive reduction in stability during reservoir drawdown conditions. The factor of safety decreased from 2.006 under full reservoir conditions to a minimum value of 1.793 during drawdown before slightly increasing toward the end of the drawdown period. The minimum factor of safety did not occur at complete drawdown but occurred at an intermediate stage of reservoir lowering which indicates that the most critical condition develops when hydraulic unloading occurs faster than the dissipation of pore water pressure. The results confirm the rapid drawdown to be the most governing of the stability performance of the dam. The observed reduction in factor of safety during rapid drawdown is consistent with the findings of (Pandey, Knoblauch, & Zenz, 2023), who reported that rapid drawdown represents one of the most critical loading conditions for embankment dams due to the lag in pore-water pressure dissipation. The occurrence of the minimum factor of safety during intermediate stages of reservoir lowering rather than at complete drawdown also agrees with the results reported by (Aniskin, Stupivtsev, Sergeev, & Bokov, 2024).

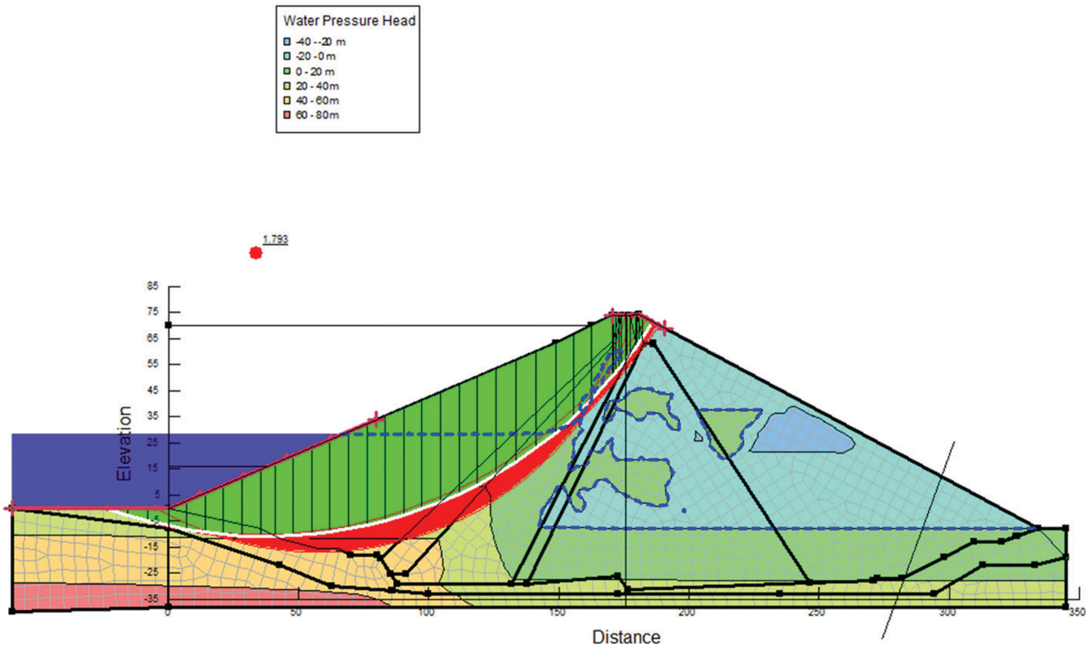

Figure 6: Critical slip surface at minimum FOS

4.4 Deformation and Settlement Behaviour

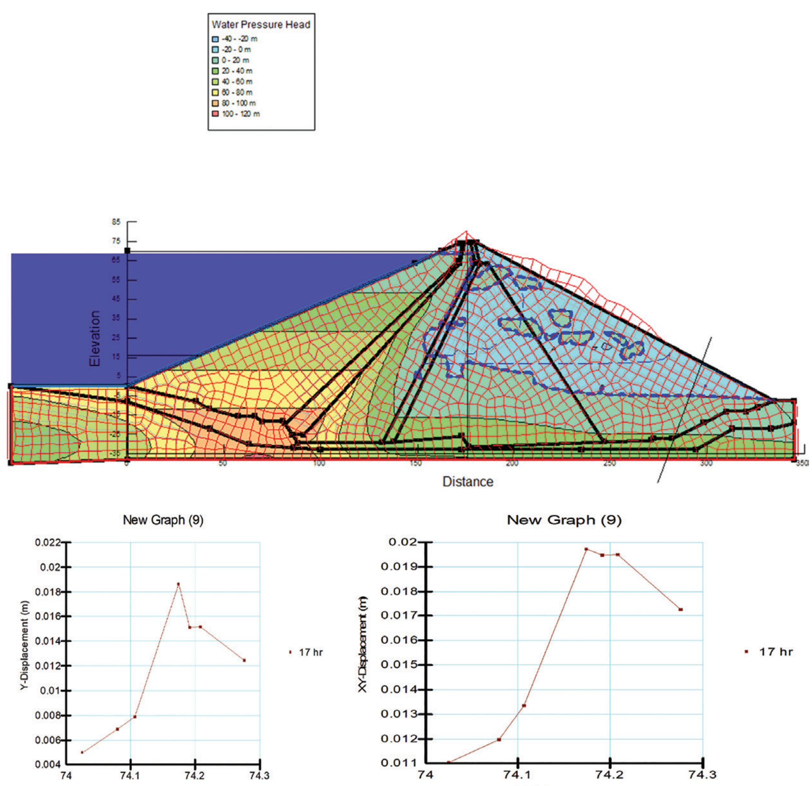

Figure 7: Plot of displacement contour and crest settlement value at FSL

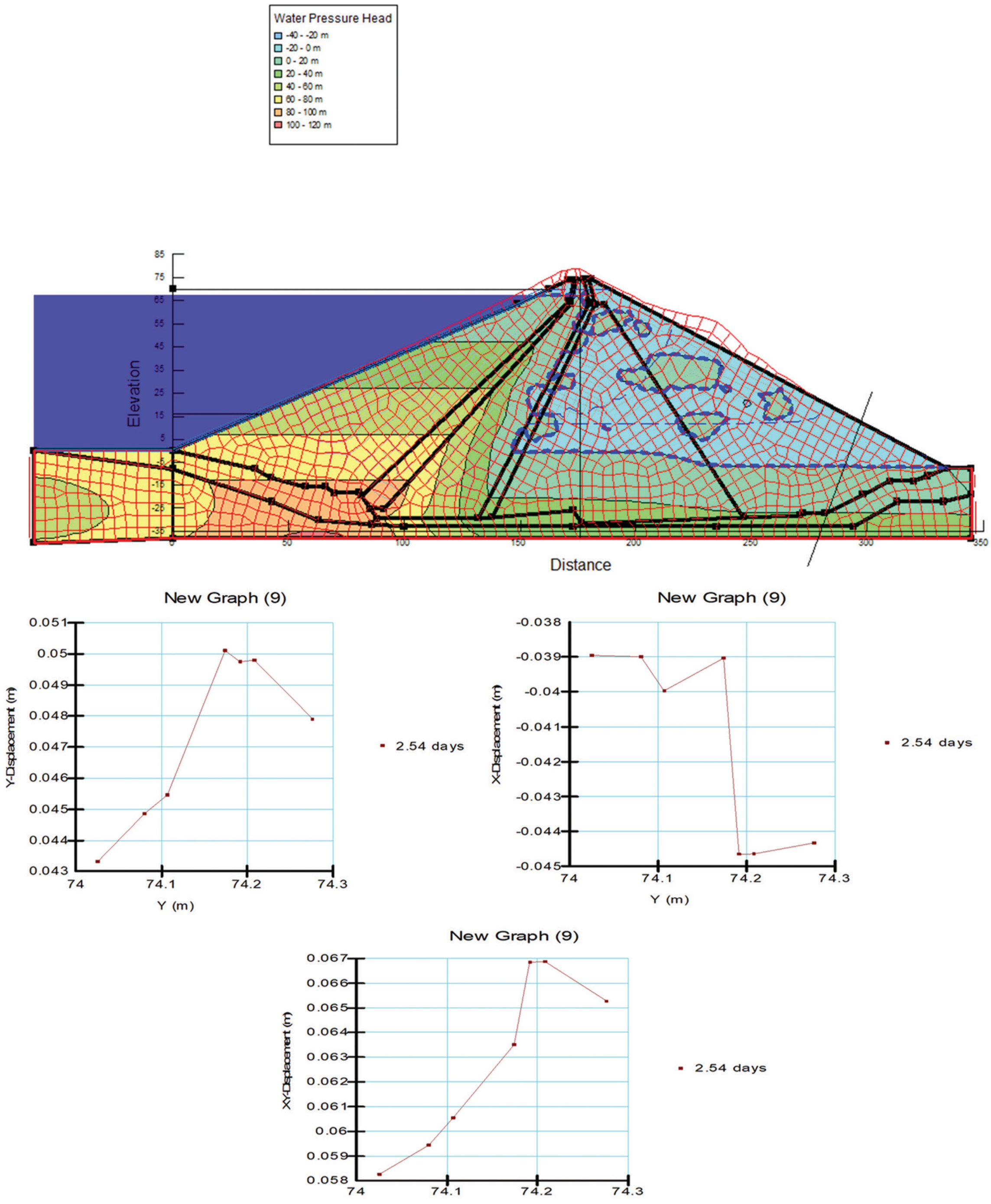

Figure 8: Plot of displacement contour and crest settlement value at intermediate drawdown

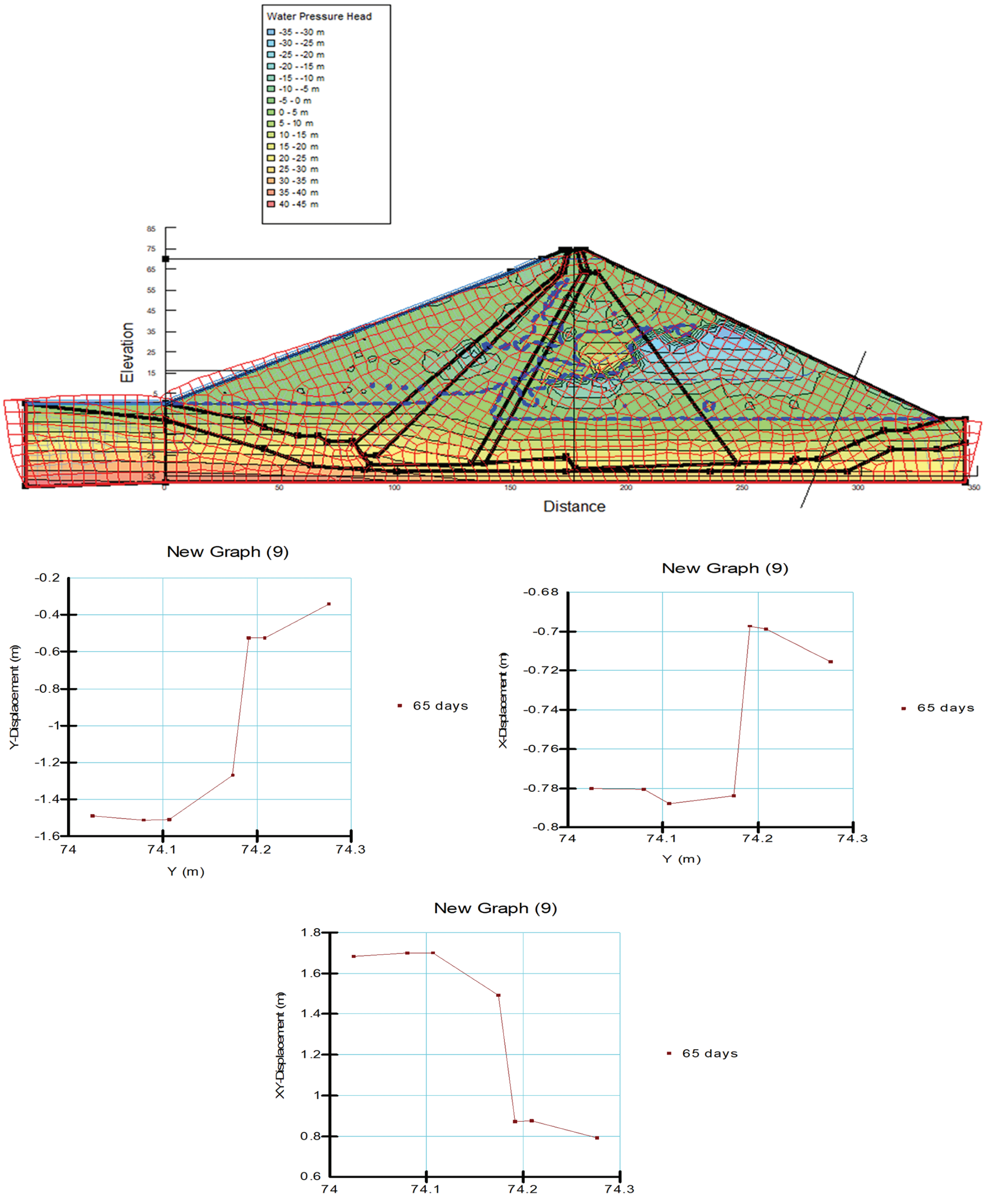

Figure 9: Plot of displacement contour and crest settlement value at full drawdown

The deformation analysis here showed progressive increase in crest settlement as drawdown advanced. The Settlement remained to be concentrated near the crest region and gradually decreased towards the foundation. The observed deformation pattern is consistent with established rockfill dam behavior resulting from stress redistribution, self-weight compression, and hydraulic unloading. The progressive increase in crest settlement observed during reservoir drawdown is consistent with the coupled seepage-deformation analyses reported by (Liu, Zhou, Zhang, Jiang, & Mi, 2024), who emphasized that fluctuations in reservoir water levels induce redistribution of stress and deformation within embankment dams.

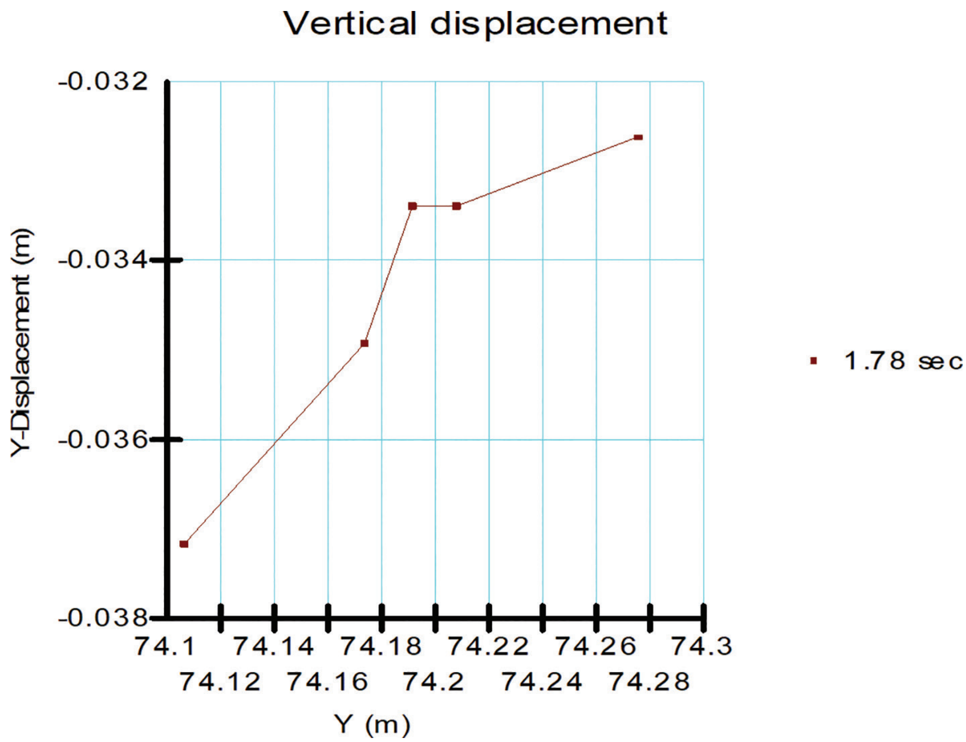

Figure 10: Plot of crest settlement using 2072 Earthquake

The dynamic analysis under the 2015 Gorkha earthquake loading condition showed a significant increase in crest settlement due to seismic excitation. The maximum vertical displacement obtained from the SIGMA/W analysis was approximately 0.38 m at 1.78 seconds representing the critical deformation response during the strong-motion phase of the earthquake. The observed settlement indicates the sensitivity of the dam's crest to cyclic seismic loading and stress redistribution within the embankment materials. Although complete time-history results could not be obtained due to numerical convergence limitations during analysis, the peak displacement value provides a representative indication of the maximum seismic deformation behavior of the dam under the applied earthquake loading condition.

4.5 Sensitivity Analysis

Table 7: Sensitivity of FOS to rapid drawdown

Drawdown rate (m/day)	Minimum Factor of Safety
1.07 m/day	1.793
2.00 m/day	1.781
2.50 m/day	1.775
3.00 m/day	1.750

Table 8: Sensitivity of FOS to Rockfill shell Friction Angle

Case	Shell friction angle ϕ (degree)	FOS
Initial	41	1.793
Reduced 1	39	1.739
Reduced 2	37	1.649

Table 9: Sensitivity of FOS to Core Friction Angle

Case	Core ϕ (degree)	FOS
Initial	30	1.793
Reduced 1	27	1.72
Reduced 2	24	1.65

Table 10: Sensitivity of FOS to Cohesion

Case	Cohesion (KPa)	FOS
Base	15	1.793
Reduced-1	12	1.787
Reduced-2	10	1.784

The sensitivity analysis revealed that the angle of internal friction is the most influential parameter affecting the stability performance of the dam. The variations in cohesion and unit weight produced comparatively minor changes in factors of safety. These findings indicate that accurate characterization of rockfill shear strength is essential for reliable stability assessment. Similar findings were reported by (Pandey, Knoblauch, & Zenz, 2023), who observed that variations in shear strength parameters, particularly the friction angle, exert a significant influence on slope stability under rapid drawdown conditions.

4.6 Dam Safety and Operational Implications

The integrated seepage, slope stability and deformation analyses performed in this study had provided important insights into the long term safety management and operational performance of the Kulekhani Rockfill Dam, Although the analyses indicate that the dam currently maintains a satisfactory performance under normal operating conditions, the results highlight the several importance to consider for the reservoir operation, monitoring, maintenance and the future rehabilitation planning. The findings of this study identifying rapid reservoir drawdown as the most critical loading condition affecting the stability of the upstream slope of the dam, suggests that reservoir drawdown operations should be carefully controlled to minimize adverse hydraulic effects. Whenever operationally feasible, the gradual drawdown procedures should be adopted to allow sufficient time for pore-water pressure dissipation within the embankment. The establishment of reservoir operation guidelines incorporating maximum permissible drawdown rates may therefore contribute significantly to improving the long-term safety of Kulekhani Dam.

Since Nepal is located within one of the world's most active seismic regions due to the ongoing convergence between the Indian and Eurasian tectonic plates, seismic safety represents a critical consideration for all major hydraulic structures, including Kulekhani Rockfill Dam. The pseudo-static analyses performed in this study demonstrated that the dam exhibits satisfactory seismic performance due to the favorable deformation characteristics of rockfill materials. However, the rockfill dams possess significant energy dissipation capacity and can accommodate substantial deformation without experiencing catastrophic failure unlike other rigid structures, but seismic hazards remain an important consideration for future safety evaluations. The changes in seismic hazard assessments, updates to national seismic design standards, and the occurrence of major regional earthquakes may necessitate periodic reassessment of the dam's seismic performance and future investigations incorporating fully coupled dynamic analyses and nonlinear constitutive models may provide a more comprehensive understanding of the seismic behavior of Kulekhani Dam.

4.7 Strengthening Measure

Potential strengthening measures were evaluated by introducing stabilization berms on the upstream slope. The introduction of an upstream stabilizing berm significantly improved stability of the Dam. The factor of safety increased approximately by 10.3% that the berm construction represents a practical strengthening measure for future dam safety enhancement. The improvement in stability achieved by the introduction of an upstream berm is consistent with recent studies on slope stabilization measures which have demonstrated that geometric modifications and additional support at the upstream face can effectively mitigate the adverse effects of rapid drawdown (Karunakaran & Wazeel, 2024).

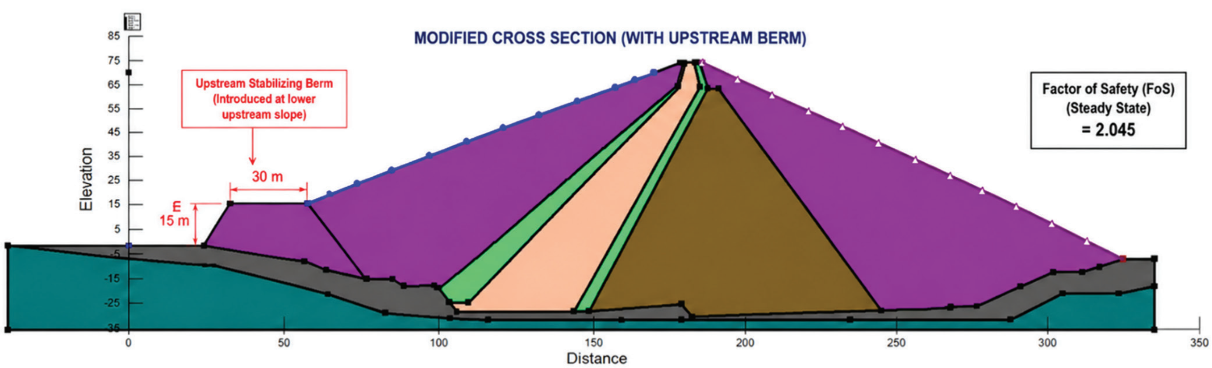

Figure 11: Upstream Berm Configuration

Table 11: Effect of Berm on Stability

Condition	Existing	Berm
Steady State	2.006	2.045
Rapid Drawdown	1.750	1.930

4.8 Model Validation

The numerical predictions were compared with historical operational records, published empirical relationships, and previous studies of rockfill dam behavior. The agreement between predicted and expected responses confirmed the reliability of the adopted numerical modelling framework. The minor discrepancies were attributed to uncertainties in material characterization, operational assumptions and simplifications inherent in the constitutive models employed for the analysis.

5. Conclusions

An integrated numerical assessment of the Kulekhani Rockfill Dam was carried out using the SEEP/W, SLOPE/W and SIGMA/W modules of GeoStudio Software Package to evaluate seepage, stability, and deformation behaviour under steady-state and rapid drawdown conditions. The results indicate that the dam performs satisfactorily under normal operating conditions while rapid drawdown represents the most critical loading condition due to delayed pore-water pressure dissipation. Sensitivity analysis identified the friction angle of the rockfill shell as the most influential parameter affecting stability. Furthermore, the introduction of an upstream stabilizing berm significantly improved stability under rapid drawdown conditions.

- The stability analysis indicated that Kulekhani Rockfill Dam remains stable under all investigated loading conditions with FOS satisfying the accepted design criteria. Among the analyzed cases, rapid drawdown was identified as the most critical condition resulting in the minimum FOS of 1.793 due to the rapid loss of upstream support and delayed pore pressure dissipation.
- The seepage analysis demonstrated that the central impervious core and drainage system effectively controls seepage and maintain the phreatic surface within acceptable limits under steady state conditions.
- The deformation analysis showed that settlements are concentrated near the dam crest and decrease toward the foundation consistent with the expected behaviour of rockfill embankments.
- The sensitivity analysis revealed that the angle of internal friction is the most influential parameter affecting slope stability which highlighted the importance of accurate shear strength characterization.
- The introduction of an upstream stabilizing berm improved the FOS under rapid drawdown conditions from 1.750 to 1.930, representing an improvement of approximately 10.3% that demonstrates its effectiveness as a stabilization measure.

Overall, the study demonstrates that integrated numerical modelling provides a reliable framework for the safety assessment and long-term management of Kulekhani Dam and similar rockfill dams.

Based on the findings of this study, the following recommendations are proposed:

- Rapid drawdown of the reservoir should be carefully controlled to minimize adverse stability effects and gradual drawdown is recommended to reduce stability risks.
- Regular monitoring of pore water pressure, seepage conditions and crest settlement should be carried out during reservoir operation to verify long term dam performance and identify any emerging safety concerns.
- Future analyses should incorporate updated material properties, seismic loading conditions, and advanced constitutive models to better represent the behaviour of rockfill materials.
- Three-dimensional numerical modeling and further studies on the long-term deformation and creep behaviour of rockfill materials are recommended to enhance the understanding of dam performance.
- Period dam safety assessment integrating numerical modeling and field monitoring data should be carried out to support the long-term dam safety management and reduce uncertainties in performance prediction.

6. Acknowledgement

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7. References

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