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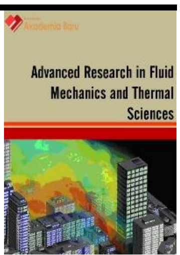

Re-Assessment of an Earth fill Dam using Finite Element Method and Limit Equilibrium Method (Case study of Latamber Dam, Pakistan)

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ABSTRACT

Dams are massive as well as the expensive hydraulic structure which needs proper attention during designing and construction. Besides earthquakes, seepage and slope instability also cause serious damages which may lead to dam failure. Keeping in view the importance of dam construction and stability, there is a need to work out its stability, seepage, and earthquake analysis very accurately. This study assesses the stability of the existing earthfill Latamber dam located in the Karak region of Pakistan. Rigorous finite element analysis (FEM) tools have been utilized to carry out seepage analysis, and dynamic analysis of the Latamber dam while for the slope stability analysis, limit equilibrium method was adopted. The results indicate that the Latamber dam is secure against seepage and piping failure, slope (upstream and downstream) failure, and dynamic loading, observing no liquefaction.

Keywords:
Earth-fill dam; finite element analysis; limit equilibrium method; seepage analysis; slope analysis; dynamic analysis; liquefaction

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1. Introduction

Water is life and it needs to be preserved, keeping in view the current situation of climate change. According to World Water Council (WWC) [1], "*Today the water crises are not about having the deficiency of water, but it cannot be properly managed to result in the suffering of billions of people and environment*". According to UNDP (United Nations Development Program) report about water crises in Pakistan, water impounding is not a priority resulting in an alarming situation regarding water scarcity in the near future. According to the experts, most of the South Asian

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countries are likely to dry up by 2025 [2]. Dams are one of the best available options to preserve water among others.

Multipurpose dams are either embankment dams or concrete gravity dams with the former being more popular and constitute about 85% of the total dams in the world [3]. Embankment dams are further categorized into earth-fill and rock-fill dams. An earth-fill embankment dam is constructed from locally available raw and subsurface materials, but they are prone to seepage failure, slope failure and liquefaction due to earthquake. Moreover, excessive water that seeps into a dam body may result in piping and reduction in the shear strength of the soil, ultimately resulting in dam failure making seepage failure a prominent issue in dam safety. Similarly, slope stability is also a major factor in dam safety mainly due to the rapid drawdown of the reservoir level. Moreover, designing an embankment dam in an earthquake-prone area will require dynamic analysis as well [4]. Since dam failures cause severe loss of life, along with property, economic, environmental, cultural and historic loss. Therefore, it needs to be designed safely and cross-checked to ensure safety. Keeping in view the importance of dam and its safety, there is a need to re-assess the existing dams against all kinds of failure. In this study, the procedure is outlined to carry out a re-assessment of an existing dam located in the Latamber region of district Karak, Pakistan. The dam will be checked for safety against slope failure, seepage failure, and Earthquake failure. Several methods have been established to perform these analyses, limit equilibrium (LE) and finite element (FE) are the prominent methods.

1.1 Limit Equilibrium Method

Slope stability analysis of soil is commonly computed using a limit equilibrium method (LEM) based on the Mohr-Column criterion, both in two and three dimensions [5]. The essence of this method is to balance the soil mass of the sloping surface that tends to slide under the force of gravity. The primary task of this method is to identify the slip surface failure mechanism and calculate the FOS (factor of safety) of the particular slope [6–11]. Numerous limit equilibrium studies have been stated in the literature. First of all, Fellenius (1936) assumes a circular slip surface of a soil mass to compute the factor of safety which is widely known as Ordinary or the Swedish method [12]. This method also presumes zero angle of friction and consider circular geometry of soil under the static condition to analyze the stress condition and compute strength. In 1955, Bishop develops a method that divides a potential soil mass into several vertical slices, satisfying the interslice normal forces but did not count the interslice shear forces [13]. Later in 1967, Janbu presents a simplified method similar to Bishop's method to calculate the factor of safety but consider non-circular slip surface and opposing moment equilibrium [14]. While Spencer assumes constant interslice forces inclination and satisfies both force and equilibrium equations [15]. Similarly, Morgenstern Price satisfied both force and moment equilibrium but define an arbitrary function for the interslice force that continuously changing along the slip surface [16]. All limit equilibrium methods and their basic concept are described in Table 1 and 2. The main difference between these methods lies in the assumptions of interslice forces, slip surface geometry and equilibrium conditions during the factor of safety calculations [17].

Later with the innovation modern-day computers, various software has been developed to solve complex engineering problems such as Plaxis, FLAC, GeoStudio, MIDAS GTS NX, etc. GeoStudio is well-known geotechnical software, which is a complete integrated software comprises of a limit equilibrium slope stability analysis and six finite element products. In this research, the SLOPE/W application of GeoStudio software using the Morgenstern-Price method [18] was employed to determine the slope stability under different conditions.

Table 1
Describing the assumptions defined by various limit equilibrium methods [19]

Limit Equilibrium Methods	Assumptions
Fellenius [12]	Ignored the interslice forces and considered a unified slip mass of soil.
Bishop's Simplified [13]	Ignored shear forces and considered that the resultant interslice forces are horizontal.
Janbu's Simplified [20]	Resultant interslice forces are considered horizontal while an empirical correction factor has been defined for the interslice forces.
Spencer [15]	The slope of the interslice resultant force will be considered constant throughout the soil mass.
Chugh [21]	Similar to Spencer's method but the force of acceleration is constant on each slice.
Morgenstern-Price [16]	An arbitrary function has been defined for the direction of resultant interslice forces.
Fredlund-Krahn [22]	Same as Morgenstern-Price's method.
Corps of Engineers [23]	The resultant interslice force direction is either equal to the average slope of the slip surface or considers parallel to the ground surface.
Lowe-Karafiath [24]	The interslice resultant direction is in line with the average of the ground surface and slope of the base of each slice.
Janbu Generalized [20]	Assume line of thrust defines the location of the interslice normal force.
Sarma – vertical slices [25]	The slope of the slice interfaces is changed until the shear strength criterion is fulfilled and the criterion is applied on the shear created at the base and both sides of every slice.

Table 2
Static equations satisfaction by various limit equilibrium methods

Limit Equilibrium Methods	Force Balanced (∑E)	Force Balance (∑X)	Moment Balance (∑M)
Fellenius Method	✓	✗	✓
Bishop's Simplified Method	✓	✗	✓
Janbu's Simplified Method	✓	✓	✗
Janbu Generalized Method	✓	✓	✓ (by interslice shear forces)
Spencer Method	✓	✓	✓
Morgenstern-Price Method	✓	✓	✓
Corps of Engineers Method	✓	✓	✗
Fredlund-Krahn Method	✓	✓	✓
Chugh Method	✓	✓	✓
Lowe-Karafiath Method	✓	✓	✗
Sarma – vertical slices Method	✓	✓	✓

1.2 Finite Element Method (FEM)

The finite element method (FEM) is a very influential computational tool in almost all disciplines of engineering. It gains its prominence in the field of civil engineering from the capability of simulating the behavior of highly complex physical structures utilizing its powerful computational tools. Infect, complicated engineering issues required finite element methods to obtain accurate and acceptable results. Nowadays, the finite element method is used the verify and validate new emerging ideas and proposed models/analyses in engineering.

The finite element method (FEM) was employed to model and simulate steady-state and transient seepage in the Latamber earthfill dam before and during the drawdown, respectively. The same method was considered for the initial static and dynamic analyses to determine the seismic performance of the existing Latamber earth-fill dam. SEEP/W and Quake/W are the two products of GeoStudio software that were utilized to assess both seepage and liquefaction through the Latamber earthfill dam body.

1.3 Literature Survey

Several studies have been conducted to evaluate seepage analysis, investigate slope stability and perform a seismic stability analysis of different earth-fill dams around the globe. Seepage analysis of Walter F. George dam (USA) was assessed employing finite element modeling (FEM) and predict that the dam is unsafe [26]. Seepage flow through sixty earthen dams was carried out by numerical modeling and comparing the output with the analytical solutions and detailing useful results [27]. It has been concluded that when a core is provided in the earth dam, the discharge rate is not affected by changing the upstream and downstream angle. Different techniques are employed to reduce seepage through a dam body and foundation. Seepage analyses were carried out using SEEP/W, in order to calculate seepage through foundations with the combination of a cut off wall and blanket on the upstream side [28]. Also, seepage analysis through the core of an Earth fill dam was investigated [29]. It has been concluded that the critical state of steady-state seepage occurs when the phreatic line touches the downstream slope and piping phenomenon occur.

Stability analysis of the Yashigou dam in China was carried out using finite element stress/strain methods and compared with the Morgenstern-Price method to find the factor of safety of slopes in three different conditions: without a water level (before impounding), a steady-state water level (normal condition), and water level drawdown (critical condition) [30]. The effect certain parameters such as the length and width of clay blanket, with of clay core, depth of dam foundation up to impermeable layer, reservoir head, and permeability of blanket and bed material have been investigated by Alam and Ahmad [31]. It has been evident that 84% of seepage reduced by increasing 30% of the original length while the rest of the parameters affect seepage significantly. Seepage through an earthfill dam has been assessed by using numerical, analytical, and experimental approach and the best design configuration were investigated [32]. Soltani *et al.,* carried out stability and displacement analysis of the Taham dam using FLAC, PLAXIS, and GeoStudio and compare the simulated results with the experimental program [33]. Vertical displacement of 1.2m, 1.7m, and 1.15m while the horizontal displacement of 0.1m, 0.17m and 0.13m were recorded using FLAC, PLAXIS and GeoStudio software respectively. After comparing the data, they concluded that the output of FLAC was similar to the experimental data. The difference in the results of numerical analysis using GeoStudio software and analytical analysis (Swedish circle method) of the Boradi earthen dam has been observed by Kumavat *et al.,* [34]. The resulting factor of safety of the Boradi earthen dam at the different conditions: without water level (empty state), steady-state water level (normal condition) and water level drawdown (critical condition). The most excellent and reliable slope stability method has been evaluated among widely known methods: Fellenius, Bishop, Simplified Bishop, Simplified Janbu, and Spencer method [35]. Using correlation index, accuracy index, and performance index, it has been concluded that the Simplified Bishop method is the best alternative method to be used for the stability analysis by obtaining about a 99% correlation coefficient. A colossal slope failed in the Butik Nanas region located in Kuala Lumpur, Malaysia, causing tremendous loss of property and life. To rehabilitate the slope, experts analyse reinforced concrete wall and soil nail option and crib wall and reinforced with soil nail alternatives in term of factor of safety using SLOPE/W, adopting Morgenstern-Price's method [36]. IT has been evident that the prior one option is much more efficient than the later one. Soil liquefaction in an embankment dam located in a highly seismic zone of Quebec in Canada was carried out by comparing three different total stress methods [37]. The most simplified solution demonstrates better results with two-dimensional analysis using QUAKE/W while one-dimensional analysis underestimates the Charlevoix Seismic Zone CSZ profile [37]. The effect of two-dimensional geometry was validated by fitting the response spectra between the two-dimensional and one-dimensional dynamic analysis with a factor of 2.

1.4 Scope of the Study

This study intended to investigate the stability of an existing earth-fill dam located in the Latamber region of Khyber Pakhtunkhwa Province, Pakistan. GeoStudio software was used to evaluate the slope stability analysis, seepage analysis and dynamic analysis of this particular earthfill dam using SLOP/W, SEEP/W and QUAKE/W respectively.

2. Methodology

2.1 Material Used

The Latamber earth-fill dam is a composite dam comprising of different soil zones: shell, bedrocks, core & blanket, a fine filter, and a coarse filter. The shell material is a compacted gravely soil, used in greater percentage than the core, blanket, fine filter, and coarse filter, composing upstream and downstream slope. Bedrock is an impermeable hard rock in the foundation. The core is the central part of a dam consisting of silty clay, hindering and lowering down seepage through the dam while the blanket is provided on the upstream side of the dam reducing seepage through the foundation. Moreover, the fine filter is sand, provided in the vertical direction adjacent to the core while the coarse filter is gravel, provided as a chimney and horizontal drain. All the materials are borrowed from a nearby locality which is a dominant cost-effective characteristic of an earth-fill dam over other types of the dam.

2.2 Geometry and Location

The Latamber dam is a composite earth-fill dam, divided into several zones. Figure 1 shows the cross-section of the dam, indicating the elevation of the dam crest, maximum conservation level, normal conservation level and bottom of the dam from sea level. The figure also depicts the upstream slope, downstream slope, slope of the core and filters and a height of 32 m. It is located on a non-perennial river named Latamber, in the northwest of Pakistan (Khyber Pakhtunkhwa Province) with coordinates 33° 7'29.07"N, 70°51'51.13"E. The dam has been designed by a consultant firm, Pakistan Engineering Services. All the required data for analysis has been requested from the design cell of Pakistan Engineering Services.

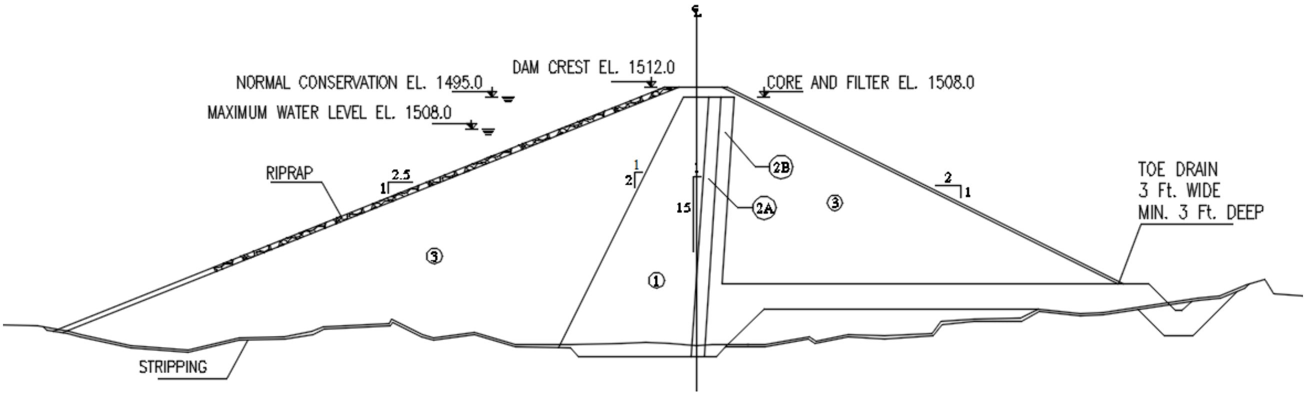


Fig. 1. Cross section of Latamber dam

The overall geometric properties of the Latamber dam are checked according to the British Dam Society (BDS, 1994) [38]. It is observed that the geometric design of the Latamber earth-fill dam is acceptable, as shown in Table 3.

Table 3
Safety status of Latamber dam, Pakistan

Geometric Parameters	Latamber Dam	(BDS) Safety Limits	Dam Status
Dam Crest	7.62m	Not less than 2m	Acceptable
Upstream Slope	2.5:1	2.5:1	Acceptable
Downstream Slope	2:1	2:1	Acceptable
Free Board	1.21m	Min freeboard = 1.50m	Acceptable because of the spillway
Bed Width of Core	16.76m	Not less than (H/3) = 7.3m	Acceptable
Core Slope	1:2	1:12	Acceptable

2.3 Material Properties

Different parameters were investigated to perform all three types of stability analysis. To perform slope stability analysis, three parameters are needed: the soil unit weight (γ), the cohesion of the soil (C), and angle of internal friction (Φ) of all material used in the construction of an embankment. Likewise, for seepage analysis, to develop hydraulic conductivity function and volumetric water content function mainly two parameters are required: the saturated horizontal conductivity (K_x) of all materials and the saturated water content based on silty clay, sand, and gravel. These tests and parameters required for modeling and simulation using GeoStudio software are described in Table 4.

Table 4
Geotechnical tests and required parameters for simulation

Geotechnical Tests	Parameters	Reference
Unit weight Test	Unit weight of soil (γ)	ASTM D7263-09 [39]
Direct Shear Test (Sand)	Cohesion (C) & Angle of Friction (Φ)	ASTM D3080/D3080M-11 [40]
Unconfined Compression Test (Clay and Silt)	Cohesion (C) & Angle of Friction (Φ)	ASTM D2166/D2166M – 13 [41]
Permeability Test (Constant & Falling)	Hydraulic conductivity of Soil (k)	ASTM_D2434-19 [42]

2.3.1 For seepage analysis

In order to perform seepage analysis, two types of functions are required to define the conductivity of water through the dam body: the hydraulic conductivity function as shown in Table 5 and the volumetric water content function as shown in Table 6.

Table 5
Hydraulic conductivity function parameters

Type of Soil	Saturated K_x (m/sec)
Shell	0.001333
Core & Blanket	1.251e-08
Drain-Coarse Filter	0.001232
Fine Filter	0.00027
Bed Rocks	3.048e-11

Table 6
Volumetric water content function parameters

Vol. Water Content	Value (m^3/m^3)
Based on Silty Clay	0.47
Based on Sand	0.30
Based on Gravel	0.001

2.3.2 For slope analysis

Unit weight, cohesion, and angle of friction of soil are the required parameters to conduct slope stability analysis using GeoStudio software. All three parameters are enlisted in Table 7.

Table 7
Parameters for slope stability

Type of Soil	Unit weight(γ) (KN/m^3)	Cohesion (C) (KN/m^2)	The angle of internal friction (Φ)(Degree)
Shell	21	0	38
Core & Blanket	17.12	25	23
Drain-Coarse Filter	19	0	30
Fine Filter	19	0	30
Overburden	19.47	0	40
Bed Rocks	-	-	-

2.3.3 For dynamic analysis

Poisson's ratio, damping ratio, and shear modulus are the crucial parameters to be considered while performing seismic analysis. All the materials are considered linear elastic and the required input parameters are enlisted in Table 8.

Table 8
Quake analysis input parameters

Type of soil	Poisson ratio	Damping ratio	Shear Modulus (KN/m^2)
Shell	0.32	0.1	154399.99
Fine filter	0.30	0.1	73399.95
Coarse filter	0.30	0.1	594699.96
Core & Blanket	0.30	0.1	73399.95
Bed Rocks	0.30	0.1	4999998.97

2.4 Seepage Analysis

Impounding water seeps through the dam body, foundation and abutments creating serious problems such as piping, gullying, etc. diminishing the soil shear strength and destabilizing the whole dam.

The Seep/w application of GeoStudio utilizes the numerical modeling tools to simulates the flow of water through any medium depicting real physical phenomenon [43]. Therefore, seep/w was employed to explore the amount of seepage occurring through the Latamber earth-fill dam utilizing two different kinds of analysis

i. Steady-State Analysis, water pressure, and water flow rates are constant
ii. Transient Analysis, pressure condition, and water flow rate change with time

2.5 Slope Analysis

Slope/w was employed to analyse the slope and find out the factor of safety (FOS) under three different conditions

i. Downstream slope analysis at the end of construction (EOC)
(When the dam is constructed impounding no water, the critical slope is downstream because it is steeper)
ii. Downstream slope analysis under full conservation level (Steady State)
(the critical slope is downstream therefore only downstream slope is analysed)
iii. Upstream slope analysis under rapid drawdown condition
(In case of rapid drawdown, the upstream slope is very critical because the amount of water remains in upstream side exerting negative pore water pressure).

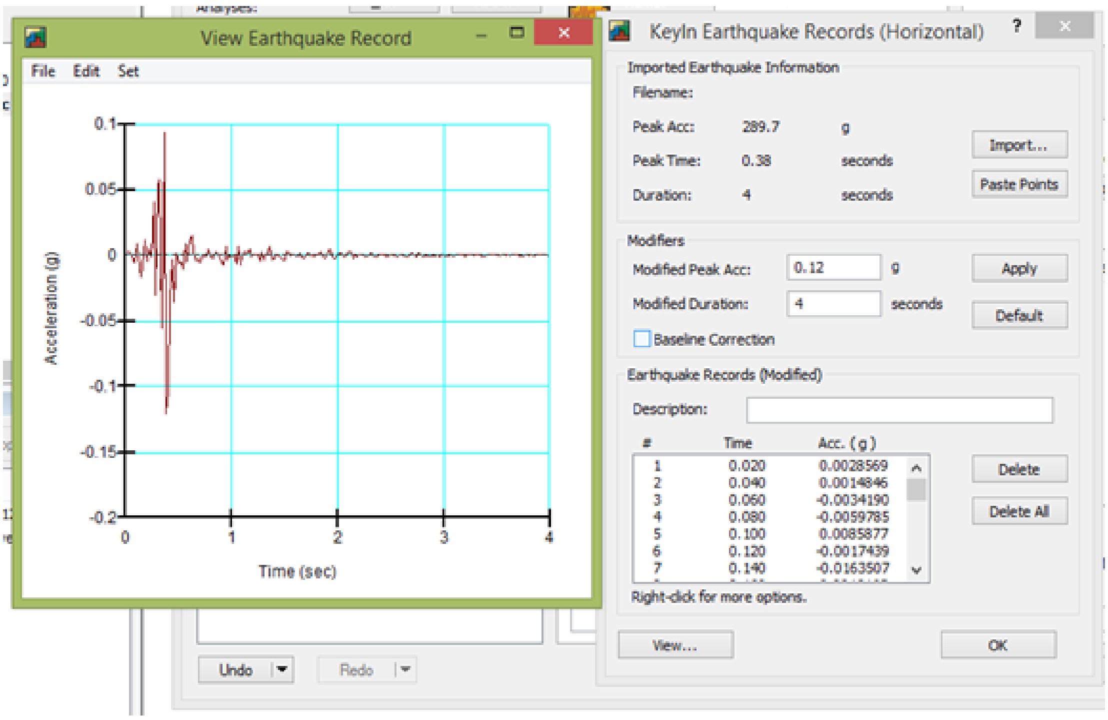
2.6 Dynamic Analysis

Quake/W, a component of GeoStudio was employed to simulate the seismic performance of the Latamber dam and evaluate meaningful parameters [44]. Quake/W comprises of two-stage analysis

i. Initial static analysis
ii. Dynamic analysis

Initial static being first analysis, acts as a parent analysis for dynamic analysis. Material definitions are considered only in initial static analysis. The boundary conditions in the case of the initial static analysis restrain the displacement of the dam body in the horizontal direction, by locking in the left-right direction. While the base of the foundation should be locked in both horizontal and vertical directions. The reservoir pressure on the dam body is also defined as the boundary condition. Overall, the dam body is locked from the base (both horizontal and vertical), while the left and right sides of the dam geometry are locked in vertical direction only allowing horizontal motion.

As it is dynamic analysis, it requires horizontal motion data i.e. acceleration vs time data. In this case, the authors have uploaded a part of the ALTADENA earthquake data, in which the peak acceleration is 289.7g at the peak time of 0.38sec, scaled down to 0.26g at the peak time of 0.38sec. The earthquake data is shown in Figure 2.



Imported Earthquake Information

Filename:

Peak Acc: 289.7 g

Peak Time: 0.38 seconds

Duration: 4 seconds

Modifiers

Modified Peak Acc: 0.12 g

Modified Duration: 4 seconds

☐ Baseline Correction

Earthquake Records (Modified)

Description:

#	Time	Acc. (g)
1	0.020	0.0028569
2	0.040	0.0014846
3	0.060	-0.0034190
4	0.080	-0.0059785
5	0.100	0.0085877
6	0.120	-0.0017439
7	0.140	-0.0163507

Fig. 2. Horizontal ground motion data entry window

3. Results

3.1 Slope Analysis

The results obtained from Slope/w 2-D limit equilibrium Morgenstern-Price analysis are presented and compared with the factor of safety limits of the U.S Army Corps of Engineer (USACE) [23] and British Dam Society (BDS) [38] in Table 9. Figure 3-5 indicate the FOS of the Latamber dam under three different cases of operation. The factor of safety obtained from all the three types of analysis is greater than the limit provided by [23] and [45] rendering it safe.

Table 9
Stability analysis results of the latamber dam with usace (2003) & bds (1994)

Critical Stability Condition	FOS of the Latamber dam	BDS (1994) Limits [14]	USACE (2003) Limits [17]	Remarks
End of construction	1.57	1.5-1.3	1.3	Stable
Steady State	1.55	1.5-1.3	1.5	Stable
Rapid drawdown	1.72	1.3-1.2	1.2	Stable

Whenever an earth-fill dam construction finishes and the reservoir is empty, the critical slope is downstream because it is steeper than the upstream slope. Therefore, it should be assessed before filling the reservoir. In this case, the FOS comes to 1.57 which indicates a stable slope as shown in Figure 3. While in the case of steady-state conditions, the reservoir was filled to its maximum conservation level and the critical downstream slope was 1.55 which is a stable slope as shown in Figure 4. A rapid drawdown condition is considered the most critical phenomenon in slope stability analysis. In the case of the rapid drawdown condition, the factor of safety was 1.72 as shown in Figure 5. It can be seen that the FOS for all the cases is greater than the minimum limit provided by BDS [38] & USACE [23], therefore the Latamber earth-fill dam is safe and no slope failure is expected.

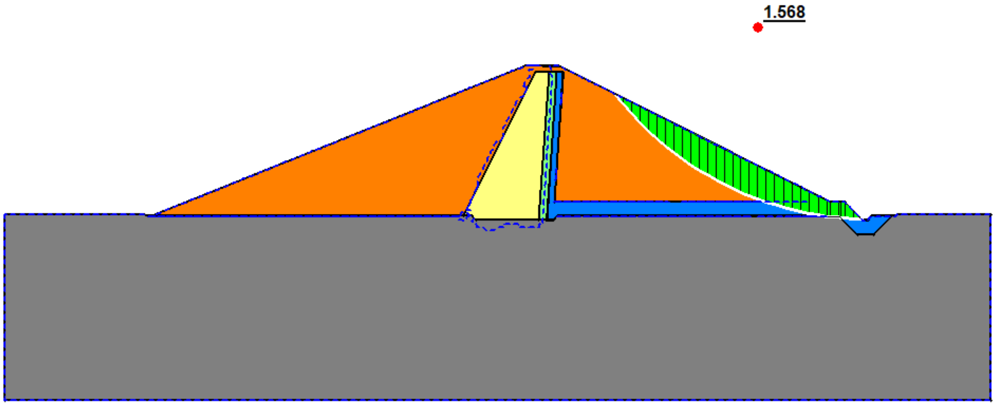


Fig. 3. FOS of downstream at the end of construction (EOC)

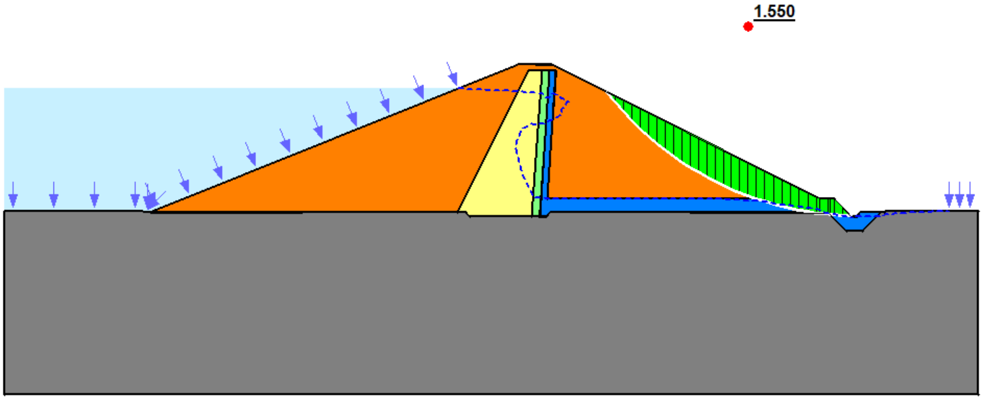


Fig. 4. FOS of Downstream under Steady-State Condition

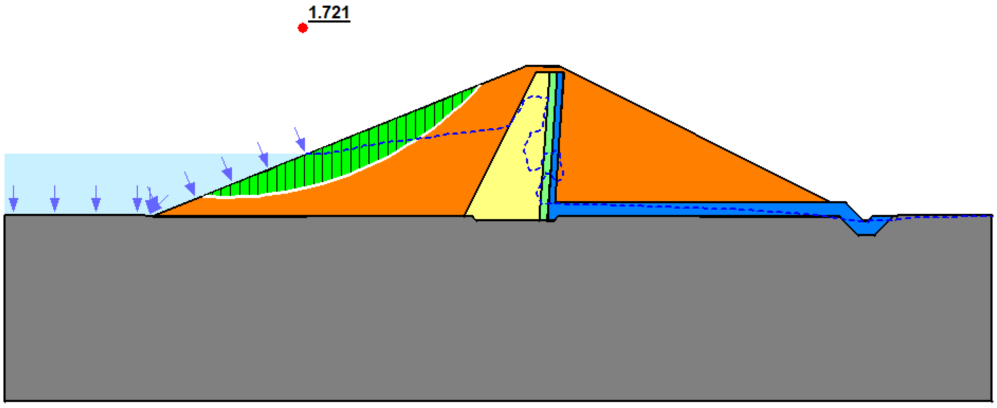


Fig. 5. FOS of upstream under rapid drawdown condition

3.2 Seepage Analysis

The steady-state seepage analysis of the Latamber dam can be seen in Figure 6. While Figures 7 and 8 denote a pore-water pressure develops due to steady-state seepage and drainage of seepage through chimney and horizontal drains respectively. Moreover, it can be clearly seen in all figures that the phreatic line is effectively lowered down by drains and thus the pore-water pressure in the inner surface is under control. In addition, the pore-water pressure at the downstream face is very low which indicates that the downstream slope is not in threat.

The total head variation shown in Figure 8 indicates that the dam is safe in seepage and fulfilling the criteria of BDS [38]. Table 10 demonstrates that the seepage flux (m^3/sec) through the Latamber earth-fill dam is acceptable according to USBR [45]. The seepage flux just before the clay core was recorded 4.60e-7 m^3/sec and just after the clay core was 8.48e-11 m^3/sec which is enough to control seepage failure.

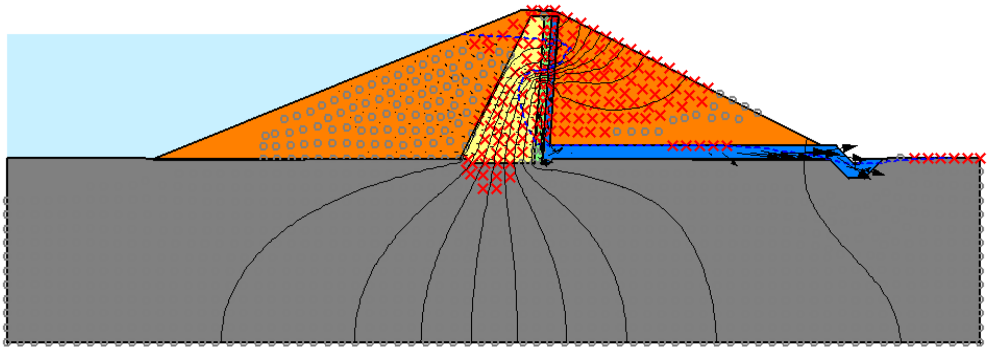


Fig. 6. Steady-state seepage analysis

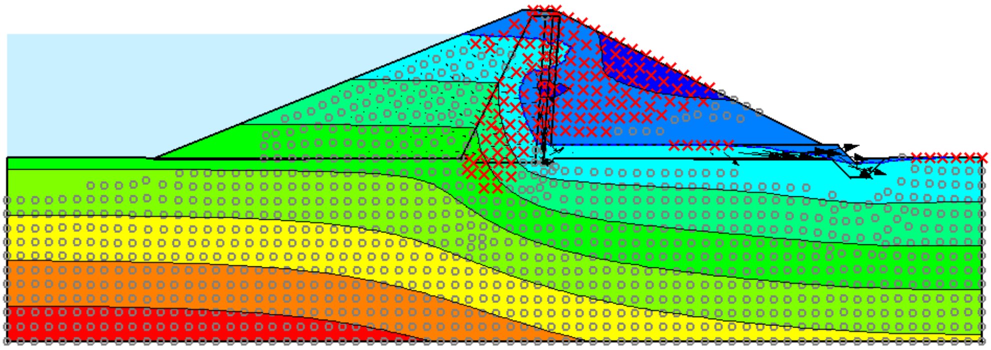


Fig. 7. Pore-water pressure variation

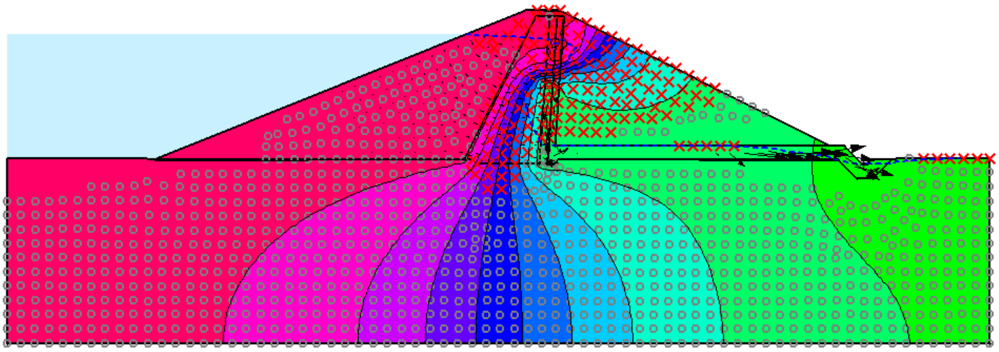


Fig. 8. Total head variation

Table 10
Seepage flux through dam

Latamber dam	Seepage flux (m^3/sec)	Status
Upstream	4.60e-7	Acceptable
Downstream	8.48e-11	Acceptable

3.3 Dynamic Analysis

The seismic performance of the Latamber earth-fill dam was investigated using the Quake/W component of GeoStudio. Figure 9 and 10 indicates the pore-water pressure in the case of initial static analysis and total stress in the Y-direction respectively. Based on the analysis of the initial static analysis, dynamic analyses were carried out and useful parameters such as relative displacement, horizontal acceleration vs time graph and a check for liquefaction at 0.26g acceleration were evaluated.

The relative displacement of the dam central part from the centreline of the dam is shown graphically in Figure 11. The displacement at 0.26g of horizontal ground acceleration is not beyond the limits that can cause a catastrophe.

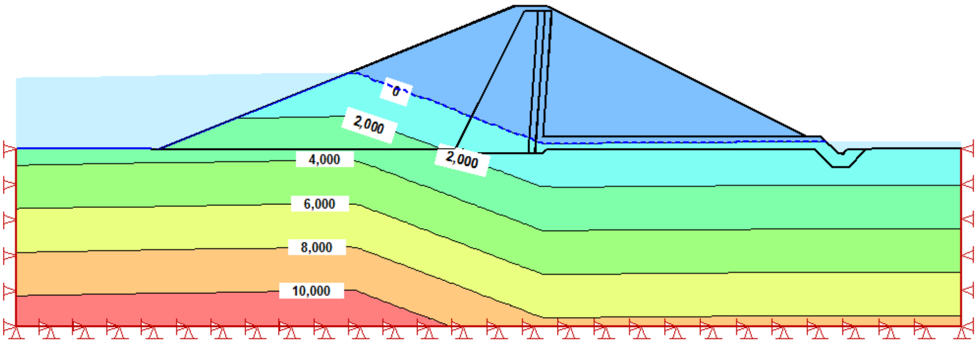


Fig. 9. Pore-water pressure in the case of initial state analysis

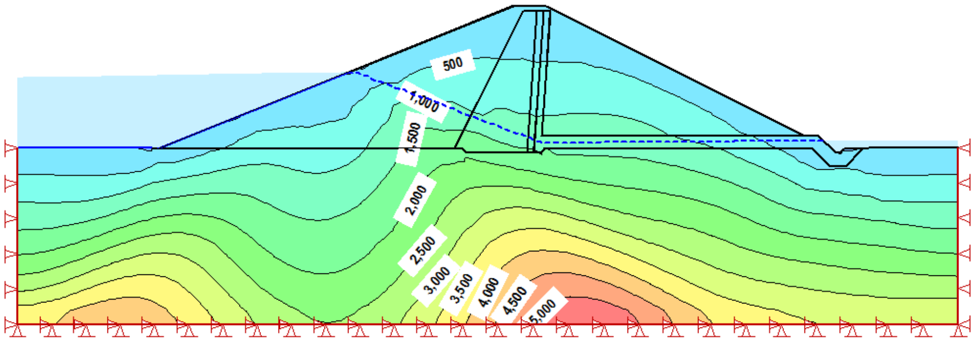


Fig. 10. Total stress in the Y direction

Two history points were defined at the time of analyses: one at the top of the dam (at crest level) while others at the base of the dam foundation. The acceleration vs time graph obtained from the dynamic analysis at those two history points are shown in Figure 12 and 13. These graphs indicate displacements at the crest of the dam and at the bottom of foundations. Figure 12 demonstrates that the X acceleration at the top of the crest is not very effective, the curves in the graph are smooth revealing that the frequency at this point is low and time period is large. Similarly, Figure 13 indicates the X acceleration at the top of the crest is effective, the curves in the graphs are sharp, revealing that the frequency at this point is large and time period is low. GeoStudio software comprises of a very powerful feature. One of them is to check the liquefaction of the dam at a given acceleration. After analysis, the liquefaction in the dam body will be denoted by the highlighted region with colours (yellow colour will be indicating the liquefaction for this analysis). Figure 14 indicates no yellow colour anywhere in the dam, showing no liquefaction resulted in the dam at 0.26g acceleration.

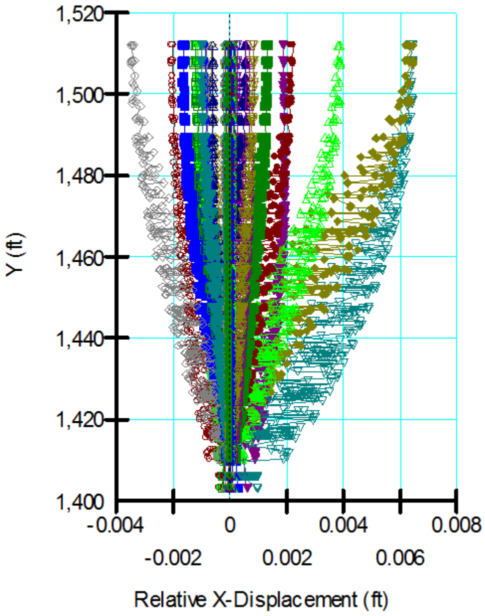


Fig. 11. Relative *lateral* displacements of the center part of the dam from the centerline

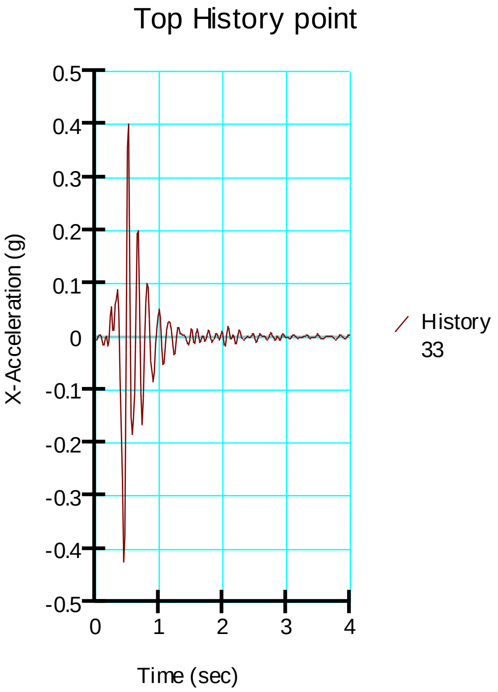


Fig. 12. X acceleration Vs Time on crest level

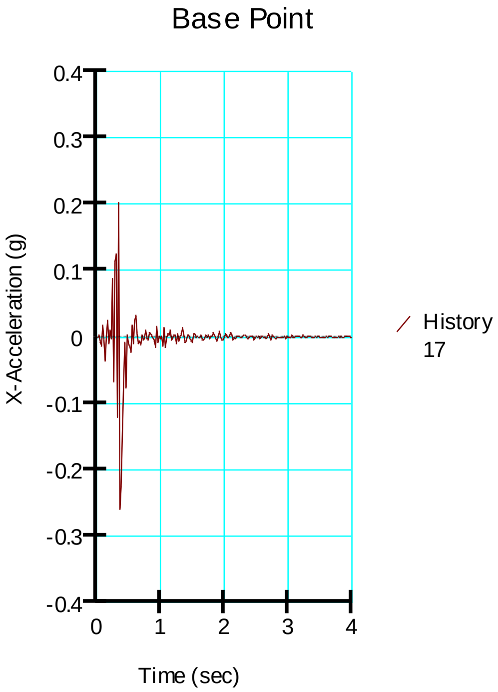


Fig. 13. X acceleration Vs Time on base level

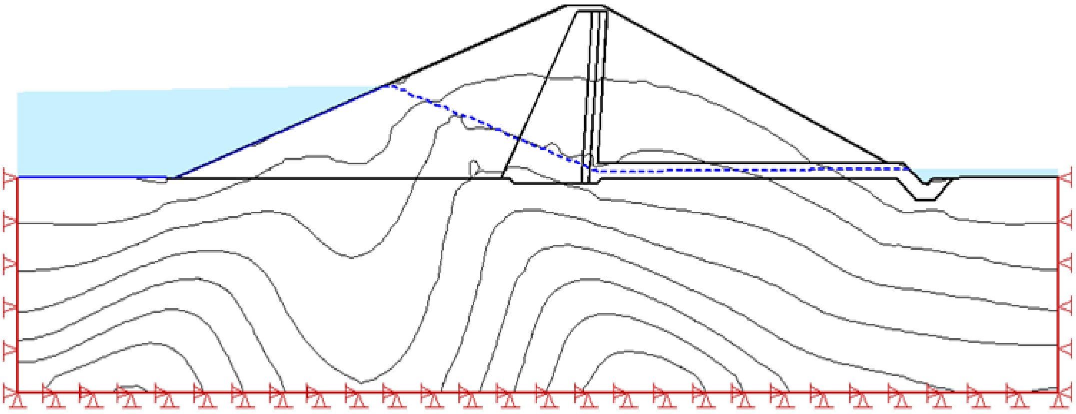


Fig. 14. Liquefaction in the Latamber dam

4. Conclusions

Three types of analysis were carried out on the Latamber earth-fill dam: slope stability analysis under three different critical conditions: at the end of construction, steady-state condition, and rapid drawdown, seepage analysis to investigate the piping phenomenon and seismic analysis to determine liquefaction triggering during an earthquake event. The following conclusions can be drawn from the above analysis

i. No seepage failure/piping was observed (controlled seepage).
ii. No slope failure was found in all three cases.
iii. No liquefaction was observed during dynamic analysis, indicating that the dam can withstand during an earthquake.
iv. The Latamber small dam has a stable geometry.

It should be worth mentioning that for more complex modern dams, the dynamic parameters should be more thoughtful to determine.

Recommendations

Latamber earth-fill dam has a safe geometry with a factor of safety higher than recommended. Some elements such as the chimney drain, core and blanket can be avoided to achieve an optimal and cost-effective design of small earth-fill dams.

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