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Enhanced Geo-technical Methods for Evaluating Slope Stability in Unconsolidated Strata: A Comprehensive Analysis

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Abstract

The study utilizes the Limit Equilibrium Method (LEM) to investigate slope movements. These movements were initially generated by construction activities at the slope's base, and subsequent events were driven by seismic activities, as the study studied area lies within the Main Karakoram Thrust (MKT) and Main Mantle Thrust (MMT) zones. Soil samples, characterized by a moisture content of 13% and a dry unit weight of 18.14 kN/m³ were analyzed. The study revealed that an increase in saturation caused by rainwater infiltration, resulted in a reduction in unconfined compression strength, decreasing from 712 kPa to 349 kPa. The shear strength and deformation parameters (cohesion, angle of internal friction, and deformation modulus) were also examined with varied degrees of saturation. The results revealed a decrease in these parameters as the percentage of saturation increased from 30% to 90%. The slope stability study revealed that the Factor of Safety (FOS) reduced from 1.85 to 0.86 as the saturation of the material raised from 30% to 90%. To assess the influence of unit weight, cohesion, and angle of internal friction on the FOS, multiple cases were considered. The analysis revealed that the FOS increased with higher cohesion and angle of internal friction, while an increase in unit weight resulted in a lower factor of safety. Furthermore, stability of the slope was evaluated by modifying the slope geometry such as lowering the height. According to the GeoStudio investigation, the slope remained steady even at saturation levels exceeding 80%.

1. Introduction

The characterization of slope stability relies on the assessment of rock mass classification parameters, and addressing the vulnerability of slopes requires a thorough investigation of geo-technical parameters, especially in cases where the slopes are composed of loose materials such as clay or soil. Geological disasters are one of the most fatal natural disasters, which result in significant costs in terms of human lives and property annually [1]. These natural disasters are outcome of abrupt change in state of natural elements due to natural forces. The existence of joints and fractures in rocks significantly impacts the behavior of the rock mass by subdividing the material into smaller units. These structural features not only increase the likelihood of instability but also contribute to the occurrence of sliding and rotational movements [2]. Conversely, in open-pit mines, the stability of slopes is governed by the structural parameters of the rock mass, particularly the persistence and spatial orientation of discontinuities [3]. Furthermore, these natural disasters are beyond human control, and often prove challenging to predict accurately when they occur. Furthermore, main natural disasters are earthquakes, droughts, floods, and landslides [4]. When natural disasters occur, its outcome has an adverse effect on the livelihood, property, human life, agriculture, education, communication, and infrastructure as well as on the environment [5]. The prevalence of natural disasters like earthquakes, tsunamis, floods, and landslides has emerged as a central and

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widespread topic of discussion over the past few decades [6]. Specifically, among the most destructive geological events, landslides substantially elevate the threat of both loss of life and property damage. The district of Hunza has experienced significant and devastating landslides in various areas. According to a study by Khan [7] the Gilgit Baltistan Province has historically been severely and regularly damaged by landslides, making it vulnerable to further landslide-related devastation in the future. At least 79 rock slide-rock avalanche incidents have been recorded in the Hunza and Gilgit River basins of the Karakoram and Hindu Raj Ranges during the course of the last two decades, according to a number of studies [8]. A catastrophic landslide occurred in Karakorum Range Atabbad, Hunza, 35 km nearby the studied area, which has killed 14 people and created a huge water reservoir, which engulfed two villages at upstream areas that caused loss more than billions of dollars. Similarly, many slope failure events happened in this valley in the past caused many human losses. Therefore Carrara [9] in his investigation, observed the possibility that if landslides could be analyzed and predicted before a disaster, approximately 90% of losses due to them could be avoided. In other terms, landslides' casualties and destruction can be somewhat decreased by predicting future landslide zones. Numerous researchers including [10-13] have previously explored the correlation between shear strength and saturation level across various soil types.

Xu [14] examined the impact of saturation on the soil's structure and the shear strength of loess. On saturated, in-situ, and remolded soil samples, triaxial and oedometer tests were run. The structure of the soil has a significant impact on how the soil's particles behave. The shear strength of both soils, however, changes dramatically as the degree of saturation rises, and it rapidly declines as the water content rises. This decrease in shear strength could start relative soil particle displacement and lead to landslides. Waseem [15] examined the slope failure that occurred in Qalandar Abad, Pakistan. The FOS for the slope was determined using the limit equilibrium method using the GeoStudio software. Furthermore, it has been determined that there is a positive correlation between the friction angle and soil cohesion, and the factor of safety exhibits an upward trend as both properties increase. On the other hand, the factor of safety exhibits a reduction in response to an escalation in overburden pressure and the unit weight of soil. Ahmed [16] studied that soil cohesion and friction decrease with increasing degree saturation. It was also that the shear strength characteristics tend to rise with increasing dry density. According to Zhang [17], the moisture level of the soil mass has a considerable impact on how landslides caused by rainfall. The particles within the rock samples are present in extensive ranges of shapes and sizes, which also caused the instability of slopes [18]. According to Fu [19], the moisture level of the soil mass has a considerable impact on how landslides caused by rainfall. Bulk density moisture content is a physical indicator that shows the characteristics of the soil and water. The size of individual blocks is an additional factor that can significantly influence slope stability. Larger block sizes, for instance, may introduce greater potential for instability. This relationship is crucial to consider in comprehensive slope stability analyses [20] because in layered and blocky rock formations, the risk of toppling failure becomes more pronounced [21]. In this type of failure, certain rock blocks fracture due to tensile stresses, while others overturn under their own weight [22]. Subsequently, a collective toppling of these blocks follows [23]. One commonly observed toppling instability in civil and mining engineering projects is the block-flexural toppling failure. In this failure mode, certain rock columns fracture due to tensile bending stresses, while others overturn due to their own weight. Ultimately, the culmination of these processes leads to the simultaneous toppling of all the blocks involved [24].

The Himalayan Mountain range is prone to slope instability in various regions, owing to its complex topography influenced by both natural conditions and human interventions [25]. The Himalayan region's rock fall hazard was investigated using GeoRock 2D; [26] focused on hard rock formations with moderate to high slopes [27]. However, there is a noticeable gap in attention regarding the stability of loose strata in the North Himalayas. A landslide occurrence on the Hussain Abad region North Pakistan led to significant road network distractions. Therefore, the current study focuses on pointing slope failure along the Hussain Abad Road incorporating the shear parameters, and other geo-technical parameters need for mitigation measures of vulnerable slope. This involves evaluating soil shear strength and deformation characteristics across varying saturation levels. Several important parameters such as cohesion coefficient, internal angle of friction, slope height, slope angle, and unit weight of slope material were utilized as the input parameters, while FOS was used as the output parameter. These parameters control the stability of soil slope [28, 29]. The dynamic response of slopes to earthquakes is typically characterized by key parameters including height, unit specific weight, cohesion, friction angle, vibration duration, and maximum horizontal acceleration [30]. Therefore, this investigation aims to understand how geo-technical parameters impact landslide occurrence and involves stability analyses to determine the factor of safety. Additionally, slope stability analysis was conducted through adjustments to the slope geometry. The outcomes of these analyses will help to modifying the slope geometry, even at a high saturation degree in landslide risks.

2. Regional Geology and Approach of Study

The intricate geography of the Himalayan Mountain range, coupled with pre-existing natural conditions and human interventions, renders several areas within the range susceptible to slope instability [31]. The studied area is located in the Hunza District of North Pakistan (Figure 1) [32]. The research region consists of Chalt volcanic and Kohistan Ireland rock masses along the Karakoram High Way, which has two significant faults known as the (Main Karakoram Thrust) KMT and (Main Mantle Thrust) MMT. The KMT serves as a pivotal tectonic boundary, delineating the convergence between the Indian and Eurasian plates [33]. This thrust plays a central role in the complex geodynamics of the Karakoram, influencing uplift and deformation patterns within the mountain range. As the Indian plate moves northward, the compression along the KMT contributes significantly to the topographical and structural characteristics of the Karakoram [34]. Complementing this, the MMT is another consequential geological feature, associated with the interaction between the Earth's crust and mantle in the region [34]. The MMT's influence extends to the structural development of the Karakoram, and understanding its activity is crucial for deciphering the broader tectonic framework, seismicity, and geological evolution of this dynamic mountainous terrain [35]. The Karakorum block, which is composed of low to medium degree metamorphism, is positioned from west to east, and that is where the research area may be found. As the Kohistan Island Arc (KIA) moves northward under the influence of the Indian plate, the metamorphic grade continuously increases. This might result in the formation of a plate boundary between the Eurasian plate and the Kohistan Island Arc, which is also referred to as the main Shyok Suture zone or Karakorum Thrust. The Karakoram Highway (KKH) connects Chalt Nagar and Hunza, and in between these two cities are six branches of the Shyok suture zone. Valleys in the Nagar and Hunza districts including Ghulmet may be affected by the crossing of the Chalt fault in close proximity to the towns. Local rocks include slate, phyletic rocks, marble, and schist, with lenses of underlying ultramafic rocks. This area is part of the Southern Karakoram Metamorphic Complex (SKM). Strong folding and faulting may be seen in the region's rocks. [36] Earthquakes and blasting are significant sources of dynamic loads, with the potential to cause substantial damage to slope stability. This risk is particularly pronounced in regions with a history of seismic activity such as the tectonically active studied area [37]. Particularly, in the context of projects like the China-Economic corridor along the Karakoram Highway, where multiple such activities are conducted, a precise analysis of slope stability becomes crucial. As illustrated in Figure 2, a specialized methodology has been designed to cater to the unique challenges of this region.

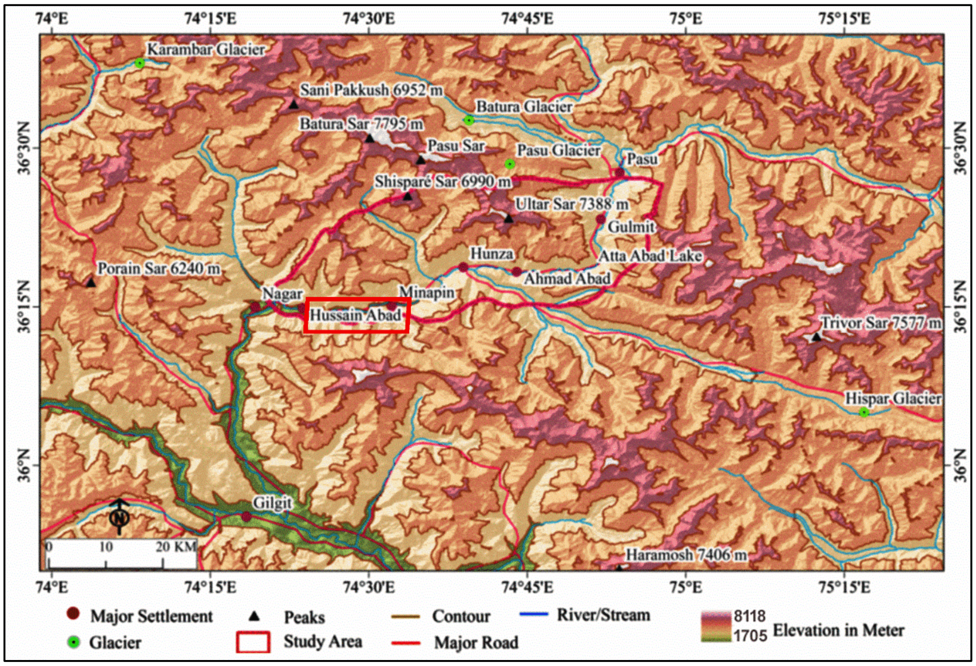


Figure 1. Location of the studied area [32].

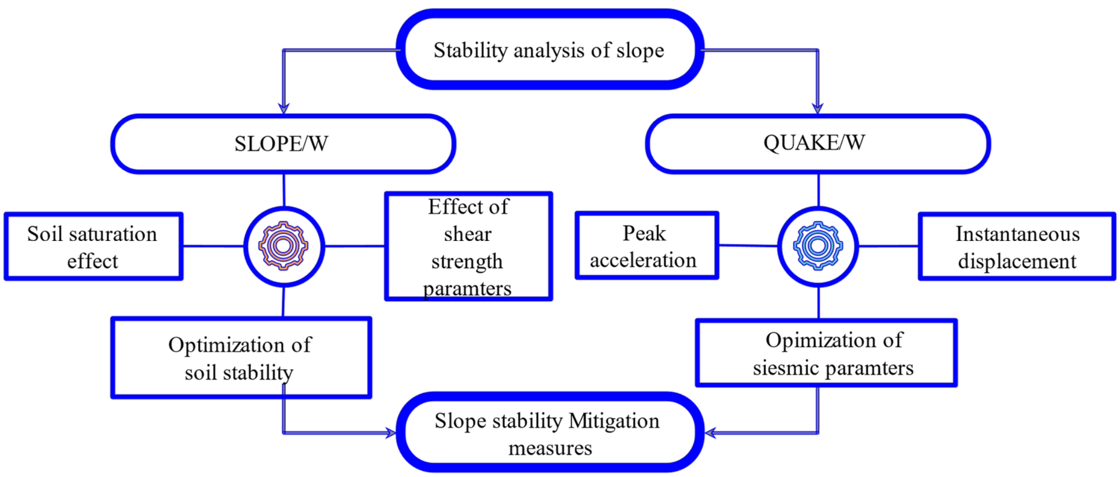


Figure 2. Schematic diagram of methodology.

During the investigation at the Hussain Abad site, several activities were conducted to evaluate the slope and the materials involved in the landslide. The slope approximate geometry was measured using a total station, determining a height of approximately 35 meters, and a width of about 70 meters from the toe. The measured failure surface slope angles ranged from 30 to 45 degrees, indicating a moderately steep slope. The slope angle stands out as a highly influential parameter in slope stability. A slope angle exceeding the optimum value raises the likelihood of significant failures [38]. The soil at the site consist of a mixture of small particles and boulder-size particles, as shown in Figure 3. The samples were collected, and laboratory tests were perofrmd to analyse shear patamters of the studied area soil. In the laboratory, the collected material was dried to prepare the samples for subsequent tests. These tests aimed to analyze the properties of the material and gain valuable insights into the factors contributing to the landslide at the Hussain Abad site.

Figure 3. Hussain Abad landslide studied area.

2.1. Soil Sample Properties

The landslide material was analyzed and found to contain various particle sizes. It consisted of 2% gravel size particles, 20% sand size particles and the majority of the material, which was 78% comprised fines. Within the fines fraction, 36% were clay size particles, and 42% were silt size particles. Furthermore, the soil's consistency limits were measured, revealing a liquid limit of 37% and a plasticity index of 14. The unit weight of soil was 18.14 kN/m^3. Table 1 represented the results of soil.

Table 1. The results of soil parameters.

Description	Results
Gravel (%)	2
Sand (%)	20
Silt (%)	42
Clay (%)	36
Liquid limit (%)	37
Plastic limit (%)	23
Plasticity index	14
Specific gravity	2.70
USCS classification	CL
AASHTO classification	A-6(6)

2.2. Shear Strength of Soil

The unconfined compressive strength is the compressive strength at failure of a soil subjected to unconfined compressive load. It provides a direct quantitative measure of consistency of cohesive soils. The triaxial set up was used for triaxial testing following ASTM D 2850-03 was utilized for the failure investigation of slides material along the road to test the immediate response of rainwater on the undrained shear strength characteristics of slide material [39]. A critical aspect in designing slopes is identifying the maximum stable span, a parameter influenced by factors such as the shear strength of the soil and the geometric properties of the slope [40]. UU triaxial compression tests were carried out, and dry unit weight was calculated by altering the saturation level from 30% to 90%. To generate a remolded sample with a regulated degree of saturation for testing, the following equations (Equation 1 and Equation 2) were utilized. The parameters used in GeoStudio are presented in Table 2.

$$\boldsymbol{\gamma d = \frac{G_s\,\gamma_w}{1+e}} \tag{1}$$

$$\boldsymbol{e = \frac{wG_s}{S_r}} \tag{2}$$

Here,

γd = dry unit weight, G_s = specific gravity, γ_w = unit weight of water, e = void ratio, W = water content %, S_r = degree of saturation.

Table 2. The soil parameters for GeoStudio slope/W.

Gs	W	γd	e	Degree of saturation
2.7	0.06	17.09	0.54	30.07
2.7	0.08	16.68	0.58	40.005
2.7	0.11	16.23	0.63	50.06
2.7	0.15	15.75	0.68	60.008
2.7	0.19	15.21	0.74	70.007
2.7	0.21	14.92	0.77	75.013
2.7	0.24	14.62	0.811	80.056
2.7	0.29	13.96	0.89	90.027

Using known values for γd, Gs, and γw, the equations determined e, which was then utilized to calculate moisture content (w) corresponding to the desired percentage of saturation (Sr). Subsequently, the prepared samples underwent laboratory triaxial testing to derive shear strength parameters. These parameters were then integrated into GeoStudio Slope/W software for conducting slope stability analyses.

GeoStudio system was developed by Geo-Studio, a world-famous geo-technical software developer in Canada in the 1970. It is a kind of numerical analysis application software widely used in geotechnical, mineral resources mining, highway construction, dam stabilization and other engineering technology fields. With the continuous version update, it has gradually developed into one of the most famous geo-technical engineering design application software in the world. Slope/W; slope analysis module is based on the classical concept of slope stability analysis limit equilibrium theory, but it is improved and optimized on the basis of the limit equilibrium theory, and the inherent limitations of the concept are solved. The application of slope stability analysis module is more extensive, and the calculation results are more scientific and reliable.

2.3. Slope stability analysis

The slope stability stands as a critical challenge in both mining and geo-technical engineering. Overlooking the significance of addressing, these issues can result in substantial losses [41]. The analysis of slope stability holds paramount importance in geo-mechanics, and among the array of methods available (both numerical and analytical), the limit equilibrium method is extensively employed. Its widespread use is attributed to its simplicity, and its results have been observed to closely align with more rigorous methods. The traditional limit equilibrium approach for slope stability analysis typically involves two sequential steps [42]. In this study, slope stability analyses were carried out using the slope/W software's limit equilibrium approach. There are several ways in Slope/W for calculating the material strength to be employed in a stability analysis. The Mohr-Coulomb method has been examined in detail. The Romana SMR (slope mass rating) classification also stands out as a valuable technique for analyzing the stability of rock slopes. It represents an evolved iteration of Bieniawski's 'rock mass rating' (RMR) system, and relies on classical set theory principles. Describing the mass characteristics of rocks can be intricate, potentially leading to some uncertainty in the process [43].

Mohr-Coulomb is a popular method for determining the shear strength of geotechnical materials. This can be calculated using Coulomb's equation (Equation 3).

$$\boldsymbol{\tau = c + \sigma \tan \varphi} \tag{3}$$

τ = shear strength (i.e. shear at failure), c = cohesion, σ = normal stress on shear plane, and φ = angle of internal friction.

slope/W provides several techniques for calculating the safety factor; yet, the Morgenstern-Price method was chosen for this investigation. Because of the Hussain Abad landslides geometry and its frequent use by scholars, this approach was chosen in similar slopes. The Morgenstern-Price method is a widely recognized and accepted approach for slope stability analysis, making it suitable for the specific conditions of the landslide [44].

3. Results and Discussion

3.1. Saturation effect on soil properties

Earlier researchers have developed the relation between shear strength and degrees of saturation, particularly in the context of sandy soils [45-48]. These investigations have determined that the water content in soil is prone to rise as a result of rainwater infiltration, depending on the amount of precipitation. This phenomenon stands as a primary element for the initiation of landslides.

Illustration from these perceptions, the goal of the current study was to determine how different saturation levels affected the soil's shear strength properties.

Shear strength parameters of the subsoil have been estimated from field as well as laboratory tests. Considering limited role of thin cover of alluvium in the slope movement several shear experiments were conducted on soil samples in accordance with ASTM3080-73. In these experiments, the angle of internal friction and intermolecular cohesion are determined. Results of these tests have been included in Table 3.

Table 3. Shear strength values obtained from direct shear test

Cohesion (C) KPa	Friction angle (φ)	Unit weight (kN/m^3)
24.4	22.3	18.14

The angle of internal friction deceases from 22.3˚ to 10.9˚ with increased in saturation. The relation of saturation and angle of internal friction is given in Figure 4a. The increase in saturation leads to a reduction in the soil's strength and shear resistance.

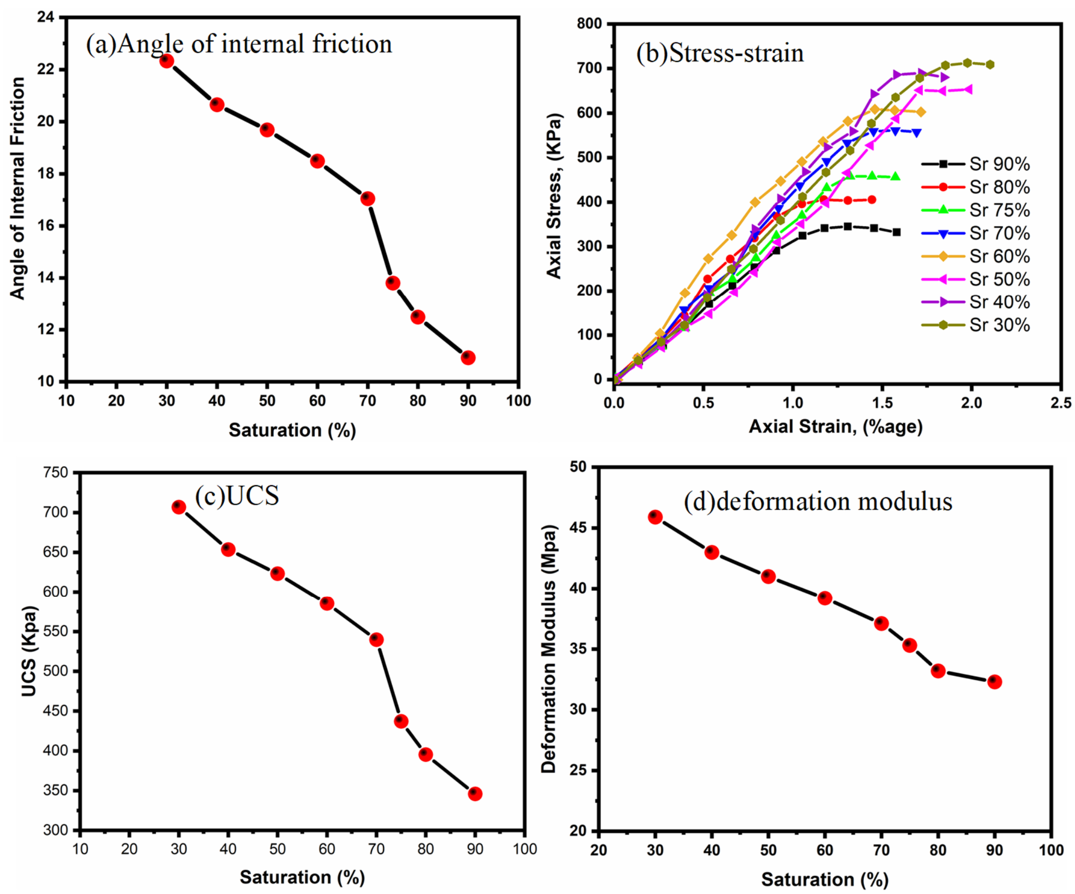


Figure 4. The effect of saturation (a) angle of internal friction (b) stress-strain (c) UCS (d) deformation modulus.

The study involved conducting unconfined compression tests on remolded samples of the soil following ASTM D 2166 guidelines. The relationship between axial stress and axial strain was used to calculate the deformation modulus (E_{50}) for each sample. Figure 4b shows the relationship between axial strain and axial stress in a modified matrix soil with a dry unit weight of 18.14 kN/m^3 and different saturation levels. The unconfined compression strength decreased from 712 kPa to 349 kPa as the level of saturation increased from 30% to 90%. This decrease in strength is attributed to the increased saturation caused by rainfall infiltration, ultimately culminating in the failure of the slope [49, 50].

Figure 4c illustrates that unconfined compressive strength of the materials has a positive correlation with the dry unit weight of the remolded sample. However, the efficacy of this attribute diminishes proportionally with the increase of the saturation level. The research work revealed a decrease in unconfined compression strength ranging from around 49.4% to 51.2% as the degree of saturation increased. The results of this study indicate that there is a decrease in the deformation modulus (E_{50}) from 46.2 MPa to 33.1 MPa when the percentage of saturation increases from 30% to 90%, as illustrated in Fig 4d. It was also observed that the decline in the deformation modulus (E_{50}) as the saturation level increases, while maintaining an in-situ unit weight of 18.14 kN/m^3.

3.2. Factor of Safety at Different Levels of Saturations

The FOS values obtained for the slope at various saturation levels provide valuable perceptions into the stability of the slope under different moisture conditions. The existing literature often neglects the impact of variable groundwater, despite its significant role. The wedge failure induced by fluctuations in groundwater remains a prevalent occurrence in sedimentary rock formations [51]. Therefore, this study also focused the effect of various unit weight, shear strength, and saturation values on factor of safety of soil slope. The FOS for the slope at 30% saturation has been calculated to be 1.88. This value indicates that the resisting forces of the slope are approximately 1.881 times greater than the driving forces attempting to cause failure. With a factor of safety greater than 1, the slope is considered stable at this saturation level, and the risk of failure is relatively low. The pore water pressure distribution of slope rock and soil mass is mainly related to the underground water level. Below the phreatic surface, the pore water pressure is positive and gradually increases downward and above the phreatic surface, the pore water pressure is negative, and reaches the minimum value at the slope surface, as shown in Figure 5a.

At 50% saturation, the factor of safety further decreases to 1.53. This decrease in FOS indicates that the slope stability is affected more significantly by the increase in moisture content. However, the slope still remains stable with a factor of safety greater than 1, as shown in Figure 5b. At 90% saturation, the FOS is only 0.907, indicating an unstable slope condition. The driving forces are significantly greater than the resisting forces, posing a high risk of slope failure, as shown in Figure 5c. Additionally, for various dry unit weights, the FOS falls below 1 between 80% and 90% of saturation.

3.3. Strain Distribution of Slope under Saturations Conditions

After the beginning of saturation, the shear strain area of the slope body was mainly located at the foot of the slope, and a small amount was also distributed on base of the lower layer of slope, as shown in Figure 6. At 34% degree of saturation, the maximum shear strength is 0.065. As the saturation increases from 34 to 44%, the maximum shear strength at 44% saturation is 0.075. The saturation is increased to 50% the maximum shear strength is 0.085. At saturation level of 58% the maximum shear strength is 0.125. At 65% of saturation level the maximum shear strength is 0.149 as the saturation level increase to 78% the maximum shear strength at that level is 0.220. The maximum shear strength at 86% saturation level is 0.24. At the highest level of saturation of 94% the maximum shear strength increases to 0.28. It is found from the results there is a consistent trend of increasing maximum shear strain as the saturation level increases. This means that as the soil becomes more saturated, it becomes more susceptible to shearing and deformation [52].

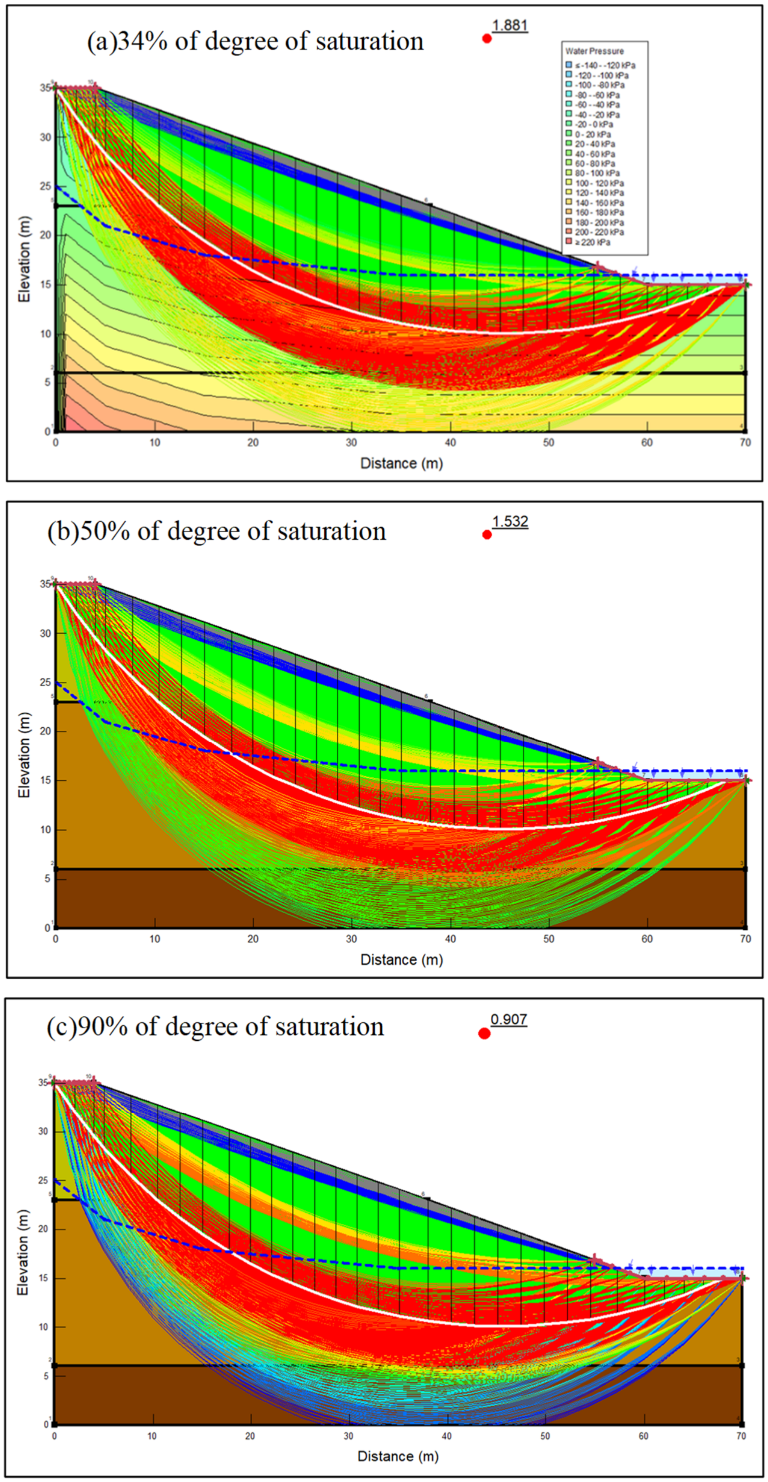
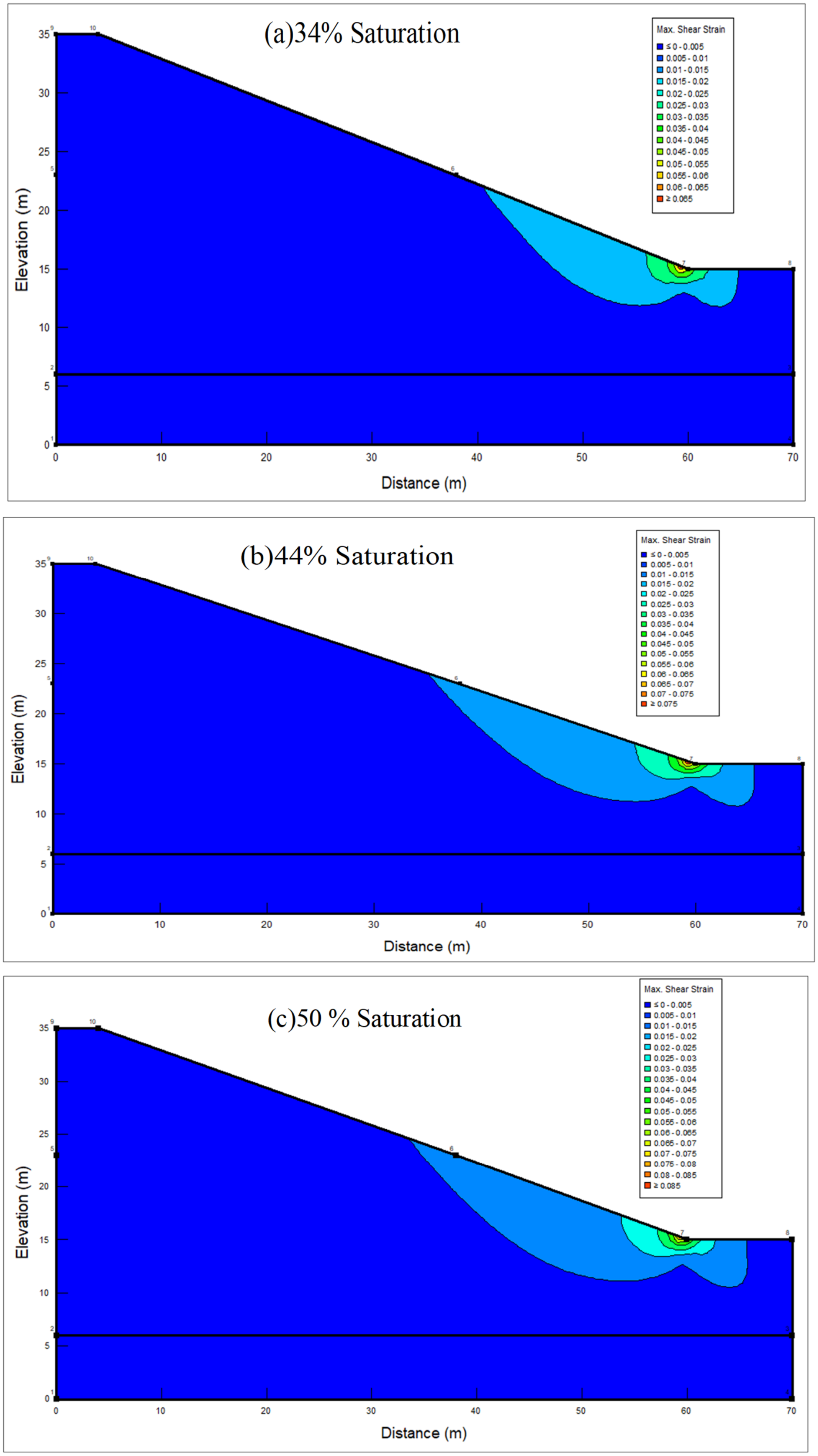
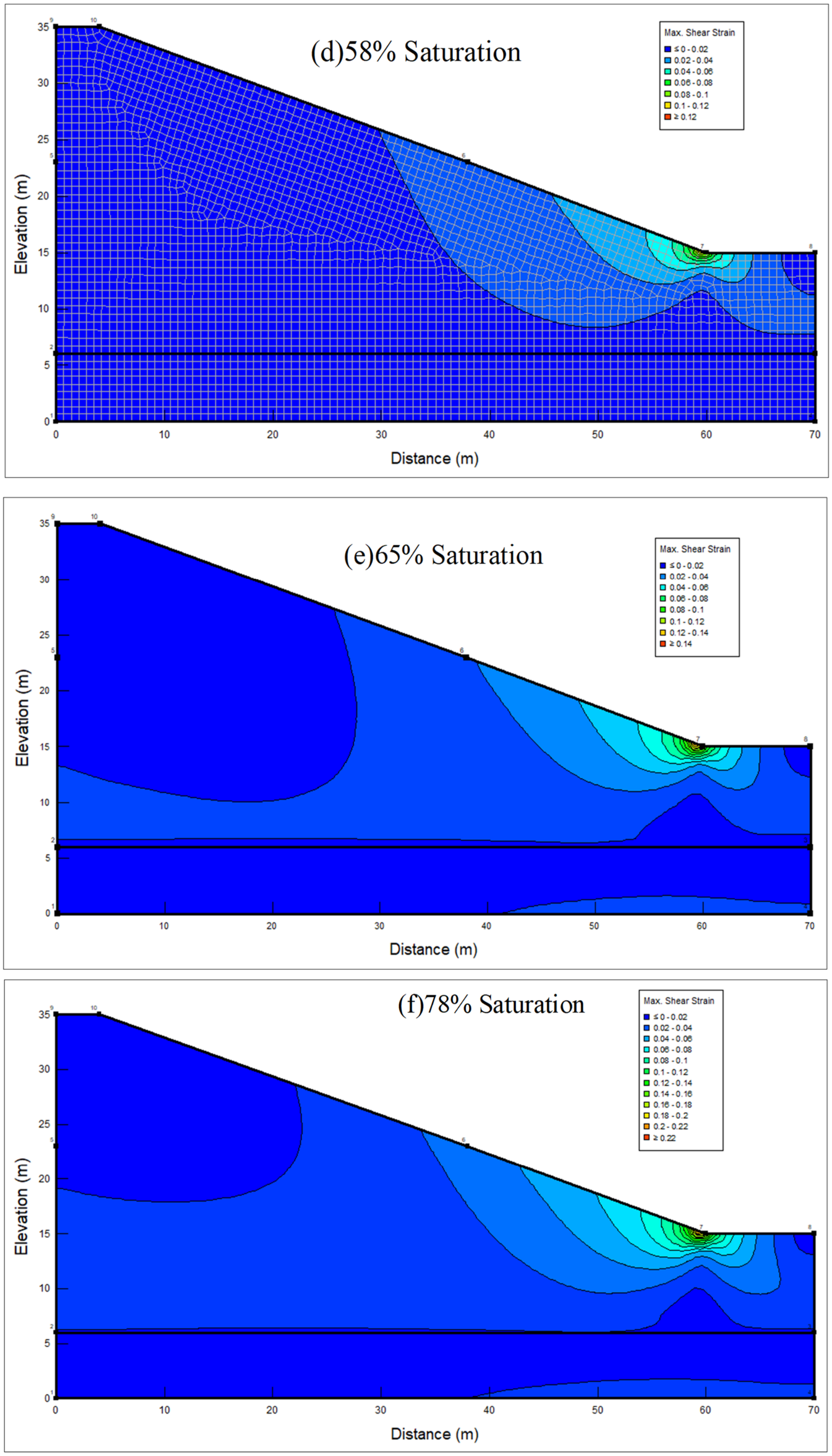


Figure 5. Factor of safety at (a) 34% (b) 50% (c) 90% degree of saturation.



Continuous of Figure 6. Distribution of maximum shear strain of slope at different level of saturations (a) 34% (b) 44% (c) 50% (d) 58% (e) 65% (f) 78% (g) 86% (h) 94.



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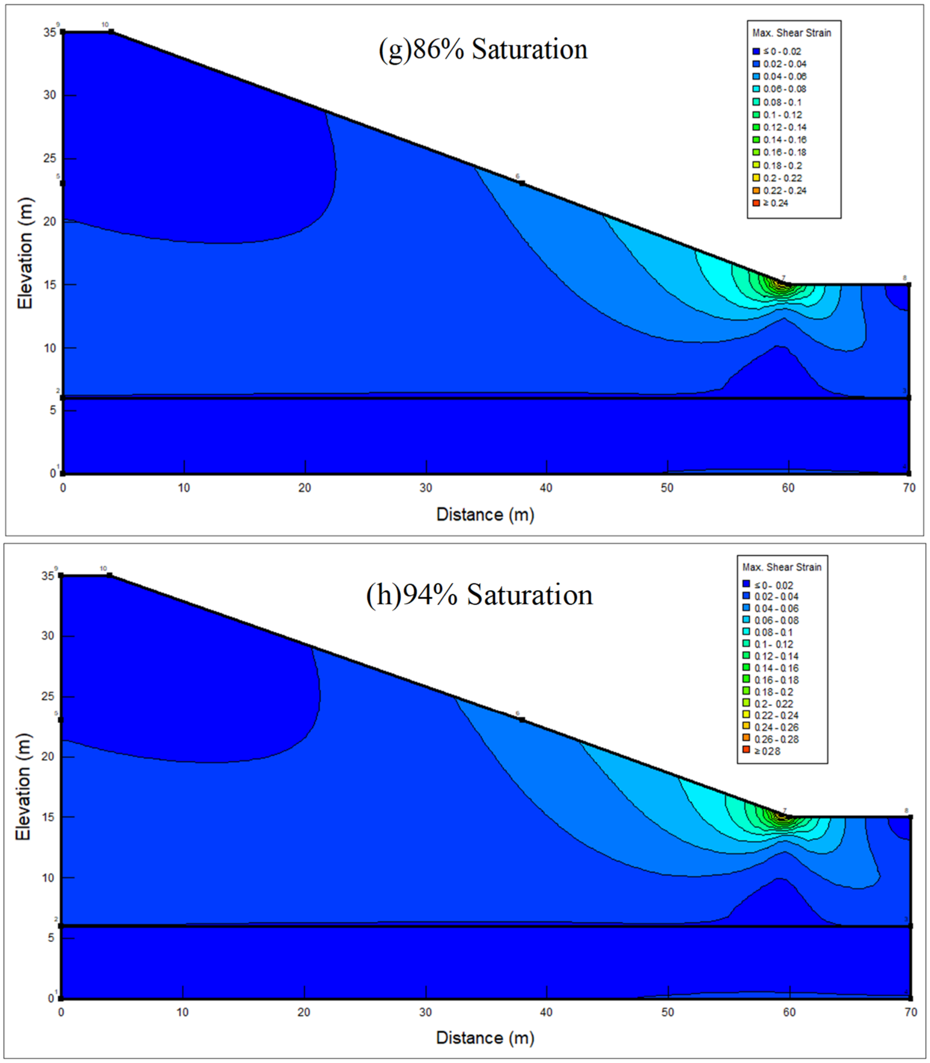

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3.4. Slope Stability under Action of Ground Motion

The dynamic load generated by the earthquake can destroy the internal rock and soil structure of the slope, resulting in the deformation and failure of the slope. Due to the randomness of earthquake action, three kinds of seismic waves with different peak accelerations are used in this section to establish earthquake models to study the response characteristics of slope under different peak accelerations. According to the information of earthquake hazard analysis of Pakistan, the basic peak acceleration of the studied area is 0.20 g. Since the basic peak acceleration in the studied area is 0.20 g, in this research seismic waves with peak acceleration of 0.12 g, 0.15 g, and 0.20 g to analyze the slope response under seismic action in the subsequent simulation. The total length of the seismic wave is 40 s, the peak acceleration is 0.32, and the horizontal peak acceleration is reached at 6.98 s. The revised seismic waves are shown in Figure 7.

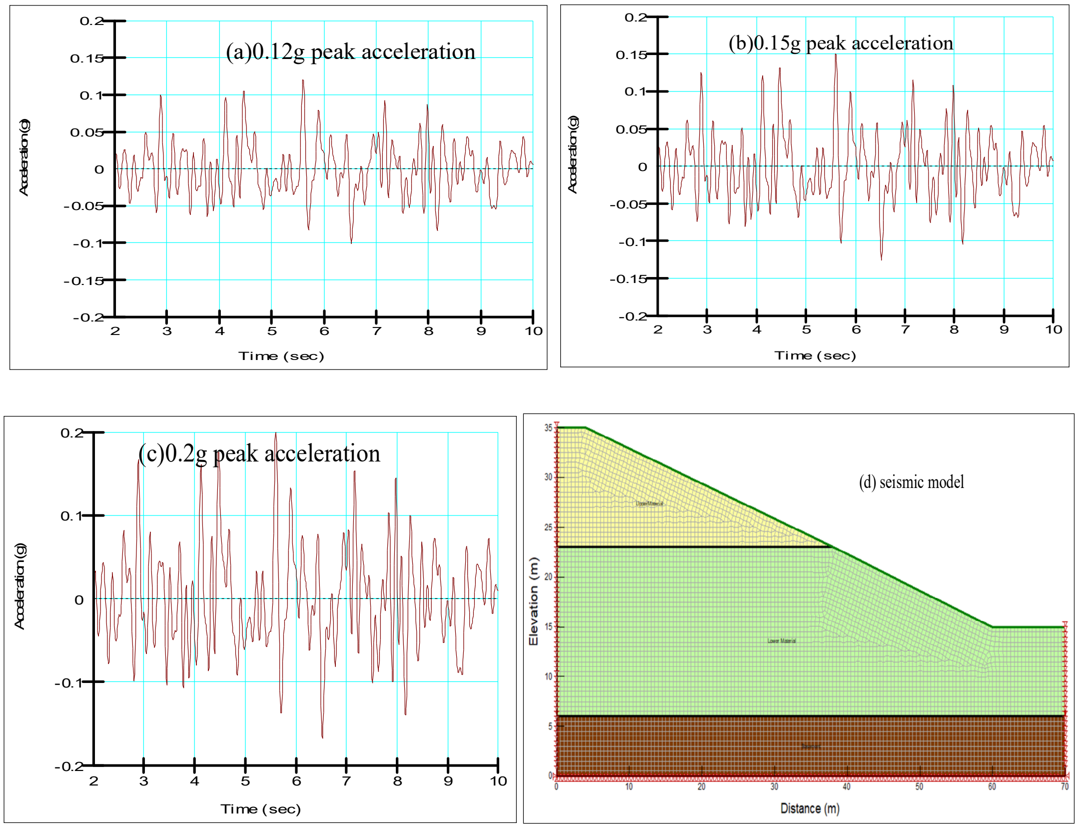

Figure 7. Seismic waves with different peak accelerations (a) 0.12 g (b) 0.15 g (c) 0.2 g and (d) seismic simulation model.

The seismic simulation model, as shown in Figure 7d, is about 35 m high and 70 m long, and the size is consistent with the actual profile. The formation of the site from top to bottom quadrilateral and triangular grids were selected for the model, with a total of 6943 grids and 6771 nodes. The bottom of the model was set as impervious boundary. In the QUAKE/W module analysis, the bottom boundary of the model is set to be fixed without deformation, and the left and right boundary is set to be fixed in the Y direction. In the setting of seismic model parameters, the basic physical parameters of each soil layer are consistent with the parameters used before. The main added parameters in the seismic model are damping ratio and soil shear modulus. The damping ratio of the seismic model in this research work is set to 0.1. In the process of ground motion, the safety factor will be centered on the safety factor of the slope before the earthquake, and oscillate up and down. At some moments, the safety factor is greater than the safety factor of the natural state. With the reciprocating movement of seismic activity, the slope will move in different directions. Figure 8a shows the displacement vector deformation diagram of the slope model in the process of earthquake by enlarging 100 times. When the deformation at a certain moment in the process of earthquake, the slope body is deformed inward. Under the condition that the other physical and mechanical parameters remain unchanged; the stability of the slope at this moment is the highest. When the slope body moves outward, as shown in Figure 8b, the stability of the slope is gradually weakened.

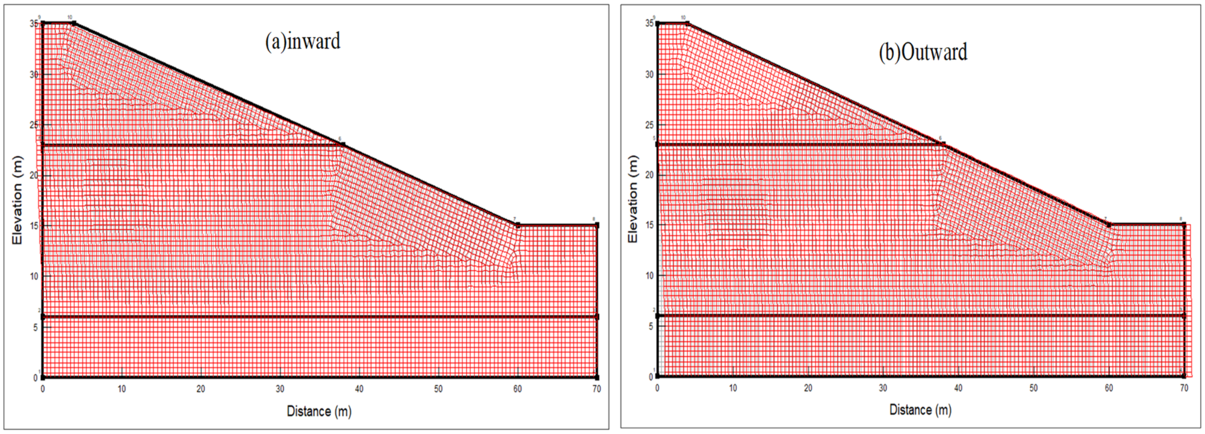

Figure 8. Instantaneous displacement of slope (a) inward (b) outward.

3.5. Slope Stability Evaluation Method under Seismic Action

The time history analysis method of slope seismic stability in this research work chooses the minimum average safety factor method. The minimum average safety factor method takes into account the randomness of slope safety factor in the process of earthquake, and can objectively and comprehensively evaluate the stability of slope. The safety factor is mainly used as the standard to evaluate the stability of slope. Most researchers investigated that the safety factor conforming to the standard can ensure the stability of slope. However, after studying the relationship between the overall stability of slope and the safety factor, some experts and scholars concluded that the value of the safety factor cannot completely represent the overall stability of slope, and the displacement of slope needs to be analyzed. In this research work, the Newmark deformation analysis method is selected as the geo-dynamic simulation method, which can estimate and obtain the permanent displacement of the sliding body along the sliding surface. Applying permanent displacement to the slope stability evaluation can make the slope stability evaluation more scientific and reasonable. Jibson has defined the relationship between the permanent displacement caused by landslides and the corresponding damage degree. The specific corresponding relationship is shown in Table 4. In this research work, the permanent displacement caused by landslides under the action of ground motion will be evaluated by the following evaluation criteria.

Table 4. Relationship table of permanent displacement damage degree.

Permanent deformation/cm	Slope damage degree
0～1	Low
1～5	Medium
5～15	High
＞15	Very high

3.6. Analysis of Displacement under Ground Motion.

As shown in Figure 9, under the action of a seismic wave with a peak acceleration of 0.20 g, the displacement of the slope mainly occurs at the part of the slope after 10 s of the earthquakes, and the displacement at the top of the slope is the largest, reaching 0.0943 m. At the same time, the posterior edge of the slope, the middle of the slope and the bottom of the slope all showed displacement. The maximum displacement of the bottom of the slope is 0.055 m, and the displacement of the rock and soil inside the slope is between 0.075 m and 0.080 m. The displacement distribution law of the slope is obvious. With the increase of elevation, the displacement of the slope gradually increases, and the displacement of the rock and soil position at the top of the slope is the largest.

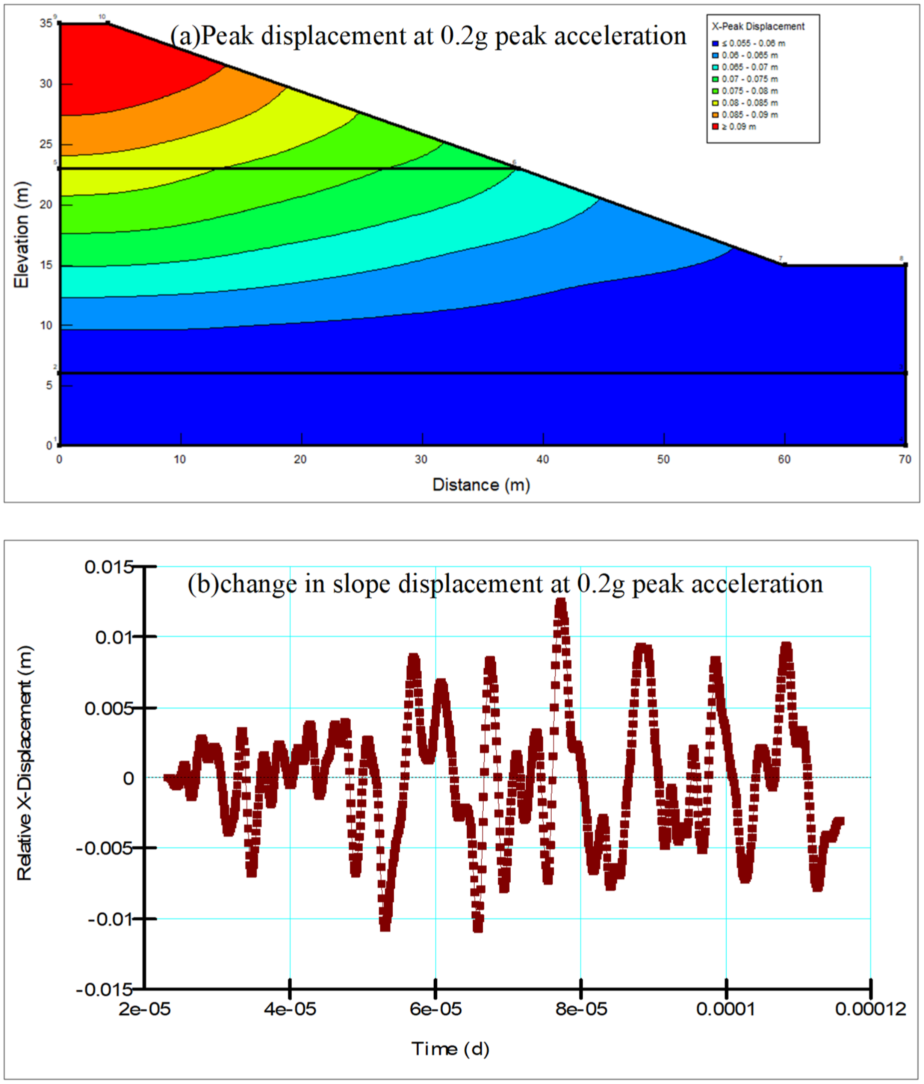

Figure 9. (a) Peak displacement and (b) Displacement change of slope under peak acceleration of 0.2 g.

3.7. Influence of Cohesion, Unit Weight, and Friction Angle in Stability of Slope

The variation of safety factor with cohesion variation of the slope materials are show in Fig 10a. The factor of safety increased with increased in cohesive nature of the slope materials [53, 54]. For variation of cohesion from 0 kPa to 30 kPa of the slope materials the FOS increased from 1.164 to 2.152 for the Morgenstern and Price method.

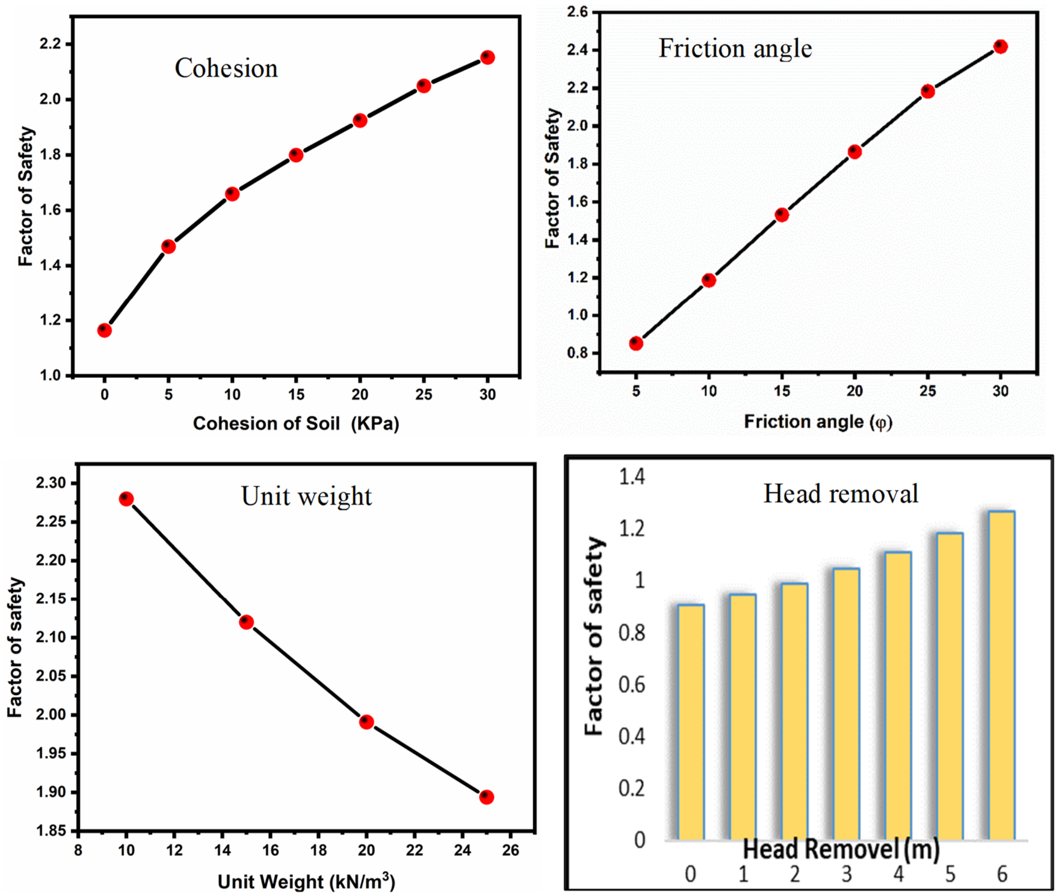

Figure 10. Relationship between Factor of safety (a) cohesion (b) friction angle (c) unit weight (d) head removal.

Figure 10b demonstrates the relationship between the FOS and the internal frictional angle of the slope materials. The factor of safety increased with increased in internal friction angle of the slope materials for all methods of analysis. For variation of friction angle from 5 to 30 of the slope materials, the FOS increased from 0.85 to 2.42 the for Morgenstern and Price method. The Morgenstern-Price method is an effective solution to compute the factor of safety of a slope against sliding. In the MP method, the soil mass above the slip surface needs to be divided into vertical slices to compute the force and moment integrals [55]. The variation of factor of safety with variation of unit weight of the slope materials are show in Figure 10c. The results suggest that there is an inverse relationship between the unit weight and the factor of safety, implying that an increase in unit weight is associated with a fall in the factor of safety. Therefore, this may result in a slope that is possibly less stable. When the saturation level exceeds 80%, the FOS for the slope decreases below 1. This shows that the bulk unit weight of the material increases in relation to the factor of safety [56]. Consequently, the slope is deemed to be in a critical state, suggesting a high probability of a landslip occurrence. By modifying the slope geometry, it is possible to enhance the FOS at this particular saturation level. A series of limit equilibrium analyses conducted on the slope, with a gradual reduction in height from 35 meters to 29 meters at one-meter intervals, revealed a significant enhancement in slope stability. The initial critical factor of safety at 90% degree of saturation was measured at 0.907, indicating an unstable slope condition. However, after the alteration in slope geometry, the critical factor of safety increased to 1.268, denoting a substantial improvement in slope stability. The reduction in slope height contributed to stronger resisting forces or a decrease in driving forces [57], resulting in the more stable slope configuration. Fig 10d shows Variation in the FOS as a result of a decrease in slope gradient. The GeoStudio-based slope stability study linked landslides along the Karakoram High Way to reduced shear strength due to increase in saturation. As saturation increased, the soil's ability to withstand sliding weakened [58]. Analyzing the factor of safety across different unit weights offered insights into soil density's impact on slope stability [59]. These results of the study will help to evaluate the stability of slopes of the studied area and other regions having the similar geology.

4. Conclusions

To achieve the basic aim of the current research study, a comprehensive triaxial compression testing was conducted, altering dry density and saturation; and GeoStudio 2021 tool was used to calculate slope stability analysis; FOS and a key indicator of slope stability; furthermore, slope geometry modifications were done to enhance the stability. The following section summarizes the conclusion.

1. A 49% considerable reduction in soil cohesion was observed when saturation increased from 30% to 90% during triaxial compression tests, indicating decrease in shear forces at increased saturation levels.
2. The friction angle started to reduce by almost 40% at said saturation level range.
3. The decrease in FOS from 1.881 to 0.907 at the saturation range of 30%-90% weakens the high risks of slope failure. A critical slope conditions around of 80% to 90% saturation indicates a general decrease in FOS from 2.28 to 1.89 as unit weight increased from 10 to 25 KPa.
4. Enhancing the friction angle significantly enhances slope stability, substantially strengthening safety against potential failures. Increasing the friction angle from 5 to 30 degrees results in an increase in the factor of safety, rising from 0.85 to 2.42. Moreover, higher cohesion values play a key role in stimulating slope stability, underscoring the main role of cohesion in resisting failure along potential sliding surfaces. Increasing cohesion from 0 to 30 kPa yields a substantial improvement in the factor of safety, increasing it from 1.16 to 2.15.
5. Slope geometry adjustments were found to mitigate landslide occurrences, even when saturation exceeded 80%. Particularly, reducing the slope height by around 6 meters significantly raised the factor of safety. The critical condition's factor of safety, initially at 0.907, improved to 1.268 after the head removal.

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روش‌های ژئوتکنیکی پیشرفته برای ارزیابی پایداری شیب در لایه‌های تثبیت نشده: یک تحلیل جامع

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چکیده:

این مطالعه از روش تعادل حدی (LEM) برای بررسی حرکات شیب استفاده می‌کند. این حرکات در ابتدا توسط فعالیت‌های ساخت‌وساز در پایه شیب ایجاد شد، و رویدادهای بعدی توسط فعالیت‌های لرزه‌ای هدایت شد، زیرا منطقه مورد مطالعه در مناطق رانش اصلی Karakoram (MKT) و Main Mantle Thrust (MMT) قرار دارد. نمونه‌های خاک با رطوبت ۱۳ درصد و وزن واحد خشک ۱۸/۱۴ کیلو نیوتن بر متر مکعب مورد تجزیه و تحلیل قرار گرفتند. این مطالعه نشان داد که افزایش اشباع ناشی از نفوذ آب باران، منجر به کاهش استحکام فشاری محدود نشده و از ۷۱۲ کیلو پاسکال به ۳۴۹ کیلو پاسکال کاهش یافت. پارامترهای مقاومت برشی و تغییر شکل (پیوستگی، زاویه اصطکاک داخلی و مدول تغییر شکل) نیز با درجات مختلف اشباع مورد بررسی قرار گرفتند. نتایج نشان داد که با افزایش درصد اشباع از ۳۰ درصد به ۹۰ درصد، این پارامترها کاهش یافته است. مطالعه پایداری شیب نشان داد که ضریب ایمنی (FOS) از ۱.۸۵ به ۰.۸۶ کاهش یافت زیرا اشباع مواد از ۳۰٪ به ۹۰٪ افزایش یافت. برای ارزیابی تأثیر وزن واحد، انسجام و زاویه اصطکاک داخلی بر روی FOS، موارد متعددی در نظر گرفته شد. تجزیه و تحلیل نشان داد که FOS با انسجام و زاویه اصطکاک داخلی بالاتر افزایش می‌یابد، در حالی که افزایش وزن واحد منجر به کاهش ضریب ایمنی می‌شود. علاوه بر این، پایداری شیب با اصلاح هندسه شیب مانند کاهش ارتفاع مورد ارزیابی قرار گرفت. طبق تحقیقات GeoStudio، شیب حتی در سطوح اشباع بیش از ۸۰٪ ثابت باقی مانده است.

کلمات کلیدی: زمین لغزش، اشباع، GeoStudio، انسجام، تجزیه و تحلیل تعادل حد.