SLOPE FAILURE ANALYSIS OF HAVELIAN LANDSLIDE, ABBOTTABAD PAKISTAN

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ABSTRACT: This research work was undertaken to evaluate the failure analysis of Havelian Landslide which was triggered by rainfall in November, 2015. A site visit was made to collect landslide matrix material samples. Basic in-situ measurements and laboratory tests were performed on reconstituted samples for determining the basic engineering properties of the samples. Series of direct shear tests were conducted on reconstituted samples at in-situ landslide matrix material density by varying percent saturation to evaluate its likely effect on the mobilized shear strength. Finally the Slope/W software was utilized to calculate the Factor of Safety (FOS) along the probable surface failure, by in putting the shear strength parameters corresponding to different degrees of saturation. The analysis revealed that the shear strength of matrix soil decreased with the increase in degree of saturation (% age) and slope become critical around 50% degree of saturation.

Key word: Landslide, degree of saturation, cohesion, angle of internal friction, slope stability.

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INTRODUCTION

Landslides are part of ongoing evolution of landscapes which occur on regular basis worldwide (Varnes, 1978; and Farooq *et al*., 2015). Mostly landslides trigger in natural slopes, but they can also occur in manmade slopes from time to time (Varnes, 1978; Rogers, 1992). Landsliding is associated with different types of hazards like damage to highways, damage to infrastructure, blockage of natural river courses and loss of human lives. The prior knowledge of the causative factors plays an important role to perform any risk analysis and mitigation work. Landsliding is a serious concern in the northern areas of Pakistan. In these areas landslides mostly occur in rainy seasons (rainfall infiltration being the most significant during the monsoon period) every year (Mustafa *et al*., 2015). A number of other factors also contribute to these events including the fragile geology, high seismicity and active faulting.

Shear strength of the landslide matrix material plays a significant role in the stability of earth slopes (Terzaghi, 1950; Rogers, 1992; and Ramamurthy, 2010). The soil like materials draw their shear strength from the resistance due to interlocking of the individual grains, sliding resistance among the soil particles and adhesion among the particles (Terzaghi, 1950; and Yazdanjou et al., 2008). An extensive literature is available related to the study conducted to understand the relationship among the shear strength, degree of saturation and pore water pressure for different sandy soils (Yoshida *et al*., 1991; Farooq *et al*., 2004, 2015; Orense *et al*., 2004; Singh *et al*., 2009; and Ahmed *et al*., 2012). Their studies concluded that the development of pore water pressure within the sandy soil because of rainfall infiltration, is one of the major cause for the initiation of landslide process. Such type of studies have also been carried out successfully for the Havelian landslide failure analysis in order to facilitate the authorities to provide proper mitigation work for minimizing landslide hazards. The main emphasis of the current research work was to note the effect of degree of saturation on the shear strength of the soil only and the pore water pressure measurements were beyond the scope of this research work due to certain limitations.

There are different options available in the laboratories to determine the shear strength of earth materials. The direct shear test is a common approach to find the shear strength of granular soil mostly and less frequently the soil having a fraction of cohesive soil (Kutara and Ishizuka, 1982; Orense *et al*., 2004; and Ahmed *et al*., 2012). The reason could be that the cohesive materials in undrained loading may cause issues in controlling the strain rates during the test. While performing the direct shear test on granular soil, the loading was assumed to be drained (Yoshida *et al*., 1991). Under the specific normal load, the shearing load gets increased from zero to the point where the sample is completely sheared.

The shear strength properties of the natural and manmade slopes, determined in the laboratory have always been found compromised because of the scale effect and the unavoidable constraints to reconstitute the samples under exact same conditions as in the field. In most of the cases where the slope failures have already been triggered, back analysis could be performed to determine shear strength parameters of the matrix material (Collins and Znidarcic, 2004). Similar approach was found suitable in this study to perform the failure analysis of Havelian Landslide by Slope/W software to investigate the variation of FOS with degree of saturation.

MATERIALS AND METHODS

Study Area: The Havelian landslide was triggered on November 21, 2015 in Havelian Tehsil of Abbottabad near Poona village (Fig-1). The incident occurred after the development of tension cracks at few places near the crest of the landslide mass during the 26th October earthquake of a magnitude of 8.1 having epicenter in Hindukush Mountains in Afghanistan. A few weeks later, the landslide occurred after an intense rainfall. As a result, a huge volume of slope material (4.16×10^6 m^3) moved down and more than 50 houses were damaged and around 700-meter long Havelian-Sajikot Satora road was blocked that was the only road that connected more than 25 villages.

The study area was seismically active and belonging to the Lesser Himalayas. The region was bounded by two thrust, in the north by Punjal thrust and in south by Nathiagali thrust formed as a result of compression and tight folding. Stratigraphy of the area indicated that it was a part of Abbottabad Formation that is predominantly limestone dolomitized at some places.

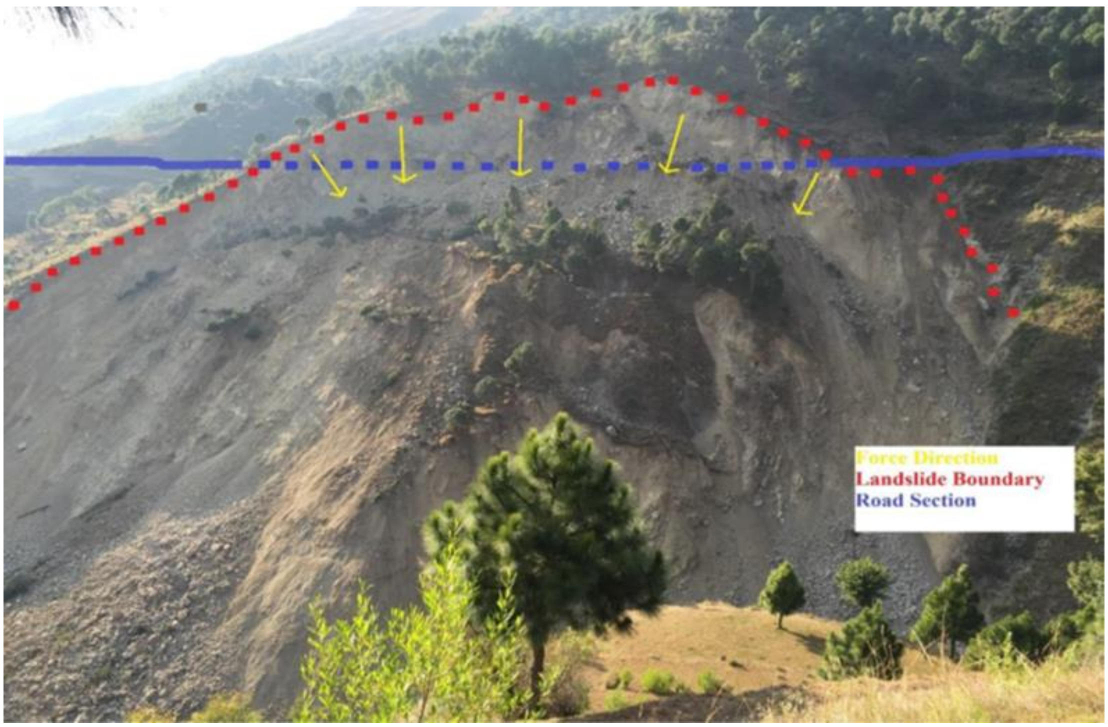

Fig- 1: Failure surface of Havelian Landslide, the collapsed section of the road is highlighted in blue.

Lithologically the landslide consisted of the weathered boulders of limestone and dolomite of varying size were embedded in clay matrix. The upper part of the landslide matrix was composed of clay (rich in organic matter) and the lower part mostly composed of crushed limestone.

Site Visit and Field Investigations: A site visit was made to collect the information about the landslide including; its lateral and vertical extend, failure surface orientation, in situ moisture content and field density measurements. The dimensions and the orientation of the failure surface were determined by Brunton compass. The disturbed matrix material samples were taken from the Havelian landslide failure surface from different locations and were brought to the laboratory to perform different tests in order to determine the basic engineering properties, classification and shear strength of the landslide material.

The in situ density of the matrix material was determined by using the sand replacement method (ASTM D1556). The test was performed at three different locations along the failure surface to find the averaged in-situ density (Fig-2).

Fig- 2: In-situ density determination by sand replacement method along the failure surface.

Laboratory Testing Methods and Analysis: The following laboratory tests were performed to investigate the engineering properties of the soil. For all the laboratory tests soil samples were sieved though No.4 size except the actual grain size distribution analysis of the matrix soil.

Determination of index soil properties: The basic index tests were performed to investigate the engineering behavior of the matrix material by using the standard test methods including; Specific Gravity test, the Particle Size Analysis, Hydrometer test, Atterburg Limits (consistency tests), Compaction tests and Permeability test using Falling Head test apparatus.

The Grain size distribution of the samples were determined by sieve analysis (ASTM D422-63), and Hydrometer test (ASTM D4221). In this context, three different trials were conducted to find the averaged gradation curve and proportion of different sizes of the particles of the landslide matrix material. A hydrometer analysis is a way to grade the fine-grained soil, silt and clay (passing sieve #200, those cannot be graded by regular sieves in the laboratory

ASTM D854-97. "Standard test method for determining specific gravity of the soil", was used for the specific gravity determination of the soil samples that was further used in combination with in situ density to find out the void ratio, porosity and degree of saturation.

The soil consistency was determined using the Atterberg limits test apparatus following the standard procedure (ASTM D4318). The knowledge of soil consistency is important in predicting how the soil might behave in the natural field condition at different moisture contents. Three different trials were conducted to get the average value of liquid limit and plastic limits of the landslide material.

The Standard Proctor compaction test method (ASTM D698-07) was performed to see the effect of moisture content on the given density and to find the maximum dry density of the matrix soil.

The falling head permeability test was used to determine the permeability of landslide matrix material (down sieve # 4). The test is suitable for fine grained materials with intermediate and low permeability such as matrix material.

Shear strength tests: There are different options available in the laboratory to determine the shear strength of earth materials. The direct shear test (ASTM D 3080) is commonly utilized approach to find the shear strength of granular soil mostly and less frequently the soil having a fraction of cohesive soil (Yoshida *et al*., 1991; Farooq *et al*., 2004; Orense *et al*., 2004; and Farooq *et al*., 2014). Series of direct shear strength tests were performed by varying degree of saturation at three constant normal loads to find out the maximum shearing load. The test was conducted by using the shear box with 6 x 6 x 2cm dimensions (Fig- 3). The relationship of specific normal stress (load) and peak shear stress at failure were plotted to for each degree of saturation to determine the shear strength parameters.

Fig- 3: Simple Direct shear test apparatus used for this study

Slope Failure Analysis: There are several methods available to perform slope failure analysis considering specific field conditions (Bishop, 1955; Janbu, 1955; and Fredlend, 1984). The limit equilibrium method is most commonly used for the soil slopes (Collins and Znidarcic, 2004). Different software packages are available in the market to perform stability analysis from simple to complex slope. SLOPE/W is one of the most commonly used software based on Limit Equilibrium approach, to analyze both simple and complex slopes. The software offers a variety of standard methods to compute the factor of safety including; Ordinary methods of slices, Bishop, Janbu and Morgenstern amongst the most common ones.

Slope failure analysis of the Havelian landslide was performed by first drawing the most probable failure surface based on field measurements and then by in putting the shear strength parameters determined for each degree of saturation at in situ density. Based on this information the FOS for each degree of saturation was determined in order to see its variation with the shear strength parameters (c and phi) to finding the particular degree of saturation at which the slope failed.

RESULTS AND DISCUSSIONS

Field and Basic Laboratory Testing: The average natural dry density of the landslide matrix soil having little organic content was determined as 15.89 kN/m^3 which indicates that the soil was not greatly compacted in natural field conditions.

All the basic laboratory tests were performed on the landslide matrix material passing through sieve #4. Because the field samples contained appreciable amount of gravels which were unsuitable to use as these were in the various laboratory tests. The matrix material was assumed to be the controlling agent in the given condition for the given slope (Ahmed *et al*., 2012). The results of the index properties of Havelian landslide soil matrix are given in the Table-1, which indicated that the soil had low plasticity index (PI = 5) and classified as GC (silty clayey gravel) according to USCS.

Table-1: Summary of index properties of Havelian Landslide material.

Sp. Gravity	**In situ (ϒ d)**	**Atterberg limits**			**Particle size analysis**			**Soil classification**	
		LL %	PL%	PI	gravel %	sand %	silt and clay %	AASHTO	USCS
2.61	15.89 kN/m^3	5	30	5	44	11	47	A-6	GC (silty clayey gravel)

Direct Shear Test Results: Series of direct shear tests were conducted on the reconstituted matrix soil samples at in-situ dry density for varying degrees of saturation from 10, 20, to 100% with the increment of 10% for each test. The direct shear strength tests were performed at situ density to investigate the strength parameters under the natural field conditions in which the landslide failed (Ahmed *et al*., 2012). The data of the series of test results by different degree of saturations were used to plot the load versus deformation curves to find the maximum shearing load values against the maximum horizontal deflection. Three different normal loads of 40 kPa, 67 kPa, and 95 kPa were selected to plot the load versus deformation curves for each degree of saturation, as suggested by Farooq *et al*., 2004 and Ahmed *et al*., 2012 in their studies. In this way three load deformation curves were obtained against every constant normal load for each degree of saturation. Fig- 4 shows the variation in the shear stress and horizontal deflection for varying degree of saturation at constant Normal load of 67 kPa as a representative of other normal loads, the overall trends show that as degree of saturation increased as the shear stress decreased, which were similar to the studies conducted by Ahmed *et al.*, 2012 and Farooq *et al*., 2015).

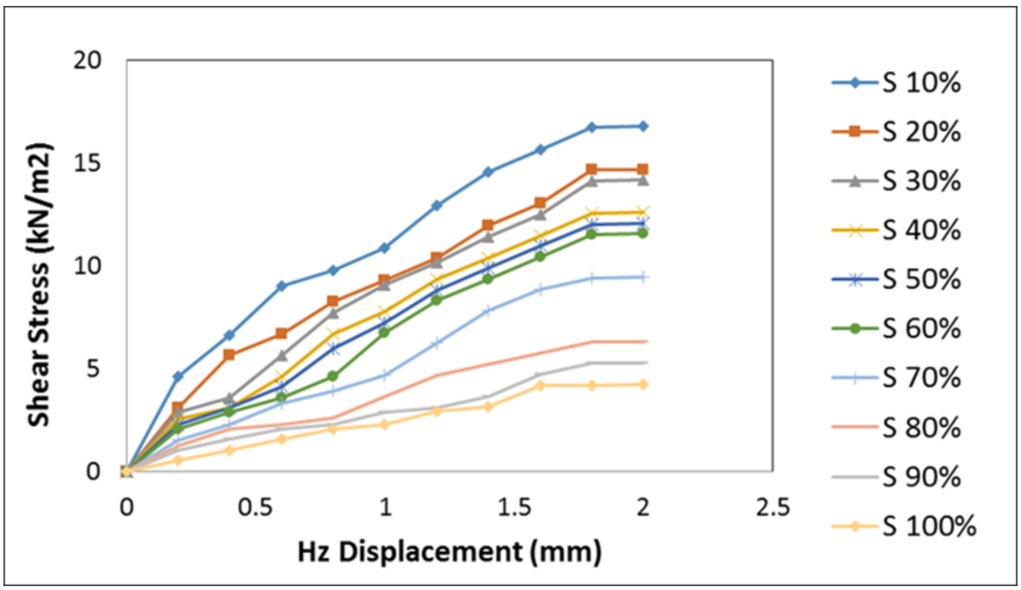

Fig- 4: variation of shear stress versus horizontal deflection at normal load of 67 kPa for different degrees of saturation.

The peak shear stress values for three different normal loads for each degree of saturation were plotted on the graph to estimate the shear strength parameters cohesion 'c' and angle of internal friction 'ϕ'. The results were combined for all the degrees of saturation which are provided in the Fig- 5. The slopes of these lines were equal to the friction angle and the intercepts of these lines to y-axis were equal to the cohesion of the matrix material at that particular degree of saturation (ASTM 1972). The series of direct shear strength test results revealed that the cohesion (c) and angle of internal friction decreased from 8.5 kPa to 1.55 kPa and from 5.8^{o} to 2.9^{o} respectively at varying degrees of saturation, from 10% to 100% with an increment of 10% for each test. The trends in the variation of shear strength parameters obtained in this study were similar to the research conducted by various researchers on similar type of soils (Orense *et al*., 2004; Tohari *et al*., 2007 and Farooq *et al*., 2015. Fig- 6 shows the summary of the shear strength parameter values obtained at various degrees of saturation. Overall the shear strength test results indicated that there was a remarkable reduction in the shear strength of the soil with the increase in degree of saturation.

Slope Failure Analysis Results: The shear strength parameters (c and ϕ) obtained from direct shear tests performed at in situ field density for varying degrees of saturation (Table-2), were utilized in Slope/W software for the slope failure analysis. The geometry of the slope was defined first in the Slope /W software to delineate the most probable landslide failure surface (Table-3). The failure analysis was performed using different methods in Slope/W software and finally the Bishop method was selected as it was more suitable with respect of the available data and landslide material type to compute the resultant factor of safety along the probable failure surface.

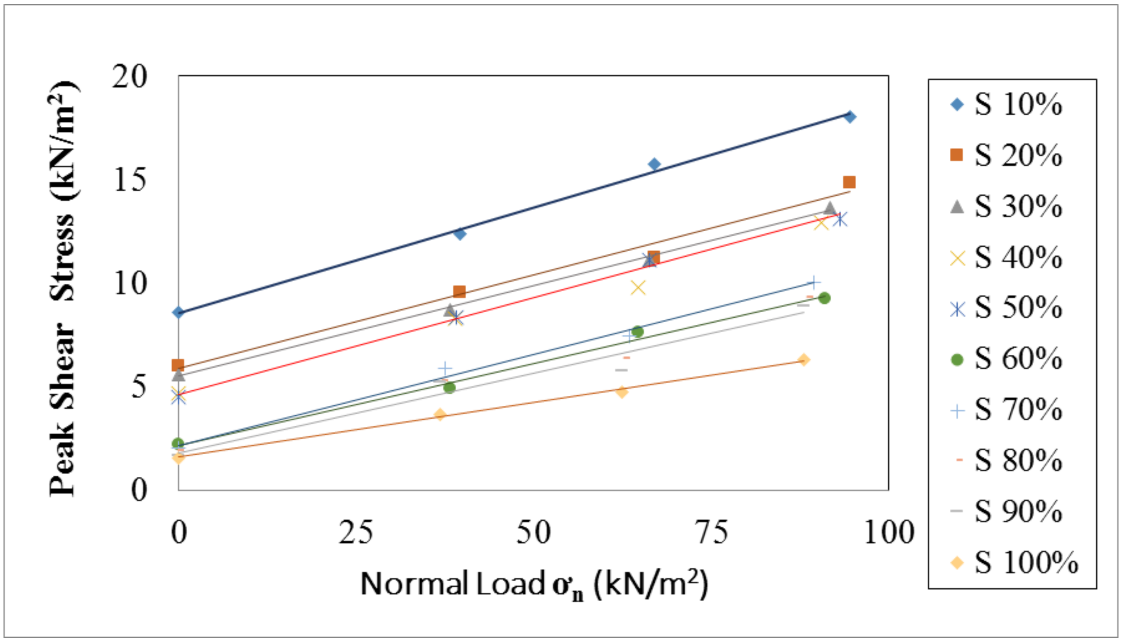

Fig- 5: Variation in the shear stress at different normal loads with varying degrees of saturation

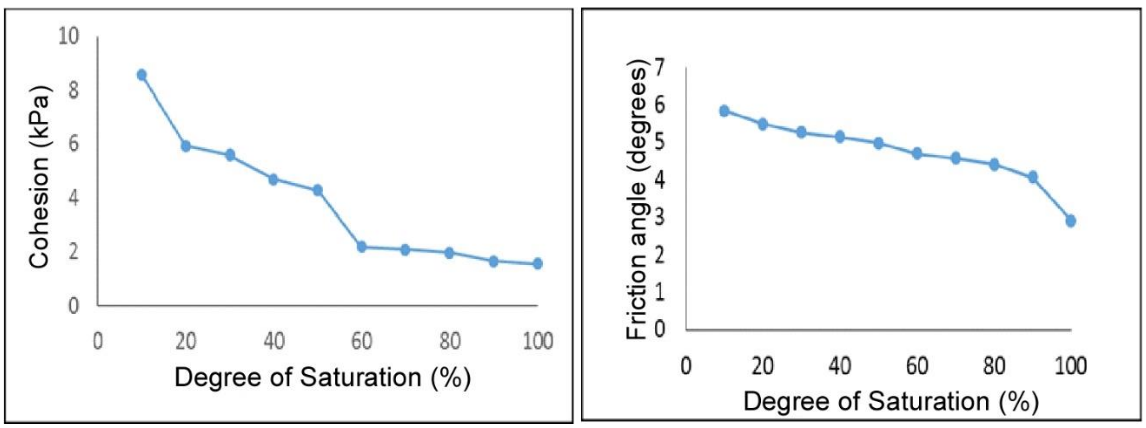

Fig- 6: (Left) Relationship between Cohesion and degree of saturation %, (Right) Relationship between angle of internal friction ϕ and degree of saturation %.

Table-2: Shear strength parameters at varying moisture contents

Degree of saturation (%)	Cohesion (kPa)	Friction angle
10	8.56	5.9
20	5.94	5.5
30	5.6	5.2
40	4.7	5.1
50	4.3	5.0
60	2.2	4.7
70	2.09	4.6
80	1.98	4.4
90	1.65	4.0

Table-3: Geometry of Havelian landslide based of field observation.

Height of slope	160.02 (m)
Length of slope	283.464 (m)
Averaged width of slope	91.7448 (m)
Averaged angle of slope	54.7°
Total volume of soil mass moved in slide	$4.16 \times 10^6\ m^3$

Fig- 7 describes the approximate geometry and the position of slip surface for the optimal model selected for slope failure analysis at different degrees of saturation. The FOS trials were repeated for each degrees of saturation by applying Bishop Method (Bishop, 1955) and the final variations of FOS values were noticed from

1.2 to 0.19 for 10, 20 to different degrees of saturation at in-situ density 14.57 kN/m^3 (Fig-8). The results show that the FOS decreased and the degree of saturation increased that is the similar trend observed in the studies conducted by Ahmed et al., 2012.

Based on the current research work it was concluded that the major causative factor behind the reduction in shear strength of landslides was intense rainfall of short duration. The landslide was triggered apparently not only due to the increase in the pore water pressure but also due to the increased degree of saturation as reported by Orense *et al*., 2004 and Farooq *et al*., 2015.

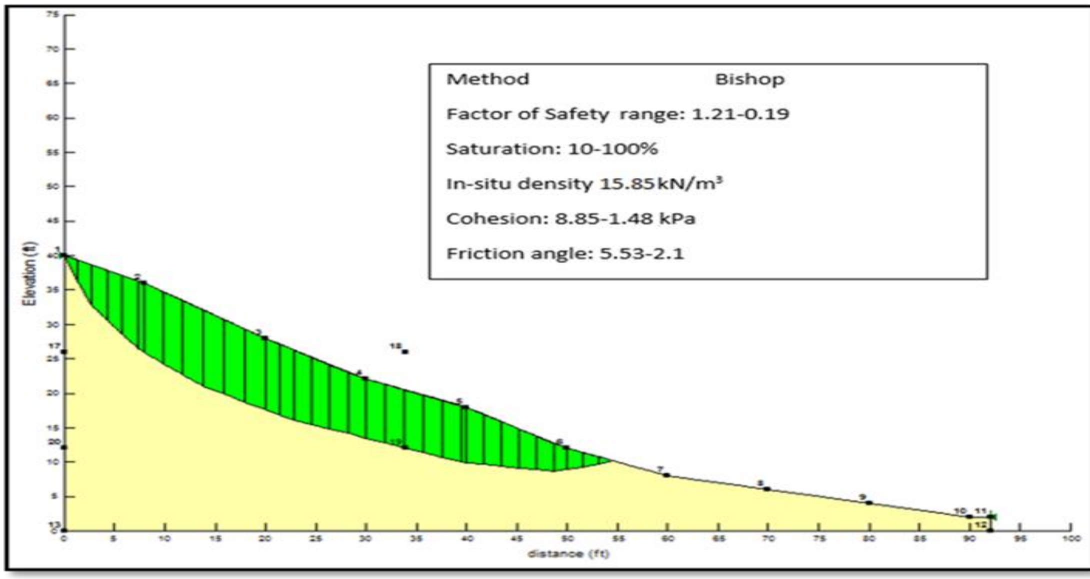

Fig- 7: Approximate Geometry of Havelian Landslide

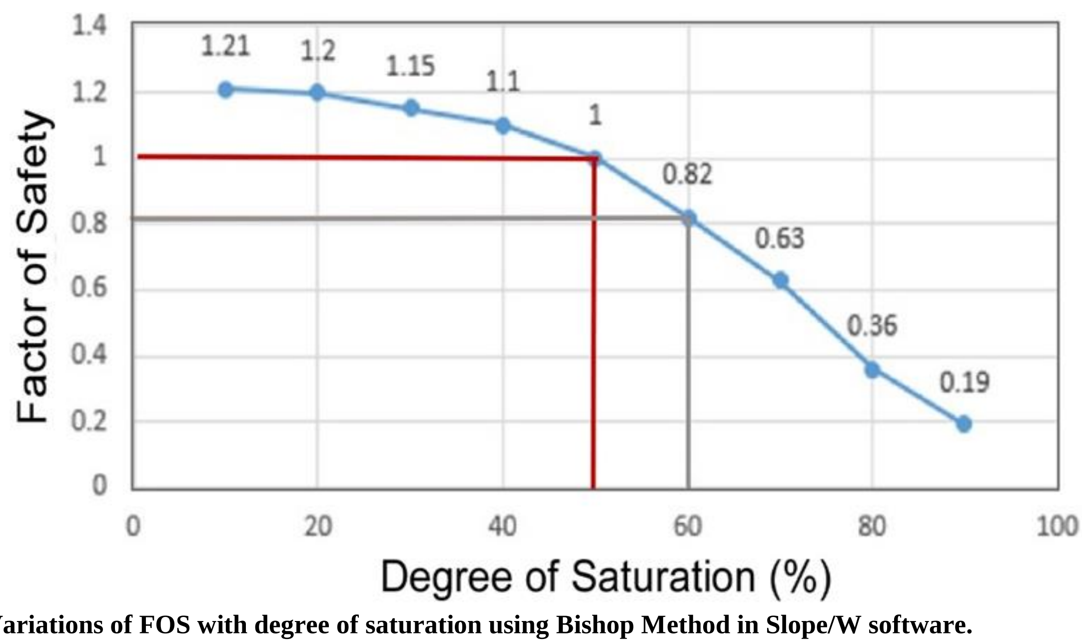

Fig- 8: Variations of FOS with degree of saturation using Bishop Method in Slope/W software.

Conclusions: This study was conducted to perform the failure analysis of Havelian landslide Abbottabad Pakistan. The analysis was based on the information obtained from the field visit of the landslide area, landslide matrix sample's basic field and laboratory tests and the shear strength tests. Based on the in situ and lab testing results the matrix soil was classified as A-6 (AASHTO) and GC silty clayey gravel (USCS). Direct shear strength tests were performed on the reconstituted samples at in situ dry density at varying degree of saturation, from 10% to 100% with an increment of 10% for each test. The tests result, showed that the cohesion (c) decreased from 8.5 kPa to 1.55 kPa and the angle of internal friction decreased from 5.8^{o} to 2.9^{o} as the degree of saturation increased from 10% to 100 %. The shear strength parameters obtained from direct shear tests at in situ field density for varying degrees of saturation (Table 1) were utilized in Slope/W software. The failure analysis of Havelian landside concluded that the factor of safety reduced from 1.21 to 0.19. The slope becomes critical as the degree of saturation approached 50%. The results concluded that the Havelian Landslide failure was likely triggered by the reduction in shear resistance of the matrix material (passing #4 sieve fraction), as a result of increasing moisture content due to rain water infiltration.

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