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Slope Stability Problem in the Chittagong City, Bangladesh

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Abstract

Chittagong, the major port city of Bangladesh is seriously and violently vulnerable for landslide from geological and geographical point of view for many specific reasons. Along with the steep slope, slope cutting, natural weathering and antecedent rainfall causes for landslide of the city during the rainy season caused by thunderclap of heavy storms. This paper presents a quantitative analysis of slope instability problem of the Chittagong city by technical and mathematical analysis of Geotechnical properties of the region from laboratory measurement and modeling the selected vulnerable slopes using a different slope stability technique for circular slicing methods. The soil samples collected from the selected locations which show that the soils are medium to very fine sand consisting of medium to fine grains ranging from 37 to 57% with a tiny amount of silt and clay instance ~7%. Very low cohesive strength was observed for loose and dry samples. Angles of internal friction from 13° to 40° were determined while slope angles from 50° to 80° or more are measured distinctly. This steepness of the slopes is caused for landslide evident from the mathematical modeling. Most of the slopes beyond the friction angle of the slope will fail if the soil will be loosened. Modeling results also show that water pressure builds up within the soil of the slopes were mainly responsible for failure from the natural setting. To protect the slope from failure, the adequate supports have to be suggested which could enable to save the lives and properties of the vulnerable area of the city.

Keywords: *Chittagong city, slope stability, sand, friction angle, cohesion*

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INTRODUCTION

An observable downward and outward movement of slope-forming soil, rock, and vegetation under the influence of gravity is defined as a landslide. Landslides may result from a range of causes such as; weaknesses in composition or structure of the rock or soil, high precipitation, changes in ground-water level, seismic activity, over-steepening of slopes, changes in surface water runoff, and heavy loads on slopes. Besides, human impacts (e.g., construction or mining activity) have a significant influence on altering natural processes in the environment. Slope stability is the ability of a slope to resist stress, excess of what is normally tolerable for the material property of the soil or rock intrinsic to the slope. Slope movements, such as translational or rotational slope failures occur when shear stress exceeds the shear strength of the materials forming the slope [1]. There are some factors that contribute to high shear stress, such as; lack of lateral support, excessive surcharges, lateral pressures and removal of underlying support. On the other hand, low shear strength, due to naturally weak materials, soil weathering (swelling, shirking and cracking) and low intergrannular force due to seepage pressure, also contribute to slope instability. However, slope failure of the Chittagong city is caused by significant loss of soil strength [2]. Khan and Chang [3] also pointed out some specific locations in the area where a number of slopes of several hills (<20 m) (viz., Dev hill, Goal hill, etc.) are seemed to be vulnerable to sliding due to the steep slope.

A critical slope surface exists when a combination of soil and slope factors create a high potential for slope face failure and subsequent erosion consecutively. Over-steepened or disturbed slopes are considered critical when resistance to surface erosion is low and shear and strength resistance tolerances are exceeded [4]. The potential for slope face failure of the slope can be compounded with inadequate slope face compaction under super saturated conditions. In such cases, soil movements are influenced by numerous parameters including angle of repose, soil structure, slope length and erodibility, etc. Some scientific and technical studies also e.g., [5–7] suggest that rainfall is one of the important triggering factor that causes landslides. The effect of rainfall infiltration on slope could result in the changing soil suction and positive pore pressure, as well as raise soil unit weight, reducing anti-shear strength of rock and soil [8–11]. The main causes of such phenomenon seem to be prolonged rainfall events of medium intensity or extreme intensity.

Factors of safety are usually used in evaluating slope stability. The factor of safety can be defined as the ratio of the total force available to resist sliding to the total force tending to induce sliding. A stable slope is considered to be in a condition where the resisting forces are greater than the disturbing forces. On the contrary, an unstable slope failure situation exists when resisting and disturbing forces are equal and the factor of safety equals to unity i.e. FS = 1. A Limit Equilibrium condition exists when the forces tending to induce sliding are exactly balanced by those resisting sliding [12]. Landslide of Chittagong city is mostly shallow slide and an inevitable problem in the Chittagong City which is extremely vulnerable to landslide hazard, with an increasing trend of frequency and damage. For example, the worst case was happened in the Chittagong city on 11 June, 2007 due to seventeen inches of rainfall in 24 h, the highest in the last 25 preceding years. Due to this landslide, 127 people died in the different spots within the city. The victims of the landslide in Chittagong city were mainly slum dwellers; most of them were infants and females living in the shanties during the disaster. It has now become a regular phenomenon in the city and a significant member of slum dwellers are dying almost every year because of landslides in the hills and hilly areas adjacent to the Chittagong city. However, very few studies related to the landslide problems i.e., [2, 3,13] have been carried out in this area. Under the circumstance, there is a huge appeal to study on the instability of the slope in this area. Therefore, it was aimed to i) determines the main engineering properties of soil for some vulnerable locations of Chittagong city, ii) slope instability analysis by limit equilibrium and finite element methods (measuring FS or strength reduction factor (SRF)) to identify the major causes for landslide of the study area, and iii) propose remedial measures for protecting the vulnerable slopes.

STUDY AREA AND GEOLOGIC SETTING

The Chittagong City (Figure 1) of Bangladesh lies between 21°54′N to 22°59′N latitude and 91°7′E to 92°14′E longitude. Chittagong is the second largest city of Bangladesh with about 168sq km area including 4 million populations. The area of Chittagong is situated within the Tertiary hill region of Folded Flank of Bengal Fore deep. The folded part is comprised of the Tipam Sandstone formation and Girujan Clay formations of Pliocene age at the bottom and DupiTilaformation of Plio-Pleistocene age at the top [3,13]. Tipam Sandstone formation is hard and compact while other sandstones are mostly moderate to loosely compacted and consisted of medium to fine grained with minor amount of silt and clay [13]. The Girujanclay formation comprises mainly of mottled clay with intercalations of sand bands and occasional coal streaks. The DupiTila [14] formation consists of sandstone and shale [13]. The city comprises of the area of small hills and narrow valleys, bounded by the Karnaphuli River to the south, the coastal plain and the Bay of Bengal to the west and the floodplain of the Halda River to the east. The highest level of the hills within the city area is about 60 m above mean sea level [15]. The hills of the study area were cut with slopes of 70°–80° despite the potential threat of landslides because of the newer settlements of slums for the homeless people.

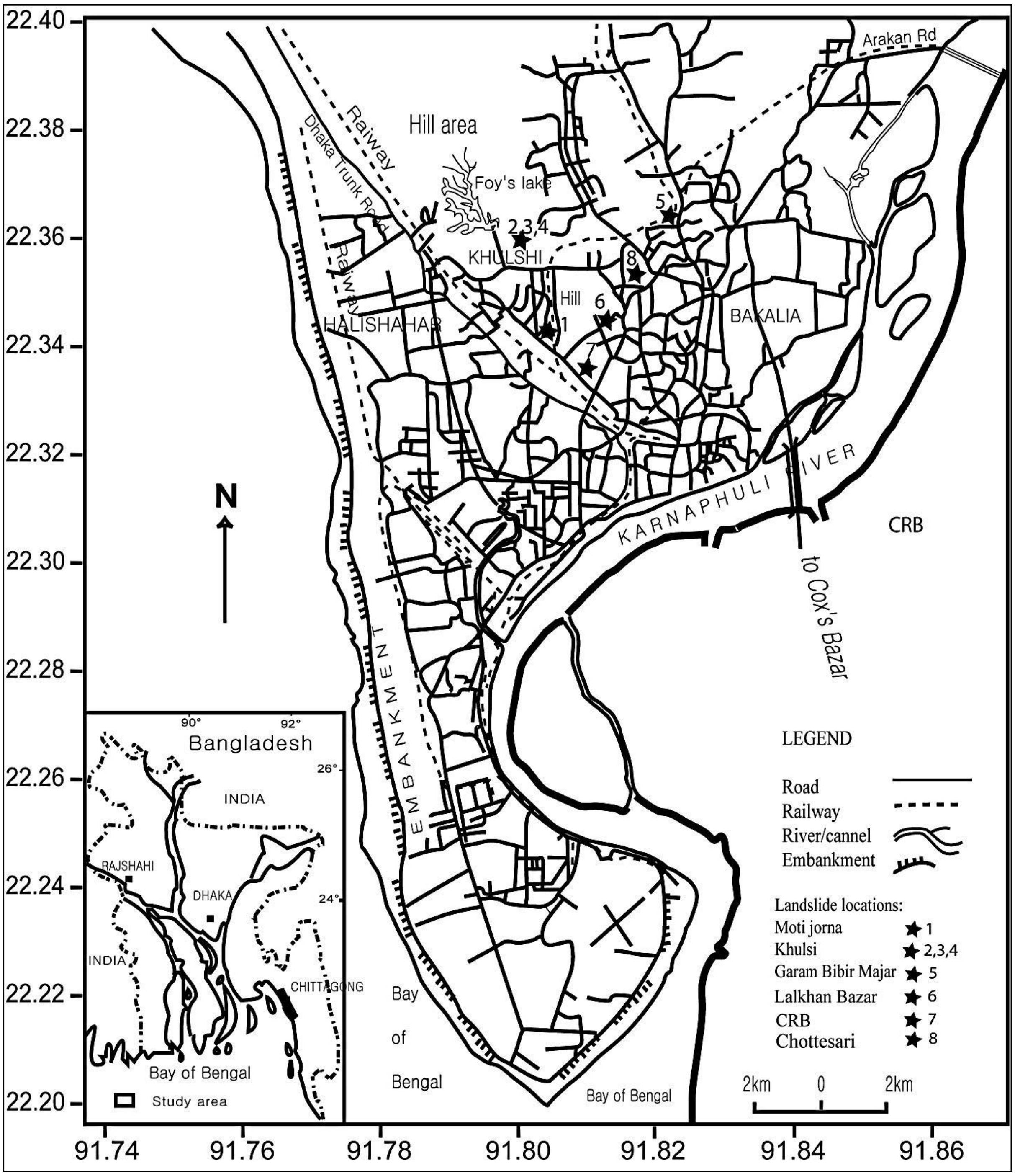

***Fig. 1:** Location Map of the Study Area (modified after Khan et al. 2012).*

MATERIAL AND METHOD

There are eight soil samples which have been collected from different location (Table 1 and Figure 2) in the Chittagong city. Height, length and slope angle were measured during sample collection (Figure 3). Furthermore, the different properties of soils such as grain size, unit weight of soil, internal angle of friction, cohesive strength, Poisson’s ratio, and Young’s modulus were measured by sieve analysis, direct shear measurement, and unconfined compressive strength test.

Motijorna Khulsi 1

Khulsi 2 Lalkhan Bazar

Fig. 2: *Photographs of the Studied Slopes.*

Table 1: *Physical Properties of Slopes and Soil Samples.*

Location	**Sample No.**	**Sediment type**	**Unit weight (KN/m^3)**	**Slope angle (°)**	**Height (ft)**	**Angle of friction (°)**	**Cohesion (KN/m^2)**	**Poisson's ratio**	**Young's Modulus (KPa)**
Moti Jorna	1	Poorly Sorted Fine Sand	0.96	75	31	23.78	0.206	0.28	15
Khulsi 3	2	Moderately Sorted Medium Sand	1.28	80	10	37	0.5	0.26	8.22
Khulsi 1	3	Moderately Well Sorted Medium Sand	1.22	80–90	60	38	0.51	0.26	8.22
Khulsi 2	4	Moderately Sorted Fine Sand	1.24	80–90	50	40	0.522	0.26	8.22
Garam Bibir Majar	5	Moderately Sorted Medium Sand	1.14	40	40-50	13.019	0.183	0.22	25
Lalkhan Bazar	6	Very Coarse Silty Very Fine Sand	0.94	90	30	15	0.192	0.22	22
CRB Coloni	7	Moderately Well Sorted Medium Sand	1.22	50	60	29.33	0.48	0.26	20
Chottessary	8	Poorly Sorted Fine Sand	0.94	55	100	14	0.184	0.22	22

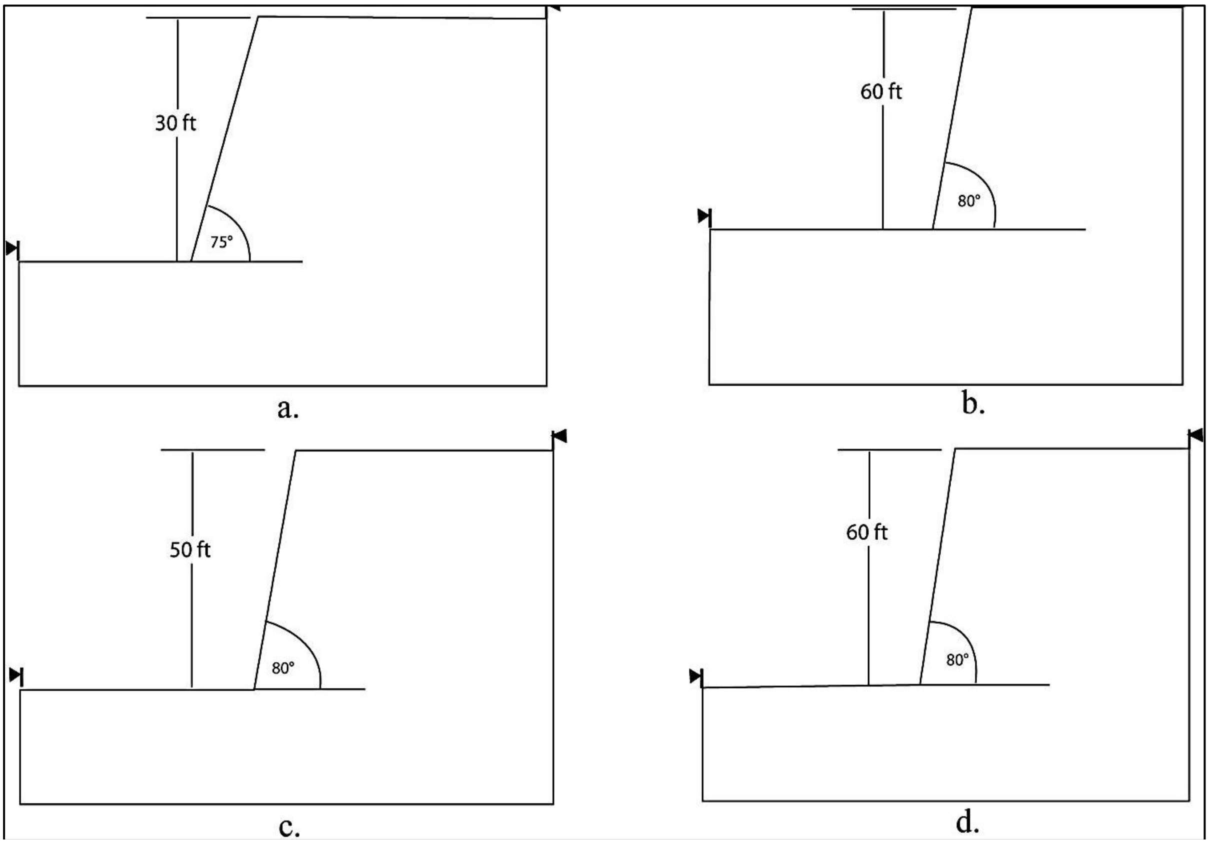

Fig. 3: *Geometric Set up on the Slopes used in the Study. a=Motijorna; b=Khulsi1; c=Khulsi 2; d=Lalkhan Bazar. All Measurements are shown in Feet.*

Sieve Analysis

All soil samples were dried and cleaned for sieve analysis. 300 cm of soil samples was analyzed by sieve shaker (Geotechnical Testing Equipment Ltd, UTG-0411) at the Department of Petroleum and Mining Engineering, Shahjalal University of Science and Technology using mesh sizes of 600, 425, 355, 280, 212, 160, 125, 75 µm and a pan. However, statistical analysis of the sieve was performed by spreadsheet of software GRADISTAT developed by Blott S [16].

Measurement of Unit Weight of Rock

Weight (W) of the each sample was measured by electronic weight machine using ASTM standard. Unit weight (γ) of the samples was measured using the equation;

$$\gamma = \frac{W}{V} \quad (1)$$

where, V is the volume of the cylindrical sampler. The unit weight values were used to determine factor of safety using **SLIDE$^{2®}$**.

Direct Shear Measurement

The test is carried out on remolded samples in the laboratory of the department of Civil and Environmental Engineering of Shahjalal University of Science and Technology using motorized direct shear apparatus (Maxim Ercon Ltd., Model S-81). The soil samples were compacted at optimum moisture content in a compaction mold and the assembled shear box. Then specimen for the direct shear test obtained using the correct cutter was provided. A normal load was applied to the specimen and the specimen was shared across the pre-determined horizontal plane between the two halves of the shear box. Measurements of shear load, shear displacement and normal displacement were recorded. From the results, internal angle of friction and cohesive strength were measured using

Coulomb's shear strength Eq. (2),

$$\tau_f = c + \sigma_{f \tan\phi} \quad (2)$$

where, τ_f= shearing resistance of soil at failure, the c = apparent cohesion of soil, σ_f = total normal stress on failure plane, ϕ = angle of shearing resistance of soil (angle of internal friction). The values of these parameters (cohesion and angle of internal friction) and unit weight were used to determine factor of safety using **SLIDE$^{2®}$**.

Unconfined Compressive Strength Test

According to the ASTM standard, the unconfined compressive strength is the compressive stress at which an unconfined cylindrical specimen of soil will fail in a simple compression test. The test was performed at the Soil Mechanics Laboratory of Civil and Environmental Engineering Department of Shahjalal University of Science and Technology is using unconfined compressive strength tester (ELE International, Model 25-3605). Measurements of strains (%) and stresses were recorded. From the results, Poisson's ratio and Young's modulus were determined. These parameters along unit weight, cohesion and angle of internal friction of samples were used to determine shear stress reduction factor using PHASE^2.

Slope Stability Analysis

Limit Equilibrium Method

The Limit Equilibrium Method is routinely used in the analysis of landslide where rotational or translational movements occur on distinct failure surface. It can analyze the factor of safety, sensitivity to changes in slope geometry and material properties and also allows for multiple material including groundwater profile and reinforcement. The representative geometry and material characteristics (e.g., soil shear strength parameters (cohesion and friction), ground water condition, support and reinforcement) are used. In all limit equilibrium methods share a common approach based on a comparison of resisting force/moments mobilized and the disturbing force/moment. A considerable progress in commercially available limit equilibrium computer software (e.g., Geo-Slope's SIGMA/W, SEEP/WSLOPE/W, SWEDGE, SLIDE$^{2®}$) allows for improved visualization and pre- and post-processing graphics. The **SLIDE$^{2®}$** is the most comprehensive slope stability analysis software with a limit equilibrium method for all types of soil and rock slopes, embankments, earth dams and retaining walls.

In this study, slope instability analyses were done with **SLIDE$^{2®}$** based on a factor of safety of the slope using the rotational methods [17, 18]. The analyses were performed under Mohr- Coulomb strength type to measure the FS. The major parameters of soil are apparent cohesion of soil (c), angle of internal friction (ϕ), unit weight of soil directly taken from the laboratory test result (Table 1) for calculating FS.

Finite Element Method- Shear Strength Reduction Technique

The Shear strength reduction (SSR) technique for slope stability analysis involves the systematic use of finite element analysis to determine a stress reduction factor (SRF) which is equivalent to factor of safety value that brings a slope to the verge of failure. The shear strengths of all the materials in a Finite Element (FE) model of a slope are reduced by the SRF. Conventional FE analysis of this model is then performed until a critical SRF value that induces instability is attained. Most existing SSR techniques are based on the use of the Mohr-Coulomb strength models for materials. The criterion is readily used in the SSR technique for expressing in terms of principal stresses, or in terms of shear and normal stresses (this makes it amenable for use in both FE and limit equilibrium analyses) to allow reduced parameters to be readily calculated when an original shear strength model is reduced. It is readily available in many existing finite element software (e.g., PHASE^2, UASlope, FLAC). In this study, state of stress, SSR and deformation of the slopes was shown using software **PHASE$^{2®}$**. **PHASE$^{2®}$** is a powerful 2D Elasto-plastic finite element stress analysis program for underground or surface excavations in rock or soil. It can be used for a wide range of engineering projects, including finite element slope stability. Slope models from **SLIDE$^{2®}$** are imported to **PHASE$^{2®}$**for getting finite element results. The major parameters of soil are Poisson's ratio and Young's modulus of soil, which were directly taken from the laboratory test result (Table 1) for calculating SRF under plane strain condition.

RESULT AND DISCUSSION

The detailed analytical results of collecting soil samples are shown in the Table 1. The sieve analysis result shows that the soil samples are medium to very fine sand consisting of medium (37%) to fine grain (57%) with small amount of silt and clay (Figure 4). Sample, 4 (Khulsi 2) and 6 (Lalkhan Bazar) consists mostly of fine grain loose sand (60 and 73%, respectively). Unit weights of soil samples are found from 0.94 to 1.24 KN/m^3. Internal angle of friction (ϕ) and cohesive strength (c) were measured from direct shear test which shows that soil of Khulsi area has higher ϕ values (37–38°) while the Lalkhan Bazar area has very low ϕ value (15°) (Table 1). Cohesive strength seems to be low due to loosening the soil sample with hammers.

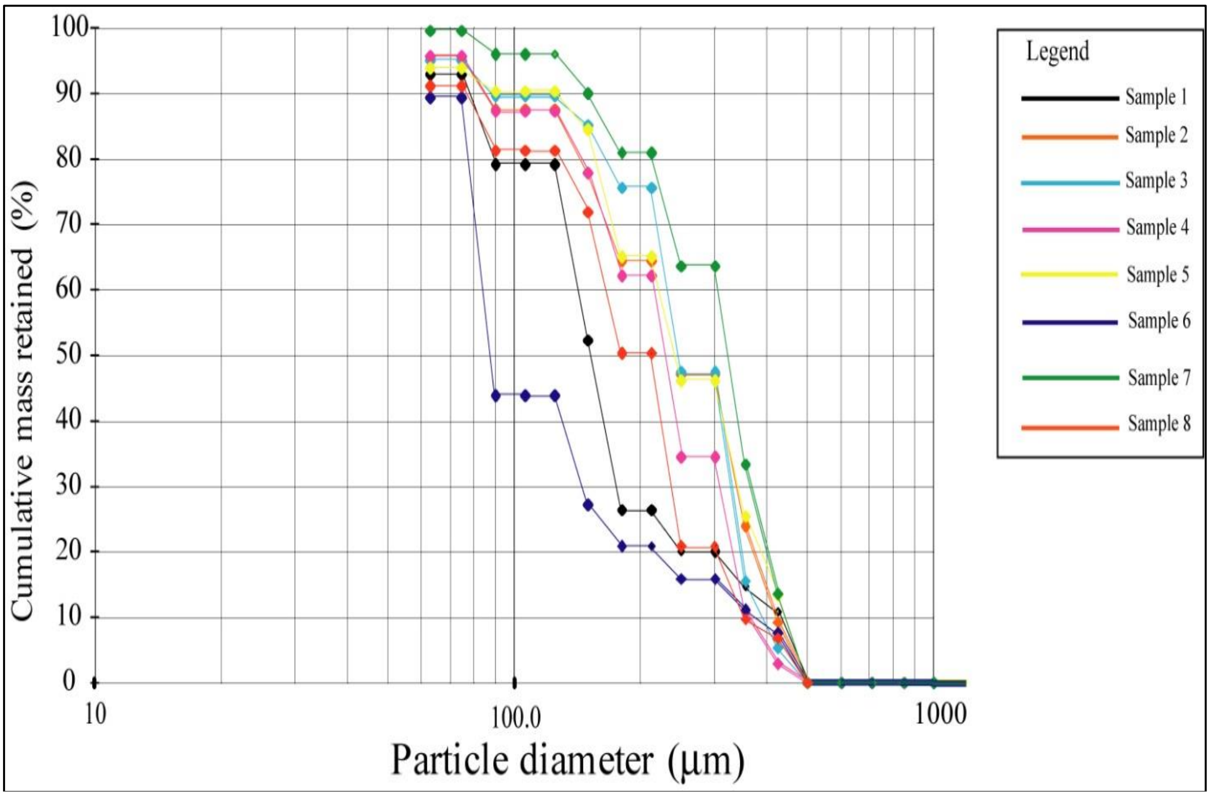

Fig. 4: *Sieve Analysis Result from Collecting Soil Samples.*

The limit equilibrium program **SLIDE** provides 2D stability calculations in rocks or soils using the rigorous and non-rigorous analysis methods for circular surface. There are four slopes (samples 1, 3, 4, and 6) based on the most vulnerability of the study area that were analyzed with an existing slope angle to minimum slope angle of 30° for its stability. The factor of safety (FS) was determined for both dry (Ru=0) and wet (Ru=0. 5) condition of the slope which are given in Table 2. The results show that most of the slopes are unstable with the existing situation and will be stable with lesser slope angle (at 30°) at dry condition (loosen soil). However, all slopes are appeared to be unstable at wet condition. However, for the rigorous analyses the limit equilibrium technique results were compared with finite element method for strength reduction factors of different slopes at better confidence (Table 2). The SRF values are in good agreement with FS values for the most cases. Figures (5–8) also illustrate that the deformation vector in the slopes is indicative for greater deformation of the upper part of the slope face.

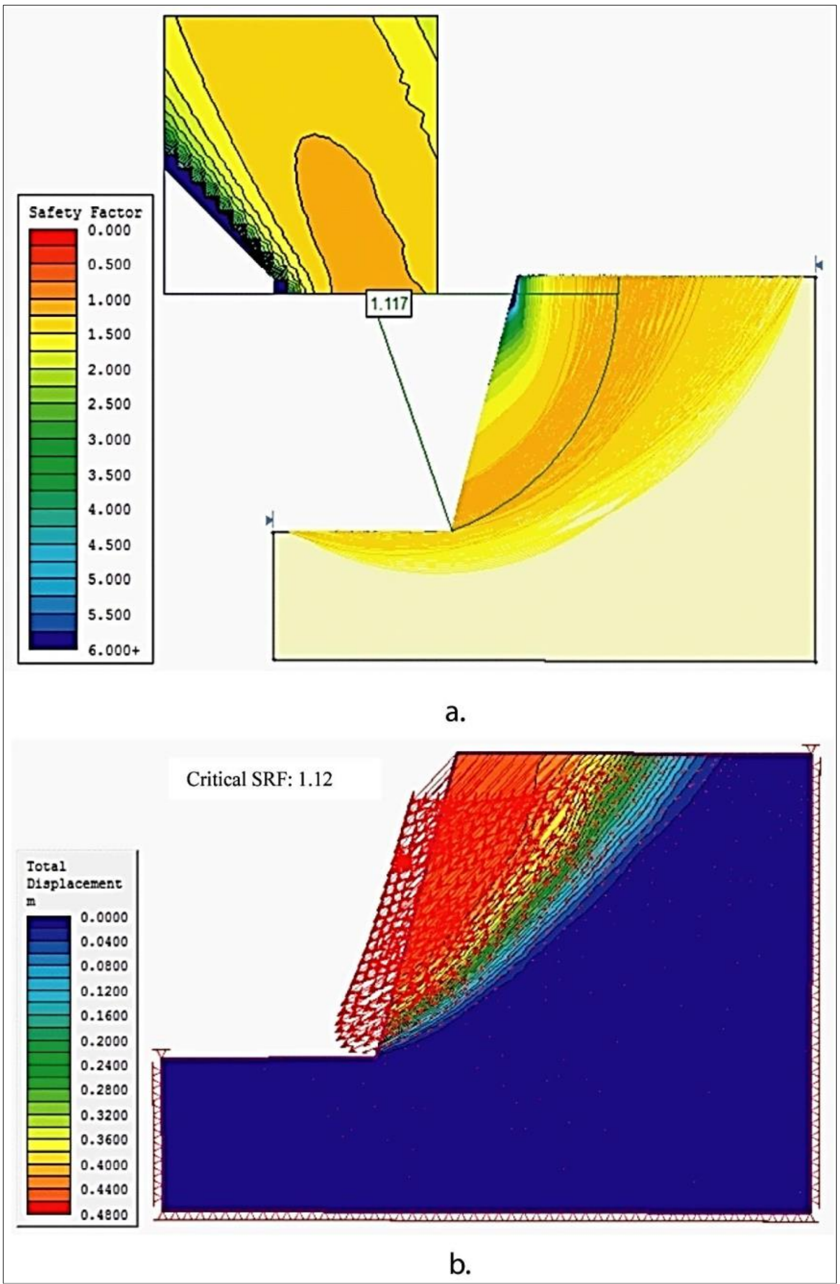

***Fig. 5: (a)** FACTOR of Safety in Motijorna Area using the Bishop's Simplified Method, and (**b)** Deformation Vector with SRF using Finite Element Method.*

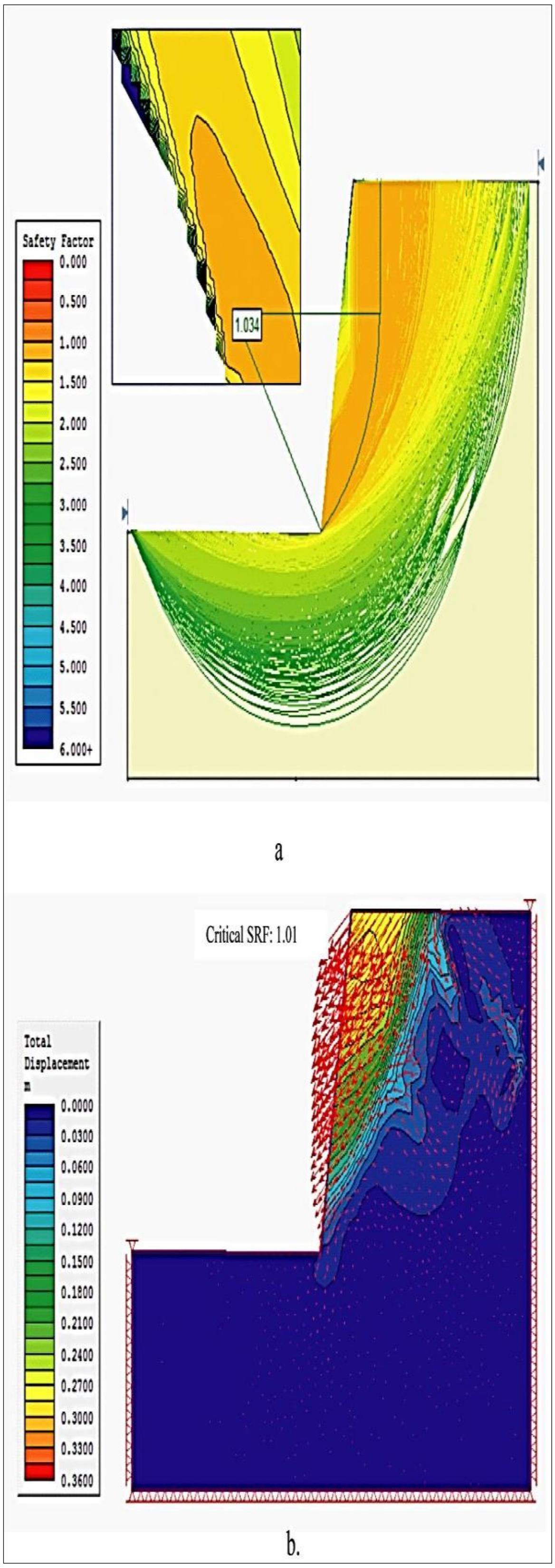

Fig. 6: ***(a)*** *Factor of Safety in Khulsi 1 Area using the Bishop's Simplified Method, and* ***(b)*** *Deformation Vector with SRF using Finite Element Method.*

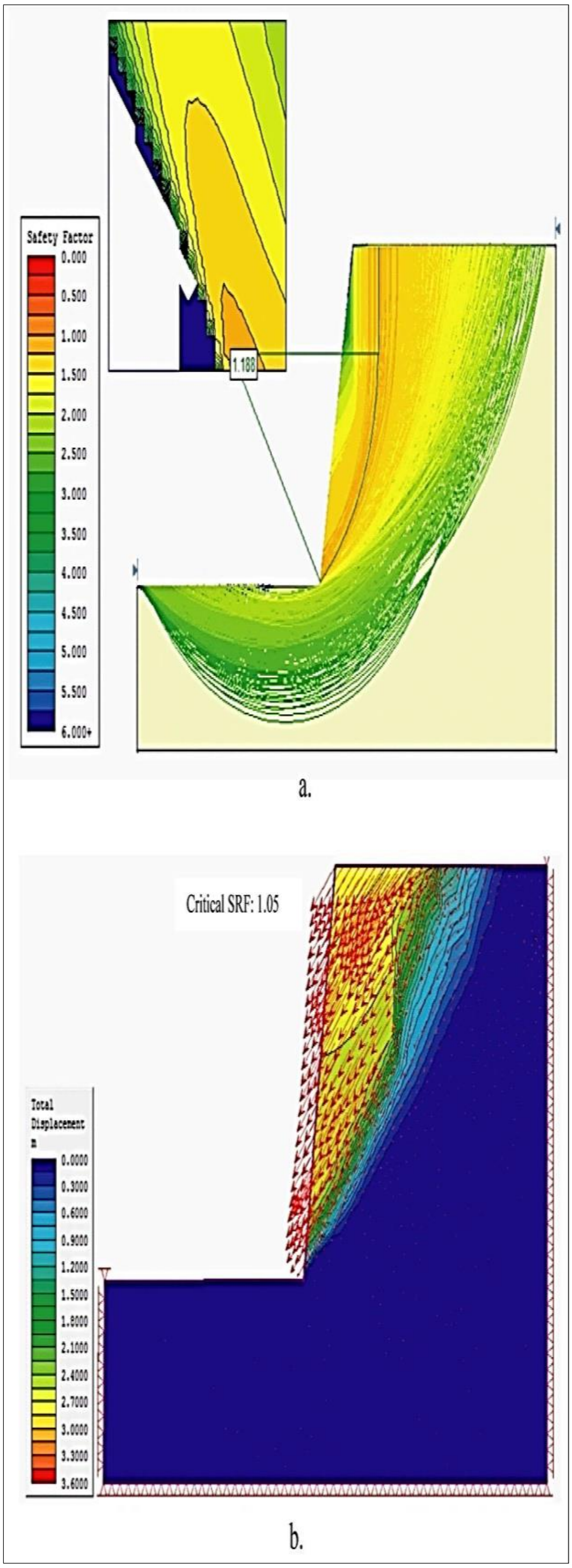

Fig. 7: ***(a)*** *Factor of Safety in Khulsi 2 Area using the Bishop's Simplified Method, and* ***(b)*** *Deformation Vector with SRF using Finite Element Method.*

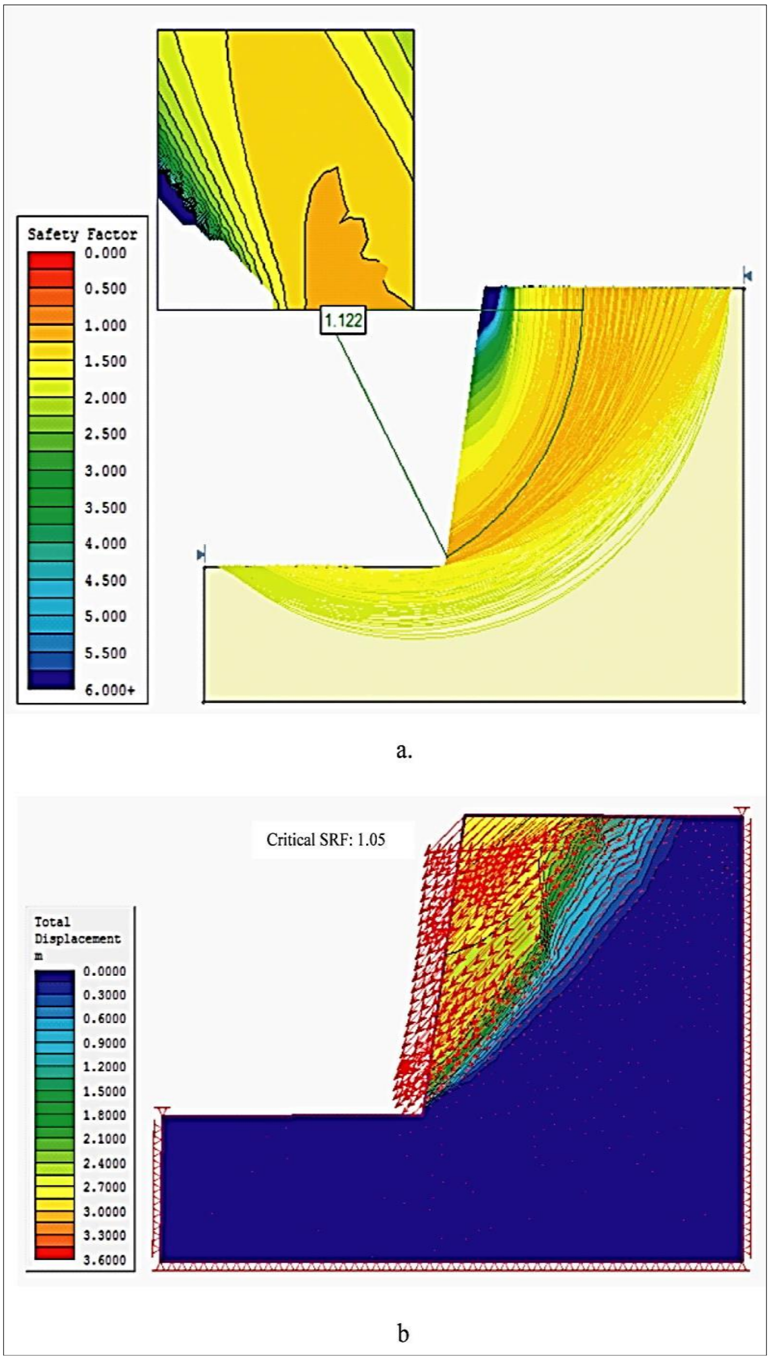

Fig. 8:* *(a) *Factor of Safety in the Lalkhan Bazar Area using the Bishop's Simplified Method, and* ***(b)*** *Deformation Vector with SRF using Finite Element Method.*

Statistical results revealed that landslide events in Chittagong City occurred mostly due to extreme rainfall intensity (for example >40 mm/day) during a short period of time (of 2 to 7 days) [15]. Landslides also may happen after cutting of hill slopes and after earthquakes when the slope stability is disturbed. However, the modeling result shows that steeper slope with lesser cohesive strength and lesser friction angle of soil is also key parameters along with excess water pressure due to heavy rainfall. The question here is that modeling results (for loose sand under dry condition; Table 2) shows failures where slopes are stable in the locations of the natural setting. This may cause for vegetation cover and undisturbed natural setting of the consolidated sediments. In this circumstance, some cohesion values were proposed for natural setting which gives excellent results for describing the slopes of the Chittagong area. The modeling results after proposing cohesion values (4, 80, 80, 120

KN/m^2 for sample 1, 2, 3, and 4, respectively) show that the slopes also failed due to water pressure. Collins and Sitar [19] examined the influence of wetting on steep slopes and showed a 60% decrease in UCS, a 50% drop in cohesion, and 80% decrease in tensile strength in moderately cemented sand upon introduction to water. Results from the modeling evident that most of the slopes of investigating the area of Chittagong area are vulnerable under wet condition (Table 2) due to build up water pressure for heavy rainfall. However, for the protection of slope failure to save the lives, 100% coverage geotextile with different support patterns (Table 3) for existing slopes are suggested. It is seen from the modeling results it is evident that if the slope angle is low, most of the sample could be stable at natural setting.

***Table 2:** Factor of Safety Analysis using Different Numerical Methods.*

Sample No	**Ru Value**	**Slope. Angle in deg.**	**FS**		**SRF**
			Bishop Simplified	**Junbu Simplified**	
1	0.0	30	0.915	0.88	0.91
	0.0	45	0.596	0.568	0.581
	0.0	60	0.428	0.4	0.410
	0.0	75	0.325	0.304	0.210
	0.5	30	0.384	0.357	0.371
	0.5	45	0.152	0.117	0.142
	0.5	60	0.011	0.004	0.015
	0.5	75	0.009	0.001	0.004
3	0.0	30	1.386	1.367	1.500
	0.0	45	0.881	0.866	0.855
	0.0	60	0.501	0.481	0.498
	0.0	80	0.244	0.216	0.230
	0.5	30	0.482	0.468	.470
	0.5	45	0.102	0.098	0.101
	0.5	60	0.008	0.001	0.004
	0.5	80	0.003	0	0.001
4	0.0	30	1.519	1.498	1.501
	0.0	45	0.843	0.822	0.840
	0.0	60	0.548	0.527	0.535
	0.0	80	0.322	0.258	0.281
	0.5	30	0.432	0.371	0.391
	0.5	45	0.039	0.033	0.037
	0.5	60	0.009	0.001	0.006
	0.5	80	0	0	0
6	0.0	30	0.494	0.485	0.451
	0.0	45	0.305	0.299	0.304
	0.0	60	0.188	0.174	0.181
	0.0	80	0.095	0.063	0.071
	0.5	30	0.178	0.172	0.175
	0.5	45	0.041	0.022	0.035
	0.5	60	0.008	0.002	0.006
	0.5	80	0.003	0	0

Table 3: *Factor of Safety Values for the Slopes at Natural Setting and Support Analysis.*

Sample No	**Ru Value**	**Slope Angle in degree**	**Slope condition**	**FS**		**SRF**
				Bishop Simplified	**Junbu Simplified**	
1	0.0	75	Natural setting at dry condition	1.059	1.205	1.120
	0.5	75	Natural setting at wet condition	0.563	0.616	0.490
	0.5	75	**Support at wet condition**	**1.359**	**1.206**	**1.160**
3	0.0	80	Natural setting at dry condition	1.034	1.059	1.010
	0.5	80	Natural setting at wet condition	0.248	0.217	0.233
	0.5	80	**Support at wet condition**	**1.269**	**1.053**	**1.15**
4	0.0	80	Natural setting at dry condition	1.188	1.338	1.050
	0.5	80	Natural setting at wet condition	0.331	0.310	0.320
	0.5	80	**Support at wet condition**	**1.441**	**1.447**	**1.310**
6	0.0	80	Natural setting at dry condition	1.122	1.354	1.050
	0.5	80	Natural setting at wet condition	0.659	0.862	0.667
	0.5	80	**Support at wet condition**	**1.151**	**1.347**	**1.050**

CONCLUSION

Based on analytical results, recent incidence, modeling results and discussions, the following conclusion can be made:

1. Statistical sieve analysis indicates that most of the soil samples are well sorted very fine to medium grain sand consisting of medium (37%) to fine grain (57%) with small amount of silt and clay (~7%).
2. Most of the slopes are steeper (more 75°) while measuring angle of internal friction are varies from 18° to 40° that might be cause for major landslide of the Chittagong city.
3. Modeling result shows that most of the slopes are unstable at dry condition even lesser slope angle (30°).
4. The natural setting of consolidated sand with greater cohesive strength is the cause of the stability of the existing slopes for the selected location. However, excess water pressure within the soil due to heavy rainfall could fail the slope.
5. For the remedial measure, support such as geotextile, masonry wall, etc. are proposed which can improve the soil stability and save the lives and properties of the port city Chittagong.

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