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RESEARCH ARTICLE

A Case Study Based Slope Stability Analysis at Chittagong City, Bangladesh

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Abstract

Heavy rainfall occurs almost every year in Bangladesh and induces landslides in the hilly regions of this country. Among them the Chittagong City has the worst scenario—as there lives a dense population, extending from the plain lands to the hilly area. So, for risk mitigation and management in this landslide prone city, slope safety margin should be determined. From this context, this article presents factor of safety (FS) values in terms of landslide hazard at Chittagong city, based on geotechnical parameters and slope geometry. Thus a preliminary idea on the allowable stress for slope design could be made from this study. In total, 16 hazard sites of the 2007 and 2008, rainfall induced, landslides were examined as a case study along with subsequent collection of in situ soil samples of the failed slopes for geotechnical laboratory analysis. For FS calculation, the limit equilibrium method for infinite slopes was deployed along with the Cousins' stability chart. FS values from 0.94 to 1.57 were found at the hazard sites. The results imply that FS value more than 1.57 should be used for slope safety margin. Moreover, from a probabilistic approach, the authors recommend FS > 1.80 as optimum value for the region. Furthermore, a relationship between slope height to slope length ratio, or slope angle and FS was established for this region for a quick calibration of FS value by simple on-field measurement of slope parameters. It is expected that this scenario based finding would contribute in mitigation of landslide hazard risk at the study area. Additionally, site specific FS values were presented in a 3D contour map. This research could ascertain the location wise slope strength requirement and be considered as a guideline for future calculation for slope safety design against rainfall triggered landslides in this city.

Keywords: Landslide hazard, slope stability, limit equilibrium method, stability chart, simple slope, allowable stress, probabilistic approach

1. Introduction

Landslide or slope instability is a result of stress exceeding the shear strength of the slope material. The excess stress could be added with increasing pore water, excessive overburden pressure due to external load, etc. Moreover, poor soil condition, weathering, slope geometry, soil stratification, discontinuities in the rock body, etc. are some other common factors to decrease soil strength for slope instability (Islam et al., 2014). Slope height and steepness is also pivotal—as described by Putra and Choanji (2016)—with increasing slope height, surface runoff and water transport energy also increase by the action of higher gravity, and at the same time steep slopes tend be eroded more quickly; both leads to instable slopes.

Chittagong city, in the southeastern hilly region of Bangladesh, is a landslide prone city, where almost every year devastating landslides result in casualties and damage to properties (Islam et al., 2017, Mia et al., 2017). Table 1 represents some of the major historic and recent landslide events. It is the second largest city of the country—also regarded as the business capital. Almost one-third area of the Chittagong City Corporation is occupied by hilly terrains. These hilly portions of the city are also being chosen for settlements due to rapid urban growth. Unsafe construction on the hills or foothills is the major cause for the worst scenario of landslide events. It is documented that excessive rainfall triggers the landslide phenomenon in Bangladesh, and is more facilitated in many places by hill cutting and deforestation (Islam et al, 2014; Islam et al., 2017; Mia et al., 2017). Population is growing in this city as well in the hill sites due to continuously incoming population for livelihood and therefore constructions are made more rapidly on the hills and foothills (Islam et al., 2017). Therefore, determination of appropriate and site specific real factor of safety (FS), based on geotechnical parameters of the slope materials where there the hazard has already been taken place, is important and would be really useful for inferring the degree of strength required for slope design.

Table 1. Historical landslides (in ascending chronology) in Bangladesh (modified after Mia et al., 2017).

Date	Location	Deaths	Total wounded	Cause of landslide
16 Jul 1968	Kaptai-Chondroghona road section	--	02	Removal of protective vegetation and heavy rainfall
26 Jun 1970	Ghagra-Rangamati Road Section	01	--	Removal of protective vegetation and heavy rainfall
30 May 1990	Chittagong University	11	25	Extremely heavy rainfall
11 Jul 1997	Rangamati, Bandarban, Cox's Bazar, and Chittagong	30	10	Heavy rainfall
15 Aug 1999	Chittagong	12	09	Heavy, incessant rainfall
13 Aug 1999	Bandarban	07	14	Heavy, incessant rainfall
11 Aug 1999	Chittagong	10	13	Heavy, incessant rainfall
24 Jun 2000	Chittagong University and City area	13	20	Torrential rainfall
11 Jun 2007	Chittagong	135	213	Extremely heavy rainfall
18 Aug 2008	Cox's Bazar	03	09	Heavy rainfall
18 Aug 2008	Chittagong	11	20	Heavy rainfall
31 Jul 2009	Lama, Bandarban	10	--	Incessant rainfall
15 Jun 2010	Cox's Bazar	50	100	A series of rainfall
26 Jun 2012	Lebubagan, Foys lake	90	150	Heavy rainfall
2 Jun 2017	Chittagong	146	20	Heavy rainfall

Factor of safety (FS) is a very popular term that civil engineers use ubiquitously for risk free infrastructure development, and as a classical approach to project the possible relationship between soil strength and expected stress. Among various geohazard, landslide is a potential one that is reported to cause serious damage to life and properties. That is why engineering structures in landslide prone areas are needed to be given proper design and strength considering the appropriate FS value along with proper site selection. In this research, FS values were determined following the conventional limit equilibrium method for slope stability analysis. Engineering parameters of soils alongside slope characteristics of sites where landslide events have already taken place, in 2007 and 2008, were the basis of this disquisition. Some authors, e. g., Islam et al. (2014), Islam et al. (2015), etc. have previously determined safety factor as per slope stability analysis at various locations of the Chittagong City, but this study provides safety factor based on data from the failed slope as a case study. Some of these data were previously used by Mia et al (2017). Notably, devastating rainfall triggered landslide events took place in the city in 2007 and 2008, which caused death of about 149 people (Khan et. al., 2012).

The limit equilibrium method is a common and widely used procedure for slope stability analysis. Simplicity and requirement of less parameters compared to other methods have hold popularity of this method up even though the method has disadvantages like constant FS along the slope plain, and negligence of ground response (Baba et al., 2012). Another important factor is that in this method of analysis there is no requirement to consider strain and uncertainties regarding engineering parameters of slope soil, and are only restricted to shear strength properties, which has also attracted civil engineers for widely accepting these methods (Kakou et al., 2001). However, the differences of FS values from this method with those of others are reportedly less than 6% and even though having some drawbacks, this method is frequently used with pragmatic experience that slopes could be comprehensively delineated by this analytical method (Duncan, 1996; Blake et al., 2002; Baba et al., 2012). In this method, FS value in terms of slope stability is assessed considering the state of equilibrium between the assumed stress and the soil strength along a surface of failure. As a result, in these methods of analysis assumption of sliding surface shape is crucial. The shapes popularly in use are straight line, circular arc, logarithmic spiral, etc., along which both linear (Coulomb's) or nonlinear failure criterion might be applied (Koranne et al., 2011). Among the various limit equilibrium methods the Culmann's method (Taylor, 1948) and the friction-circle method consider the whole mass to move freely while the others divide the whole mass into vertical slices to assess the equilibrium condition individually for each slice and are known broadly as the methods of slices (Koranne et al., 2011). In addition, another categorization of this analysis could be mentioned where one is based on the assumption of infinite slopes whereas the other considers the slopes as a finite surface. However, in this article simple limit equilibrium model of infinite slopes—with materials having both cohesive and frictional strength—was used along with Cousins' (1978) stability chart for simple slopes to determine the FS values: as the existing data best facilitates. Slope stability chart was proposed primarily by Taylor (1937), and now it is ubiquitously used for assessment of FS of simple slopes with characteristically uniform soil (Sun and Zhao, 2013; Javankhoshdel and Bathurst, 2014). These graphical methods require simple calculations, rendering quick estimation of FS of a slope. Hence, these charts could be particularly useful for preliminary design and estimating purposes.

All of the limit equilibrium methods compare the forces, moments, or stresses resisting sliding of a mass with those that could render instability to a slope by examining the equilibrium condition of a slope in response to gravitational pull. Factor of safety (FS) values could be obtained at the end of the analysis that is the ratio of the shear strength to the shear stress.

Moreover, critical slip surface is assumed to be the location where there has the lowest value of FS.

As dynamic slope stability is related to its static stability, static factor of safety for each point, e.g. in-situ field measurements on slope can yield dynamic stability of a slope. As per regional analysis we used a relatively simple limit equilibrium model of infinite slope with material having both frictional and cohesive strength. In general, FS is determined by the following formula:

$$FS = \frac{s}{t} \quad (1)$$

where, s = shear strength and t = shear stress.

FS is exploited to infer the terrain's stability, which is the ratio between the forces that prevent the slope from failing i.e., shear strength of the slope to that make the slope fail i.e., shear stress (Kakou et al., 2001). In common practice, FS > 1 indicates stable conditions whereas FS < 1 unstable.

Slope stability analysis with inhomogeneous dip and/or soils are now done by software. But, slopes with homogeneous inclinations and isotropic soils are conventionally studied, for slope safety, by charts as a quick tool. Taylor (1937) is one of the pioneers who introduced such chart (Michalowski, 2001; Sun and Zhao, 2013). Moreover, these charts could rapidly render FS value with easier calibration process and also could be handy for preliminary site characterization, design and planning (Sun and Zhao, 2013; Huang, 2014). The stability number, pertaining to the chart, a dimensionless parameter ($\lambda_{c\varphi}$) for homogeneous soil slopes, he defined using the chart is also widely used and were later adopted and described by a number of authors, e, g., Janbu (1956), Cousins (1978), Rahman and Khan (1995), Michalowski (2002), etc., and generally is expressed as:

$$\lambda_{c\varphi} = \frac{\gamma H \tan \varphi}{c} \quad (2)$$

where, γ = unit weight, H = slope height, φ = angle of friction, and c = cohesion of soil.

For cohesionless (c = 0) soils $\lambda_{c\varphi}$ becomes infinite; this is when the circle runs on the point where there is slope toe in a 2D view and then critical slip surface becomes plane parallel to the slope surface (Rahman and Khan, 1995; Duncan and Wright, 1980). Cousins (1978), however, used simple slope with homogeneous soil (Fig. 1) for his stability chart, known as Cousins stability chart (Fig. 3). Hence, as the next step of this analysis we used Cousins (1978) stability chart for simple slope, and finally FS values were calculated using the following Cousins' (1978) equation:

$$FS = N_F \frac{c}{\gamma H} \quad (3)$$

where, N_F = Cousins stability number, which would be determined from Cousins chart (Fig. 2). Cousins (1978) assumed the critical plane of failure as a circular arc passing through the toe of the infinite slope. He variably utilized the friction-circle method to construct the chart from which FS values, critical slip circles and toe circles could be yielded for soils having both friction and cohesion. But this chart could be used for slope angles (β) up to 45°. Because of this, FS values of some places (samples CTG03, CTG05, CTG07 and CTG09), where slope angle is more than 45°, could not be determined using this chart. Estimation of the FS values with Cousins chart was performed manually.

Later, an optimum FS value was recommended for the study area based on probabilistic regression. After that, spatial distribution of the FS values were also presented by a 3D map to show site specific and spatial variation of the degree of slope strength requirement within the region. The amount of allowable stress could also be inferred from the FS values. The authors expect that the FS values presented in this article would be useful in landslide hazard risk management and proper land use planning in this region.

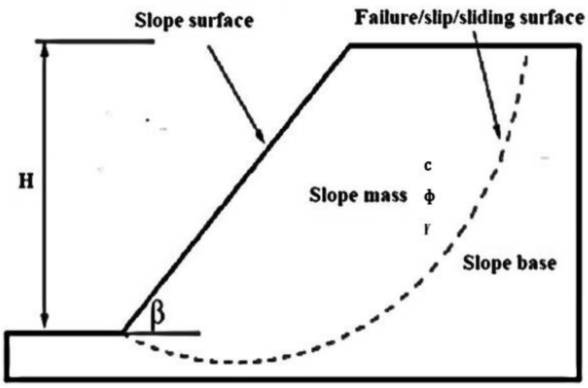

Fig. 1. A typical simple slope with isotropic soil.

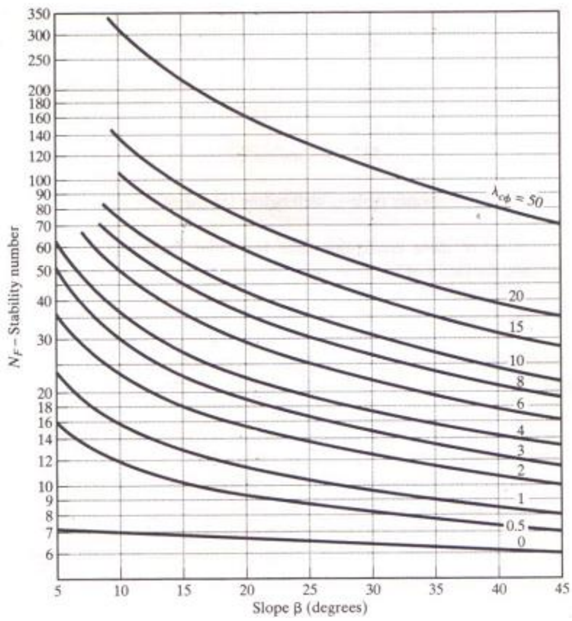

Fig. 2. Cousins (1978) stability chart for simple slopes.

2. Study Area

The Chittagong City is located between 22°14 to 22°24 30 north latitudes and between 91°46 E to 91°53 east longitudes (Fig. 3). It is the second largest city of Bangladesh after the capital city Dhaka.

The city comprises almost of 160.99 sq. km area with a total population of about 2,068,082 (Bangladesh Population Census, 2011). This tropical region experiences monsoon mostly from the month of June to October, with average rainfall recorded more than 2540 mm in this period (Islam et al., 2017).

2.1 Geology and geomorphology

The study area comprises a part of Chittagong hill tracts, which is geologically in the western margin of the Chittagong-Tripura folded belt (CTFB) and more precisely in the plunged zone of the Sitakund anticline (Islam et al., 2018). This Tertiary fold belt in the eastern margin of the Bengal basin—the basin itself is situated in the eastern periphery of the Indian plate—has come into existence because of intricate interaction among the Indian plate, the Eurasian plate, and Burmese platelet (Rahman et al., 2017; Farazi et al., 2018). Like all other anticlines of CTFB, Sitakund anticline also has NNW-SSE axial trend. Therefore, various rock formations, i.e., Dupi Tila Sandstone Formation, Tipam Sandstone Formation, and Bokabil Formation, are exposed from east to west in the study area. Sandstones of the Dupi Tila Formation lie at the top and, therefore, exposed at the surface of the hill tracts of the city. Sandstones of this formation are loose and friable, hence, has less shear strength whereas sandstones of Tipam Formation are mostly hard and compacted unless highly weathered (Islam et al., 2015).

Varied geomorphology and topography is observed in Chittagong City because of its position in the hilly region. The northern and the eastern part of the city has hilly terrains. Otherwise, the western portion is surrounded by the coastal plain and the Bay of Bengal while the southeastern, and the northeastern parts pf the city is covered by Karnafuli River and the floodplain of the Halda River, respectively (Mia et al., 2017). Three geomorphologic units are largely seen in this region—1) hills and associated valleys in the north, with 12-80 m elevation, 2) fluvio-tidal plains in the west and south, including tidal plains of the Bay of Bengal, with 5-10 m elevation, and 3) the Karnafuli River floodplain having 5-10 m elevation (Mia et al., 2017).

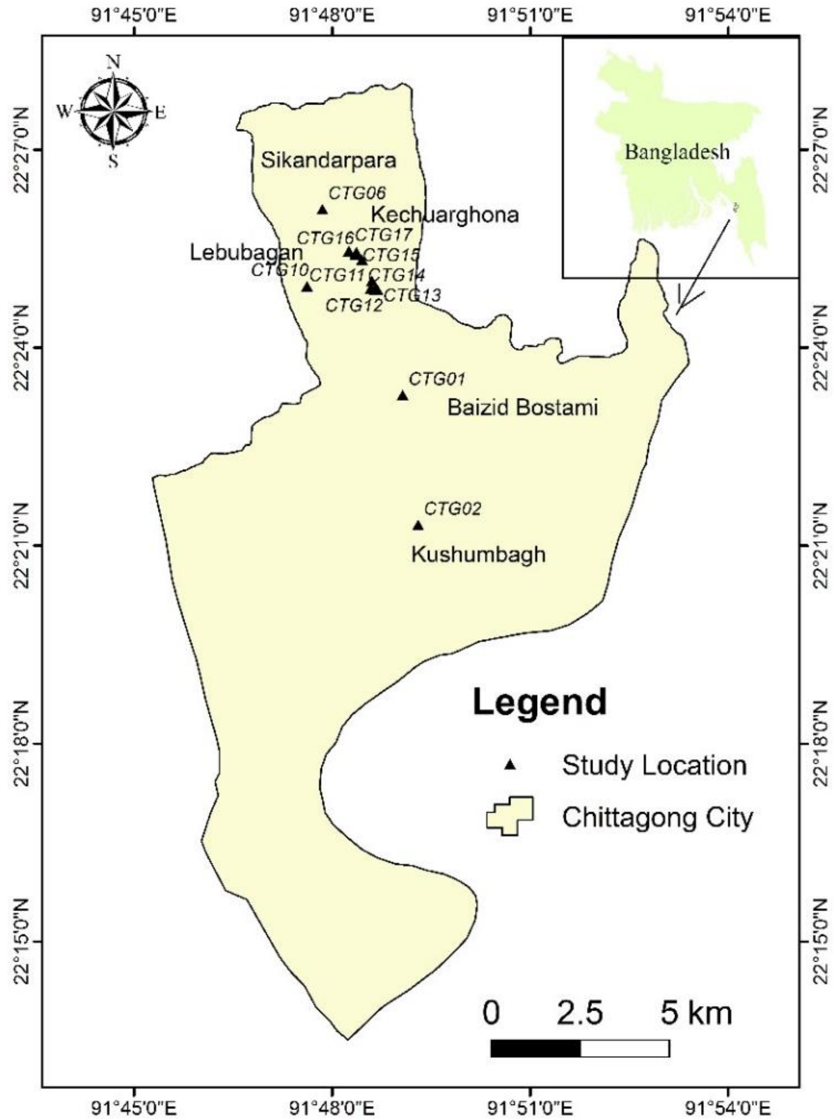

Fig. 3. Location map of Chittagong city showing the study locations of 2007 and 2008 landslide sites.

3. Materials and Methods

This article examines factor of safety (FS) values of the slopes of the landslide hazard sites of the Chittagong City to recommend the minimum FS value that should be considered in this region. Therefore, in-situ samples from 16 hazard sites of 2007 and 2008 landslides were collected along with necessary slope parameters, i.e., slope height and slope angle or inclination, to calibrate FS values against landslide as a case study. FS values were calculated by means of the Cousins' (1978) chart combining with simple limit equilibrium method of infinite slopes. The collected samples of the slope materials belong to the Dupi Tila Sandstone Formation. Slope geometry was measured in the field by measuring tape and clinometer. Notably, during the investigation we found that the slumping took place principally with the sandstones of the Dupi Tila Formation. So, samples of this formation were collected by augar for laboratory analysis. Table 2 represents the slope characteristics and geotechnical parameters of soil samples regarding this study. Strength parameters, i.e., friction angle and soil cohesion of the soil samples were obtained by direct shear test under consolidated drained condition at the Engineering Geology Laboratory of Geological Survey of Bangladesh (GSB). ASTM D3080 standard was followed for this analysis.

Following the estimation of the FS values, a power based regressive curve for these values against the tangent of the slope angles (tanβ) was drawn (Fig. 4).

Table 2. Slope geometry or parameters, and soil characteristics or engineering parameters of soils of 2007 and 2008 landslide locations used in this study.

Sample ID	Slope parameters		Soil parameters			Lithology of landslide materials
	Height (m)	Angle (º)	Unit weight (N/m³)	Angle of friction (º)	Soil cohesion (Pa)	
CTG01	10	48	950	33	460	Yellowish brown medium to fine grained sandstone occasionally interbedded with shale
CTG02	30	64	950	33	562	Yellowish brown medium to fine grained sandstone with carbonaceous matter
CTG03	38	84	950	32	460	Yellowish brown medium to fine grained sandstone with silty shale in places
CTG05	14	55	940	32	443	Light yellow to brown medium to fine grained sandstone with minor shale beds
CTG06	8	24	940	32	448	Grey to yellow, fine to medium grained sandstone
CTG07	16	47	946	34	360	Grey to yellow, fine to medium grained sandstone
CTG08	16	41	948	30	450	Grey to yellow fine to medium grained sandstone
CTG09	18	50	947	29	540	Yellowish brown fine to coarse grained sandstone, but lower part is interbedded with shale
CTG10	14	43	946	27	580	Yellowish brown fine to coarse grained sandstone, but lower part is interbedded with shale
CTG11	15	37	946	26	607	Grey to yellow fine to medium grained sandstone
CTG12	6	36	949	32	320	Grey to yellow fine to medium grained sandstone
CTG13	7	35	946	26	600	Grey to yellow fine to medium grained sandstone
CTG14	6	42	941	27	480	Grey to yellow fine to medium grained sandstone
CTG15	12	40	949	33	530	Yellowish brown medium to fine grained sandstone interbedded with shale
CTG16	20	45	948	33	500	Yellowish brown medium to fine grained sandstone interbedded with shale
CTG17	12	43	948	33	662	Yellowish brown medium to fine grained sandstone interbedded with shale

In this case, it should be noted that tanβ is the ratio of the slope height to slope length. The reason behind selecting the power based regressive curve is that the highest value of the coefficient R^2 was found for power curve compared to other curves like linear, logarithmic, exponential, etc. Again, Islam et al. (2017) showed that all the failed slopes in the Chittagong City has slope angle (β) > 15°. Therefore, we assumed the FS values below the crossing point of the line representing tan15° and the best-fit curve as unsafe and the FS values above the point as safe in terms of rainfall induced landslide hazard in the study region. Thus the optimum FS value we inferred from this probabilistic approach was > 1.80. Additionally, we found from this probabilistic approach that the relationship between tanβ (x) and FS (y) is:

$$\tan\beta = 1.227FS^{-.035} \quad (4)$$

This relationship could be used as a quick tool for on-field primary estimation of the requirement of the degree of strength for slope design in the study area, in terms of the optimum FS value, by simply measuring the slope height, slope length and/or slope angle.

After derivation of FS values at various hazard sites, they were plotted on a 3D map (Fig. 5) was produced using ArcGIS software and finally a map showing spatial variation of the FS values by means of contour lines of equipotential FS value. The map represents spatial variability by means of contour lines with equipotentil FS values. The map was produced in ArcGIS environment, and contouring was performed by interpolation. Moreover, 30 m digital elevation model (DEM) was used for 3D mapping. In this work contouring was performed by Kriging method in ArcGIS environment.

It should be noted that the sand dominating soil samples were not truly homogeneous at each of the locations as presented by Table 2. Rather, minor shale beds were present within the sand dominating units at some places. But, still we assumed the slope materials as homogeneous for simplification of this study.

4. Result and Discussion

Table 3 represents site specific factor of safety (FS) values in terms of landslides—based on the data collected at various landslide hazard sites at the Chittagong Metropolitan area as per deciphering slope stability condition there. This study was carried out by simple limit equilibrium method for infinite slopes, and Cousins (1978) chart, which was the best suit within the limitation of current facilities and data. These data were collected from 2007 and 2008 landslide locations. As the use of the Cousins chart is limited up to slope angles of 45°, FS values of the locations regarding samples CTG03, CTG05, CTG07 and CTG09 could not be determined. We found that the FS values in this area range from 0.94 to 1.57. The highest value was found at Sikandarpara (CTG06) and the lowest at Kusumbagh (CTG02). Here, it should be kept in mind that whatever the FS value is, it is from a failed slope.

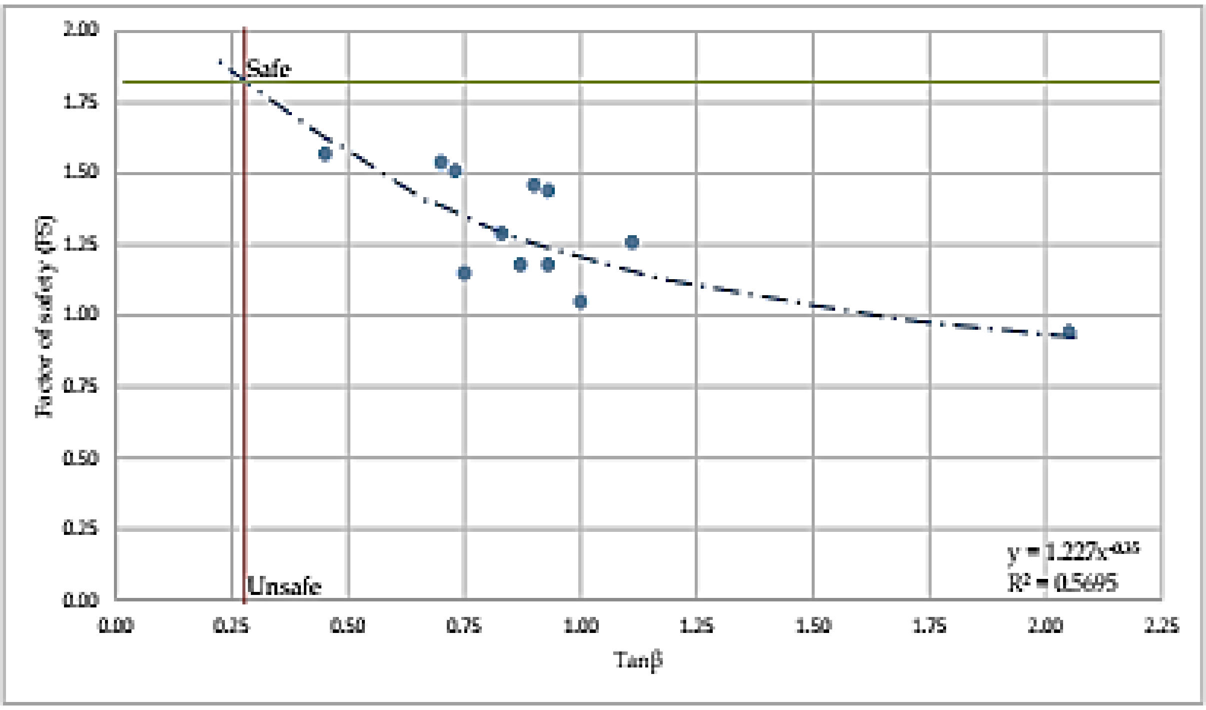

Fig 4. Power based regression curve from the plot of tanβ vs FS. The red line indicates tan15° = 0.27. FS values above the crossing point of the regression curve and the line representing tan15° has been marked safe (FS > 1.80, above the green line) and the values below the point has been marked unsafe (FS < 1.80) for Chittagong City.

Table 3: Factor of safety (FS) values in terms of slope stability at various locations of Chittagong city.

Sample ID	Location name	Latitude	Longitude	Factor of safety (FS)
CTG01	Baizid Bostami	22°23' 17"	91°49' 04"	1.26
CTG02	Kusumbagh	22°21' 19"	91°49' 18"	0.94
CTG03	Lalkhanbazar	22°20' 49"	91°48' 59"	_
CTG05	Sikandarpara	22°26' 07"	91°47' 51"	_
CTG06	Sikandarpara	22°26' 06"	91°47' 51"	1.57
CTG07	Sikandarpara	22°26' 04 "	91°47' 52"	_
CTG08	Lebubagan	22°25' 01"	91°48' 36"	1.18
CTG09	Lebubagan	22°24' 58"	91°48' 36"	_
CTG10	Lebubagan	22°24' 56"	91°47' 37"	1.18
CTG11	Lebubagan	22°24' 54"	91°48' 35"	1.15
CTG12	Lebubagan	22°24' 53"	91°48' 39"	1.50
CTG13	Lebubagan	22°24' 53"	91°48' 41"	1.54
CTG14	Kechuarghona	22°25' 20"	91°48' 27"	1.46
CTG15	Kechuarghona	22°25' 27"	91°48' 22"	1.29
CTG16	Kechuarghona	22°25' 25"	91°48' 21"	1.05
CTG17	Kechuarghona	22025' 48"	91°48' 15"	1.44

This research was conducted upon failed slopes of 2007 and 2008 landslides, and the FS values were calculated within particular failure blocks, which means that FS value as high as 1.57 is not enough for slope design for this region, or in other words there is full probability that this value is inadequate for slope safety. So, FS > 1.57 could be recommended for safe slope design in this region. But, being further advanced a probabilistic approach for more accurate evaluation of slope strength requirement was employed in this study. The FS values above the crossing point of the regressive curve from the plot of tanβ vs FS and the line presenting tan15° was assumed safe (Fig. 4). Thus FS > 1.80 would render slope safety while FS < 1.80 would provide unsafe condition. Moreover, a relationship such as $\tan\beta = 1.227FS^{-.035}$ (Eqn. 4) was established between tangent of slope angle (tanβ), or slope height to slope length ratio and FS for this region. Using this probabilistic relationship, FS values could be used for slopes with slope angle (β) > 45° for the hills of the city and thus the limitation of Cousins' chart could be overcome. Another advantage of the outcome of this probabilistic approach could be that the relationship between tanβ and FS could be used as a quick tool for estimation of FS and slope safety requirement as well. Simply, on-field measurement of slope height and slope length, or even only measurement of the slope angle (β) could serve the purpose. Because, tanβ is the ratio of slope height to slope length.

In addition, spatial variability of FS values were presented by a 3D contour map (Fig. 5), so that site specific strength requirement or allowable stress could be discerned. This map could practically substitute the existing geographic information system (GIS) and DEM based landslide hazard potential maps for the Chittagong City.

Notably, it could be seen from Table 2 that all of the failed slopes has slope angles exceeding internal frictional angle, except for the sample CTG06. The exception was made probably by hill cutting, which escalated the landslide phenomena at that particular place.

Geotechnical engineers use FS conventionally is based on experience. FS is useful because it minimizes the degree of uncertainty and helps assessing the risk associated with slope stability analysis as accurate computation is nearly impossible (Duncan, 1999; Huang, 2014). Furthermore, stress design or the stress limit, he maximum stress that soils of a particular location can absorbs without rendering collapse, or damage, could be inferred from FS values. Because we know from Harris (1995), Farazi and Quamruzzaman (2013), etc. that:

$$Allowable\ stress\ (\sigma_a) = \frac{Total\ stress\ (\sigma)}{Factor\ of\ safety\ (FS)} \quad (5)$$

So, the FS values of failed slopes of the Chittagong City would be highly useful in proper slope design prior to construction at the hilly portions. Engineers and planners would get a guideline from this article about the strength of soil required and the stress limit for infrastructure development and/or about which area is suitable for masonry work. Therefore, this article can show a primary way out for landslide hazard risk free civil engineering work, and eventually for capacity building and sustainable development in this region.

5. Conclusions

Slope stability analysis with the notion of factor of safety (FS) was performed at 16 locations of Chittagong City. The analysis was carried out by limit equilibrium method for infinite slopes and Cousins stability chart. Slope geometry data and in situ soil samples for this research were collected from failed slopes of 2007 and 2008 rainfall induced landslide locations. We found FS values ranging from 0.94 to 1.57 within the study area. So, it is clear from this study that 1.57 is not the adequate value in terms of slope safety requirement in this region. Further, based on a probabilistic approach, we recommend that FS > 1.80 should be used for slope design with proper strength. On top of that, a relationship between slope height to slope length ratios, or tangent of slope angles (tanβ) and FS values was established for this particular region that is: $\tan\beta = 1.227FS^{-.035}$. This relationship could be handy for a quick assumption of FS value and hence, slope safety requirement by simple on-field measurement of slope height and slope length, or only slope angle. Another important factor is that at each of the hazard sites slope angle exceeds the internal friction angle of soils, except one site that we inferred because of hill cutting. Spatial variation of the FS values were depicted in a 3D contour map, from which site specific strength requirement or maximum allowable stress for slope design would be predicted as a nascent guideline. Stability charts provide the preliminary design purpose of slope by slope stability analysis. The FS values and their relation to slope geometry, and the engendered map from this article would act as a primary guideline for landslide risk mitigation and risk management in this locality as well as a base for future estimation of slope safety requirement. Besides, this article could also play a useful role in taking remedial measures, ground improvement, and risk informed landuse planning for this city.

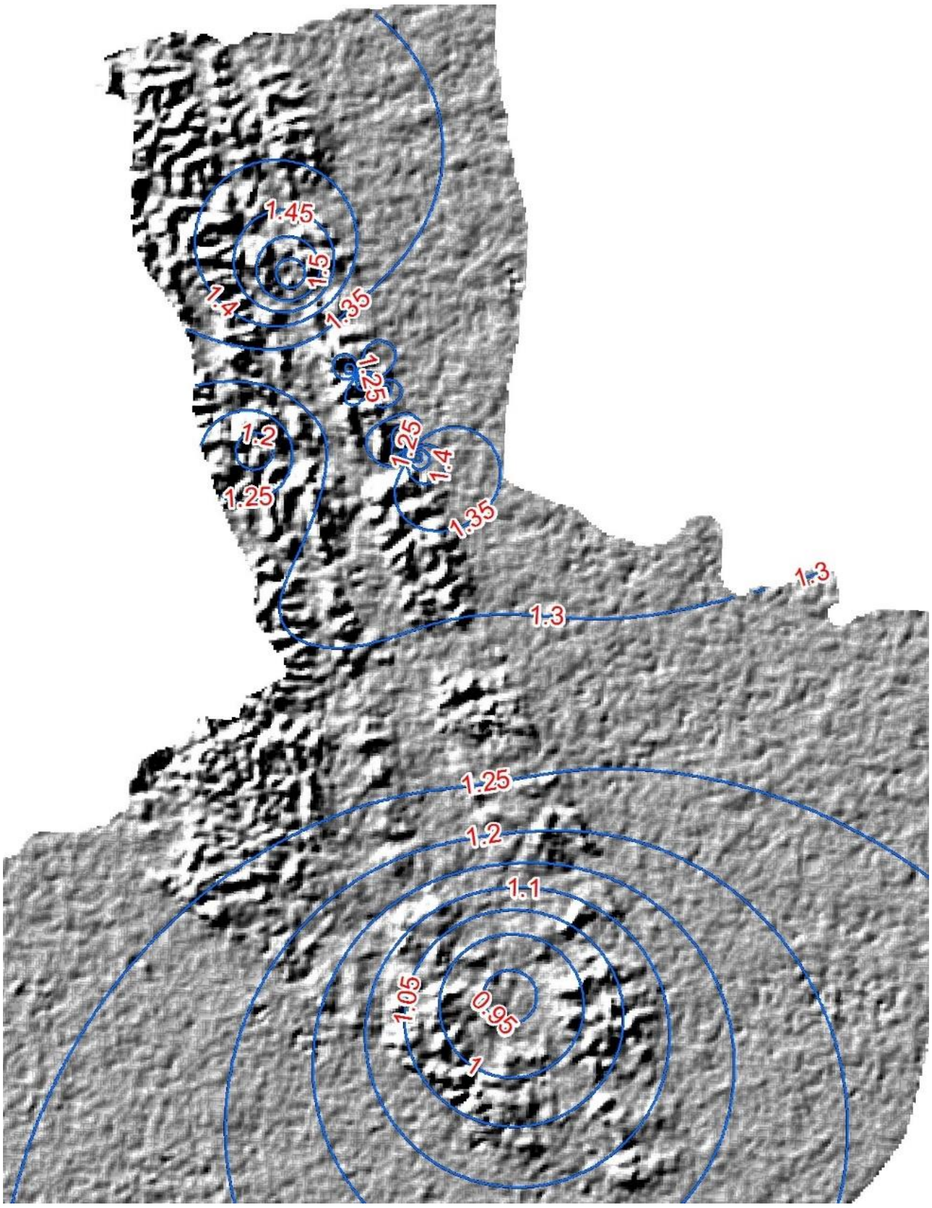

Fig 5. A 3D contour map showing spatial variation of factor of safety (FS) of slopes within the hilly areas of Chittagong City.

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