GIS-based slope stability evaluation of a landslide complex – case study from Paglajhora, Darjeeling Himalaya, India

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Abstract

Detailed mapping (1:5000 or larger) along with finer-resolution (1 m X 1 m pixel) deterministic stability assessment are pre-requisites to understand the behaviour of any active and complex landslide. Geological mapping of the affected slope is the first step towards any such stability assessment which provides fundamental inputs about slope parameters such as morphometry, type and nature of slope forming material (both rock and overburden), geometry of probable failure surface, past landslide movements, their failure modes/ mechanisms, hydrological situation, anthropogenic interferences and land cover, etc. Through detailed geological mapping of above said parameters, probable causal mechanisms involved during the temporal evolution of the slope are ascertained. These thematic maps and related information are used by the planners/geotechnical engineers to understand the slides and design appropriate protective structures in consultation with geologists.

This paper deals with the detailed geological mapping of a large and complex landslide carried out in Darjeeling Himalaya (Paglajhora) revealing various critical slope parameters and relevant geological characteristics, which were subsequently used for the evaluation of the slide and applied as a vital input for the GIS-based stability assessment of the slide complex. Pixel-wise factor of safety (Fs) under three hypothetical saturation conditions were calculated using slope parameters from map and determined shear parameters of representative insitu slope-material. The above stability model confirmed substantial portion of stable slopes (Fs > 1.7) under dry condition becoming unstable (Fs < 1.0) under various increasing saturation conditions. Under dry condition, only 25% of slope was potentially unstable, which increased up to 51% and 65%, respectively, under

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intermediate and total saturation conditions. This stability modeling could be more effective with use of measured depth-to-failure surface, pore-water condition, and larger spatial variability of the determined shear parameters.

Introduction

Deterministic slope stability models are primarily based on determination of physically-based shear parameters of potentially-failing material and developing an insitu hydrological model for subsequently using both the determined physical and hydrological parameters for the calculation of slope instability indicators such as Factor of Safety or *Fs* (van Asch, 1992). The *Fs* value is a quantitative measure representing the ratios between resitising force and the sliding forces. The same is used as a metric to classify topographic slope as per their inherent instability. Application of this model for a large landslide complex needs to apply the same in a spatially-distributed manner and preferably be determined in a GIS platform, which always remained to be a challenge to the researchers, since, 2-D or 3-D deterministic techniques using compatible hydrological models are always mathematical complex and has an inherent limitation to use in 2-D GIS environment. One of the simplest ways to excute this application within a GIS is to prepare boundary conditions for a one-dimensional infinite slope model, where by considering some basic assumptions, *Fs* values at each unit of study or grid-cell can be determined. The above stability calculation can also be carried out outside the GIS, but reproducing the results of such distributed deterministic stability models again onto a map sometimes are problematic due to incompatibility in the data formats of the two systems (Terlien *et al.*, 1995). Therefore, it is always preferable that for distributed deterministic analysis, we attempt to employ the entire stability calculation inside the GIS system through incorporating mapped features representing topograpghy (slope), material properties from geological attributes and from spatially-distributed thematic layers representing physically-determined different shear parameters.

In this paper, a GIS-based method is presented where detailed-scale geological and topographic mapping of a large landslide complex in Darjeeling Himalaya was used as the primary source information of various input parameters for a spatially-distributed deterministic slope stability model. For this, the simple one-dimensional infinite slope model was applied and predictive *Fs* maps under three hypothetical ground saturation scenarios were generated. Scenario-based deterministic stability analysis performed using the above method quantitatively delineated how the extents of instability increase with increase in ground saturation. Application of this model also revealed the inherent limitations of the model and recommends further for incorporation of more site-specific physically-determined hydrologic and shear parameters as model variables to improve the performance of stability calculation.

Study area, topography and geology

Paglajhora slide complex, located south of Kurseong town in between 35 Km and 41 Km stretches of National Highway -55 (NH-55) has been reported to be an active subsidence and slide zone since more than the last five decades (Fig. 1). This slide complex has severely affected the above-mentioned national highway (the road leading to Darjeeling town from Siliguri) in between Gayabari - Mahanadi (Lower Paglajhora) and Mahanadi - Giddapahar (Upper Paglajhora) sectors for a cumulative length of about 3 Km (cf. Fig. 2). The NH-55 passes through this slide complex both along lower level (*m.a.s.l.* 1130 m to 1190 m) and along upper level (*m.a.s.l.* 1280 m to E.L. 1335 m) (cf. Fig. 1).

Paglajhora slide is located within the upper catchment areas of Shiva nala (cf. Fig. 1), a southerly-flowing tributary Mahanadi river. The entire slide complex has numerous prominent and discontinuous active to dormant rock as well as debris scars, which has been activated during a number of landslide events spread over a temporal period of six decades. The slope is mainly drained by Paglajhora (a local name for the

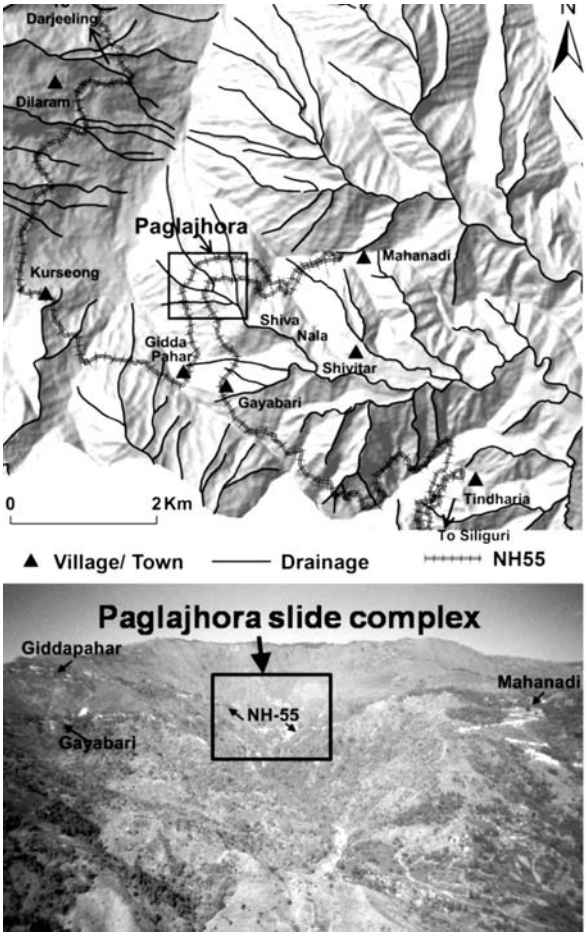

Fig 1. Location map and field photograph of Paglajhora slide complex.

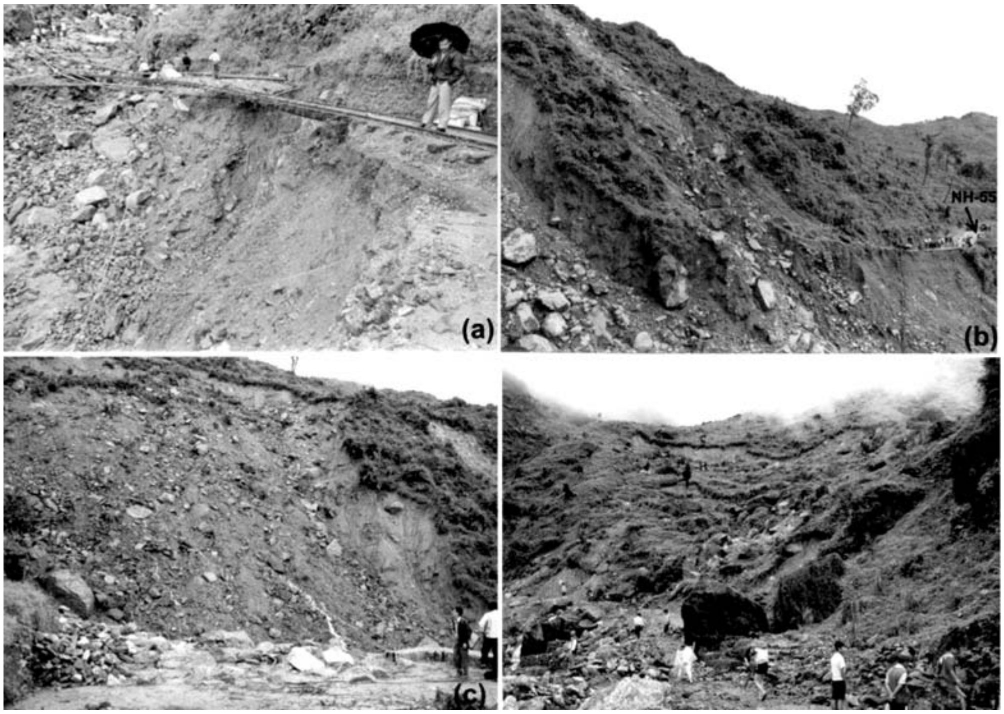

Fig 2. Field photographs of different fresh and active landslides within upper and lower sections of Paglajhora slide complex (examples are from 1998-landslide event): (a) & (b) Complete damage of rail-road bench of NH-55 in the Lower Paglajhora section, (c) A shallow translational debris slide in Upper Paglajhora section, and (d) Failure and subsidence of the left bank slope of Pagla nala (Lower Paglajhora Section)

main lower order tributary of Shiva nala) and other numerous SE-ly to southerly flowing tributaries of Shiva nala. Locally, the top part of the slide complex is moderately steep-to-steep and the middle part is gentle followed by moderately steep to steep lower part near the banks of Shiva nala. The NE part of the slide complex is bounded by a steep south-westerly sloping rocky spur (cf. Fig. 3 a). Similarly, towards SW, exposed rocky stratum marks its southern boundary. The area around Paglajhora slide is mainly traversed by exposures of fresh to weathered quartzo-feldspathic gneiss of Central Crystalline Gneissic Complex (CCGC) (cf. Fig. 3 a). Along the left bank of Pagla Jhora within the middle slope, highly sheared and weathered gneiss is exposed in the middle part of the slide. Towards south, a sheared and fractured phyllonitic rocks are exposed

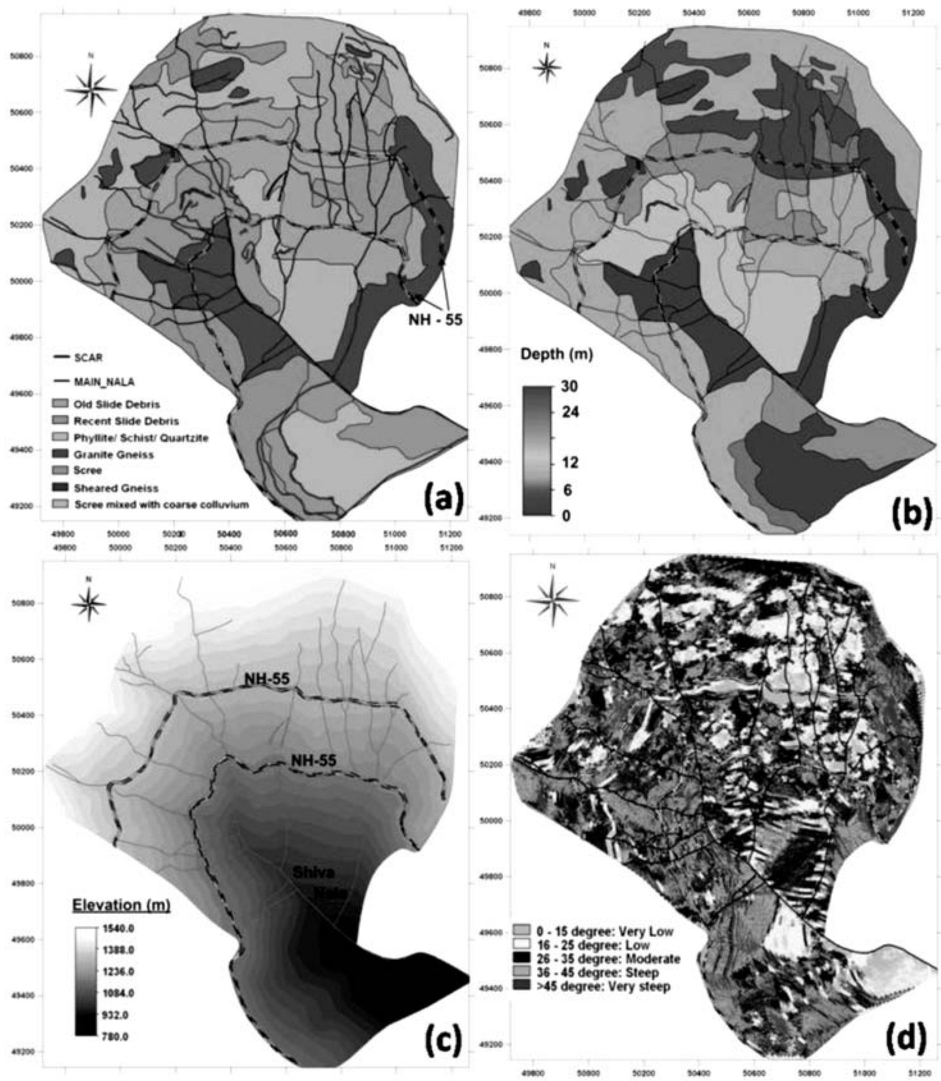

Fig 3. Different mapped themes of the Paglajhora slide complex: (a) Map showing distribution of different lithology (both bedrock snd overburden), including other mapped elements such as active rock and debris scars and NH-55, (b) Interpreted depth to bedrock map, (c) 1 m X 1 m resolution DEM and (d) Classified slope map, prepared from DEM.

adjacent to highly-fissile schists and fractured quartzites of Daling Group are exposed. It is inferred that the Main Central Thrust (MCT) probably is passing along the basal part of sheared phyllonite that is along the southern-most boundary the main Paglajhora slide complex. At this location, within Paglajhora slide complex, a very active deep-seated retrogressive rock slide is present, which is locally called as "14 Mile Slide". Since the rockmass of this area is highly folded, wide variation in the attitudes of the pervasive planar fabric i.e. the foliation plane has been observed. In general, the foliation planes strikes N40°-70°E with dips 30°-50° NW (askew within the hill). But foliation planes having attitudes N55°-80°W/30°-40°NE has also been observed towards the eastern arm of the Paglajhora slide. Apart from foliation-parallel joint, the rockmass is traversed by at least 4 sets of continuous, rough planar steep joints are present. The joints are dipping towards WNW, SSE, NNE and East respectively.

Material and methods:

To document the geological and morphometric attributes of the Paglajhora landslide complex, different surface features were mapped in 2006 on detailed scale (1:2000) using Total Station Surveying Instrument (cf. Fig. 3). During detailed geological mapping, all such mappable elements on ground such as different rock outcrops with prominent structural orientation data, boundaries of different overburden materials, rock and debris scars and all the protection structures such as contour and stepped chute drains, protection wall and road were surveyed and documented. All these mapped elements were later used to generate different derived geofactors theme layers in a GIS for stability analysis (e.g. Fig. 3 b & d). During detailed scale geological mapping, for understanding the slope morphometry, spot elevations (in m) at closer interval were recorded from the entire mapped area of the slide complex, which, were later used to generate a digital elevation model (DEM) with 1 m x 1 m grid scale resolution (cf. Fig. 3 c) using open source GIS software ILWIS 3.x. This DEM was used to calculate further the slope (Fig. 3 d), aspect and relative relief rasters using open source GIS software ILWIS 3.x to understand the slope morphometry in detail of the entire slide complex.

In this research, an attempt has been made to create the quantitative slope stability or distributed *Fs* maps of Paglajhora slide complex using a simple one-dimensional slope stability model (the Infinite Slope model) under a raster-based GIS environment (cf. Terlien *et al.*, 1995; Soeters and van Westen, 1996). As input data, shear parameters of insitu samples (C & ϕ) from overburden material and data of detailed-scale (1:2000) geological map (e.g. lithology) and other interpretative parametric maps (e.g. depth) of Paglajhora Slide area were used simultaneously to generate a number of derived thematic layers based on the distribution of different shear parmeters of varying overburden material. The above derived thematic maps were later directly used in a GIS for calculation of *Fs* values for each grid-cell of the mapped area. In this research, the above raster-GIS-based deterministic slope stability analysis was carried out using open source GIS software ILWIS 3.x Software (cf. van Westen, 1993).

Deterministic slope stability analysis:

For preparation of the quantitative stability model, the degree of instability is determined quantitatively for each pixel by calculating the Factor of Safety (*Fs*), which is the ratio between the forces that make the slope fail and those that prevent the slope from by using the following the basic stability equation (cf. van Westen, 1993).

$$F_s = \frac{C + (\gamma - m\gamma w) z \cos 2\beta \tan\phi'}{\gamma \sin\beta \cos\beta}$$

Where, C = Cohesion, γ = Unit weight of soil, $m = Zw/Z$, Zw = Height of the water table above failure plane, Z = Depth of failure plane below ground surface, β = topographic inclination (°) and ϕ = Effective angle of shearing resistance.

To apply the above one-dimensional slope instability model, it was assumed that most of the slides of Paglajhora areas are translational in nature (Fig. 2). The depths of probable failure surfaces are considered to be the depths to the bedrock, since the interface between overburden and bedrock are always found to be the most susceptible plane of least shearing resistance, along which, in general the translational slides occur frequently and depth to length ratios are in the range of low (≤ 0.2).

From the map data, an inferred overburden thickness map was prepared (cf. Fig. 3 b), which has empirically been considered as the depth of possible failure surfaces (*Z*) of different slope portions for the sake of this stability analysis. Thus, to have a broad quantitative empirical estimate for the above stability analysis, the above overburden thickness map has been used for the estimation/ assumption of depths of probable failure surfaces. In the above stability analysis, following three hydrological scenarios - dry, wet and completely saturated were assumed. For Dry, m (*Zw/Z*) was assumed to be 0, for wet, *m* was considered 0.5 and for completely saturated scenario, it was assumed that the phreatic surface coincides with the natural soil line (NSL), and therefore, *m* (*Zw/Z*) was considered 1. To incorporate the exposed rocky areas within the ambit of above slope stability analysis, the mapped bedrock areas are assumed to be filled up with a thin (0.2 m to 0.5 m) veneer of scree material. Using our map data, we selected 10 different insitu soil sample locations keeping in mind the lithological variability of overburden material mapped. The shear parameters of the collected insitu soil samples under different saturation conditions were tested using tri-axial shear test and corresponding variation in the *C*, γ & ϕ values under dry, wet and full saturations were estimated. Using these values, derived shear parameter maps (Fig. 4) are prepared, which represented spatially-distributed variability of shear parameters of soil samples for use in *Fs* calculation in each grid-cell.

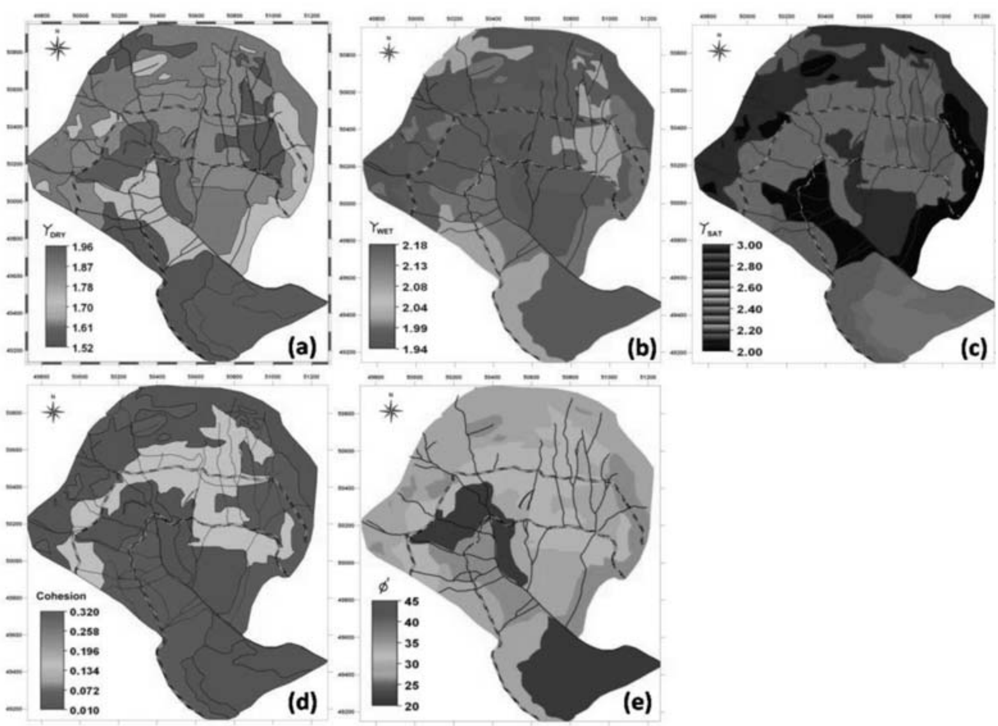

Fig 4. Map showing spatial distribution of different shear parameters of overburden material; The quantitative measure of different shear parameters were obtained from the tri-axial shear test of 10 representative soil samples from the different types of overburden material. (a) Unit weight ( ) in gm/ cc tested under dry situation, (b) Unit weight ( ) in gm/ cc tested under wet situation, (c) Unit weight ( ) in gm/ cc tested under completely saturated situation, (d) Cohesion and (e) Residual friction angle .

Results:

Detailed geological mapping and evaluation of Paglajhora slide complex:

Paglajhora slide complex represents an ensemble of numerous individual slide zones of varied dimensions, which are characterised by a number of well-developed prominent and discontinuous debris as well as rock scars (cf. scars in Fig. 3 a). Overall, the entire influence zone of this slide complex is wider in the upper part towards north and northwest and is narrow or constricted towards its toe in southeast. The detailed scale geological map of the slide complex shows that the maximum length along the slope of this slide complex is about 1.52 Km, whereas the maximum width comes about 1.55 km elevation-wise, the uppermost border of the Paglajhora slide complex is at *m.a.s.l.* 1540 m and the toe part goes down to *m.a.s.l.* 780 m located adjacent to the right bank of Shiva Nala. At the central or axial part of Paglajhora Slide complex, a distinct zone of depletion has been observed from spoon-shaped concave geometry, whereas the relatively gentler slope towards its flanks and the middle portion represents the zone of accumulation. The accumulation zone is filled up with a considerably thick (approximately 5-20 m) heterogeneous slide debris (cf. Fig. 3 a). Adjacent to the Paglajhora slide complex (towards its south), there exists a most prominent active rock slide, which is locally known as 14 Mile slide. This rock slide in the present form has been developed since the monsoon of 2002 due to the rapid retrogression of a smaller rock slide on a moderately steep slope within the last 7-8 years. Presently, the crown of the 14 Mile slide has reached up to the NH-55 road level and has damaged the road bench for a width of about 500m. The maximum width of this particular slide is ~ 520m and crown to toe slope length is ~ 703m. Elevation wise, the present crown is at *m.a.s.l.* 1125 m and toe reaches down to the right bank of Shiva Nala at *m.a.s.l.* 780 m.

Elevation wise, the entire influence areas of Paglajhora Slide can be divided into three separate morphometric domains - A, B and C. Domain-A represents part of the Paglajhora slide complex from the NH-55 road bench level up to its northern boundary towards upslope. In this domain, two distinct triangular debris cones or zone of accumulation have been delineated. Apart from the two accumulation zones, the rest is covered mainly with thin (<5 m thick) colluvium with/ without fresh debris and bare rock exposures. The zone of accumulation or debris cones is in general thick having tentative thickness of ~10-15m. These debris cones become thicker more towards down slope areas i.e. within Middle Paglajhora (Domain-B). Within the colluvium-covered areas, a number of prominent slide scars are identified and mapped, whereas, within debris-filled areas, discontinuous and prominent debris scars are plenty. Within this domain, the slope-forming material is predominantly consisted of greater concentration of large-sized, angular gneissic boulders set in minor constituents of coarse grained sandy to pebbly matrix. Three prominent exposures of quartzo-feldspathic gneiss are present in Domain-A i.e. two along its two flanks and one at the west-central location, where a prominent rocky scar is observed near the NH-55 road bench. Apart from the above slide scars, in the upper Paglajhora NH-55 road bench, adjacent to Domain A, three prominent stretches of road sinking have been mapped, where the present road bench is found to have subsided/ sunk (maximum 0.5m) from its static level. These sinking zones at NH-55 road level spatially coincide with the zones of debris accumulation present in this area. Within this zone, wherever bedrock (quartzo-feldspathic gneiss) is exposed, the rock is fresh and competent in nature. The prominent foliation within bedrock strikes N35°E - S35° W with dips 25-35° NW i.e. askew to the hill mass. Along rock scar face, two sets of prominent valley-ward dipping (N25°E/ 80° SE and N60°E/ 75-80°SE) continuous joints are observed. Towards eastern boundary of the slide complex, a continuous rocky arm is observed right from Domain-A to Domain-B and C, wherein the scar face is marked by a well-developed westerly dipping joint plane (N40°-45°E/ 40°-50° NW). All the rock scars present in the uppermost levels of Domain-A clearly bears the signatures of several episodes of past rock sliding, which contributed the formation of thick debris heap down below.

Domain-B represents the middle Paglajhora region bounded by upper and lower Paglajhora NH-55 road benches. This zone is broadly bounded by the NH-55 road benches passing through this terrain at two different elevations. In Domain-B, from west to east, three prominent geotechnical zones are identified. Along the axial portion, through which, the main Pagla Jhora flows is found to be the most affected/ distressed part of Domain-B, where clear evidences of recent mass movements are noticed as evidenced by concentration of both arcuate and longitudinal slide scars and prominent zone of depletion. The lower Paglajhora road section marks the border of Domain-B, which registered the maximum rate of subsidence (maximum 5m) at three prominent stretches. Within this domain, along the right bank of Pagla Jhora, a linear rock scar is longitudinally exposed, which is represented by a highly sheared, shattered and fractured quartzo-feldspathic gneiss with prominent penetrative planar fabric dipping lowly 15-20° towards N40°W. Presence of this sheared rocky scar infers possible presence of a prominent shear sub-parallely disposed to the trend of the main Paglajhora nala. Apart from this thin shear, the entire slope is covered with thick slide debris and slope wash deposits. The slope forming material is broadly heterogeneous in nature and is represented by a coarse admixture of large to medium sized boulders of gneiss set in a micaceous sandy to silty matrix. In this zone, differential concentrations of finer as well as coarser matrix both in space and at different elevations are noted.

Domain-C represents the part of the slope below the lower Paglajhora NH-55 road bench down to the banks of Shiva Nala. Domain - C represents the inner lowermost part of the arcuate catchment slope of Shiva Nala. In this domain, slope adjacent to the right bank of Pagla Jhora and Shiva Nala is steep and mostly scree with/ without bedrock (quartzo-feldspathic gneiss) covered. Wherever, bedrock is exposed on slope, it is fresh and competent in nature. Along the left bank of Shiva Nala, the slope is moderate to steep and is mostly covered with scree, debris (both old and younger loose). Towards eastern flank, the slope becomes steeper and is characterised by a exposed bedrock, which has been observed right from Domain-A down to the left bank of Shiva nala. This rocky ledge marks the easternmost boundary of the entire Paglajhora Slide Complex.

The shape of whole mapped area is amphitheatre like within the upper catchment slope of Shiva Nala and is being drained towards SE by all its lower order tributaries. Amongst the three morphometric domains, the Domain - B is the most failure-prone and consists of a number recent debris scars, a prominent zone of depletion in the central part and accumulation of failed colluvium. Within this zone, the NH-55 road bench at two elevation levels is situated, which suffers maximum amount of subsidence.

GIS-based stability analysis:

Considering all the model assumptions, values of all the above-mentioned raster map data, the *Fs* maps for Dry, Wet and Completely Saturated are prepared after slicing *Fs* maps into the following three categories - Unstable (Fs<1.0), Critical (1.0<Fs<1.7) and Stable (Fs>1.7). The upper limit of *Fs* values within the critical category has been kept as 1.7 because, the *Fs* map database indicates that pixels having a maximum *Fs* values 1.7 under Dry scenario can also be unstable (Fs=0.9) in completely saturated condition. Therefore, an intermediate threshold zones having *Fs* values between 1 and 1.7 is delineated, which was termed as “Critical". Under Dry condition, about 60% area is stable, 35% area is critical and 25% areas are unstable (cf. Fig. 5 a). Whereas, in wet situation, stable portion is reduced to 28% areas, about 50% areas become unstable and 22% areas become critical (cf. Fig. 5 b). Under completely saturated condition, only 5% stable areas area lost, but the amount of unstable slope increased substantially that is about 65% from the 50% in the wet condition (cf. Fig. 5 c).

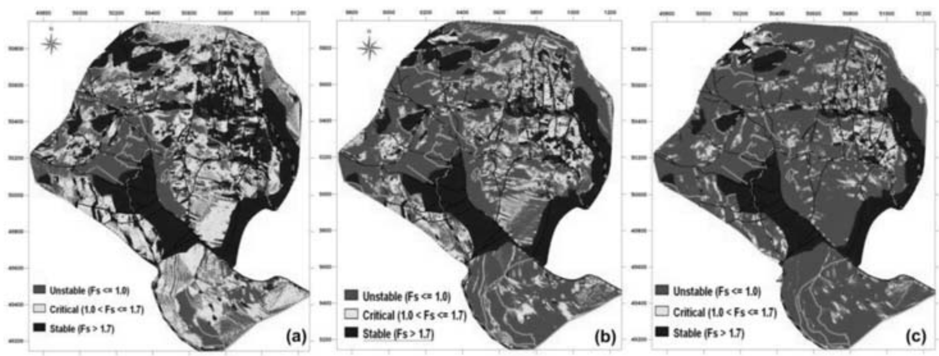

Fig 5. Spatially-distributed stability map (a) Dry condition, (b) Wet condition and (c) Completely saturated condition.

Conclusions and Discussion

The Paglajhora slide has broadly three domains. The uppermost domain contains mostly the rocky scars, whereas the middle and lower domains contain mainly discontinuous debris scars as evidenced from various types of scars spread within the accumulated thick colluvial material. Physiographically, the Paglajhora catchment is traversed by a number of prominent SE-ly flowing streams, maximum of which are having strong erosion potentiality, which favours continued slope instability in this area. Broadly, the primary causes of different types of slides in Paglajhora slide complex are enumerated below:

- Moderately steep to steep upper and lower slopes.
- Influence of a regional tectonic fabric (MCT), which is passing across the slide complex along its southern boundary.
- Presence of thick and fractured sheared gneiss along the axial part, sub-parallely disposed to the course of Paglajhora.
- Accumulation of highly anisotropic and heterogeneous debris material of very low shearing strengths in the middle and lower part. On differential saturation, this slope-forming material easily loses its shearing strengths and fails selectively. This type of failures is very common in the middle and lower part of the slide.
- Arcuate physiographic configuration of the Paglajhora slide complex favour accumulation of surface and ground water mostly in the axial zone, where during monsoon pore water pressures becomes so high that failures are rarely

be avoided in this region. This can be evidenced by development of a deep zone of depletion in the axial part of the slide and major subsidence and lateral shifting of the road bench in the lower Paglajhora reach.

- A number of un-guided tributaries of Shiva Nala are present in the slope, which erodes and accentuates toe cutting of debris-filled slope at a number of places. These actions trigger the failures in debris-accumulated slope.
- Presence of flat areas in the Domain-B favours concentration of high recharge, which trickles downward up to Domain-C and also favours piping of finer material. This was evidenced from the size distribution of slope forming material from upper reaches to lower levels. At lower elevations, debris and slope wash material are found to be relatively finer than its counterparts in Domain-A and upper part of Domain-B. This piping action is more severe in the lower reaches i.e. in the lower part of Domain-B and in Domain - C. Because of the severe piping in the lower reaches, the lower Paglajhora road bench registers maximum amount of road sinking in comparison to its upper counterpart.

Spatially-distributed deterministic stability analysis indicated that substantial areas become unstable with increase in saturation condition. An estimation of about 25% areas as unstable in dry condition is perhaps the result of limitations of the assumption of the model to consider depth to bedrock as the depth to failure plane in all locations. Since in dry situation in Paglajhora slide complex, rarely any slope instability occurs. Furthermore, several other following limitations have also contributed the performance of the above deterministic model, which can substantially be improved if several model assumption and limitations are reduced.

- Lack of in-situ instrumental data (e.g. inclinometer etc.) designed to know the actual depth and pattern of slip surface.
- A simple one-dimensional translational slide has been assumed to attempt the infinite slope model for stability analysis, which may not always be true in all the domains of Paglajhora Slide Complex, especially the middle part, where, some rotational failures (with multiple failure planes) and/ or higher depth to length ratios of individual failures overestimated the *Fs* values.
- Lack of peizometric monitoring data to know the depth of actual phreatic surface. That is why, in the stability equation, proper estimation of pore water pressure could not be incorporated. In this context, availability of an insitu hydrological model would definitely add values to the predictive power of the

deterministic process.

- In general, the debris in Paglajhora is mostly heterogeneous and anisotropic in nature, thus assuming a part of the area in terms of compositional homogeneity for the sake of the model at times leads to erroneous results. But in the same time, it should also be noted that this problem can to some extent be lessened, if more number of representative insitu soil samples both spatially and depth-wise could be collected for laboratory analysis.

Therefore, as part of a future research, Paglajhora slide complex can be considered a suitable site for developing a 2-D and/ or 3-D failure susceptibility model incorporating 3-D hydrological model parameters incorporating piezometric data to understand better the behaviour of the complex instability processes of such a hydrostatically-induced large landslide complex.

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