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Research Paper

A composite fall-slippage model for cliff recession in the sedimentary coastal cliffs

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ABSTRACT

A composite fall-slippage model is proposed in this study for the Tertiary sedimentary coastal cliffs of Varkala in the western coastal tract of Peninsular India which are retreating landwards due to the combination of several factors. The fall model in the present study accounts both spring seepage and wave action, resulting in undercutting and this fall affects only the topmost laterite and the just below sandstone in the cliff. Slippage in this area affects all the litho-units and hence the geologic characteristics of all the litho-units are considered for developing the slippage model. This mathematically derived model can be used in other cliffs exhibiting the same morphology as well as the one controlled by the same influencing factors. This model differs from other models in incorporating multi-lithounits as well as multi-notches. Varkala cliffs form a part of the aspiring geopark in the Global Geopark Network and hence a study on the cliff recession is a pressing requirement.

1. Introduction

Various cliff recession models have been proposed &by different authors to study the retreat of coastal cliffs. The Bruun-rule model (Bruun, 1962; Bray and Hooke, 1997) deals with sea level fluctuations. Models based on historic data (Hall et al., 2002; Drake and Phipps, 2007; Fall, 2009) often use statistical analysis. The CLIFF-PLAN model of Lee et al. (2002) uses Monte Carlo simulation to represent uncertainty in the cliff recession process. Process-response models (Walkden and Hall, 2005, 2011; Trenhaile, 2009; Castedo et al., 2012, 2013) incorporate geology, environment, hydrodynamic regime and climate. In addition, the Castedo et al. (2012) model incorporated geotechnical parameters too. A composite fall-slippage model, based on geological, geotechnical, tidal, wave, historic and geophysical data, is attempted here. Such a study will be a first attempt at melding such a vast and diversified data. Thus this study will bridge the gap left by other studies making use of process-response model, models based on sea-level fluctuations and models based on historic data incorporating statistical analysis as well as Monte Carlo simulations (cf. Budetta et al., 2000; Collins and Sitar, 2008; Ashton et al., 2011). This study is carried out in a coastal village called Varkala in the state of Kerala, South India.

The state of Kerala, a linear stretch of land sandwiched between the Western Ghats and the Arabian Sea, exhibits a variety of physiographic features ranging from tall mountains such as Anaimudi (2695 m) to the water-logged lands below mean sea level at Kuttanad. The coastal geomorphology of this state is usually manifested as dunes, beaches, cliffs, marshes and backwaters. Of these coastal landforms, the most conspicuous components are the coastal cliffs. Varkala, a coastal town fringing the Arabian Sea in the state of Kerala, exposes three such cliffs *viz.* Edava cliff, North cliff and South cliff (from north to south) with a maximum elevation of ~40 m and running for 5.5 km.

A study on coastal landslides and coastal recession modelling is of utmost importance in this part of the world because such a cliff edging the sea and extending for several kilometers is rare in a region experiencing tropical climate. Moreover, these cliffs form a part of the recently declared national geopark, which is also an aspiring geopark in the Global Geopark Network (GGN). These cliffs and the adjacent beaches sustain a thriving tourism industry, with

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property prices in the very-high bracket (Rajan, 2011). The present study is concentrated on the North cliff which is the most important tourist destination.

Varkala is situated about 55 km northwest of Thiruvananthapuram – the capital of Kerala (Fig. 1). It falls within the Survey of India (SOI) topographic sheet 58D/10 (1:50,000 scale). The picturesqueness of the place attracts a large number of domestic and international tourists round the year. The charm of this place is the presence of beautiful wave-cut cliffs and confined beaches. Tourism activities are mainly concentrated in and around the North cliff, which runs for a length of 1.6 km between Papanasham (a ritual place for performing ablutions for ancestors) (8°43′59.34″N, 76°42′19.91″E) and Black Beach (8°44′35.75″N, 76°41′54.21″E) and hence the present study is only concentrated on this cliff.

The main aim of the study is to create a composite fall-slippage model on the basis of various geologic and climatic parameters. A detailed geological mapping (including cliff face mapping, preparation of lithostratigraphic sections and geologic profiles), determining the geotechnical parameters of the difficult lithounits, analysis of rainfall, tidal and wave data, shoreline changes over a

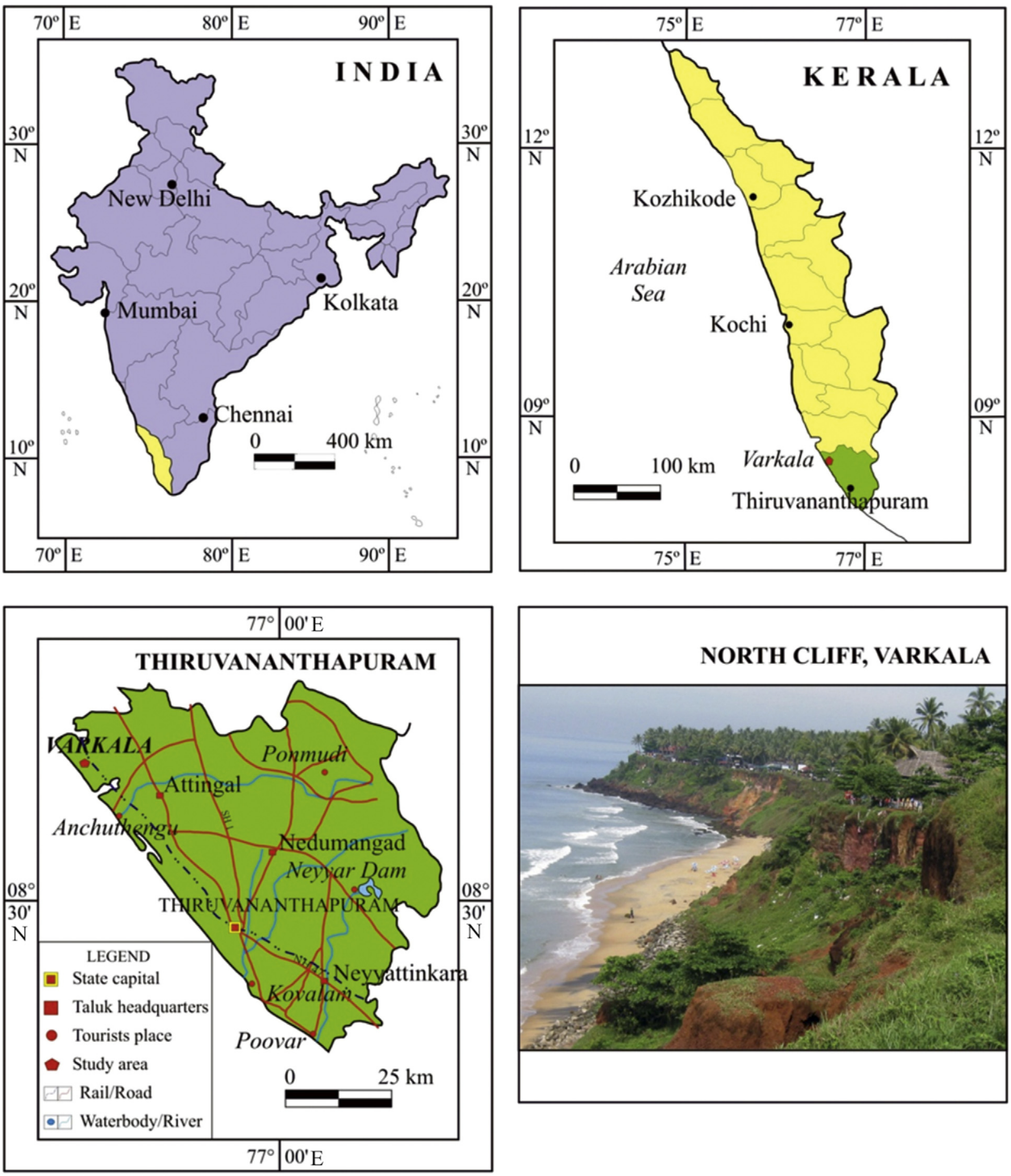

Figure 1. Location map of the study area with respect to India, Kerala State and Thiruvananthapuram District. The photograph is a view of the North cliff.

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Table 1
Stratigraphy of North cliff Varkala. There is no representation of Palaeozoic and Mesozoic. Laterites are weathered product of underlying sandstone.

Age	Lithology
Recent (*Kadappuram Formation*)	Beach sand
Recent to sub-recent	Laterite
Tertiary (*Warkalli Formation*)	Current bedded friable variegated sandstone inter-bedded with plastic clay and variegated clays Carbonaceous and alum clays with lignite seams Gravel and pebble beds Base marked by gibbsitic clay
	Unconformity
Precambrian (*Kerala Khondalite Belt-KKB*)	Khondalite/Charnockite

period of 100 years and deployment of gravity technique to trace out concealed geologic features constitutes the part of study carried out.

Detailed geological mapping was carried out using a total station survey instrument on 1:2000 with an aim to depict all the minute details that the cliff possesses. Cohesion, angle of internal friction and Uniaxial Compressive Strength are the main geotechnical parameters studied to understand the strength of the cliff materials. Rainfall data were collected from the Indian Meterological Department (IMD) and tidal and wave data from the National Centre for Earth Sciences (NCESS). Coastal cliff retreat was studied for a period of 100 years using the Survey of India topographic sheets and google earth imageries. Gravity method of geophysical survey was carried out by means of a gravimeter (using Autograv CG–03 gravimeter, Scientrex, Canada). The ultimate aim of the study is to collate all these data to model the cliff recession.

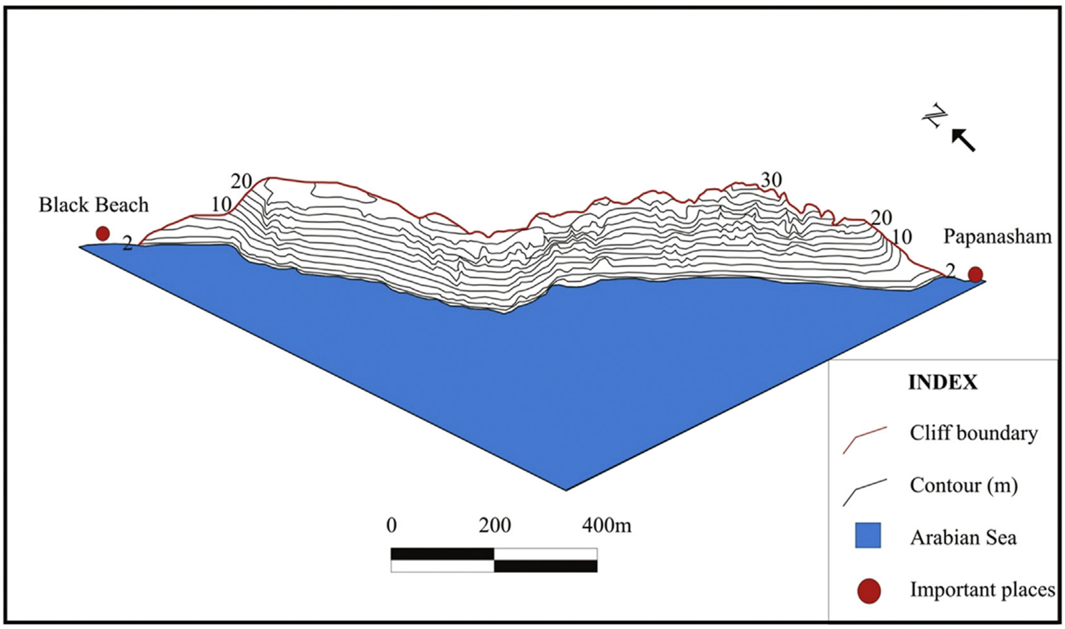

Figure 2. Contour map of North cliff, Varkala. The projected central portion is the major promontory seen in North cliff.

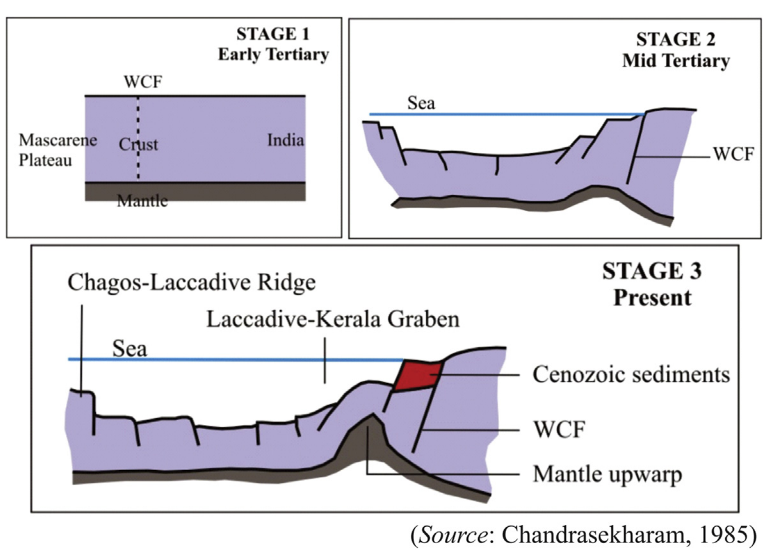

Figure 3. Model representing formation of WCF and Cenozoic sediment deposition. Stage 1 shows the time during which Indian and Mascarene plates were together whereas in stage 2 the two plates were separated and stage 3 shows the basins formed by the plate rifting provided avenues for riverine sediments to get trapped.

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2. Geology, geomorphology and hydrogeology of Varkala coastal cliffs

Varkala and adjacent areas form a part of Kerala Khondalite Belt (KKB) of the Southern Granulite Terrain (SGT) of India. The Precambrian crystallines of this area are unconformably overlain by the Tertiary sequence of Warkalli (*sic*) Formation with no representation of the Palaeozoic and Mesozoic formations. Varkala cliff forms the type area for the Warkalli Formation of Mio-Pliocene age (King, 1882), where the cliff exposes all the lithounits of this formation viz. unconsolidated sands, variegated clays, white plastic clays and carbonaceous sandy clays enclosing

Figure 4. (a) Fall/toppling in the cliff which are the most commonest form of landslide in these cliffs. (b) Tension cracks developed in a part of the cliff. Usually these cracks are formed parallel to the cliff edge. (c) Groundwater spouting as springs at the contact of sandstone and carbonaceous clay in the cliff. A spring line exists all along this litho-contact. (d) Slippage which is mainly initiated by wave erosion and fail along planes which will be usually concave in shape. (e) Sea notches formed by wave action. Less resistant material will be eroded fast than the most resistant ones.

impersistent seams and lenses of lignite (GSI, 2005). These beds are almost horizontal in nature. The unconsolidated sands are very angular and assorted. The carbonaceous clay and lignite are often impregnated with sticks and nodules of marcasite which indicates a reducing environment (Soman, 2002). On the basis of lithology and spatial distribution, Rao (1968) suggested the Warkalli Formation to be shallow water shoreline littoral deposits. The beach sand of Varkala and adjacent areas have rich concentrations of ilmenite, rutile, zircon, monazite, sillimanite and garnet. The black beach, which marks the northern limit of the North cliff, derived its name from the abundance of these placers, particularly, the ilmenite. The modified generalized stratigraphy by Paulose and Narayanaswami (1968) is shown in Table 1.

The sedimentary cliff is a unique geomorphological feature on the otherwise flat Kerala coast (Muraleedharan et al., 2012) (Fig. 2). This cliff is carved out by a combination of fluvial and marine processes and ultimately elevated due to tectonic forces (Sajinkumar and Muraleedharan, 2014). The coastal landscape forms a part of the lowland planation surface. The narrow confined beaches usually get submerged during high tides. The numerous springs emerging from the cliffs form rivulets and join the Arabian Sea. A few stretches of marshy land are also seen in the southwest of the North Cliff.

The Warkalli Formation together with laterite forms a major aquifer system. Groundwater occurs under confined conditions in the Warkalli Formation whereas it is in phreatic condition in the overlying laterite. Exploration by Central Ground Water Board

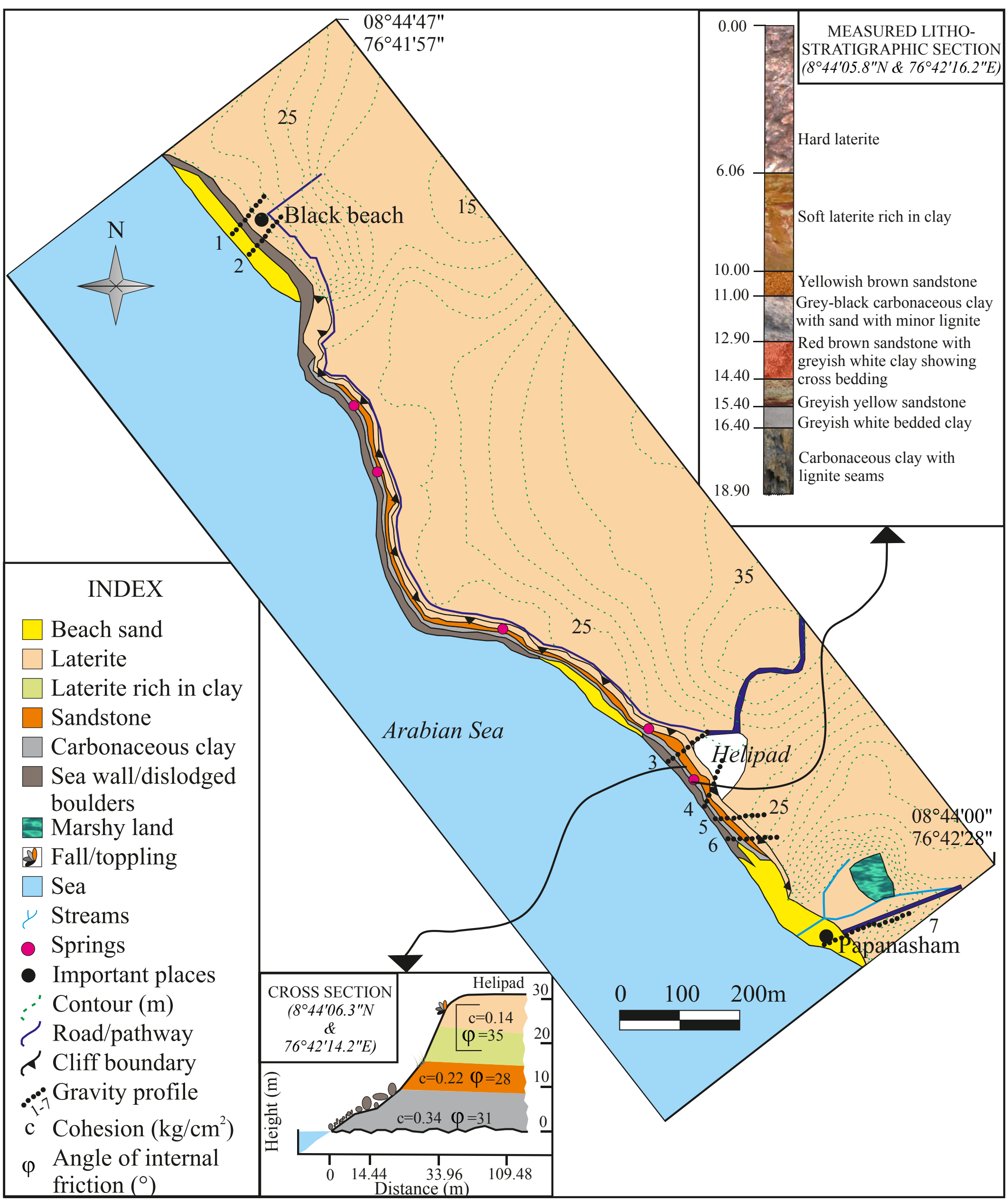

Figure 5. Geologic map of the North cliff prepared on 1:2000 scale. The measured lithostratigraphic section as well as a cross section provides more information about the geology of the North cliff. Shear strength parameters (cohesion, c and angle of internal friction, φ) as well as gravity profile locations are also shown.

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(CGWB) encountered 2 to 3 granular zones in the Warkalli Formation which are potential zones for tapping groundwater (CGWB, 2001).

3. Origin of Varkala cliff

The west coast of India witnessed several episodes of tectonic activities which finally resulted in the formation of a straight west coast when compared to the east coast of India. One of the most prominent of the tectonic activities is the formation of West Coast Fault (WCF). WCF was formed in two stages (Chandrasekharam, 1985): initially as a narrow fracture along the northern part of the margin during the late Jurassic–early Cretaceous (Owen, 1976; Biswas, 1982) and extended further south during the Tertiary (Owen, 1976). Chandrasekharam (1985) constructed three models describing the structural evolution of the western continental margin of India. Model 3 of Chandrasekharam (1985) (Fig. 3) shows the structure along 9°15′N and suggests that it was developed mainly due to the counter clock wise rotation of the Indian plate during the early Tertiary due to the parting of the Mascarene plateau from the southern part of the western margin of India (Owen, 1976). Vertical movements of the block adjacent to the WCF during the late Tertiary promoted deposition of marine and continental sediments (Raha et al., 1983). Campanile et al. (2008) estimated the total sediment volume in the Kerala–Konkan Basin as 464,000 km^3.

4. A glimpse on the potential threat to the cliffs – the landslides and its influencing factors

4.1. Fall and slippage

The shores containing 'soft-rock cliffs' and which are exposed to wave action, have a tendency towards instability and rapid retreat (Kumar et al., 2009). Fall and/or topple and slide or slippage are the common forms of landslides occurring in the North cliff (Muraleedharan et al., 2012). Fall is restricted to the top portion of the cliff face whereas slippage affects the whole cliff.

Fall and toppling (Fig. 4a) are initiated by tension cracks (Fig. 4b). Presence of tension cracks facilitates water percolation and hence an exertion of hydrostatic force which ultimately lowers the factor of safety (Muraleedharan et al., 2012). A phreatic aquifer is usually formed in the laterite and the just below sandstone because of the presence of an impermeable clay/carbonaceous clay layer. Because of these conditions, these upper layers get over-saturated and a high pore-pressure develops. Springs usually spouts at the contact between these two permeable and impermeable layers (Fig. 4c). Usually the top laterites are more prone to fall and topple and such lateritic boulders are seen strewn all along the slope of the cliff and at places this often serves as a sea barrier reducing the sea wave impact at the cliff face.

Slippage (Fig. 4d) occurs mainly due to undercutting by wave action. The failure plane will be concave in nature, joining the notch and the horizontal surface. Fig. 4e shows the formation of marine notches due to wave action. The geotechnical parameters determined (Fig. 5) shows a good cohesion between the lithounits and hence the slippage will not be rapid and prominent. The role of gravity (weight of overlying material) and cohesion here acts as the resistive force against slippage and the water content will accelerate the slippage by reducing friction. The bottommost peat/lignite horizon is having cohesion (c) of 0.31 kg/cm^2 and angle of internal friction (φ) 31°. The lower the value of c the more the material is prone for erosion and similarly for φ. Since this lithounit forms the basal part of the cliff the recession is more. The just above lying sandstone horizon also exhibits lower values (c = 0.22 kg/cm^2; $\varphi = 28°$). These sandstones are at places continues to the basal part of cliffs where the underlying peat/lignite horizons dies out at depth. The c value of the topmost laterite horizon exhibits lower value (0.14 kg/cm^2) and a higher φ value (35°).

4.2. Factors influencing fall and slippage

Fall and slippage are inter-related because fall will decrease the weight of the overburden right above the cliff edge which will in turn reduce the resisting force of gravity and hence enhancing the slippage. These failures are usually influenced by a combination of factors such as geology, wave action, rainfall, slope, groundwater and anthropogenic activities.

4.2.1. Geology

Geology of the North cliff plays an important role in influencing landslides. The Warkalli Formation in this area is capped by hard laterites which are formed during the second lateritization cycle witnessed in Kerala (Soman, 2002). North cliff exposes carbonaceous clay with lignite and sandstone below the laterite (Fig. 5). The Varkala Cliff is exposed to continuous wave action. These soft friable sandstones are easily eroded by seawater, often forming wave-cut notches (Fig. 4e) and making the top laterite overhang the cliff face. In due course of time, tension cracks develop in the surface which ultimately leads to landslide. The measured lithostratigraphic section and a cross section are also shown in Fig. 5. These sections help in a quick understanding of the geology of the North cliff.

4.2.2. Waves and tides

Tidal prediction using C-Map software was used to model the tidal height in Varkala. The C-Map software was developed by Danish Hydrological Institute (DHI), Denmark, which generate a ±10 cm tidal difference. The nearest tidal gauge for Varkala is

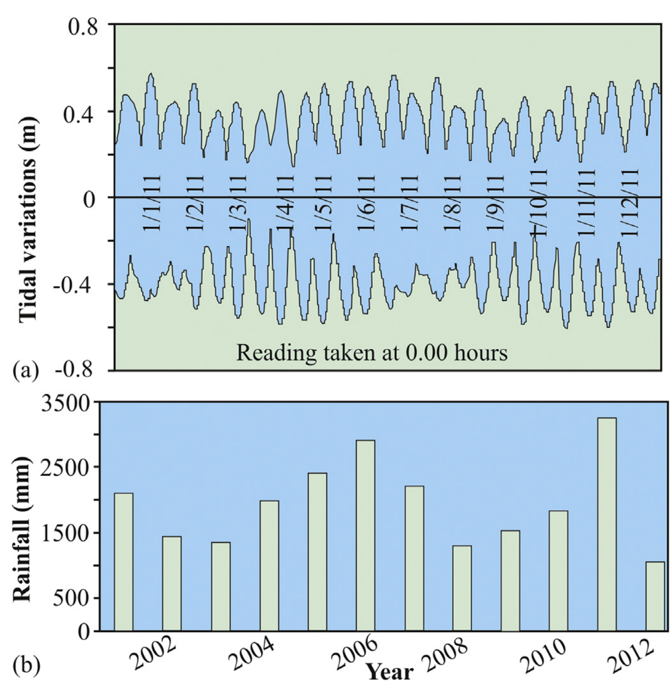

Figure 6. (a) Tidal prediction in Kollam using C-Map software used to model the height of tide. Tidal height varies between +0.60 and −0.60 m. (b) Annual rainfall (in mm) of Varkala rain gauge, managed by Indian Meterological Department. As this area experiences tropical climate, precipitation usually crosses 2500 mm. The maximum and minimum is recorded in the adjacent years: 2011 (3156 mm) and 2012 (1128 mm).

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Kollam. Chart datum of Kollam is 0.67 m below MSL. The data is produced for each half-an-hour and hence totalling to 48 readings a day. Data for a period of one year (2011) was collected (Fig. 6a). The maximum height achieved was 0.56 m above MSL during February whereas the minimum height was −0.59 m below MSL during October. During the time when the tidal height achieves the maximum, the confined beaches will be submerged as well as sea notches will be formed at the base of the cliff.

4.2.3. Rainfall

Rainfall plays a fundamental role in the onset of spatial and temporal evolution of mass movements. Wilson and Wieczorek (1995) have suggested that precipitation can induce the formation of a saturated zone and the subsequent rising of the water table, especially where shallow bedrock exists. The shallow bedrock can be correlated here with the carbonaceous clay which is impermeable. The influence of rainfall in this particular geomorphic feature is very much different from the debris flow triggered by rainfall occurring during southwest and northeast monsoons in different parts of this state (Sajinkumar et al., 2014a,b,c; Sajinkumar, 2015; Sajinkumar and Anbazhagan, 2015; Sajinkumar et al., 2015). This area experiences heavy rainfall, though less when compared to the hilly regions of Kerala (Sajinkumar et al., 2014d). The annual rainfall is usually to the tune of ~1900 mm and in some instances the area experiences more than 2500 mm of rainfall (Fig. 6b). The effects of rainfall in this area are: (1) increase in pore-water pressure and (2) augmentation of the groundwater which emerges as spring in the cliff section.

4.2.4. Slope

Slope gradient is a critical factor controlling the distribution of landslides as failure occurs only on slopes exceeding the critical angle for the materials to be moved (Thomas, 1974). A landslide occurs when the downslope component of the force exceeds the shearing strength of the material (Panicker, 1995; Sajinkumar, 2005; Anbazhagan and Sajinkumar, 2011; Sajinkumar et al., 2011). As the slope increases, shear stress in soil generally increases as well. Varkala cliff is nearly a vertical cliff (85°–90°), formed due to west coast faulting.

4.2.5. Anthropogenic activities

As far as anthropogenic activities are concerned, the surface of the earth is continuously altered by human beings for their sustenance. Being an important tourist destination and the main attraction being the cliffs, the tourist influx is increasing year after year (Rajan, 2011). The cliff slopes were littered by the local population (Fig. 7a). Construction of resorts, restaurants and other shops has encroached upto the brim of the cliff (Fig. 7b and c). Vehicular movements along the edge of the cliff and parking of vehicles in the helipad area have added vulnerability to cliff failure.

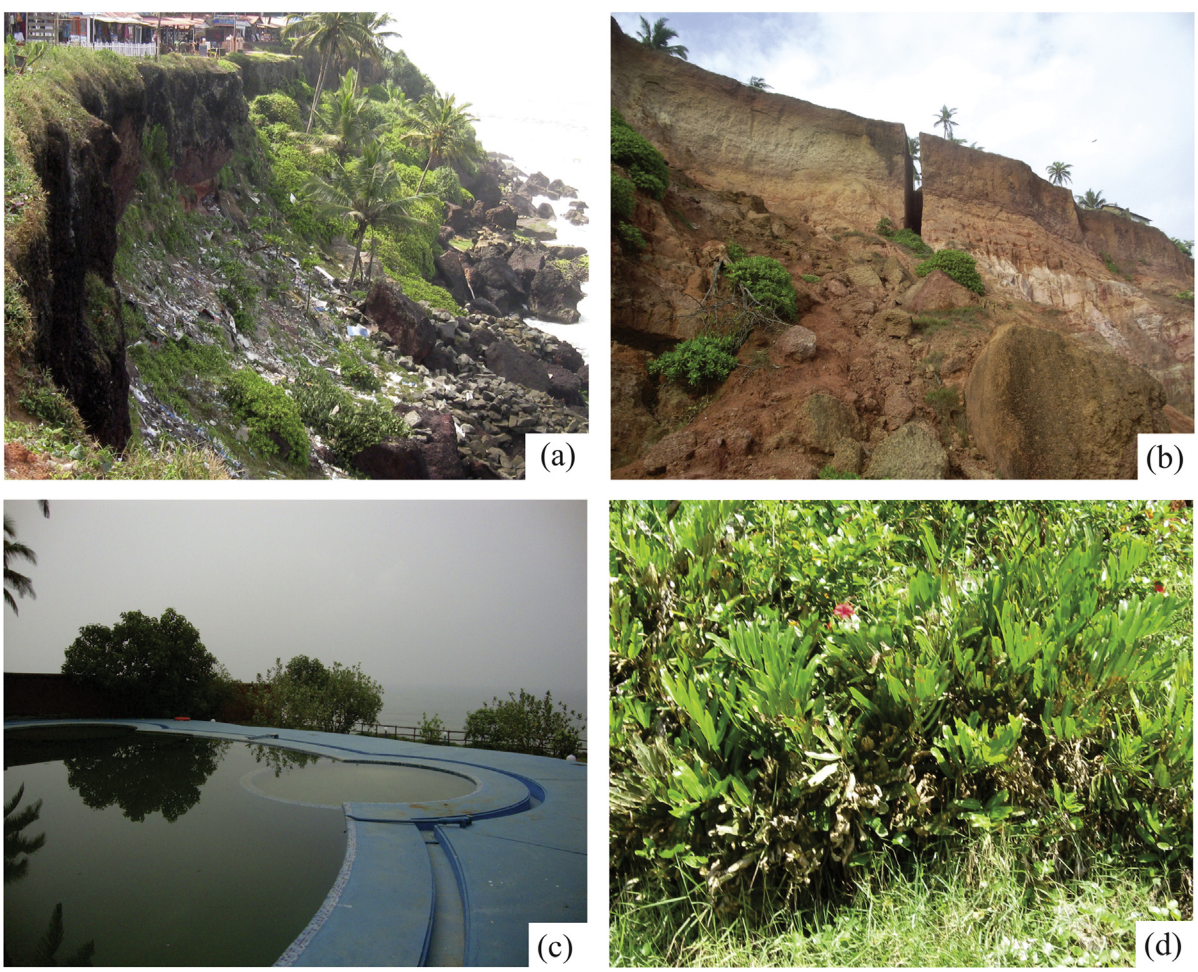

Figure 7. (a) The entire cliff slopes are littered with wastes from the adjacent resorts and restaurants. (b) A pathway constructed by disrupting the continuity of the cliff. Such practices pose serious threat to the cliff. (c) Swimming pool constructed by private hoteliers atop as well at the brim of the cliff. A minor breaching or leaking will increase pore-water pressure in the cliff. (d) Golden leather ferns, which grow in marshy conditions, are general indicator plants for identifying springs.

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4.2.6. Groundwater

Groundwater condition in Warkalli Formation is under confined condition. In Varkala the sandstone above the carbonaceous clay acts as an aquifer and the carbonaceous clay acts as an impermeable zone. And hence water will spout as spring along the contact between sandstone and clay (Fig. 4c). A spring line itself exists along the cliff. Seepage through the spring can be seen throughout the year and the seepage zone is characterized by the presence of *Acrostichum aureum* plant (Golden leather fern) (Fig. 7d). This seepage facilitates mass wasting phenomena. The annual discharge from these springs is estimated at 14.62 million litres (Padmalal et al., 2012).

A gravity geophysical survey (using Autograv CG–03 gravimeter, Scientrex, Canada) was carried out to study the perched aquifers and other underground features. Seven different profiles were laid across the cliff (profile locations are shown in Fig. 5). One traverse was taken near Papanasham; two traverses were laid in the Black Beach and the remaining four near the helipad area, atop the cliff. Theoretical gravity formula of the year 1980 (Moritz, 1980) was used for latitude correction. The density used for Bouguer correction is 2.67 gm/cc. The finally reduced Bouguer gravity data is used for preparing the Bouguer profile map (Fig. 8a) and Bouguer anomaly map (Power Spectrum) (Fig. 8b and c). The edge portion of the cliff, Papanasham and Black Beach, shows a more or less steady gravity profile whereas the cliff portion encountered a low gravity zone. This low gravity zone is suspected to caused by highly porous horizon which may be the aquifer and feeder to the different springs spouting from the contact of carbonaceous clay–sandstone interface exposed at the cliff face.

5. Cliff recession history

Cliff recession history of Varkala for a span of 100 years was analysed using Survey of India (SOI) topographic sheets of 1915, 1965 and 1978; and Google earth imagery (Google Earth) of 2015 (Fig. 9). On a GIS platform, these data were used to delineate the temporal variation of the coastline (cf. Thieler et al., 2009) and this reveals a landward recession north of the major promontory in North cliff of between 10 and 20 m and south of the promontory the recession varies between 25 and 40 m. Due to seasonality in the change of wave direction there will be difference on the erosion seen on both the sides of the promontory. The historical data show that south of the promontory was the most affected when compared to the north of the promontory during the period from 1915 to 2015. The recession has resulted in the demolition of the beautiful cliff, loss of various small scale coast protection measures.

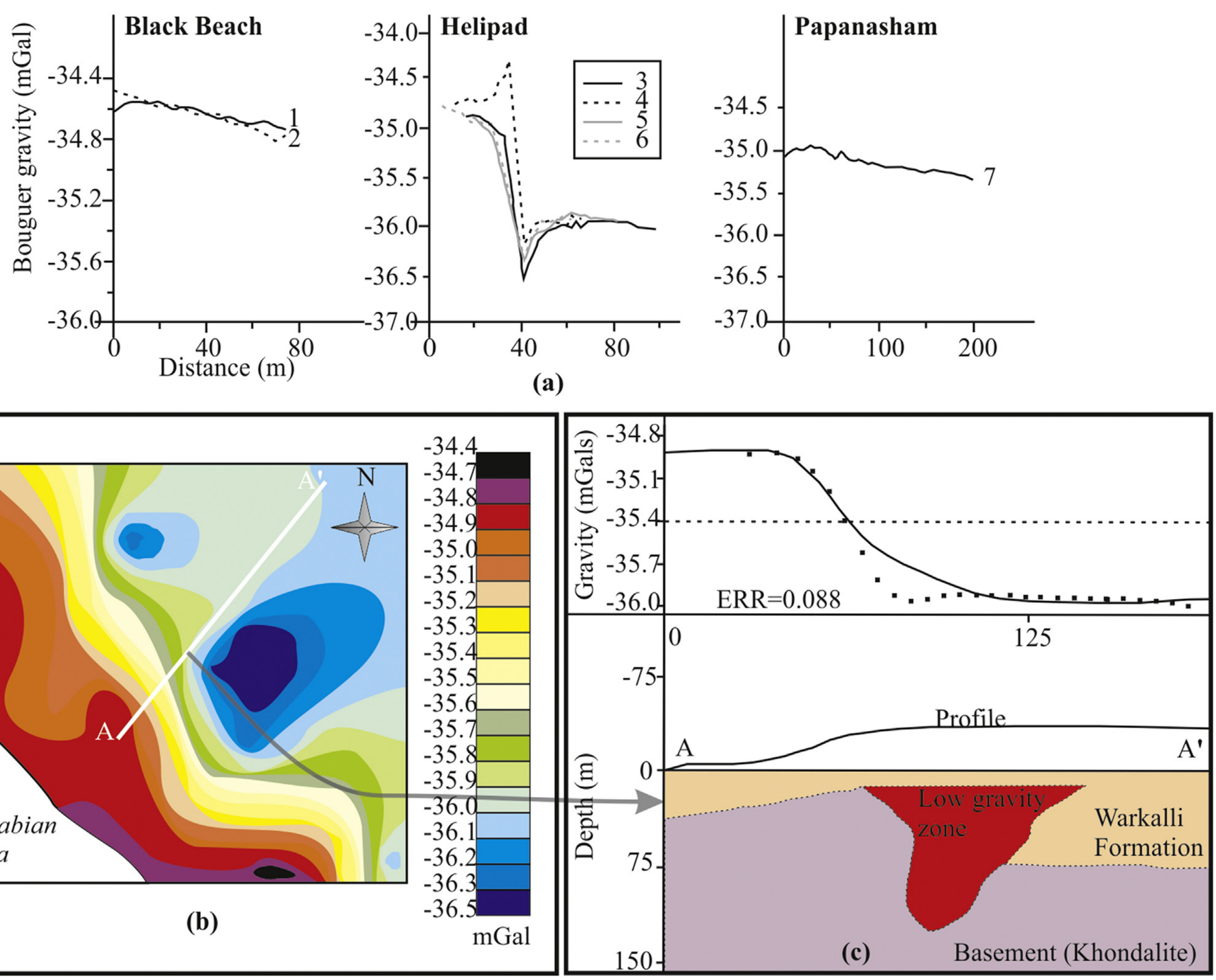

Figure 8. (a) Gravity profiles derived from gravity method of geophysical survey laid at Papanasham, helipad and Black Beach, North cliff. (b) Gravity anomaly map of the North cliff prepared on the basis of the gravity values obtained from the survey. (c) Gravity model in the North cliff. Low gravity zone deciphered is suspected to be porous horizon.

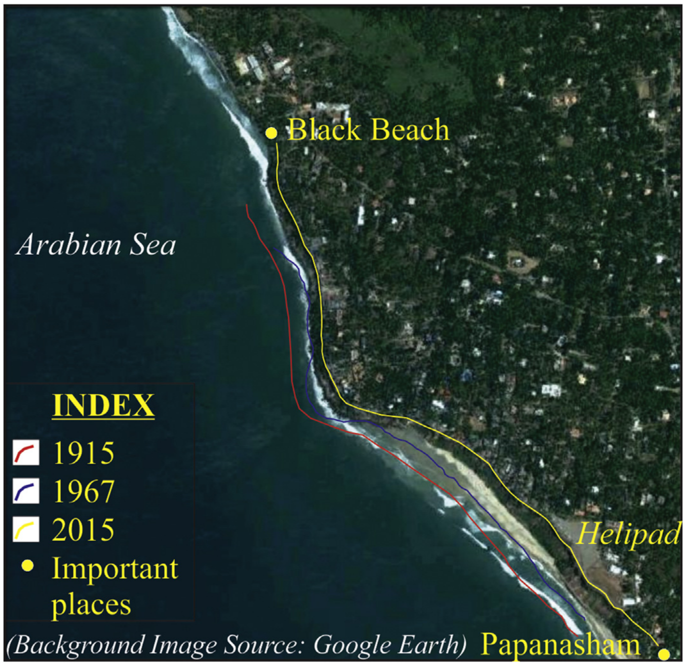

Figure 9. Landward retreat of cliff. Temporal changes taken from historic data (for the years 1915, 1967) impregnated in google earth imagery of 2015. A width of 10–40 m landward retreat was identified from these historic data.

6. Composite fall-slippage model

The composite fall-slippage cliff recession model (Fig. 10a) presented here was developed by incorporating geology, geotechnical, hydrogeology, tidal, geophysical and historical data. This model illustrates how fall and slippage occurs in a sedimentary coastal cliff.

In Varkala cliffs, recession occurs either as fall or slippage. Fall is confined in the AB portion whereas slippage in the PQ portion in Fig. 10a. AB portion is composed of upper hard laterite and lower friable sandstone (laterite occupies the major part) and the base of AB is marked by the contact between sandstone and carbonaceous clay. Laterite and sandstone have vertical slope and are porous and permeable. In this zone, a phreatic aquifer exists which spout as spring all along the contact between this upper horizon and the lower impermeable carbonaceous clay and thus a spring line is formed.

In the present model, fall is based on the ideas of Kogure et al. (2006) and Kogure and Matsukura (2010) except for the process involved in undercutting where spring seepage as well as wave action is accounted instead of wave action alone. The cantilever beam model explains the distribution of stress inside the cliff assuming that tensile stress acts on the upper section and compressive stress on the lower section (Timoshenko and Gere, 1978). The maximum bending stress ($\sigma_{\text{t-max}}$) inside a cliff is expressed as

$$\sigma_{\text{t}-\text{max}} = M/Z$$

where M – bending moment

Z – modulus of the section (Fig. 10b)

$$M = 1/2\gamma d h_{\text{failure}} L_{\text{n}}^2$$

$$Z = 1/6dh_{\text{failure}}^2$$

where d – distance along the cliff face

h_{failure} – height of failure notch depth

L_{n} – notch depth

γ – material unit weight

These models typically use Mohr–Coulomb strength parameters to limit the shear stress that a zone may sustain. The tensile strength (σ_{t}) is specified and limited which in many analyses is taken to be 10% of the rock mass cohesion (Wyllie and Mah, 2004). In this case, the rock mass behaves in an isotropic manner since both laterite and sandstone in the present scenario have same characteristics (laterite here is a weathered product of sandstone). A collapse occurs when the maximum bending stress ($\sigma_{\text{t-max}}$) exceeds the tensile strength of the mass (σ_{t}).

Slippage in the study area affects all the lithounits and hence this present model includes all the lithounits viz., laterite, sandstone and carbonaceous clay. The slippage zone (PQ in Fig. 10a) includes the fall zone (AB) also. Slippage in the study area are rare because of the fact that the fall and/or topple reduces the volume of material to be receded by slippage and most of the time slippage is aborted. The length of the slip (glide) plane can be measured by using the basic formula for calculating the length of arc (Fig. 10c):

$$\text{Length of arc} = n^{\circ}/360^{\circ} \times 2\pi r$$

where n – degree of arc $2\pi r$ – circumference of the circle

In the present case n is 90° because the slope is vertical and the top of the cliff is horizontal and hence the length of the slip plane is $\pi r/2$. The stress acting on this plane can be expressed by the basic equation

$$s = F/A$$

The forces acting on this area having the arc length $\pi r/2$ are overburden thickness, pore-water pressure and tidal effect. Hence the equation proposed by Castedo et al. (2012) can be modified to

$$s = \frac{g\sum_{i=1}^{3} d_{\text{i}}v_{\text{i}} + u_{\text{i}}(t,Q) + a_{\text{g}}(Z,T)}{A}$$

where s – stress acting on the plane

g – acceleration due to gravity
i – No. of layers; in the present scenario three different lithounits are considered
d – density of lithounits
v – volume
$u_{\text{i}}(t,Q)$ – fn of pore-water pressure dependant on 't' time and 'Q' spouted water from the spring
$a_{\text{g}}(Z,T)$ – fn of tidal force dependant on 'Z' modulus of section and 'T' tidal period
A – area having the arc length $\pi r/2$

Note: The carrying capacity of Varkala during peak season is 1000 (Rajan, 2011) and hence any excess should also be accounted to the force 'F' both for fall and slippage.

The stress exceedance results in fall and slippage which finally results in cliff recession. Hence the cliff recession can be expressed by the equation (modified after Castedo et al., 2012).

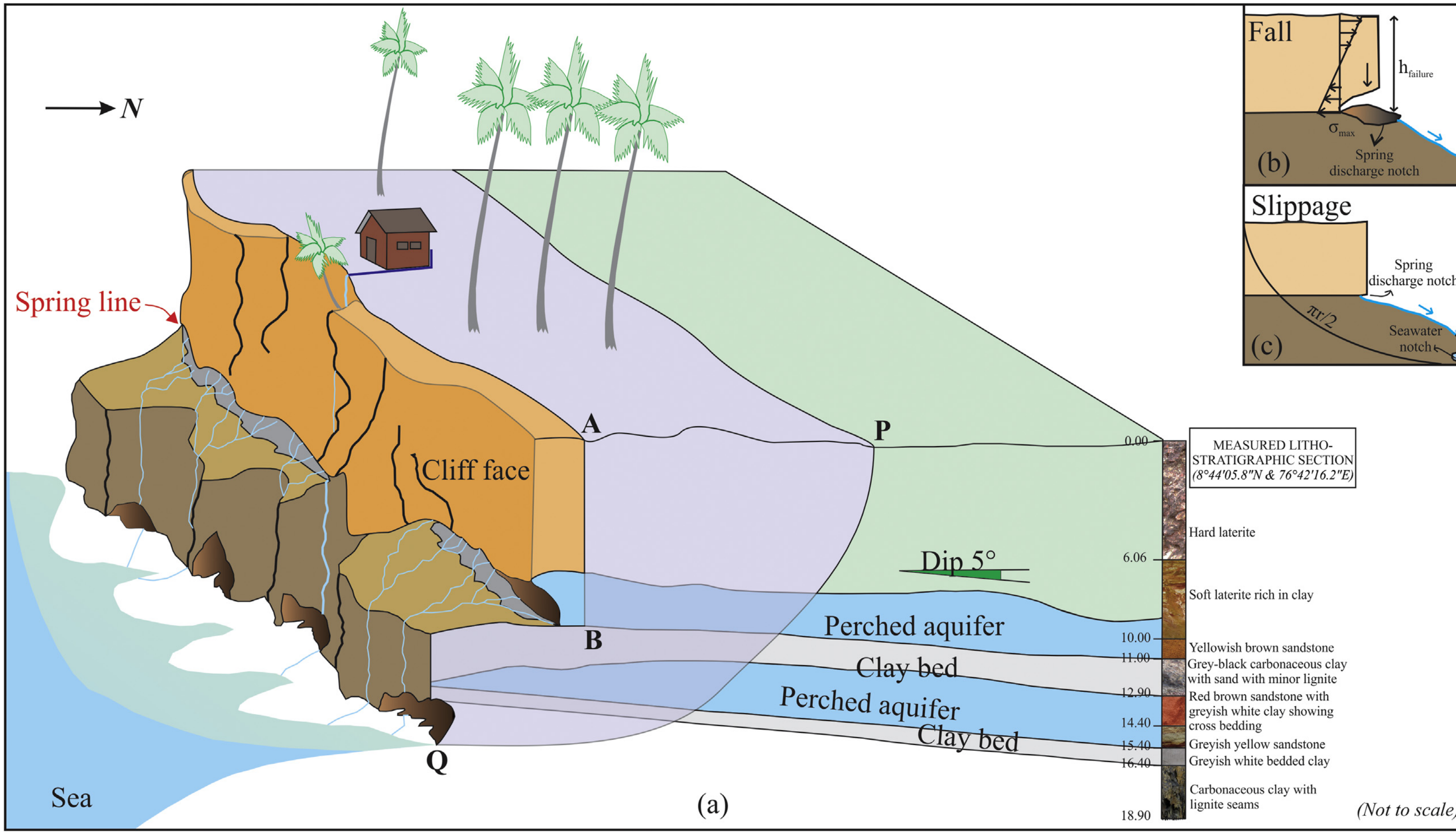

Figure 10. Schematic sketch which depicts the cliff recession in the North cliff. (a) The composite fall-slippage is shown here along with the measured lithostratigraphic column to understand which are the lithounits supposed to be affected. (b) Typical fall and (c) typical slippage. Laterite and sandstone are considered as a single lithounit as laterite is the weathering product of sandstone.

$$\delta Y(Z,T) = \frac{H_b{}^{3/4}T^{3/2}}{K\sigma_{c-mass}(Z)} \times \tan\beta \times p_w(Z,T) + F(\varDelta Q)$$

where $\delta Y(Z,T)$ – erosion rate (m/year) along Y direction

H_b – mean breaker height (m)
T – tidal period (s)
β – local slope
$p_w(Z,T)$ – erosion shape function (m/s)
$F(\Delta Q)$ – fn of spring water discharge
K – hydrodynamic constants ($m^{13/4}$ $s^{7/2}$/kg)
$\sigma_{c\text{-mass}}$ (Z) – UCS for rock mass (kPa) along Z direction

This cliff recession model differs from the one mentioned by Castedo et al. (2012) by the introduction of the factor of fresh water discharge from the spring.

7. Discussion and conclusions

This study is an attempt in incorporating several data spanning from geologic to geotechnical and historic to geophysical. The combination of such data have resulted in filling-up the crucial gap left by other studies like the process-response, Monte Carlo simulations and so on. This composite fall-slippage model also differs from other model by considering different lithounits. The introduction of fresh water seepage in both the fall and slippage class as well the scope of adding carrying capacity of the tourist destination to the slippage model, makes the model viable to run in any multi-parameter influencing conditions. Such an attempt can also be done in other cliff section characterized by the same lithology seen in different stretches in the adjacent area. The study on a whole provided some insights into the factors governing the stability of the cliffs.

Hence this study can be concluded by pinpointing the salient features of the present study:

(1) This method is based on field data deciphered through geological, geotechnical, hydrogeological, geophysical and historical data.
(2) This sort of study can be experimented in other adjacent cliffs and also in other parts of the world.
(3) The model can be ran for multi-lithounits whereas other models are mainly aimed at single lithounit.
(4) The possibility of including anthropogenic activities by considering the carrying capacity can also be included.

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