TEMPORAL CHANGES OF COASTAL CLIFFS: A CASE STUDY FROM VARKALA

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Abstract - The coastal landforms along the Varkala is the only place in Southern Kerala where cliffs are found adjacent to the Arabian Sea and have undergone remarkable change in terms of shape and disposition due to marine and terrestrial processes and often by natural and anthropogenic activities. Red laterite cliff fringing the Papanasam beach is a famed tourist spot here. The authorities, however, seem to be unaware of the need to protect the cliff, which has geological significance. Fissures have developed at several spots along the 2.5m pathway, used by tourists to walk to the beach and the helipad areas. Hundreds of local people staying on the northern side of the cliff also use the pathway, dotted by many shops. Huge chunks of earth precariously hang from the top of the cliff at several places. Unauthorised constructions and piling work atop the cliff and movement of vehicles on the pathway are cited as the main reasons for frequent landslips. The primary objective of this study is to estimate the decadal changes caused in Varkala Beach, India by comparing the Satellite Imageries (2003 and 2019) with Survey of India 1966 Toposheet. The new shoreline was captured from the imageries using overlay analysis techniques of GIS applications. Coastal erosion may have a direct impact on the virtual quality of the landscape. QGIS (3.6) has been used as a tool to delineate the cliff erosion hazard for proper planning and management of coastal developments.

Key Words: Coastal cliffs, cliff retreat, shore expansion, shore widening, cliff erosion

1. INTRODUCTION

Sea cliffs are steep geological features with slopes typically larger than 40° (Goudie, 2004), and around 80% of the world's oceanic coastlines have sea cliffs (Emery and Kuhn, 1982). Their evolution occurs mainly by slope mass movements of different types and sizes (Trenhaile, 1987; Sunamura, 1992). Conflict between human activity and the inherent instability of coasts cliffs has become a growing problem in recent decades mainly due to the steady increase of human occupation and activities in coastal areas (Nunes et al., 2009; Teixeira, 2014).

Sea cliff morphodynamics, especially slope angle and erosion rate, are influenced by marine processes (e.g. waves and tide), subaerial processes (e.g. mass movements, weathering, and bio-erosion), and characteristics of rock materials (Masselink et al., 2011; Emery and Kuhn, 1982). Sea cliffs are steep when marine processes are pre-dominant and are gentle when subaerial processes are predominant (Masselink et al., 2011). Sunamura (1992) states that the resistance to cliff erosion mainly depends on rock hardness.

Due to expansion of settlements and infrastructure and due to the rapid population growth, the land transformation on the natural land use and land cover features has quickened (Mujabar and Chandrasekar, 2012). The changes in coastal land use and land cover due to human activities have wrought in the earth's life support system causes major issues worried by many people in recent decades (Luong, 1993; Jaiswal et al., 1999; Misra et al., 2013). Such negative changes leads to the vulnerability of places and people to climatic, economic or socio-political perturbations of the regions (Nicholls and Small, 2002; Yagoub and Kolan, 2006; Kaliraj et al., 2014). Increasing of population and climatic variability produces pressure on the land use and land cover and cause the greatest environmental impact on vegetative cover, shoreline change, landform degradation, loss of biodiversity, seawater intrusion and groundwater pollution, deterioration of soils and air along the coastal regions (Chandrasekar and Kaliraj, 2012; Chauhan and Nayak, 2005; Mahapatra et al., 2013; Kaliraj et al., 2014). This will result in the total destruction of the ecosystem - both land and aquatic. Even if the main cause of cliff retreat is wave erosion, other processes contribute to the total amount of cliff recession (Bird, 2016).

Subaerial processes, biological weathering and other marine processes can significantly increase the recession rates. Weathering processes is more active on the top of the cliffs, while erosion processes dominate the cliff foot. Coastal landslides involve large masses of rocks, earth or debris at the foot of a coastal slope. The instability of a cliff can be due to the weight of a massive cap-rock and develops with an increase of shear stress or a decrease in shear strength (Bird,2010). The global distribution of coastal cliffs is shown in the Fig-1:

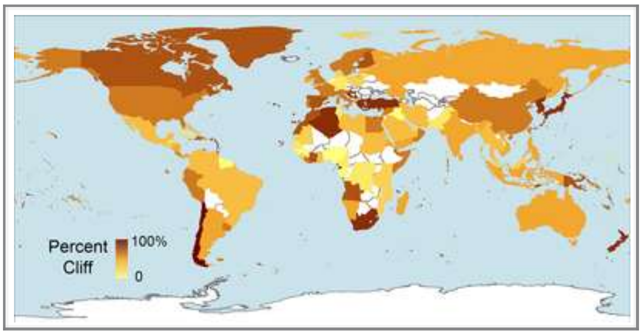

Fig-1: Global Distribution of Coastal Cliffs

Cliffs and other landforms of rocky shores can be eroded by many different interrelated processes, such as hydraulic action, corrosion, attrition, solution and quarrying and cavitation. Runoff processes also involve sea cliffs, since rain and melting can generate water flowing down a cliff slope. On soft rock outcrops it washes away sediments producing rills and gullies. The materials accumulated at the cliff foot are subsequently removed by wave action and in some cases can protect the cliff from wave attack (Furlani et al., 2011). Sea spray can also generate runoff down the cliff. It contributes to weathering promoting processes of wetting and drying, when crystals of salt pluck the rock surface forming pits, honeycombs and tafoni (Bird, 2016). Winds blowing against a cliff can remove fine-grained particles from the slope and create upto small caves (Bird, 2016). The water coming from rainfall or melting snow percolates into the rock mass through fractures, joints and cavities. Groundwater seepage from a cliff face can wash out finer particles leaving cracks and crevices up create an apron at the cliff base (Bird, 2016).

1.1 Study Area

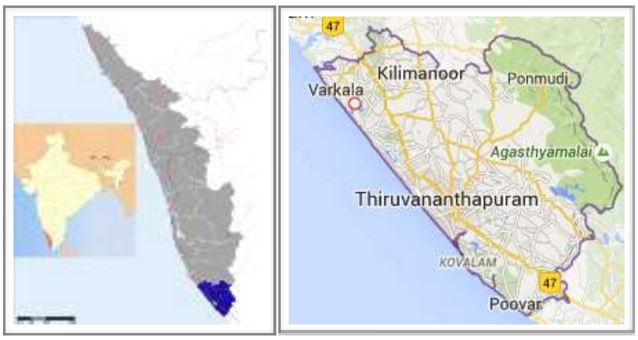

Fig-2: Location Map

Varkala is located 40 kilometres from Thiruvananthapuram which is the capital city of Kerala. The study area is shown in the Fig-2. Varkala is the only place in southern Kerala where cliffs are naturally formed adjacent to the Arabian Sea. Köppen-Geiger climate classification system classifies Varkala's climate as tropical monsoon. It has heavy rains during June–August due to a southwest monsoon. In summer, the temperature rises to a maximum of 32°C (90°F) and 31°C (88°F) in the winters. Record high temperature in neighbouring Thiruvananthapuram is 39°C (102°F). Annual average rainfall is 3,100 mm (120 in).

Varkala is an important place as Kerala Geology is concerned as it exposes sedimentary rocks found on Cenozoic age, popularly known as the Warkalli formation. The study area from Google Earth is shown in the Fig - 3 below:

Fig - 3: Study Area (Source: Google Earth)

The Warkalli formation of Mio-pliocene age (type area is Varkala) is made up of alternating beds of sand exposed along the Varkala cliffs. Thin seams of lignite of the Warkalli formation suggests good vegetation at the time of deposition of the clayey sediments. Vertical ridges or speleothems can be formed because of local precipitation of carbonates. The accumulation of groundwater in permeable rocks can increase the instability of rock masses. The increase shear stress due to the additional loading of groundwater can result in cliff collapse. As it has a unique geological feature, a national geological monument has been declared by the Geological Survey of India for their protection, maintenance, promotion and enhancement of geotourism.

Varkala is a well-known tourist destination. Around 20 plus resorts is situated in the municipality. Tourism started thriving by the end of last century at the Varkala beach (Papanasam), famous for Vavu Beli, a Hindu custom performed at the beach. There are numerous water spouts and spas on these cliffs. In 2015, Ministry of Mines, Government of India and Geological Survey of India (GSI) have declared the Varkala Cliff as a Geo-heritage site.

Human impact is very significant as it can modify, directly and indirectly, sea cliffs and bluffs, such as quarrying sand and rocks, loading the cliff- top with buildings, building roads, vehicular movement, removing and weakening rock masses for fossils searching. This study uses the application of GIS to assess the change in cliff position over three particular years from satellite images and topographical maps using QGIS software and analyse the role of both natural and anthropogenic factors likely to drive clifftop retreat. The collapsed images of cliff is shown in the Fig- 4 below:

Fig - 4: Cliff image (Image taken from the study area)

2. LITERATURE REVIEW

A study by Young and Carilli (2018) uses two approaches to capture information on the worldwide existence and erosion of coastal cliffs: a detailed literature survey and imagery search, and a GIS-based global mapping analysis. The results suggest that the global coverage to estimate cliff occurrence across 89% of the world vector shoreline and coastal cliffs likely exist on about 52% of the global shoreline. Ahmed (2011) describe the causes of major changes in land use pattern of the coastal zone of Bangladesh and identify the effects on the environmental degradation obviously considered as a man-made disaster in the area. The paper shows that the way of using the lands in the coastal areas are gradually changing, i.e., diverse, competitive and alarming. An attempt is made by Kaliraj et al (2017) to map the coastal landforms along the coast using remote sensing and GIS techniques.

The study apart from providing insight into the decadal change of coastal settings also supplements a database on the vulnerability of the coast, which would help the coastal managers in future.

Ikeda and Testik (2019) investigated for eight coastal sites near Santa Barbara, California on the interactions among sea cliff morphology, beach morphology, and coastal hydrodynamics. Among the study sites, the widening of the buffer zone was larger for wider beaches, while the cliff slopes were gentler. Their analysis indicated that long-term cliff erosion in Southern California may be estimated by using adequate wave-induced cliff erosion models. Pian and Menier (2019) combines the application of GIS with spatial and statistical analysis to assess the role of both natural and anthropogenic factors likely to drive clifftop retreat. This approach aims at identifying the main factors associated with differing rates of clifftop retreat in order to produce an effective set of data for coastal managers. The study focuses on two cliff systems located in South Brittany (France): the sheltered and weathered low cliffs of the Gulf of Morbihan, and the rocky cliffs of the Quiberon Peninsula.

Since a range of process-based models have been used the influence of varied vertical lithology has yet to be quantified, Carpenter et al (2014) describes modifications to the 2D SCAPE (Soft Cliff and Platform Erosion) model, to explore interactions between vertical changes in cliff resistive strength and prevailing coastal conditions. The results have important implications for the management of coastal cliffs exhibiting variable stratigraphy, combined with the potential for future interactions with sea-level rise.

Castedo et al (2012) developed a new model to incorporate the behavioural and mechanical characteristics of coastal cliffs which are dominated geologically by over-consolidated clays (tills) and an associated protective colluvial wedge. This model is capable of providing precise and stable responses to some of the inherent uncertainties in cliff recession processes including those caused by different failure mechanisms e.g. colluvium generation, groundwater and erosive tidal cycles. Material strength is incorporated using the unconfined compressive strength of the material that composes the cliff. The model is thus validated through profile evolution assessment at various locations of coastline retreat on the Holderness Coast, UK. Higher groundwater content also produces an increase in the number and size of the slope failures. The results represent an important step in linking material properties to the processes of cliff recession.

Young et al (2018) used Airborne LiDAR data collected in 1998 and 2009–2010 to measure coastal cliff erosion and retreat between the Mexico/California border and Bodega Head, California. Recent decadal-scale cliff retreat is quantified for 595 km of the California coast. Large magnitude historical and recent cliff retreat rates were inversely correlated. Cliffs fronted by beaches retreated 49% farther than cliffs without beaches. Cliff retreat rates are used to detect cliff steepening and areas prone to future cliff top failure. Vitousek et al (2017) present a shoreline change model for coastal hazard assessment and management planning. The model, CoSMoS-COAST (Coastal One-line Assimilated Simulation Tool), is a transect based, one line model which predicts short term and long term shoreline response to climate change in the 21st century. The proposed model represents a novel and modular synthesis of process based models of coastline evolution due to longshore and cross shore transport by waves and sea level rise.

Young et al (2014) described a Modified sand balance coastal retreat model for sea level rise. New modifications include conditionally independent beach and cliff retreat. The model includes subaerial processes and external sand sources and deficits. Model validation and application in southern California are explored. The results underscore the influence of protective beaches on cliff retreat. Understanding changing thresholds and mechanisms for soft rock cliffs retreat is important under changing climates.

This can be achieved through combining detailed field observation, long-term process and morphological monitoring and numerical modelling which is explained by Brooks et al (2012). They quantify annual cliff retreat for every year from 1993 to 2010 and retreat is grouped high, intermediate and low. Process explanations are sought using detailed archival data and numerical modelling. Marine and terrestrial controls are identified. Hence they suggest a model to explain different rates of cliff retreat in soft rock cliffs.

Westoby et al (2018) used SfM-MVS methods in which input photosets of coastal cliff faces can be acquired by non-specialists using a consumer-grade digital cameras. Placing GCPs along the cliff top and base at a spacing approximate to cliff height produces acceptable model accuracy. Correspondence between intersecting TLS and SfM detected rockfall volumes improves beyond threshold. Kilometre scale, TLS and SfM derived erosion rates are comparable. Erosion patterns are spatially variable and can locally exceed the background erosion rate by over an order of magnitude.

An analytic model is proposed by Finzi and Harlev (2016) for evaluating regional cliff retreat rate based on a DEM and GIS analysis. Cliff height and inclination were used to establish relative retreat rates of cliffs within the Makhteshim Country, Israel. Further improvement of the model is achieved by addressing scarp-talus interactions evident from the DEM. Known retreat rates of two cliffs enabled model calibration and derivation of retreat rate estimates for many cliffs. The model reveals significant variations in current retreat rates along the cliffs in the study area. To assess the sea cliff failure susceptibility of low retreat rate cliffs Queiroz and Marques (2019) states logistic regression as an effective method. They states that anthropogenic influence on cliff instability has changed along time and proved to have some relation with cliff failures. The number of large cliff top failures increased along time, suggesting that the triggering factors have also changed.

Stanchev et al (2017) applied DSAS to shoreline changes and cliff retreat, Shabla, Northeast Bulgaria. The goal was to provide reliable data and useful information for the development of a pilot marine spatial plan for Shabla Municipality. The study was focused on the analysis of shoreline movement and cliff retreat utilizing GIS. Cliff erosion hot-spots with high priority were identified. Recommended strategy to the pilot MSP for Shabla Municipality.

Three shoreline prediction methods have been used and compared for Holderness coast by Castedo et al (2015). Empirical models predict recession values with high variability and uncertainty. Process-response models (PRM) predict reasonable recession values with low uncertainty. PRM results are less sensitive to the change of one parameter than empirical models. PRM can be used to inform when/where to intervene along rapidly eroding coasts. Brooks and Spencer (2012) test five shoreline response models to accelerating sea level rise. The SCAPE model is the best predictor of shoreline response in soft rock cliffs. Future shoreline positions are found to 2050 and 2095 on a rapidly retreating coast. They quantify considerable sediment release to the nearshore zone in future.

A study was made by Kaliraj et al (2017) on the coastal land use and land cover features in the South West coast of Kanyakumari which are dynamically regulated due to marine and terrestrial processes often controlling by natural and anthropogenic activities. The primary objective of this study is to estimate the decadal changes and their transformations of land use and land cover (LULC) features under Level II category of USGS-LULC Classification System using Landsat ETM+ and TM images using Maximum Likelihood Classifier (MLC) algorithm for the time period 2000 – 2011.

This study delivers the basic pre-requisite information for understanding the trends in landuse and land cover changes and transformation in the coastal area. A composite fall-slippage model is proposed in an another study by Sajinkumar et al., (2016) for the tertiary sedimentary coastal cliffs of Varkala in the Western coastal tract of Peninsular India which are retreating landwards due to several factors. Slippage in this area affects all the litho-units and hence their geologic characteristics 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.

3. METHODOLOGY

The landforms of the coast are highly sensitive to marine and terrestrial forces to maintaining equilibrium and stability to the morphological structures, and hence analysis of the changes in coastal landforms are important for coastal zone management. The assessment of shoreline changes and coastal cliff retreat is usually carried out by field and aerial surveys combined most recently with high resolution satellite or orthophoto images (Morton and Miller, 2004; Hapke and Reid, 2007; Perez-Alberti et al., 2012; Hapke et al., 2016). Shoreline positions can be marked by several different features such as the vegetation line, the high water line, the low water line, or the wet/dry line (Thieler et al., 2009).

Earlier studies have demonstrated that the GIS approaches is an effective tool for analysis especially by incorporating time-line data to inquire into morphological change of the coastal landforms. Thus in the present study, GIS technique employed for extracting the coastal geomorphological landforms at high resolution. The various types of spatial data sources such as topographical map (scale 1:25,000) published by Survey of India in the year 1966, high resolution image of Google Earth acquired for 2003 and 2019 are used for mapping the coastal landforms through a series of systematic geo-processing operations with QGIS 3.6 software. They were scanned, geo-referenced and plotted. Four corner points were taken and they were geo-referenced for four coordinates.

After geo-referencing, shape files have been created for three images and thus a path along the cliff was drawn using line feature for three images each. For interpreting the extent of shifting of the cliff, the 1000m long cliff area is divided into ten equal segments at 100m each (ie., 100m to 1000m) on the shape file of 1966 topographical map.

The distance from these base points to the shape file path of 2003 and 2019 are measured using measuring scale on QGIS software. The shape file thus obtained is thus shown in the Fig - 5:

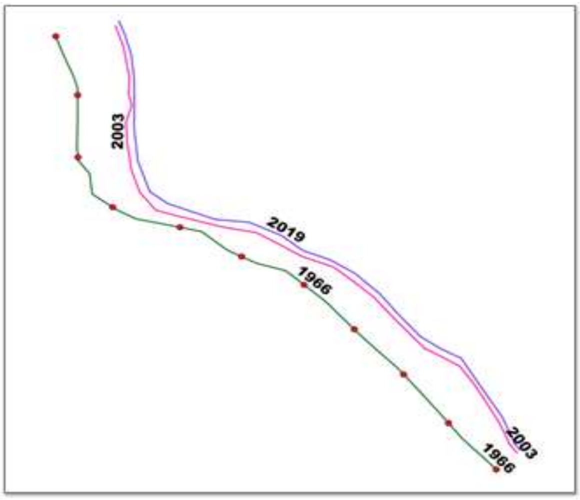

Fig - 5: Segmented line

The variation of cliff retreat over 2003 and 2019 from the year 1966 measured and a graph plotted showing the deviations on cliff retreat by making the shape file path of topographical map of 1966 (scale 1:25,000) published by Survey of India as data.

4. RESULTS AND DISCUSSION

The spatial distribution of cliff top retreat values along the Varkala cliff among the years 1966, 2003 and 2019 is represented. The lines drawn using each shape files over each geo-referenced maps are then compared for shifting of the coastal cliff for those three years (1966, 2003 and 2019). The extent of shifting of the cliff is interpreted by dividing the shape file path into ten equal units at 100m each on the shape file of 1966 topographical map. The corresponding distance from these base points to the shape file path of 2003 and 2019 are measured using measuring scale on QGIS software and the datas obtained are listed in the Table - 1:

Table -1: Shifting of cliff on study area

Distance	Year	
(Metres)	1966-2003	1966-2019
0	84.5	91
100	71.6	79.2
200	72.1	83.2
300	54	70.5
400	16.8	29.9
500	43.3	54.3
600	44	53.5
700	54	63.2
800	54.6	65.8
900	62.8	69.5
1000	39.5	46

A graph is plotted showing the variation of cliff retreat over the years 2003 and 2019 from the year 1966 and is shown in the Chart - 1:

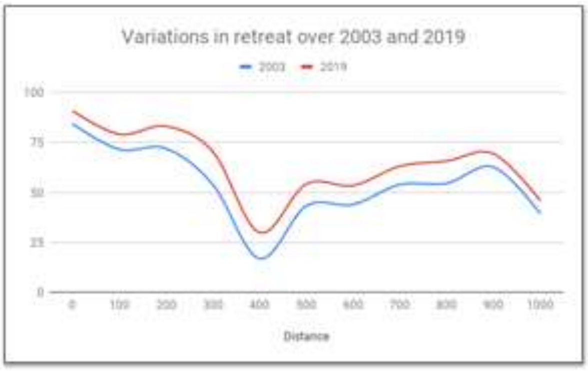

Chart - 1: Variations in retreat over 2003 and 2019

From the Chart, it is interpreted that deviation has occurred from 1966 to 2003 and from 2003 to 2019. There was a huge shift in cliff within 37 years ie., an average shift of 1.47m/year in the cliff than for 16 years ie., from 2003 to 2019 itself, as it shows an average deviation of only 0.67m/year. The sinusoidal graph represents the varying nature of the cliff surface over years. Somewhat uniform shifting is seen in between the years 2003 and 2019. Finally, the shifting of layers for the years 1966, 2003 and 2019 are separately prepared for geo-database with the attributes using QGIS software.

Furthermore, these classified images are involved for accu- racy assessment using post field verification technique (Kaliraj et al., 2017).

The shifting of cliff may be due to natural as well as anthropogenic reasons. The impact of anthropogenic reasons may be due to increase in human activities above the cliff surface. Constructions as well as vehicular movement on the cliff top is increasing year by year. The increasing number of buildings over the cliff top from 2003 to 2016 as per the data collected from Varkala Municipality is listed in the Table - 2:

Table -2: Newly constructed buildings (Unpublished report; Source: Varkala Municipality)

Year	Number of buildings newly constructed
2003	39
2004	61
2005	54
2006	56
2007	46
2008	76
2009	71
2010	50
2011	29
2012	36
2013	28
2014	9
2015	42
2016	3

The number of constructions are increasing yearly over the cliff top. Both legal and illegal constructions are there at the cliff top. There are certain regulations for constructing a building at the cliff top, but illegal construction activities are taking place. At 2003, there were only 460 buildings, but at present there are1299 buildings. The datas presented here are only about legal constructions, i.e., more than these numbers, there are unauthorised buildings also.

4. SUMMARY AND CONCLUSION

Coastal zones are interaction zones between land and sea, and thus many environmental, economic and social issues will lead to coastal erosion. An estimation of the decadal changes caused in Varkala Beach, India by comparing the Satellite Imageries (2003 and 2019) with Survey of India Toposheets 1966 has been made in this study in order to analyse the cliff retreat over a stretch of 1km extending from Black Beach to Helipad on the Varkala cliff area. With the aid of GIS technique the change in the cliff was clearly brought out. Deviation has occurred from 1966 to 2003 and from 2003 to 2019. There was a huge shift in cliff within 37 years ie., an average shift of 1.47m/year in the cliff than for 16 years ie., from 2003 to 2019 itself, as it shows an average deviation of only 0.67m/year. Coastal processes involving wave, current wind, tide, rainfall, gradient and anthropogenic activities mainly influence the characteristics of landforms especially coastal cliffs. GIS provides an effective platform for assessment of cliff changes and transformations over time. In this study area, it is observed that area in beach face landforms are converted into settlements and built-ups and it is increased from 1966 to 2019 due to human encroachment and urban expansion activities. The pressure on the cliff due to illegal construction and free movement of vehicles along the cliff edge were the reasons for cliff retreat. Under the rule, only temporary constructions can be undertaken two metres from the pathway bordering the cliff. But it is seldom followed and the authorities do not initiate action against those violating the rule. Thus regulations for construction activities and vehicular movements should be followed as well as shore protection techniques should be implemented for preventing further erosion of coastal cliff.

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