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LANDSLIDE IN ROCKS OF JODHPUR GROUP AT MASURIA HILL IN JODHPUR, WESTERN RAJASTHAN, INDIA: ITS CAUSES AND THREAT TO SIGNIFICANT GEOHERITAGE

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ABSTRACT

The first disastrous landslide at Masuria Hill (MH) damaged many houses and properties in residential colonies in the Jodhpur city, Western Rajasthan, India. The present landslide created panic and posed a severe concern to geoscientists and local administration. Geologically, MH is represented by rhyolite of Malani igneous suite (MIS) of Cryogenian age occur at the base which is overlain by siliciclastic rocks of Jodhpur Group (JG) of the Marwar Supergroup (MSG). Rocks of JG in Jodhpur are divided into three formations viz: lower Umed Bhawan Formation, middle Soorsagar Formation (SSF) and upper Motisar Hill Formation (MHF). The landslide occurred in horizontally disposed rocks of Umed Bhawan Formation (UBF) of JG. UBF can be divided into a clay-dominated soft sediment zone with sheet and release joints at the

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base, followed by a rigid sand zone with orthogonal jointing. This disposition of soft and rigid pattern of sedimentation of UBF is identified as the vital horizon responsible for the landslide with shale horizon as the failure plane. The causes of landslides can be explained based on the model of BPSZ (Bedding Parallel Shear Zone). BPSZ is attributed to the liquefaction, mass wasting, and shear stress that caused the landslide. Paper also discussed the geoheritage elements of educational, geotourism and cultural values that are endangered and threatened to landslide along with seven other similar hills of UBF in the Jodhpur.

Keywords: *Masuria Hill, Landslide, Soft and rigid rock zones, Bedding Parallel Shear Zone, Geo resources, Mitigation measures.*

INTRODUCTION

Recently, the NE part of Masuria Hill (MH) experienced ever first landslide on 4th September, 2019 in Jodhpur, which damaged significant georesources along with many houses, properties and also injured many people in the Bank colony of Jodhpur city, Western Rajasthan, India (Fig. 1). Landslide at MH not only spread panic among people but undoubtedly is an alarm for future disaster in Jodhpur. During Landslide Rock materials ranging from dust particles to massive boulders upto 3m in size fall to surrounding residential areas. The geological disposition at MH is represented by rhyolite of MIS at the base, which forms the basement for the overlying rocks of UBF and SSF of JG (Fig. 2). The UBF at MH is represented by a coarsening upward siliciclastic cycle having shale at the base followed by shaly siltstone, siltstone, fine, medium and coarse-grained sandstone at the top. The soft clay zone-rigid sandstone zone of UBF played an important role in the present landslide. The physical action on rocks of two zones since Ediacaran period yielded several structural elements (Davis et al., 2012), leading to weaker planes to siliciclastic sequences at MH. Additionally, the present study also identified seven similar hills of UBF that are under significant threat to landslides, which may harm people and destroy the surrounding residential areas of Jodhpur in the future with significant geoheritage elements (Fig. 3).

Under such geological scenario, the present paper discusses the stratigraphic setup of UBF and its significant geoheritage at MH, which are under great threat to damage by a landslide. Further, the causes of landslides are explained utilizing a model of BPSZ (Bedding Parallel Shear Zone) and suggest mitigation measures to protect significant georesources, houses, properties, and people of Jodhpur residing in surrounding areas of the hilly landscape of UBF.

Fig. 1: Google image showing the location of Masuria Hill and surrounding residential area.

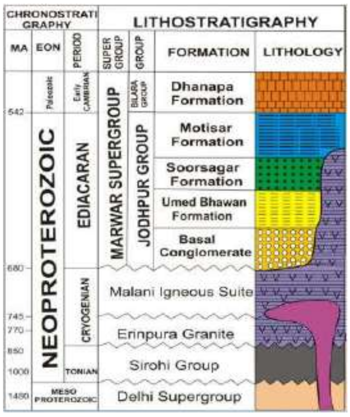

Fig. 2: Lithostratigraphy of Jodhpur Group of study area (Mathur et al., 2019a).

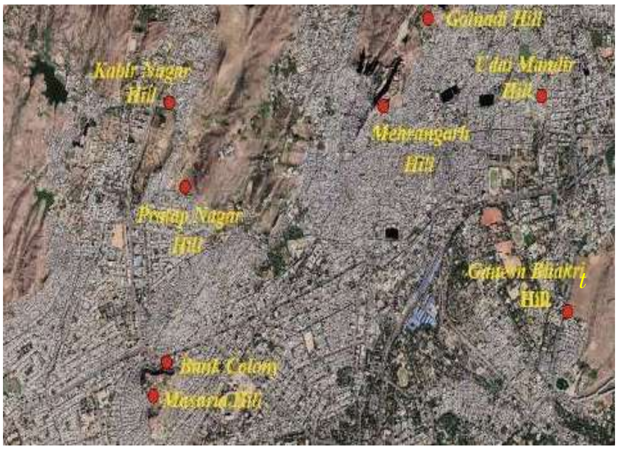

Fig. 3: Google image showing landslide-prone hills and residential areas in Jodhpur.

Three passive factors were taken into consideration, which affected the geological structure and landforms on the development of mass movement processes at MH. These factors are liquefaction, slumping (mass wasting), and shear stresses during material flow.

MATERIAL AND METHODS

To understand various factors of landslide, a field study was conducted to identify rock types of MH also utilizing lithological and petrographic techniques, identification of jointing patterns, and various georesources in each lithological unit of MH. A generalized litholog of MH was prepared based on field, lithological and petrographic studies to identify soft zone and rigid zone stratigraphy for explaining passive factors responsible for a landslide at MH.

Geological Setting

Outcrops of UBF of basal Jodhpur Group (JG) of MSG occur mainly at Masuria, Udai Mandir, Lal Sagar, Kabir Nagar, Pratap Nagar, Mehrangarh hill, Gol Nadi hills along the fort road, Ganesh Bhakti Hill (GBH) in Jodhpur (Fig. 3). Stratigraphically, 220m thick UBF at its type area at GBH overlies the Malani Igneous Suite of rocks (745 to 681Ma) and underlies the Soorsagar Formation (SSF) of Ediacaran age belonging to JG of MSG. At MH, about 90m thick coarsening upward UBF is represented by shale at the base followed by silty shale and shaley siltstone (Clay dominate soft zone); fine-grained, medium-grained, coarse-grained sandstone, and pebbly sandstone at the top (rigid sand zone; Fig. 4a, b, and c). Dominantly, preserving trough and festoon cross-bed in UBF indicates a Fluvio-deltaic environment (c.f. Mathur et al., 2019a; Mathur et al., 2019b). SSF displays fine and medium-grained sandstones which occupy the top of MH. It has been found that the distribution

Fig. 4: a. Outcrop of coarsening upward siliciclastic facies of UBF developed on rhyolite basement. b. The horizontally disposed soft clay zone and rigid sand zone of UBF at MH. c. Soft clay zone having sheet and release joints, while the rigid sand zone shows orthogonal jointing of varied spacing in UBF sequences.

and deposition of sediments of JG at MH is governed by the configuration of uneven basement rock exposed at the foothills of MH (Fig. 4a).

RHYOLITE BASEMENT

Voluminous rhyolite occurs in the subsurface of all the surrounding residential areas of MH and its outcrops on the surface can also be found along the road from *Akhaliya* circle to New Kohinoor Cinema Hall and on the road that goes to Veer Durga Das Park, at and around Ram Dev temple and Masuria colony (Fig. 1). The outcrop distribution indicates that residential colonies, roads, and other infrastructures were developed by destroying vast rhyolite georesources having remarkable and significant features of geoheritage values as evident from Mehrangarh Ridge of Jodhpur (Mathur et al., 2017; 2021). At MH, the hard, tough, and brown colored rhyolite displays fine-grained texture with numerous small rounded to elliptical vesicles on its surface (Fig. 5a). The petrographic study indicates that Masuriarhyolite is

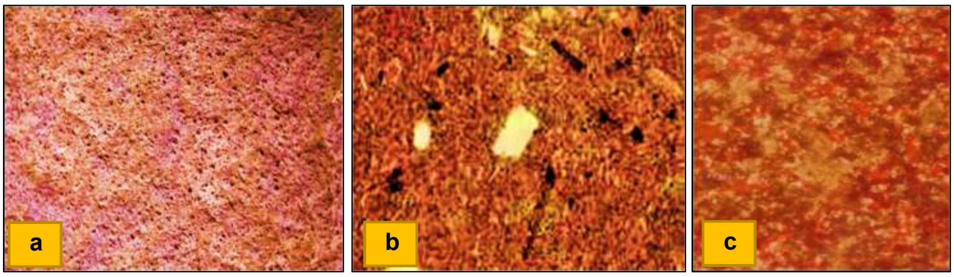

Fig. 5: a. Fine-grained rhyolite showing numerous small rounded to elliptical vesicles. b. Thin section of Rhyolite showing laths of feldspar and biotite in an extremely fine-grained quartzo-feldspathic matrix. Crossed Nicols.10X. c. Thin section of shale showing an extremely fine-grained matrix of clay minerals with few silt size quartz and feldspar with iron oxide cement. Crossed Nicols.20X.

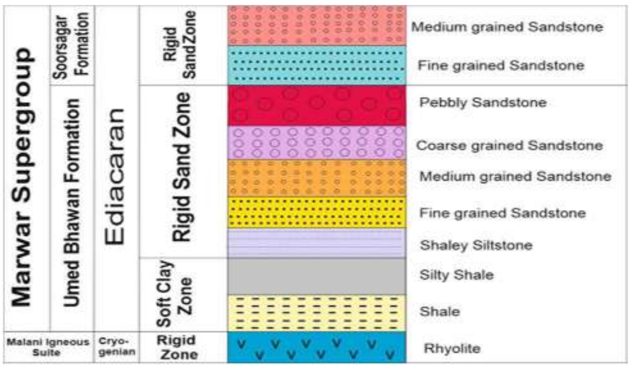

Fig. 6: Generalized lithostratigraphy of JG at MH showing the distribution of soft and rigid zones.

composed of quartz, feldspar, biotite, and iron oxide of extremely fine-grained with a few small-sized feldspar phenocrysts (Plate 5b). Rhyolite is overlain by fine-grained shale (Plate 5c) of UBF (Fig. 6).

Rocks of UBF

UBF forms a coarsening upward sedimentary sequence at MH, which is represented by shale (Fig. 5c) at the base followed by silty shale, shaley siltstone, fine-grained sandstone, medium-grained sandstone, coarse-grained sandstone (Fig. 6; Fig. 7 a, b, and c) and pebbly sandstone at the top. JG at MH is distinctly divided into three zones in chronological order; (i) Clay-dominated soft-sediment zone at the base and (ii) Sand-dominated rigid zone in the middle (Fig. 4b) and rigid zone of rocks of SSF on the top (Fig. 6). The soft zone shows gradational contact in sedimentation and is represented by shale at the base, followed by silty shale and shaley siltstone. The petrographic study suggests that brown-colored silty shale is an extremely fine-grained rock dominantly composed of clay minerals (Fig. 7a). Field observation reveals that the rocks of the soft zone characteristically have a sheet and release joints (Fig. 4b). Due to the increasing amount of silt size detritus the shale grades into silty shale and shaley siltstone at the top in the soft zone. The shaley siltstone grades upward into fine-grained sandstone followed by medium-grained sandstone, coarse-grained sandstone and pebbly sandstone at the top, constituting the rigid sand zone of MH (Fig. 7b). The sandstones of the rigid zone have orthogonal joints with varied spacing and are highly fractured (Fig. 4b and c). The sandstones of the rigid zone are dominantly composed of mono-crystalline, sub-angular to sub-rounded clastic quartz grains with few feldspar grains and are cemented by iron oxide (Fig. 7c). With the same mineralogical composition, only the textural differences make four sandstone

Fig. 7: a. Thin section of shaley siltstone showing extremely fine-grained silt size quartz and feldspar in a groundmass of clay minerals and iron oxide. Crossed Nicols.10X. b. Outcrop of sandstones of rigid zone showing fracturing and jointing. c. Thin section of coarse-grained sandstone showing monocrystalline subangular to sub-rounded quartz and few felspar grains set in the cement of clay and iron oxide minerals.

facies in the rigid sand zone. Fine to medium-grained sandstone of SSF of Ediacaran age represent the top of the section of JG at MH (Mathur et al., 2019a and b). SSF at MH display excellent preservation of copy book style ripple marks and other sedimentary structure represent beach to near coastal environment (Mathur et al., 2019a and b). The textures, structures and features present in various rocks of MH display significant geoheritage that make it an outdoor museum of high educational and geotourism values.

RESULTS AND DISCUSSION

Geoheritage of Masuria Hill

The geological framework of basement rhyolite and siliciclastic rocks of JG indicate that MH is significantly endowed with igneous and sedimentary types Georesources (c.f. Ruban, 2010) of India showing their educational and geotourism significance similar to Mehrangarh Ridge of Jodhpur (Mathur et al., 2021). The identification and characterization of Georesources of MH discussed above are under great threat to destruction due to landslides and rapid urbanization and illegal encroachment activities. Hence, georesources of MH should be protected, and conserved *in situ* for present students, tourists and future generations as an outdoor museum of spectacular rocks and their geoheritage elements representing two significant periods (Cryogenian-Ediacaran) of the Earth history as discussed below:

Geoheritage in Rhyolite

Basement rhyolite of MH belongs to MIS which is considered as the world's third and India's first largest, felsic and terrestrial igneous province formed due to extensional tectonics in this eastern Gondwana land **(**Bhushan, 2000; Maheshwari et al., 2009). The extensional tectonics of MIS is related Pan-African orogeny and splitting of Rodinia Supercontinent indicating its international significance as evident from Mehrangarh ridge in Jodhpur (Mathur et al., 2021). Rhyolite at MH showcases the basement cover relationship through the interface between MIS (rhyolite) and overlying JG (shale of UBF). Being rare among the vast outcrops of JG, this non-conformity between sedimentary and volcanic rocks (interface of Cryogenian and Ediacaran period) was declared as the National Geological Monument at Mehrangarh ridge (GSI, 2001 and Mathur et al., 2021). This rare outcrop is of sequence stratigraphic significance. Besides all these features, textbook-style vesicular structures, porphyritic structures (Plate 1d and e), onion-shell weathering structures, and beautiful flow structures in rhyolite impart spectacular views to the outcrop, especially near Masuria temple (Fig. 1) are of great geoheritage values. This outcrop can be an excellent outdoor museum with remarkable features of great educational and geotourism value for students researchers and tourists.

Geoheritage in rocks of UBF

Coarsening upward siliciclastic sequence of fluvio-deltaic environment displaying gradational contacts between rocks of UBF (Mathur et al., 2019a and b) is an ideal outcrop for students to observe and learn such sedimentation patterns and features in the field. This sequence also preserves spectacular and textbook-style sedimentary structures like laminations, beddings, graded bedding, planar cross beddings (Fig. 8a, b and c), trough cross beddings, and chromatographic structures (Fig. 9b and c); making UBF a significant geoheritage site of regional and national significance. As such, the outcrops of UBF and their significant georesources at and around Veer Durga Das Park on MH (Fig. 1 and 9c) can be an excellent outdoor field museum and rock park similar to the Rao Jodha rock park of great educational, tourism, and cultural values developed at Mehrangarh hill in Jodhpur (Mathur et al., 2021).

Fig. 8: a. Beautiful laminations and beds in fine-grained sandstone of UBF. b. Coarse to medium-grained sandstone of UBF showing graded bedding. c. Fine-grained sandstone of UBF showing planar cross-bedding.

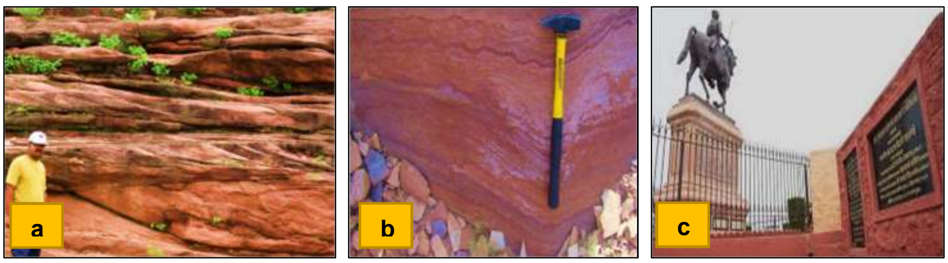

Fig. 9: a. Medium-grained sandstone of UBF showing well-preserved trough cross-bedding. b. Medium-grained sandstone of UBF showing beautiful chromatographic structures. c. Veer Durga Das Rathore Park of MH of historical and cultural heritage values.

Historical and cultural geoheritage

Land of Marwar is rich in history, culture, and tradition with numerous heroes by which it inspired the whole world by their bravery, velour, and sacrifices (Pollard and Aydin, 1988). One such person of Marwar is Veer Durga Das Rathore and MH is also popularly named as Veer Durga Das hill. He is credited for having saved the regime of the Rathore Dynasty following the effects of the death of King Jaswant Singh in the year 1678. In the memory of Veer Durga Das, an equestrian statue has been erected at top of MH (Fig. 9b and c) through the efforts of Chief Patron HH Maharaja Shri Gaj Singh Ji of Veer Durga Das Smriti Samiti, Jodhpur, and with the help of the Rajasthan Government. Statue of Veer Durga Das Rathore was unveiled by then Prime Minister of India, Mr. Atal Bihari Vajpayee, on October 3, 1998. To respect him, a stamp was also released by the central government to attribute respect to him. To honour him, Veer Durga Das Rathore Memorial Award is also given every year on his birth anniversary to people contributing to the welfare of society in various fields. Authors (SCM and SSR) got this prestigious award in 2014 for his outstanding research work in the field of the geology and hydrogeology of Marwar. Earlier, to convert this hill into a synoptic tourist destination, Shri Mathura Das Mathur, the then education minister, initiated and planned to make MH an attractive tourist place. Later on, this project was extended by the efforts of Mr. Jagat Singh Ji, Director of Veer Durga Das Smriti Samiti. Hence, presently, it is a beautiful historical and monumental cultural heritage of Jodhpur with a big statue of Durga Das Ji, a museum, library, lush green garden with restaurant, open air theatre, musical fountain, facilities for children, and sports entertainment for local people and visitors (*www.aapnojodhpur.com/veer-durgadas-rathore*). All these important heritages (geological, historical, and cultural) occur in thirteen hectares of land make MH an excellent geoheritage site similar to Rao Jodha Rock park of Jodhpur. Like MH, significant georesources at six other hilly areas of UBF in Jodhpur (Fig. 3) are under considerable threat due to landslides. Hence, understanding of causes of landslides at MH would be helpful in conserving significant geoheritage with suggested mitigation measures at other hills of UBF in Jodhpur is also urgently required.

CAUSES OF LANDSLIDE AT MH

Geological Attributes

It is clear from geological attributes that MH has hard-soft-hard (rhyolite-clay-sand) depositional sequences from the basement to the top of UBF, and this sequence has not been tectonically deformed. Among structural elements, mainly joint patterns have played a crucial role in weakening the rocks of UBF. Further, it is observed that soft sediments (shale, silty shale, and shaley siltstone) dominantly have a sheet and release joints that are formed near the surface (Fig. 4b and c). These joints formed due to the effect of frequent exposures of soft rocks to the diurnal temperature cycle in summer. As a result, the rocks heated, expanded, and stressed in the daytime, cooled and contracted at night, and finally relaxed elastically. This repeated physical action built up stresses that eventually exceeded the tensile strength of the bedrock.

Further, compressive stresses are released along with pre-existing structural elements such as bedding planes and cleavage, i.e., planar and platy minerals (Girty, 2009) present in the clay zone of MH. Repetition of this process resulted in the formation of sheet and relaxed jointing in the clay zone. Similarly, in the rigid zone, this physical action of diurnal thermal cycling creates stresses in clastic grains of sandstone (being more brittle) which leads to creating joints and fracturing, whose one set (vertical) is persistent and abut at the soft-sediment surface to make “T” intersections (Rai et al., 2014). This fracturing pattern produced orthogonal jointing dividing the rigid sandstone into characteristic big blocks as shown in photographs (Fig. 10a, b and c). The jointing pattern and varied spacing between two consecutive joints determine the size and shape of the resulting blocks i.e., sometimes closed and sometimes ample space between joints (Fig. 4b and c) resulted into variable sizes of clasts from pebbles to boulder size blocks. The fall of these clasts destructed houses and properties in the Bank colony (Fig. 10 a, b, c, and Fig. 11 a, b and c). Under above geological attributes and physical scenario two zones at MH, the causes of the Masuria landslide can further be explained by a model of BPSZ (Bedding Parallel Shear Zone). BPSZ (Habibah et al., 2011)at MH is attributed to three main mechanisms: liquefaction, slumping (mass wasting), and shear stresses exerted by the material flow during a landslide.

Fig. 10: a, b and c. Small to bigger sized sandstone pebbles, boulders and cobbles that fall from MH.

Fig. 11: a, b and c. Damage to the houses and property at Bank colony, Jodhpur due to severity of landslide.

Liquefaction

Liquefaction occurred at MH due to the coherent mass of loosely consolidated materials (soft zone). A rock layer moved a short distance along a planar surface, i.e., various joints and bedding planes. Additionally, at MH the permeable layer (sand zone) overrides an impermeable surface (clay zone) which leads to blocking slumps (Fig. 10a) along the planar surface in which one or more related block units move down the slope as a relatively coherent mass. Rains also provide lubrication for the material to slide by increasing pore pressure. Instabilities are caused by density contrasts and the movement of pore water and rainwater infiltration through the sediments. It is also corroborated that Jodhpur has received an increasing trend of rains since the last decade and experienced six times more rainfall in the monsoon season of 2019 (https://www.accuweather.com and www.weather-ind.com, Jodhpur).

Slumping (mass wasting)

Slumping at MH occurred due to mass wasting, which occurs when a coherent mass of loosely consolidated clay zone and rigid sandstone moves a short distance down a slope. Due to erosion, results in the mass movement of rock blocks, soil, and debris down a slope in form of rock slides, debris flows, and earth flows (Fig. 4c).

Shear stresses during the flow of material

During slumping, detachment of sandstone blocks at MH occurred when stresses imposed became more significant than the strength of the clay zone to hold them in place. Further, under the influence of gravity, the blocks were mobilized when the shear stress imposed on a surface exceeds the shear strength. It resulted in the fall of a range of material from clay-sand size to large boulders on the houses below from the cliff-like face of MH in Bank colony and damaged houses, properties, and significant georesources of MH (Fig 10 and 11).

The spectacular and isolated hillock of Masuria (Fig. 1) is amid from the surrounding plane area to attain a height of 145m. It is a popular place in Jodhpur for tourists and recreational activities for local people. Since many residential colonies have been developed legally and illegally on Masuria Hill as well as at and around the foothill are under great threat in future as evident by present landslide. Significantly, under the present study, the soft clay zone (mainly clay horizon) is identified as a failure plane, and fall of clay, sand, pebbles, boulders, and cobbles from the rigid sand zone was responsible for damage as per the processes following the model of BPSZ discussed above. The present study also found two such critical zones spread all along the 1.81 km peripheral area surrounding MH. Hence, all colonies on the peripheral region of MH are under great threat to landslide in the future viz a viz significant geoheritage. Since landslide has been initiated at MH, which is situated in the heart of the city, many human activities in the surrounding would also aggravate the landslide in the future. These factors are mainly: earthwork and construction of buildings; vibrations from machinery and traffic, blasting for breaking and removing rocks leads to disturbing the natural disposition of rock sequences of MH especially soft clay zone.

Additionally, the present landslide occurred when Jodhpur received more rainfall in the year 2019 along with excess rain in the first week of September 2019 (www.weather-ind.com, Jodhpur), which may have aggravated the process of liquefaction and erosion at MH. Evidently, during the same period, a small-scale landslide also occurred at hillock with the same rock disposition of UBF at Uday Mandir area in Jodhpur (Fig. 3), which killed three persons

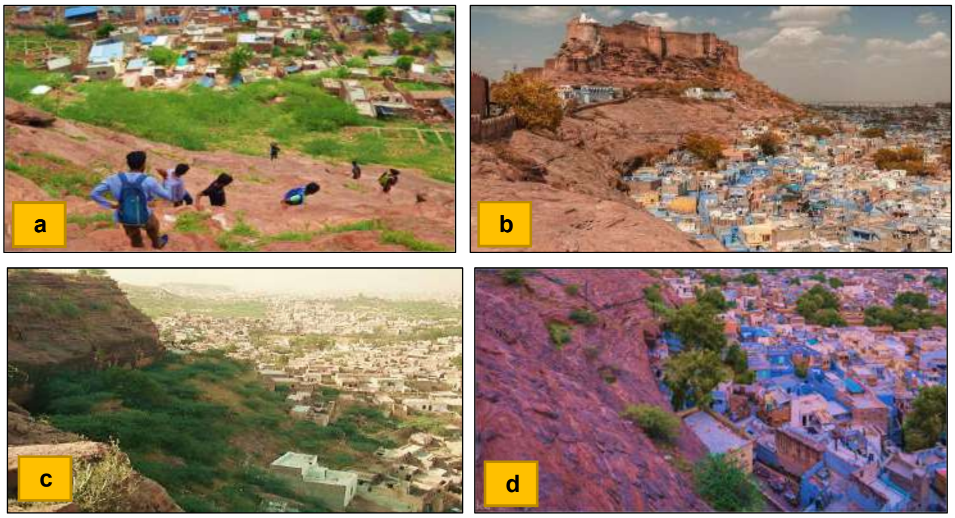

Fig. 12: a, b, c and d. Field photographs showing similar to MH landslide-prone area and disposition of hills in a different part of Jodhpur.

and many were injured. Hence, these two evidences are an alarm for future disasters in Jodhpur. The residential areas around seven hills of UBF, i.e., Masuria hill, Udai Mandir hill, Kabir Nagar hill, Pratap Nagar hill, Mehrangarh hill, Gol Nadi hill along fort road, Ganesh Bhakti hill, Goda Ghati as shown in Fig. 3, are high-risk zones concerning landslide similar to MH (Fig. 12 a, b, c and d). Local administration should declare these areas a landslide-prone zone to save houses, properties, people, and significant geoheritage of the Jodhpur.

Both passive and active mitigation tools can mitigate landslides in rocks of UBF. Looking to the geological disposition and nature of rocks of UBF, Passive mitigations can be done by using drape nets, rock-fall catchment fences, and constructing diversion dams as generally utilized in landslide prone areas are preferable and tend to be more sustainable. Active mitigations require human intervention to operate properly and can be done by using rock bolting, slope retention systems, and shotcrete. These are usually applied based on the character and location of rocks (Habibah et al., 2011). Accordingly, local administration should take serious cognizance of the 4th September, 2019 disaster of the ever first landslide at MH by adopting suggested mitigation measures to avoid such future disasters in the Jodhpur city.

CONCLUSION

The first landslide on 4th September, 2019 at MH is a severe alarm to Jodhpur city for future landslide disasters. Sedimentation and disposition of the soft and rigid pattern of UBF and clay zone are identified crucial horizons and shale as failure plane for landslide at MH. The present study found that model of BPSZ (Bedding Parallel Shear Zone) can explain the causes of a landslide of MH attributed to liquefaction, slumping (mass wasting), and shear stress mechanisms. About 1.81km peripheral area surrounding MH is critically very susceptible and under great threat to landslide in future along with surrounding residential colonies of other six hillocks having similar rock disposition of UBF in Jodhpur. Landslide at MH damaged the houses and properties and destructed the significant igneous and sedimentary types geoheritage of educational and geotourism values. Notably, the georesources of MH, along with six other hills, are under substantial threat, which is of great educational and cultural values of national and international significance and need urgent protection. These can be protected by applying suggested mitigation measures and can conserve as Veer Durga Das Rock Park.

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DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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