Disastrous landslide episode of July 2005 in the Konkan plain of Maharashtra, India with special reference to tectonic control and hydrothermal anomaly

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We report here the disastrous landslide episode of July 2005 that killed 190 people and gave rise to hydrothermal anomaly. Field investigations were carried out to study the physical framework covering climatic, geologic, geomorphologic and seismologic information of the affected area. Structured interviews through an appropriately designed questionnaire were also conducted to collect first-hand information from the people who had witnessed the events and those who were involved in rescue operation to throw light on the causative factors responsible for the landslides and generation of hydrothermal anomaly. A meagre record available at the revenue and the police departments was also referred. It has been observed that all the landslides occurred within a short span of 20 h between 8 pm of 25 July and 4 pm of 26 July 2005. Majority of events took place speedily, but a few with a rumbling noise coupled with a phenomenon resembling lightening, releasing of dust and steam in the form of fountain leaving behind deep but narrow depressions that ultimately triggered the landslides. The temperature of muddy water was appreciably high in such cases. The data revealed that seismicity of the region has been responsible for developing fissures parallel to N–W to NNW–SSE trending fracture-controlled streams along which majority of landslides occurred following incessant rains. The genesis of hydrothermal anomaly developed at six places has been explained using dilatancy–diffusion model. The symptoms of slope instability observed before the episode at ten places indicate that sliding surfaces had already crossed geological threshold; as a result, landslides occurred without development of hydrothermal anomaly.

Keywords: Hydrothermal anomaly, Konkan plain, landslides, tectonic control.

THE physical set up of the study area, included in the Toposheet No. 47F/8 of Survey of India (Figure 1), is conducive to landslides that fall in the Foothills Groundwater Sub-province[1]. It is characterized by hot and humid climate[2], with an average yearly rainfall of 2610 mm. Data for the year 2005 revealed that the area received 781, 1694, 992 and 939 mm of rainfall during June–September 2005 respectively. Further, the area experienced incessant rains from 23 to 26 July 2005, when almost one-third of the average yearly rainfall (as high as 878 mm) was recorded.

The area constitutes a part of the Deccan Volcanic Province, which is known for horizontally disposed basaltic flows. The flows typically exhibit spheroidal weathering; and columnar or block jointing. The area up to 100 m altitude is occupied by compound flows belonging to Bhushi Formation[3]. The flows contain several hummocky lobes effused at a short interval but essentially within a single spasm of eruption. Individual lobes display a basal section with pipe-amygdales, a middle section of massive rocks with or without joints and an upper highly vesicular section (Figure 2). The flows are covered by *in situ* regolith. Thickness and extent of regolith is found to be controlled by the physiographic set-up.

This highly dissected terrain, up to 530 m in height from the mean sea level, is a part of the foothills along the western flank of the western mountain chain of peninsular India. A westerly flowing Savitri river passes through the area that drains into the Arabian Sea. The lower graded stretch of the Savitri, therefore, remains under tidal influence. A number of N–W to NNW–SSE trending tributary streams meet the Savitri almost at right angles. The lower-order streams originating in the upper reaches of the basin show dendritic-to-sub-dendritic pattern, which is indicative of erosional control over uniform basaltic lithology. The higher-order streams in the lower reaches, on the other hand, exhibit parallel-to-sub-parallel courses with sinus trends suggestive of structural control[4]. Evidences of uplift such as knick points that give rise to cascades and falls, presence of pot-holes much above the present channels and deep incision are seen all along the stream courses.

The Konkan coastal plain has been experiencing tremors of varying magnitude since 1964. The epicentres of these earthquakes are clustered in and around Koyna, Chandoli, Chiplon, Khed, Mahad, Khardi and other locations in Raigad and Ratnagiri districts[5,6]. The study area falls in the Zone Five as observed from the isoseismal map and constitutes a northern sector of NW–SE trending Chiplon lineament that bifurcates in the N–S direction as evident from the satellite imagery data[7].

The data of structured interviews and field investigations revealed that out of sixteen events studied, four events, at Jui, Rohan, Dasgaon and Kondvite, turned out to be fatal – the death involved in them respectively being 94, 15, 48 and 33 people. Over 400 houses were totally or partially damaged. The landslide at Tudil damaged a school building but fortunately after the school hours, i.e. at 8.30 pm on 25 July. The area below the 20 m contour was under flood water for over 48 h due to incessant rains and tidal influence. Transportation routes, telecommunication and electricity supply systems were paralysed for 4 to 6 days.

All the landslides occurred within the altitude range of 20 and 100 m involving basaltic regolith resting on spurs to cause debris flow, leaving behind concave-shaped scarps. Out of sixteen landslides, twelve are oriented in

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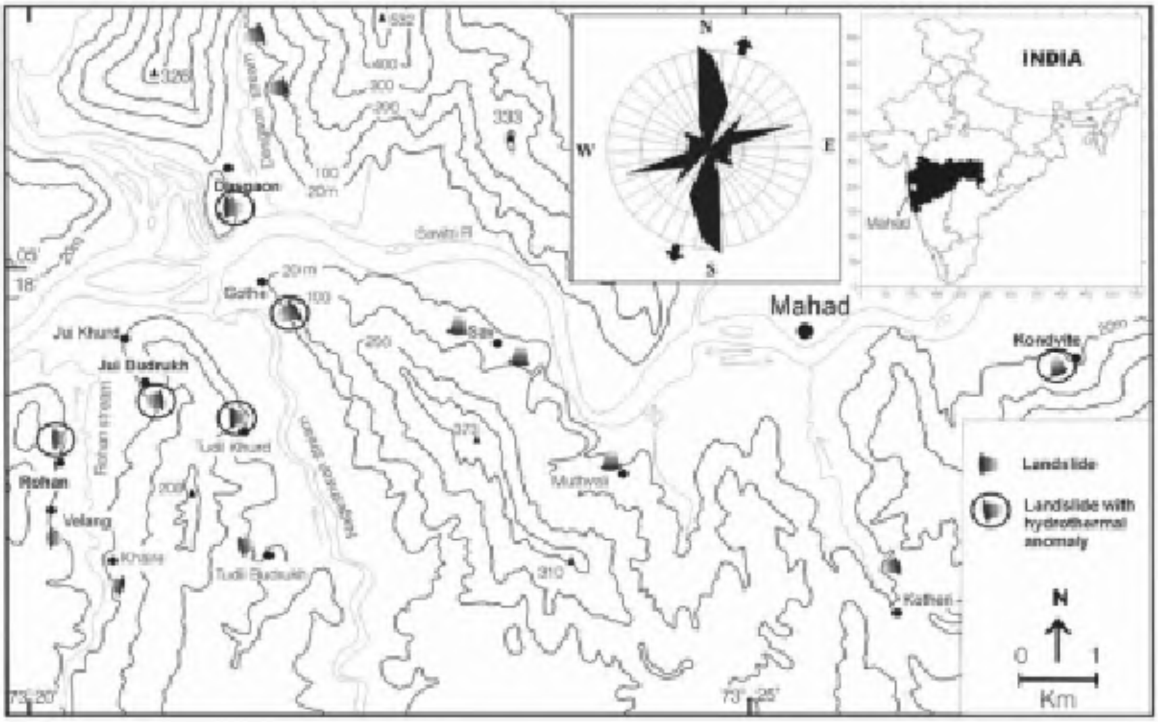

Figure 1. Map showing location and orientation of landslide. (Inset) Azimuth frequency diagram for lineament in Konkan plain (after Widdowson and Mitchel[7]).

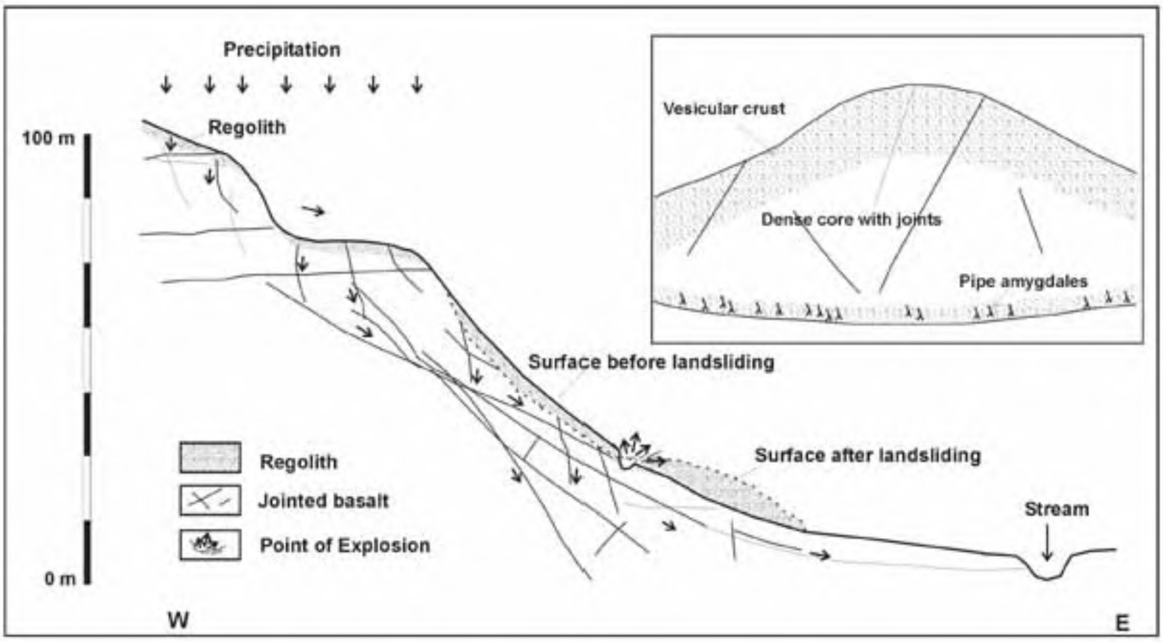

Figure 2. Schematic cross-section explaining the landslide process. (Inset) Cross-section of typical hummocky lobe of compound flow.

N–W to NNW–SSE direction mainly along the Rohan, Nageshwari and Dasgaon streams and rest in E–W direction along the Savitri river (Figure 1). The height of the landslides varies from 30 to 50 m and the width from 45 to 70 m.

Several evidences indicating anthropogenic causes responsible for bringing slopes into in-equilibrium were recorded. These include blasting during laying of the Konkan railway and construction of the tunnel, widening of roads, levelling on rolling spurs for horticulture, playground or other purposes, deforestation, etc. Though there is no record of seismicity of any magnitude during the episode, seismic activity in the region since Koyna earthquake of 1967 has been responsible for shattering of regolith and developing fissures, particularly in NNW–SSE direction[5,8].

Several symptoms of landsliding, few years to few days prior to the episode, were experienced by habitants, unfortunately without realizing their serious consequences. These include surface deformation in the form of minor fissures and/or creeping up to a metre, tilting of trees, loosening of boulders resting on the slopes, cracks on floors or walls of the houses and so on. Further, symptoms such as release of warm water from underground, rapid development of fissures leading to creeping, cracks around trees and subsequent tilting were experienced four to twelve hours prior to the landsliding at places such as Jui and Rohan.

The episode is unique in several respects and is different from earlier episodes recorded in the region[8–10]. It involved maximum death. Huge trees were broken into pieces. Dense basalt was broken into pieces of varying sizes from pebble to boulder, whereas vesicular-type turned friable and powdery. Green incrustations on amygdales released from the vesicles became white and soft, and spread all over. The landslide at Kond dammed the water of southerly flowing Dasgaon stream that subsequently broke due to impoundment of water and caused floods downstream.

The most anomalous observation recorded was the development of hydrothermal anomaly at six localities where landslides occurred speedily with a rumbling noise coupled with a phenomenon resembling lightening, releasing dust and steam in the form of fountain leaving behind deep but narrow depressions. These localities include Dasgaon, Kondvite, Rohan, Jui Khurd, Bathe and Turil Khurd. The temperature of muddy water at Kondvite was sufficient enough that few dead bodies were found partially burnt. People involved in rescue operation also experienced heat of muddy water and suffered from boils on the skin. Burning effect was also observed on tree leaves, branches and stems around the point of explosion. It took more than a day for the temperature to reach normal in the midst of incessant rains.

The data thus suggest that mountainous topography, heavy rainfall, tectonic setting, seismic history and anthropogenic changes were factors conducive for bringing slopes on the threshold of equilibrium and in-equilibrium. The rains before the episode ensured displacement of air from pores by percolated water through regolith up to basalt, thereby increasing pore-water pressure and weight of the slopes. Incessant rains during the episode acted as triggering mechanism that ultimately caused landslidings.

The structural fabric of Konkan region (Figure 1) is believed to be the signature of uplift that is taking place since Tertiary[11,12]. The NNW–SSE flowing streams are considered to be the manifestation of underlying Dharwarian weak planes onto the Deccan basalts[7,13,14]. Data of Konkan landslide episode of 1983 that occurred about 90 km south of present area revealed[5,6] that majority of landslides took place along the NNW–SSE trending fissures developed within regolith during the Koyna earthquake of 1967. As postulated by Valdiya[15] and looking at the orientation of majority of landslides (Figure 1), it seems that seismicity in the region is not only responsible for opening up of weak planes in the form of deep-seated fractures on which streams flow, but also for opening of major joints running parallel to the fracture-controlled streams. Opening of joints, in turn, can develop fissures within regolith resting over the rock due to repeated tremours of varying magnitudes. It appears that slow creeping along the fissures, a few years before the episode, as evident by symptoms described earlier has gradually brought slopes on the threshold of equilibrium and in-equilibrium state. And such slopes on geological threshold were ultimately triggered during incessant rains of July 2005.

The hydrothermal anomaly generated at six places during the episode, i.e. at Dasgaon, Jui, Rohan, Turil, Gothe and Kondvite was unique. There are no reports of occurrence of such a phenomenon in the past, except the landslide that caused forest fire in a remote area of the Los Padres National Forest, California[16]. The genesis of hydrothermal anomaly can be explained applying dilatancy–diffusion mechanism, which suggests that as the groundwater under the effect of stress is forced through the pores or newly created cracks, the streaming potential is produced which in turn induces electric current along the pattern of groundwater flow[17–20]. It appears that rainwater, while percolating from regolith into the upper vesicular portion of lobes of compound basalt, flows through the pores and newly developed cracks produce streaming potential through electro-kinetic effect. Having reached the critical point, energy was released bursting the rock and giving rise to a fountain of dust and steam, leaving behind a narrow but deep depression, and ultimately triggering landslides (Figure 2).

It is noteworthy to mention that precursors of landslides were observed just a day or two or even a few hours before at six localities mentioned earlier. In the remaining ten events the landslides occurred without development of hydrothermal anomalies where precursors were recorded at least two years prior to the episode. It can, thus, be said that the slopes were either not reached or just reached the geologic threshold as a result streaming potential was developed during incessant rains. In the rest of the cases, sliding surface, i.e. regolith/basalt interface, had already crossed geological threshold as a result landslides occurred without development of hydrothermal anomaly.

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