DEPARTMENT OF GEOLOGY AND MINES
MINISTRY OF ECONOMIC AFFAIRS

Monitoring of Landslide at Tsimasham, Reldri and Box-Cutting using GPS

Department of Geology and Mines

Monitoring Period: August 2015 to May 2017

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ABOUT DEPARTMENT OF GEOLOGY & MINES (DGM)

Established in 1981 as Division initially and upgraded later to department, Department of Geology and Mines under Ministry of Economic Affairs is the only geo-scientific institution in the Kingdom of Bhutan mandated to carry out and manage geo-scientific and mining activities. Currently, the mandates of the department are fulfilled through four divisions namely: (1) Geological Survey Division; (2) Earthquake and Geophysics Division; (3) Mineral Development Division; and (4) Mining Division.

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ABOUT THIS REPORT

This report is in accordance with the work plan of the Department of Geology and Mines, MoEA under the National Adaptation Programme of Action II (NAPA II) Project titled *'Addressing the Risks of Climate-Induced Disasters through Enhanced National and Local Capacity for Effective Actions*, funded by GEF-LDCF through UNDP and implemented by RGOB.

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Forward

Located in the eastern part of the Himalayas, the Kingdom of Bhutan is a small landlocked country between India and China. Being a part of young (ca. 55 million years) fold-thrust Himalayan mountain belt, more than 90 percent of the country's area is topographically rugged and geologically very fragile. In the foothills where rainfall is heavy during monsoon, the occurrence of landslides is significant. In recent years, landslide related risk to lives, livelihoods, infrastructures, properties and environment in the country is on rise because of intense and erratic rainfall pattern most likely induced by climate change and interactions of human activities with the nature.

Thus as an intervention to reduce risks associated with climate change induced landslide geohazard, the Department of Geology and Mines (DGM) under Ministry of Economic Affairs (MoEA), Royal Government of Bhutan (RGoB) has carried out the following two key activities under Outcome 1 and Output 1.3 of Second National Adaptation Programme of Action (NAPA-2) Project themed *'Addressing the Risks of Climate-Induced Disasters through Enhanced National and Local Capacity for Effective Actions*, funded by Least Developed Countries Fund (LDCF)-Global Environment Facility (GEF) through United Nations Development Programme (UNDP) and RGoB implementing partner National Environment Commission (NEC) between 2014 and 2017:

1. Integrated geohazard risk assessment and mapping of four critical landslide or landslide affected areas viz.: (1) Moshi landslides and (2) Arong/Lamsorong landslide on Samdrupjongkhar-Trashigang highway; (3) Box-cutting landslide on Gelephu-Zhemgang highway; and (4) Barsa watershed under Phuntsholing Dungkhag, Chukha Dzongkhag; and

2. Landslide monitoring and threshold development of six landslides namely: (1) Moshi landslide, (2) Arong/Lamsorong landslide, (3) Box-cutting landslide, (4) Tshimatsham

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on Phuentsholing-Thimphu highway under Chukha Dzongkhag, (5) Reldri landslide under Phuentsholing Thromdey, and (6) Lem landslide, Phongme Geog under Trashigang Dzongkhag.

The goal and objectives of these studies were to: (1) map and assess the four critical landslide affected areas using geo-scientific methods to provide findings and recommendations on suitable mitigation measures (both long term and short term); (2) monitor landslides using geoscientific methods to understand the movement behaviours and record landslide events; (3) develop rainfall thresholds for landslide initiation in the selected monitoring sites; (4) forecast or issue landslide warnings in regions with similar geological and topographical conditions through National Weather and Flood Forecasting and Warning Center (NWFFWC); and (5) share findings and recommendations of these studies with relevant users (national, district, local government, and others) for awareness and importantly for incorporation of the mitigation measures in their plans and implementations for reduction of risks associated with landslide geohazards.

In this regard, DGM on behalf of the Ministry and RGoB is pleased to publish the reports and maps for the four-critical landslide affected areas and six landslide monitoring sites in the country, whose findings and recommendations were shared to the relevant stakeholders during the two-day workshop held at Phuentsholing from 13-14, November 2017.

On behalf of the department, I acknowledge the effort put into publishing these reports and maps and I am hopeful that these documents will be useful to the relevant stakeholders who are responsible in dealing with risks associated with landslide in the study areas.

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Director General

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ABSTRACT

Monitoring of landslide movement rate, particularly creep type of landslide, is important to understand the behaviour of the landslide and its threat to lives and properties. The information on landslide behaviours mainly displacement and rate of movement will help in timely decision making in dealing with the landslides to reduce risks. In this study, GPS monitoring of three critical landslides at Tsimasham, Reldri and Box-Cutting in southern Bhutan were carried out twice a year (pre-monsoon and post-monsoon) between August 2015 to May 2017.

Tsimasham and Box-cutting landslide monitoring sites are located on the National Highways that connect Indian border towns to the inner districts of Bhutan and therefore form a lifeline for transportation of goods and economic development in the region. Reldri landslide monitoring site is located near to Reldri School under Phuentsholing Dungkhag posing threat to school and settlements in the area. Tsimasham landslide falls within Thimphu Formation composed of moderately weathered mica. Reldri landslide falls within Phuentsholing Formation belonging to Buxa Group and comprises of quartzite, greenish grey, variegated and carbonaceous phyllite. Box-Cutting landslide falls under Buxa formation, consisting of dark grey phyllite, greenish grey quartzite intercalated with thinly foliated talcose phyllite.

GPS monitoring of 4 control points in and around Tsimasham landslide, 3 control points in and around Reldri landslide, and 6 control points in and around Box-Cutting landslide between August 2015 to May 2017 show All monitoring points moved between each set of GPS observations (refer Table 4 for movement data and Appendix 9 for figures showing movement of each points). In Tsimasham area, not much horizontal movement is observed while the GPS data collected over the time suggest a uniform downward movement of the landmass. In Box-Cutting area, not much horizontal movement is observed in the mid segment of the slide while the GPS data collected over the time suggest a uniform downward vertical movement of the landmass in the lower and upper segment of the slide. The rate of movement of the landmass is slightly faster in the lower part (i.e. below road) of the slide.

The net average velocity (movement rate) of 0.296 mm per day at Box-Cutting landslide falls under very slow to slow category of movement rate. The net average velocity (movement rate) of 0.0008 mm per day at Reldri landslide and 0.007 mm per day at Tsimasham landslide fall under the extremely slow category of movement rate. The net average movement rates of the Tsimasham and Reldri landslides can be classified as stable movement and therefore indicate a normal situation. The net average movement rate of the Box-Cutting landslides can be classified as large seasonal fluctuations and therefore indicate an alert situation.

However, since the GPS observations are made only on the surface or near-surface of the landslides with only few control points, therefore, monitoring using integrated monitoring systems approach (both contact and remote) that help determine more representative and accurate movement of these landslides is recommended. This will include but not limited to monitoring using instruments or techniques such as inclinometer, extensometer, piezometer, total stations, and satellite and terrestrial remote sensing.

Like monitoring points for GPS, all the 9 tension cracks in the three landslides showed movement. The maximum number of cracks developed has been displaced.

Keywords: *Landslide, Monitoring, Movement, GPS, Tension Cracks, Tsimasham, Reldri, Box-Cutting.*

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Acronym

BRO- Border Road Organization
GEF- Global Environment Fund
GIS- Geographic Information System
GPS- Geological Position System
LDCF- Least Developed Countries Fund
NAPA- National Adaptation Programme of Action
NCHM- National Centre for Hydrology and Meteorology
UNESCO- United Nations Educational, Scientific and Cultural Organization

1. INTRODUCTION

Terzaghi (1950) defined landslide as a rapid displacement of a mass of rock, residual soil, or sediments adjoining a slope, in which the centre of gravity of the moving mass advances in a downward and outward direction and similarly the International Geotechnical Societies UNESCO working party on the World Landslide Inventory defined it as “The movement of a mass of rock, earth or debris down a slope” (Cruden, 1991; Anon 1997). Landslides are one of the major natural hazards, often causing property damage and other economic loss in terms of high reconstruction costs to the infrastructures such as highways, building etc. Landslides are triggered by different factors, both natural and anthropogenic (Althuwaynee et al., 2012).

Bhutan being a mountainous country, most of landslides are found on cut slopes and embankment of roads and highways. Landslides in Bhutan are mostly rainfall triggered and caused by anthropogenic activities blocking the highways, thereby threatening the life and property. Monitoring of landslide movement rate, particularly creep type of landslide, is important to understand the behaviour of the landslide and its threat to lives and properties. The information on landslide behaviours mainly displacement and rate of movement will help in timely decision making in dealing with the landslides to reduce risks.

Under the NAPA II project, six critical landslides were selected for monitoring. These landslides were selected based on the strategic location of the landslide and overall as a representative landslide to represent landslide in the country. This report is based on monitoring of three landslides at Tsimasham, Reldri and Box-Cutting. Tshimasham and Box-cutting landslide monitoring sites are located on the National Highways that connect Indian border towns to the inner districts of Bhutan and therefore form a lifeline for transportation of goods and economic development in the region. Reldri landslide monitoring site is located near to Reldri School under Phuentsholing Dungkhag posing threat to school and settlements in the area. The locations of these three sites are shown in Figure 1. Given the destructive nature of these landslides to property and economic loss, therefore monitoring of these landslides was undertaken.

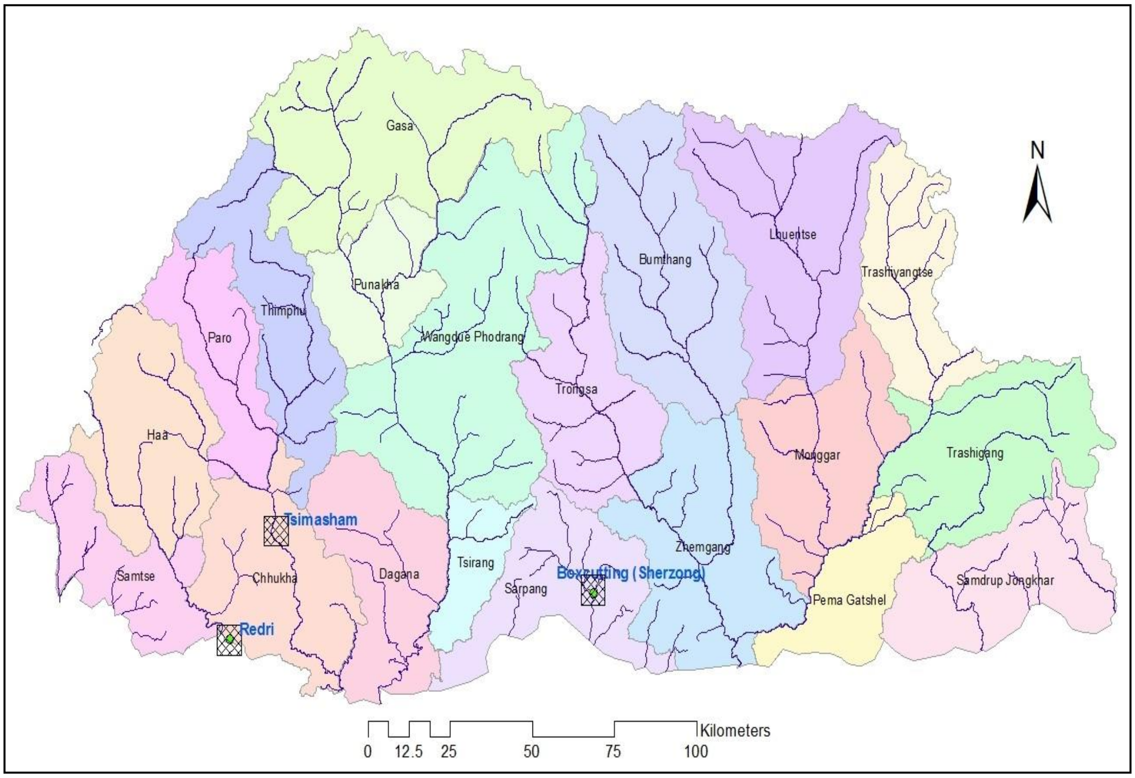

Figure 1. Location map of three landslide monitoring sites shown by a black square box.

1.1. AIM AND OBJECTIVES

The study in the three selected landslide areas were carried out to understand the behaviour of each landslide based on the displacement (horizontal, vertical rate of movement) with respect to geographical location. This information on landslide behaviours mainly displacement and rate of movement will help in timely decision making in dealing with these landslides to reduce risks.

1.2. STUDY AREA

Tsimasham is a small town located in between Phuntsholing and Thimphu. The slide is located at 72 km from Thimphu towards Phuntsholing along Thimphu-Phuntsholing Highway and approximately about 500 m away from Tsimasham town towards Thimphu

(Figure 2). The landslide is located within the geographical coordinates: N: 27˚6'9.3", E: 89˚32'6" and Elevation: 2202 m. An approximate dimension of the slide is: Length: 250m and Breadth: 40 m (Figure 2). The slope angle of the area is 25˚ and direction of landslide towards north-westerly. The area usually has warm wet summer and cool dry winter.

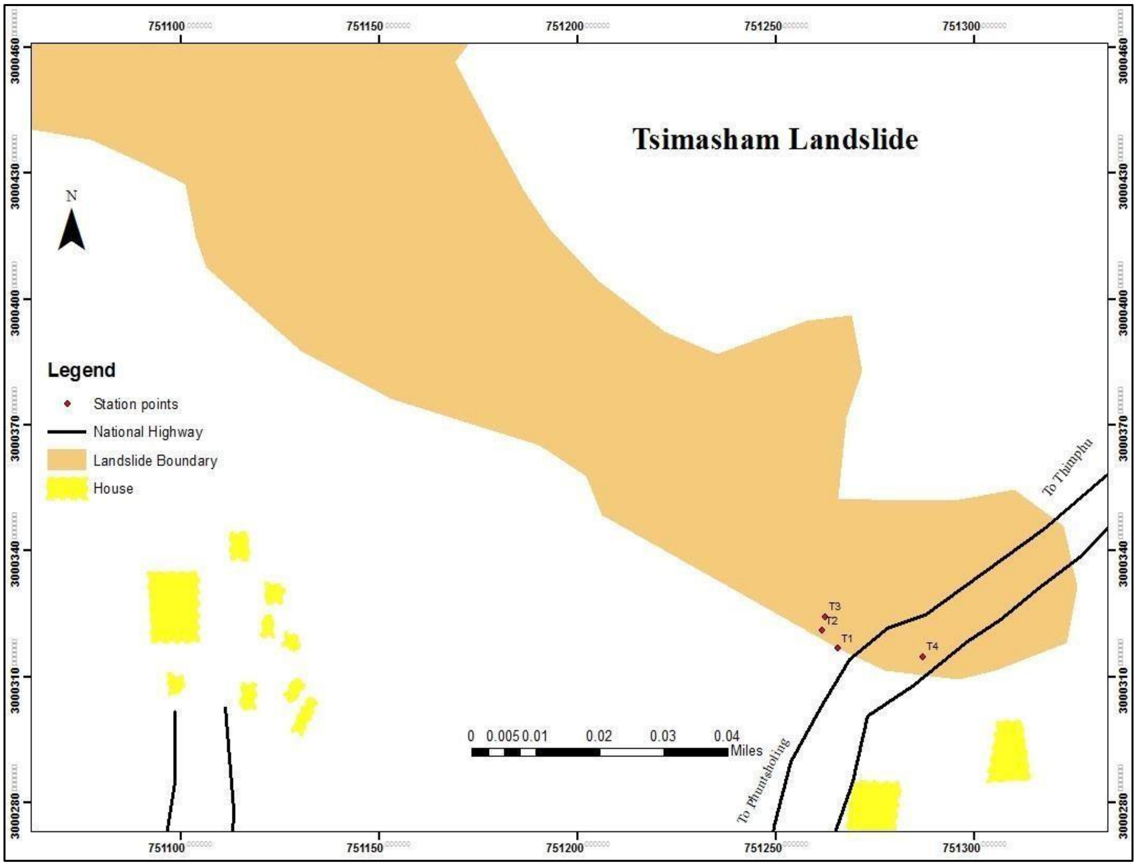

Figure 2. Tsimasham landslide map showing prominent features and location of GPS Observation points.

Reldri landslide is located west of Reldri School. This is one of the active landslides, propagating towards north-easterly direction threatening the infrastructure of the Reldri Higher Secondary School. This landslide is located within the geographical coordinates: - N: 26˚50'52.4", E: 89˚24'16", Elevation: 408m. An approximate dimension of slide is: Length: 60m, Breadth: 80m (Figure 3). The above area forms a part of the Himalayan foothill belt with a youthful topography, abruptly rising from the plains like a rampart up to 400m from Mean Sea Level (MSL). The area experiences a humid tropical climate. The summer is warm between March and October with a temperature rising to 35˚C. The winter months between Novembers to February experiences quite a pleasant climate, whereas the monsoon months experience heavy rainfall between June and September.

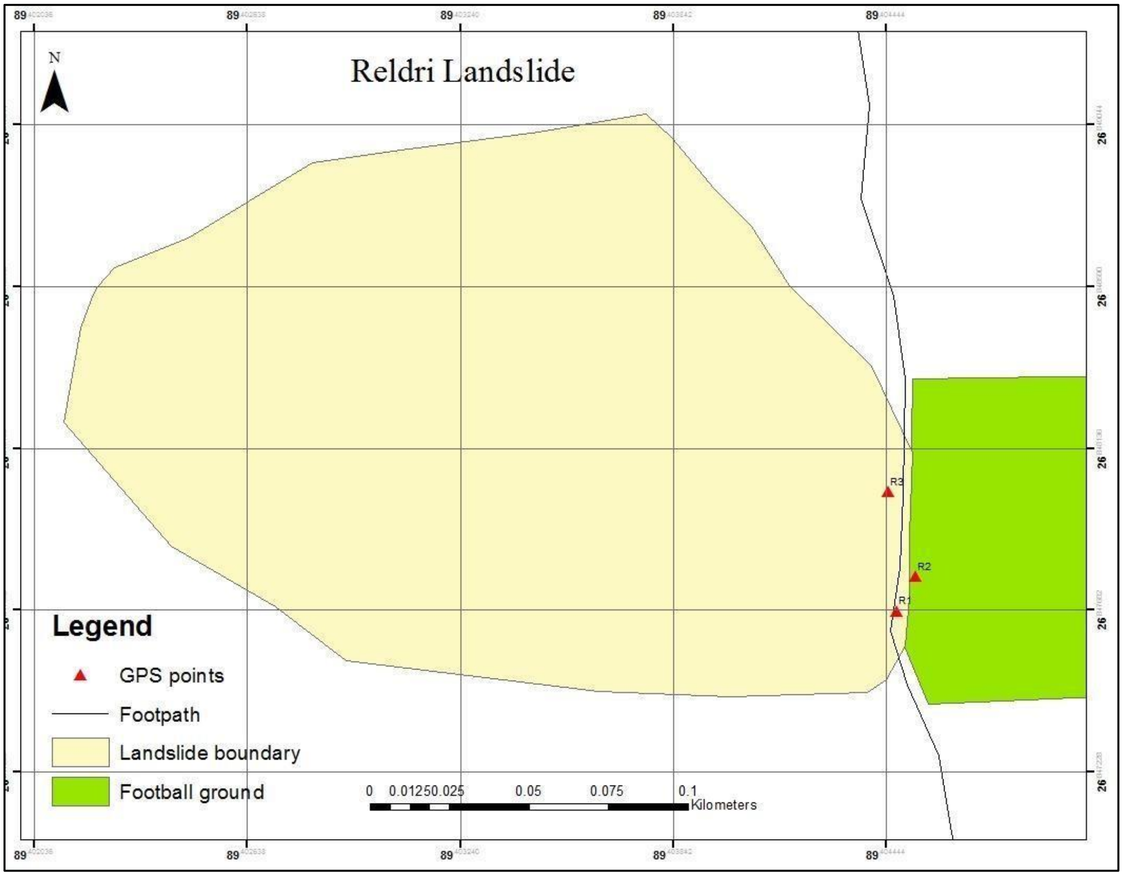

Figure 3. Reldri landslide map showing prominent features and location of GPS Observation points.

Box cutting is about 16 km away from Gelephu town towards Zhemgang (Figure 4). This landslide is in geographical coordinate N: 26˚57’9.5”, E: 90˚31’33.4”and elevation: 787m. An approximate dimension of the landslide is length 150m and breadth 200m (Figure 4). It is a major landslide prone on the high way. This is the most active slide zone occurring along Gelephu- Zhemgang highway. Every monsoon, the area experiences landslide causing road blockages, thereby risking to human lives and properties. The slide in this area becomes active during rains and colluvial/talus material moves downward towards the road in the form of debris flow. The climate is hot and wet in summer and cold and dry in winter. Maximum rainfall takes place in summers between May and September. The slope angle of the area ranges from 38˚to 43˚ towards 315˚ north-westerly direction

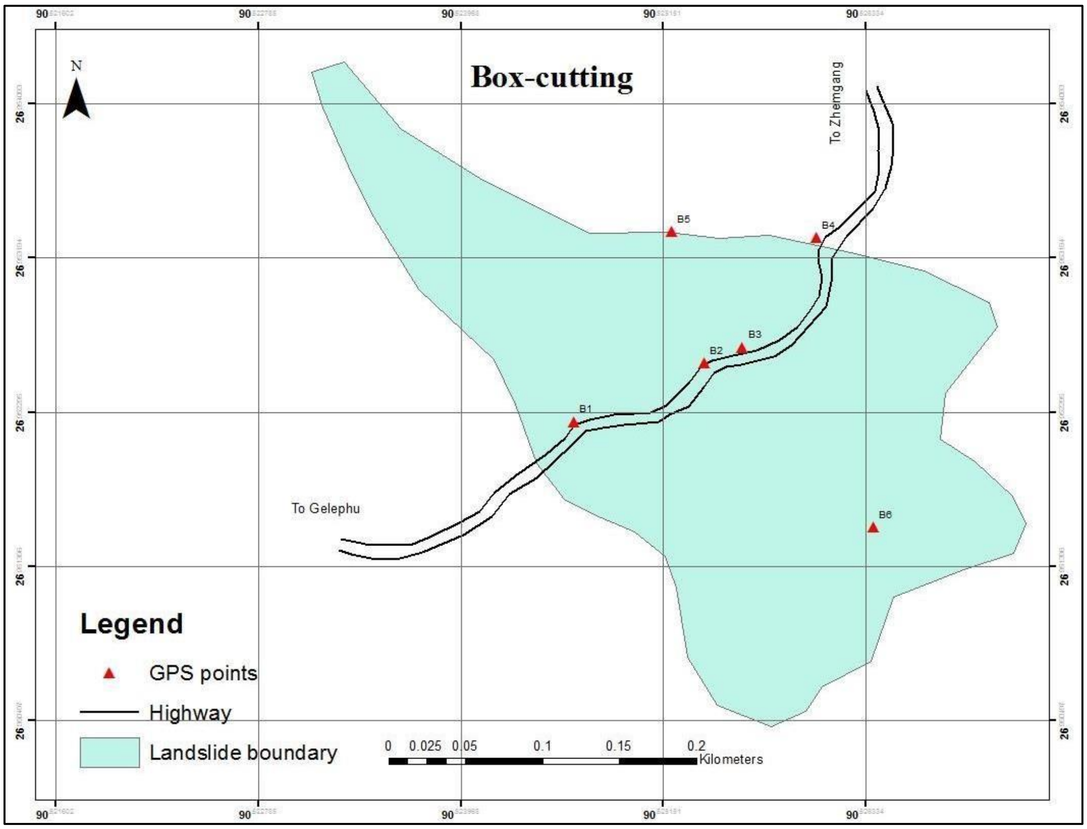

Figure 4. Box-cutting landslide map showing prominent features and location of GPS Observation points.

2. GEOLOGY OF THE SITES

2.1. GEOLOGY OF TSIMASHAM SITE

The rocks of Thimphu Formation are exposed in the area. The bedrock is not exposed at the crown of landslide except outcrop at the toe of the landslide. The material type that makes the slope of 25° to 30° is colluvium, composing of angular boulders, cobbles, pebbles with little fines and clays. The parent rock of these materials is mica schist. At the toe of landslide well exposed of mica schist was found dipping 25^{o} at 320^{o} north-westerly direction. The rock is moderately weathered and fractured and highly disturbed due to ongoing road cutting process near dam site construction, THPA. But in the body of landslide huge debris were found continuously moving making area unstable. Generally, the soil is reddish brown in colour. Gravelly sand with the occasional presence of angular boulders, cobbles of mica schist with little fines i.e. silt and clay. They are loosely compact.

2.2. GEOLOGY OF RELDRI SITE

The rocks of Phuentsholing Formation belonging to Buxa Group are exposed in this landslide which comprises of quartzite, greenish grey, variegated and carbonaceous phyllite. Predominantly, Carbonaceous phyllite is the dominant rock type in the area followed by variegated phyllite and a thin band of grey quartzite. The rock types are highly to completely weathered and fractured. Clay bands were observed at several places. The rock is found to be dipping 34˚ towards 25° NW. Reddish brown to greyish brown residual soil were found to expose at the crown of the landslide

2.3. GEOLOGY OF BOX-CUTTING SITE

The area falls under Buxa formation. The litho-units recorded in box cutting along Gelephu- Zhemgang highway mainly consists of dark grey phyllite, greenish grey quartzite intercalated with thinly foliated talcose phyllite. The rocks are thinly foliated with the intrusion of quartz veins. The rock in the area has a general orientation of 36° dip amount with 40° NW directions. It is highly to completely weathered, fractured and crumpled. At places, the rocks have been completely decomposed to clay. The soil is light brown to reddish in colour with angular fragments of phyllite and quartzite with little fines and clay which seem to be highly friable, highly saturated and permeable in nature.

3. METHODOLOGY

The assessment of the three selected landslides behaviour is undertaken by means of monitoring scheme. The monitoring of the landslides was undertaken on the seasonal basis i.e. the field observation of the landslide was undertaken twice a year starting from August 2015 to May 2017 (Table 1). The first data observation was undertaken in August 2015 and 13 control points were installed around and, on the landslides, (Rawat et al., 2011). The control points were evenly distributed in stable areas around the periphery of the slide. The purpose of the control points is to monitor the seasonal movement of the slide using GPS (Coe and Lidke, 2003). At each control points, 2mm diameter rod with 1.5 feet was hammered into the ground for the GPS measurement (Figure 5B). The next observation was subsequently undertaken in May 2016 (7 months), September 2016 (4 months) and May 2017 (7months). The observation of the station point is given in Table 1.

Table 1. Date of Observation of GPS points.

Sl. No.	Seasonal Type	Date
1	Post-monitoring	30-08-15- 11-09-15
2	Pre-monitoring	01-06-16- 16-06-16
3	Post-monitoring	19-09-16- 09-10-16
4	Pre-monitoring	21-05-17 - 08/06/17

The map of the landslide area and the horizontal movement between the previous monitoring points of the landslide area was prepared using ArcGIS version 10.4.1. The conversion of coordinates of the monitoring points from one coordinate to another was done using Lat-Long converter software. The digitization of features like road, landslide boundary and houses were done on geo-referenced google earth image as a base map by ArcGIS version 10.4.1. The google earth image is geo-referenced using Elshayal Smartgis.

Along with the GPS observation of the crack found on the landslide areas, change in the dimension of the crack was measured using tapes and wire method.

3.1. GPS METHOD

The following GPS surveying is based on the seasonal movement of the Slumgullion landslide as determined from GPS observation, July 1998-July 1999(Coe and Lidke 2003; Anon 2000). The primary task of GPS surveying is to measure the distance between the satellite and the location of the earth (Figure 5). Once the distance has been measured, coordinates of positions on the earth are calculated by triangulation. Distance is measured based on the amount of time required for an electromagnetic GPS signal to travel from the satellites to ground-based antennas and receivers. Antennas collect the satellite signal and convert the electromagnetic waves into electric currents that can be recorded by the receiver (Rawat et al., 2011).

Figure 5. GPS used for the observation of point at Tsimasham.

Satellites transmit precise time and location information in three binary codes, precise code, coarse and acquisition code and navigation code. The codes are transmitted on two carrier waves that are part of the L-band of the microwave electromagnetic spectrum. The two carrier waves have frequencies called L1 and L2.

There are two main GPS surveying methods, kinematic and static surveying. In kinematic applications, receivers are in motion during the measurement period and real-time positioning solutions are available based on the pseudo-range observables in static applications, receivers are stationary for long measurements periods (generally >30minutes) and both pseudo-range and carrier phase data are post-processed for precise positioning solutions. Rapid static applications are the same as static techniques except that occupation times are short, generally from 5 to 20 minutes, and post-processing relies on code and L1 and L2 carrier phase observations.

The type and accuracy of positioning in kinematic and static surveying is dependent on the number of receivers available. There are two types of positioning, single point and relative. Single-point positioning is the determination of a ground position using one receiver and observables from one or more satellites. Single-point positioning relies on the pseudo-range observable. The accuracy of the single-point positioning increases with the number of satellites available. Relative positioning is the determination of a ground position using two or more receivers and two or more satellites. Relative positioning allows for the elimination of clock and atmospheric errors in the carrier-phase signal by combining simultaneous observables (referred to as differencing in GPS terminology) from multiple receivers and satellites during post-processing. Relative positioning determines the precise vector (baseline) between receiver positions. When the coordinates of one of the receiver positions is known, that receiver is referred to as a base station, and the known coordinates and baseline can be used to determine the precise coordinates of the unknown points.

In relative positioning, data is stored in the receivers and is post-processed using computer software to calculate baselines, determine unknown coordinate positions, and estimate horizontal and vertical errors for calculated positions. If baselines are calculated from two or more base stations, the baselines and coordinates of unknown points can be further refined through the use of a least-squares adjustment performed by holding the base station positions fixed while adjusting the baselines and coordinate positions of the unknown positions.

A requirement of relative positioning is that the receivers are capable of recording at least one of the carrier phases. Although many types of receivers are available, dual-frequency receivers are commonly used for relative positioning because they record all GPS codes, as well as the L1 and L2 carrier phases. In addition to recording all components of the GPS signal, dual frequency receivers generally have 12 channels, which allow them to simultaneously record the signals of up to 12 satellites.

4. FIELD OBSERVATIONS

4.1. CONTROL POINTS

Dates of observation, coordinates, height and positional errors for all 13 monitoring points are given in Table 3. Positional errors are given as standards errors and are always less than 2 cm for both horizontal and vertical points.

4.2. MOVEMENTS AND VELOCITIES OF MONITORING POINTS

The seasonal horizontal and vertical movement as compared with the previous point and seasonal velocity is given in Table 4 (Coe and Lidke, 2003).

5. RESULTS AND DISCUSSIONS

The results for the observations of the data of the landslides are divided into two sections: (1) Movement of GPS points, and (2) Tension cracks.

5.1. MOVEMENT OF GPS POINTS

5.1.1. Tsimasham Landslide

At **Tsimasham** landslide, four observation points have been used for observation of horizontal and vertical movements. All the observations are located at the crown of the landslide. Due to inaccessibility and road construction at the toe of the landslide, no points were observed at the body and toe of the landslide. The maximum annual vertical movement is observed at point T1 with the vertical movement of 0.109m and minimum at point T3 with vertical movement of 0.002m from 29/08/2015 to 10/05/2017. While seasonal vertical movement is observed maximum at point T1 with the movement of 0.1m from 29/08/2015 to 13/06/2016 and minimum at point T2 with the movement of 0.001m from 30/08/2015 to 14/06/2016 (refer Table 4).

Table 2. Description of the rate of movement of the landslide.

Rate description	Varnes (1978) rate/period	WP/WLI (1995) millimetre/second
extremely rapid	>3metres/second	> 5 by 10^{3}
very rapid	>0.3 metres/minute	> 50
rapid	>62.5 millimetres/hour	> 0.5
moderate	>50 millimetres/day	> 5 by 10^{-3}
slow	>4.1 millimetres/day	> 0 by 10^{-3}
very slow	>0.164 millimetres/day	> 50 by 10^{-3}
extremely slow	<0.164 millimetres/day	< 0.5 by 10^{-3}

The maximum annual horizontal movement is observed at point T1 with horizontal movement of 0.004123m and minimum at point T4 from 29/08/2015 to 10/05/2017, Whereas the seasonal movement is observed maximum at point T3 with movement of 0.005831m from 15/06/2016 to 21/09/2016 and no movement at all at point T4 with 0 movements from 22/09/2016 to 10/05/2017 (refer Table 4).

Out of four observations, the maximum seasonal vertical velocity is observed at point T1 with a velocity of 0.00035088m/days (Figure 6). The point T1 is located just below the road. Overall, in Tsimasham area, not much horizontal movement is observed while the GPS data collected over the time suggest a uniform downward movement of the landmass.

The velocity of the control points in the mm/day (Figure 6) is correlated with the description of the movement of the landslide (Table 2). The horizontal velocity of all the points is <0.012 mm per day and therefore fall under the extremely slow category of movement rate as per classification of Varnes (1978).

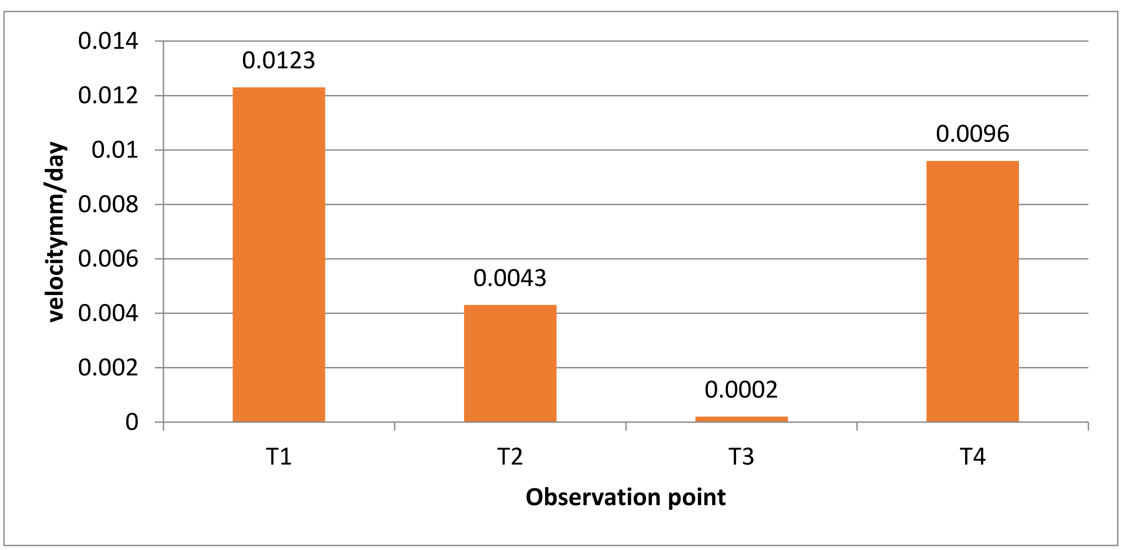

Figure 6. Graph showing the rate of movement of control points at Tsimasham landslide.

5.1.2. Reldri Landslide

At **Reldri** landslide, three observation points have been used for observation of horizontal and vertical movement. The maximum annual vertical movement is observed at point R3 with the vertical movement of 0.0116m and minimum at point R2 with the vertical movement of 0.0025m from 03/09/2015 to 23/05/2017. While seasonal vertical movement is observed maximum at point R3 with the movement of 0.006m from 05/09/2015 to 11/06/2016 and minimum at point R2 with the movement of 0.001m from 10/06/2016 to 28/09/2016 (refer Table 4).

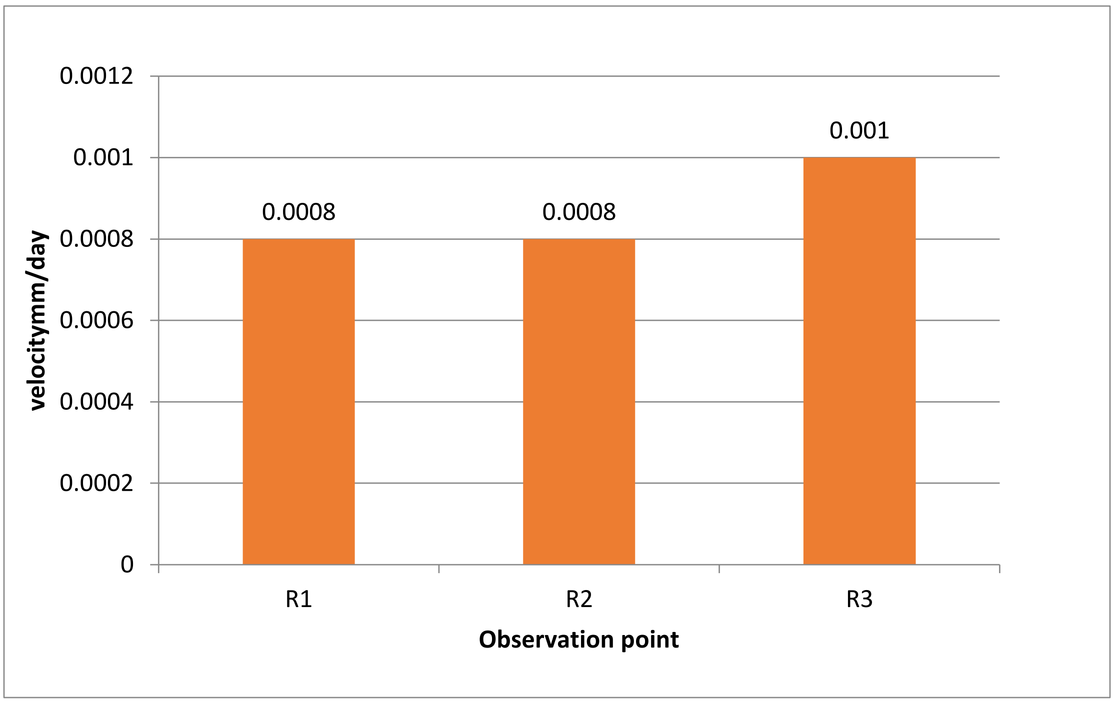

Figure 7. Graph showing the rate of movement of control points at Reldri landslide

The maximum annual horizontal movement is observed at point R3 with horizontal movement of 0.010198m and minimum at point R2 with movement of 0.002236m from 03/09/2015 to 23/05/2017, whereas the seasonal movement is observed maximum at point R3 with movement of 0.007071m from 05/09/2015 to 11/06/2016 and minimum movement is observed at point R2 with movement of 0.001m from 10/06/2016 to 28/09/2016 (refer Table 4).

Out of three observations, the maximum vertical seasonal velocity is observed at point R3 with a velocity of 0.0000215m/days from 05/09/2015 to 11/06/2016 while minimum velocity is observed at point R2 from 10/06/2016 to 28/09/2016 (Figure 7). The point R3 is located at the left flank of the landslide. Overall, in Reldri area neither horizontal nor vertical movement of the landmass is suggested by GPS data.

The velocity of the control points in the mm/day (Figure 7) is correlated with the description of the movement of landslide (Table 2). The horizontal velocity of all the points is <0.001 mm per day and therefore fall under the extremely slow category of movement rate as per classification of Varnes (1978).

5.1.3. Box-Cutting Landslide

At **Box-Cutting** landslide, six observation points has been used for observation of horizontal and vertical movement. The maximum annual vertical movement is observed at point B5 with vertical movement of 4.913m and with no movement at point B1, B2, B3 and B4 with vertical movement of 0m from 07/09/2015 to 06/03/2017. While seasonal vertical movement is observed maximum at point B5 with movement of 2.17m from 06/06/2016 to 10/08/2016 and no movement in point B1, B2, B3 and B4. The seasonal vertical velocity is observed maximum at point B5 with velocity of 0.0064m/days from 10/08/2016 to 02/06/2016 (refer Table 4).

The maximum annual horizontal movement is observed at point B5 with horizontal movement of 0.006083m and no movement at point B1, B2, B3 and B4 from 07/09/2015 to 06/03/2017, Whereas the seasonal movement is observed maximum at point B6 with movement of 0.004214m from 10/09/2016 to 03/06/2017 and no movement is observed at point B1, B2, B3 and B4 with 0 m movement (refer Table 4).

Out of six observations, the maximum seasonal vertical velocity is observed at point B6 with velocity of 0.0064m/days from 10/08/2016 to 02/06/2017 (Figure 8). It is observed out of six observations, the point B1, B2, B3 and B4 has no movement at all in all seasons from 07/09/2016 to 03/06/2017 and these points are located at the body of the landslide along Gelephu-Zhemgang highway. while point B5 and B6 has maximum displacement where B5 is located at the toe of the landslide (just below the road) and B6 at the crown of the landslide.

Overall, in Box-Cutting area, not much horizontal movement is observed in the body of the slide while the GPS data collected over the time suggest a uniform downward vertical movement of the landmass in the lower and upper segment of the slide. The rate of movement of the landmass is slightly faster in the lower part (i.e. below road) of the slide.

The velocity of the control points in mm/day (Figure 8) is correlated with the description of the movement of the landslide (Table 2). The horizontal velocity of all the points is <0.389 mm per day and therefore fall under very slow to slow category of movement rate as per classification of Varnes (1978).

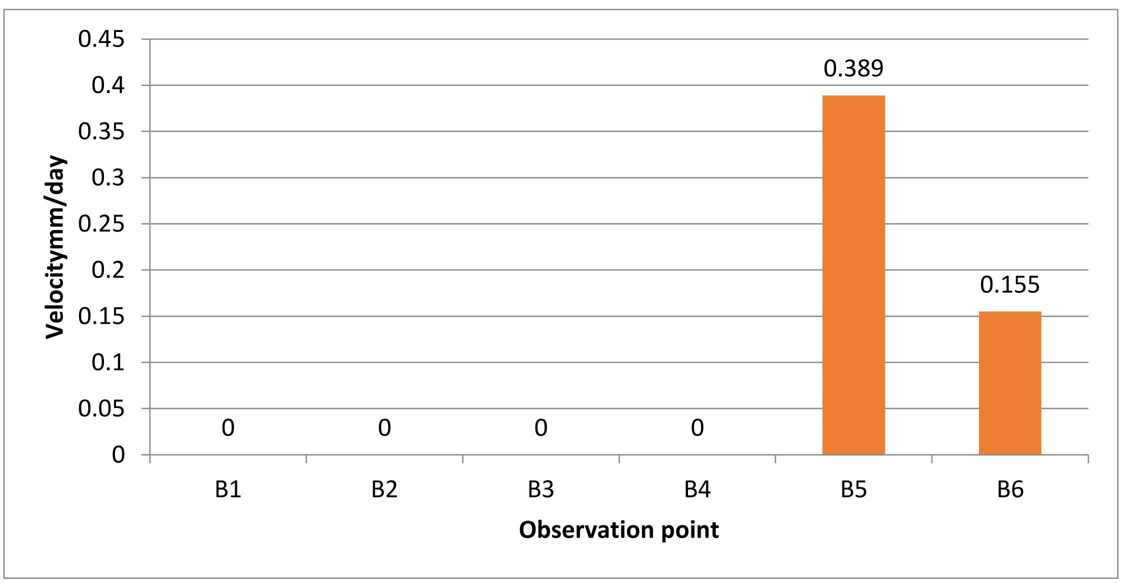

Figure 8. Graph showing the rate of movement of control points at Box-cutting landslide

5.2. TENSION CRACKS

While monitoring the landslide about 9 major tension cracks has been monitored using a measuring tape. The data of the tension crack and the GPS survey of the control points were collected during the same duration. The observation of measurement of the tension cracks has been given in Table 5.

5.2.1. Tsimasham Landslide

During the first observation at Tsimasham, no tension cracks were observed at the crown of the landslide but subsidence of the ground of this landslide was observed during fieldwork. Tilted trees are common phenomenon indications of the landslide in the area. However, during second observation in May 2016, three new tension cracks have developed on the crown of the landslide (Figure 9). The location and dimension of individual tension is given in Table 5. In May 2017, the tension located within geographical coordinate 27.10250˚ E: 89.53556˚ T1 and T3 N: 27.10247˚ E: 89.53534˚ has displaced with slip face angle ranging from 65-70˚ (Figure 9) while T2 located at N: 27.10251˚ E: 89.53541 have varied by width and depth of 0.5m and 0.2m respectively from the previous dimension.

Figure 9. Tension crack developed on the crown of the landslide at Tsimasham (Picture taken in May 2016) and (B) showing displaced crack (Picture taken in May 2017).

Figure 10. The sinking of Gabion wall indicating active mass movement at Tsimasham landslide (Picture taken in September 2016)

Figure 11. Gabion wall has completely submerged by 1 m at Tsimasham landslide. Refer Figure 10 for comparison (Picture taken in May 2017).

5.2.2. Reldri Landslide

At Reldri, three tension cracks were observed during the first landslide monitoring (Figure 11). All the tension cracks were developed on the crown of the landslide specifically at the crown of the landslide. The coordinate of the tension cracks is T1 N:26˚50’52.4” E:89˚24’161” E:406m, T2 N:26˚50’52” E:89˚24’16” E:405 m and T3 N:26˚50’52.7” E:89˚24’16.1” E:411m. Thedimension of each crack is given in Table 5. The inclinometer which was installed on the crown of the landslide by French consultancy under NAPA II project has been washed away along with the displacement of crack. In May 2016, it was observed that all the tension had been washed away (Figure 12) and as of May 2017, no tension has been formed in the study area. Moreover, it is observed that there is no lateral extension of the slide but active mass movement along a longitudinal section at coordinate N: 26.84782˚ E: 89.40452˚ at an elevation of 403 m is found to very active.

Figure 11. Tension crack developed at Reldri shown by red dotted line (Picture taken in August 2015)

Figure 12. Tension crack completely washed away at Reldri (Picture taken in May 2016).

5.2.3. Box-cutting Landslide

In September 2015, three tension cracks have been developed at the crown of the landslide with wide openings at box-cutting landslide (Figure 13), which rainwater could infiltrate during the rainy season and trigger landslide further. A tension crack has been developed with an average length of 6 m, breadth 5 to 10 cm and depth of about 60 cm in a geographical coordinate T1 N: 26˚57'01.2", E:90˚31'35.6". In geographical coordinate T2 N: 26˚57'01.3", E: 90˚31'35.2" a tension crack of length 5m, breadth ranging from 15 to 20 cm and depth 40 cm has been developed. A tension crack T3 having a length of 6m, breadth ranging from 50 cm to 1 m and depth 40 cm has been developed at this coordinate N:26˚57'02.3", E:90˚31'35.2". However, in May 2016, it was observed that there was variation in dimension by 0.20 width, 0.4 depth in T1, while in T2 3m length, 0.06 m width, depth 1.9m and length 6m, width 1m and D=1.5m in T3. In May 2017, all the three tension cracks have been displaced with a slip face angle ranging from 60-70˚.

The surface runoff was observed eroding the materials downhill blocking the National Highway Gelephu-Zhemgang Highway.

Figure 13. Tension crack developed at Box-cutting (Picture taken in August: 2015).

Table 3. Positions of monitoring points for each GPS observation along with the standard error for easting, northing and elevation (Coe and Lidke 2003; Anon 2000).

Station	Date of GPS observation	Easting(m)	Standard Error of Easting value	Northing(m)	Standard Error of Northing value(m)	Elevation (m)	Standard Error of Elevation value(m)	Days since previous observation
T1	29/08/2015	751265.792	±0.298	3000316.760	±0.079	2181.21	±0.873	N.A
T1	13/06/2016	751265.781	±0.122	3000316.762	±0.132	2181.111	±0.232	285
T1	19/09/2016	751265.785	±0.008	3000316.764	±0.009	2181.1	±0.093	
T1	07/06/2017	751265.788	±0.871	3000316.761	±0.567	2181.101	±0.633	270
R1	03/09/2015	738922.817	±0.992	2971829.671	±0.048	397.969	±0.433	
R1	09/06/2016	738922.811	±0.100	2971829.672	±0.006	397.967	±0.200	279
R1	27/09/2016	738922.814	±0.103	2971829.673	±0.090	397.964	±0.214	
R1	21/05/2017	738922.815	±0.991	2971829.672	±0.344	397.961	±0.679	236

B1	07/09/2015	254256.780	±0.101	2983552.604	±0.040	580.633	±0.213	
B1	02/06/2016	254256.780	±0.051	2983552.604	±0.046	580.633	±0.253	244
B1	04/10/2016	254256.780	±0.118	2983552.604	±0.009	580.633	±0.113	
B1	29/05/2017	254256.780	±0.655	2983552.604	±0.887	580.633	±0.379	370
T2	30/08/2015	751261.723	±0.119	3000320.926	±0.187	2179.926	±0.353	
T2	14/06/2016	751261.722	±0.095	3000320.925	±0.127	2179.925	±0.266	288
T2	20/09/2016	751261.721	±0.118	3000320.924	±0.008	2179.924	±0.218	
T2	08/06/2017	751261.723	±0.122	3000320.925	±0.177	2179.92	±0.222	320
R2	04/09/2015	738927.875	±0.111	2971840.495	±0.112	396.049	±0.311	
R2	10/06/2016	738927.876	±0.188	2971840.494	±0.076	396.046	±0.199	279
R2	28/09/2016	738927.877	±0.109	2971840.494	±0.100	396.045	±0.210	
R2	22/05/2017	738927.876	±0.896	2971840.493	±0.761	396.0422	±0.773	236
B2	08/09/2015	254332.748	±0.246	2983588.862	±0.245	598.358	±0.269	
B2	03/06/2016	254332.748	±0.118	2983588.862	±0.023	598.358	±0.219	268
B2	05/10/2016	254332.748	±0.100	2983588.862	±0.018	598.358	±0.200	
B2	30/05/2017	254332.748	±0.882	2983588.862	±0.919	598.358	±0.721	267
T3	31/08/2015	751262.581	±0.465	3000324.226	±0.034	2179.226	±0.561	
T3	15/06/2016	751262.579	±0.189	3000324.229	±0.094	2179.229	±0.232	288
T3	21/09/2016	751262.582	±0.044	3000324.224	±0.141	2179.227	±0.091	
T3	09/05/2017	751262.581	±0.001	3000324.228	±0.002	2179.224	±0.003	230
R3	05/09/2015	738919.629	±0.233	2971866.629	±0.244	397.124	±0.461	
R3	11/06/2016	738919.628	±0.007	2971866.622	±0.244	397.118	±0.222	279
R3	29/09/2016	738919.627	±0.201	2971866.618	±0.0204	397.114	±0.212	
R3	23/05/2017	738919.627	±0.091	2971866.619	±0.006	397.1124	±0.083	236
B3	09/09/2015	254355.287	±0.412	2983598.732	±0.044	603.354	±0.413	

B3	04/06/2016	254355.287	±0.112	2983598.732	±0.065	603.354	±0.122	268
B3	06/10/2016	254355.287	±0.108	2983598.732	±0.009	603.354	±0.099	
B3	31/05/2017	254355.287	±0.199	2983598.732	±0.112	603.354	±0.244	267
T4	01/09/2015	751287.234	±0.155	3000314.764	±0.005	2179.226	±0.314	
T4	16/06/2016	751287.238	±0.099	3000314.766	±0.144	2188.357	±0.322	288
T4	22/09/2016	751287.233	±0.111	3000314.767	±0.099	2188.355	±0.211	
T4	10/05/2017	751287.233	±0.109	3000314.767	±0.432	2188.351	±0.227	230
B4	10/09/2015	254399.247	±0.821	2983668.896	±0.340	603.404	±0.417	
B4	05/06/2016	254399.247	±0.091	2983668.896	±0.003	603.404	±0.453	268
B4	07/10/2016	254399.247	±0.114	2983668.896	±0.107	603.404	±0.097	
B4	01/06/2017	254399.247	±0.511	2983668.896	±0.032	603.404	±0.222	267
B5	11/09/2015	254315.647	±0.671	2983674.582	±0.450	561.202	±0.382	
B5	06/06/2016	254315.644	±0.111	2983674.584	±0.113	560.172	±0.189	268
B5	08/10/2016	254315.643	±0.182	2983674.583	±0.049	558.002	±0.113	
B5	02/06/2017	254315.641	±0.881	2983674.581	±0.329	556.289	±0.220	267
B6	12/09/2015	254428.944	±0.833	2983481.117	±0.555	691.162	±0.371	
B6	07/06/2016	254428.946	±0.006	2983481.119	±0.009	691.007	±0.095	268
B6	09/10/2016	254428.947	±0.191	2983481.120	±0.049	666.644	±0.293	
B6	03/06/2017	254428.945	±0.692	2983481.116	±0.444	690.155	±0.712	265

Table 4. Summary of movements, the direction of movements, and velocities of monitoring points (Coe and Lidke, 2003; Anon, 2000).

Station	Date of GPS observation	Easting	Northing	Elevation (m)	Seasonal horizontal movement (m, from previous position)	Seasonal horizontal velocity (m/d ay, since previous position)	Annual horizontal movement (m, net) 29/08/2015 to 03/06/2017	Seasonal l vertical movement (m, from previous position)	Seasonal vertical velocity (m/ day, since the previous position)	Annual vertical movement (m) from 29/08/2016 to 03/06/2017	Days since previous observation
T1	29/08/2015	751265.792	3000316.76	2181.21							N.A
T1	13/06/2016	751265.781	3000316.762	2181.111	0.01118	0.00003923		0.1	0.00035088		285
T1	19/09/2016	751265.785	3000316.764	2181.1	0.004472	0.00001038	0.004123	0.01	0.0000232	0.109	431
T1	07/06/2017	751265.788	3000316.761	2181.101	0.004243	0.00001571		-0.001	-0.0000037		270
R1	03/09/2015	738922.817	2971829.671	397.969							
R1	09/06/2016	738922.811	2971829.672	397.967	0.006083	0.0000218		0.002	0.00000717		279
R1	27/09/2016	738922.814	2971829.673	397.964	0.003162	0.00000683	0.002508	0.003	0.00000648	0.008	463
R1	21/05/2017	738922.815	2971829.672	397.961	0.001221	0.00000517		0.003	0.00001271		236
B1	07/09/2015	254256.780	2983552.604	580.633							
B1	02/06/2016	254256.780	2983552.604	580.633	0	0		0	0		244

B1	10/04/2016	254256.780	2983552.604	580.633	0	0	0	0	0	0	463
B1	29/05/2017	254256.780	2983552.604	580.633	0	0		0	0		370
T2	30/08/2015	751261.723	3000320.926	2179.926							
T2	14/06/2016	751261.722	3000320.925	2179.925	0.001414	0.00000491		0.001	0.00000347		288
T2	20/09/2016	751261.721	3000320.924	2179.924	0.001414	0.00000307	0.001	0.001	0.00000217	0.006	461
T2	08/06/2017	751261.723	3000320.925	2179.92	0.002236	0.00000699		0.004	0.000125		320
R2	04/09/2015	738927.875	2971840.495	396.049							
R2	10/06/2016	738927.876	2971840.494	396.046	0.001414	0.00000507		0.003	0.00001075		279
R2	28/09/2016	738927.877	2971840.494	396.045	0.001	0.00000215	0.002236	0.001	0.00000215		465
R2	22/05/2017	738927.876	2971840.493	396.0422	0.001414	0.00000507		0.0028	0.00001186	0.002596	236
B2	08/09/2015	254332.748	2983588.862	598.358							
B2	03/06/2016	254332.748	2983588.862	598.358	0	0		0	0		268
B2	05/10/2016	254332.748	2983588.862	598.358	0	0	0	0	0	0	465
B2	30/05/2017	254332.748	2983588.862	598.358	0	0		0	0		267
T3	31/08/2015	751262.581	3000324.226	2179.226							

T3	15/06/2016	751262.579	3000324.229	2179.229	0.003606	0.00001252		-0.003	-0.00001042		288
T3	21/09/2016	751262.582	3000324.224	2179.227	0.005831	0.00001259	0.002	0.002	0.00000432	0.002	463
T3	05/09/2017	751262.581	3000324.228	2179.224	0.004123	0.00001793		0.003	0.00001304		230
R3	05/09/2015	738919.629	2971866.629	397.124							
R3	11/06/2016	738919.628	2971866.622	397.118	0.007071	0.00002534		0.006	0.00002151		279
R3	29/09/2016	738919.627	2971866.618	397.114	0.004123	0.00000883	0.010198	0.004	0.00000857	0.0116	467
R3	23/05/2017	738919.627	2971866.619	397.1124	0.001	0.00000424		0.0016	0.00000678		236
B3	09/09/2015	254355.287	2983598.732	603.354						0	
B3	04/06/2016	254355.287	2983598.732	603.354	0	0		0	0		268
B3	06/10/2016	254355.287	2983598.732	603.354	0	0	0	0	0		441
B3	31/05/2017	254355.287	2983598.732	603.354	0	0		0	0		267
T4	01/09/2015	751287.234	3000314.764	2188.359							
T4	16/06/2016	751287.238	3000314.766	2188.357	0.004472	0.00001553		0.002	0.00000694	0.008	288
T4	22/09/2016	751287.233	3000314.767	2188.355	0.005099	0.00001167	0.008	0.002	0.00000458		437
T4	05/10/2017	751287.233	3000314.767	2188.351	0	0		0.004	0.00001739		230

B4	10/09/2015	254399.247	2983668.896	603.404							
B4	05/06/2016	254399.247	2983668.896	603.404	0	0		0	0		268
B4	07/10/2016	254399.247	2983668.896	603.404		0	0	0	0	0	439
B4	01/06/2017	254399.247	2983668.896	603.404	0	0		0	0		267
B5	11/09/2015	254315.647	2983674.582	561.202							
B5	06/06/2016	254315.644	2983674.584	560.172	0.0036	0.00001343		1.03	0.00001449		268
B5	08/10/2016	254315.643	2983674.583	558.002	0.001414	0.00000343	0.006083	2.17	0.00526699	4.913	412
B5	02/06/2017	254315.641	2983674.581	556.289	0.002828	0.00001059		1.713	0.00641573		267
B6	12/09/2015	254428.944	2983481.117	691.162							
B6	07/06/2016	254428.946	2983481.119	691.007	0.002828	0.00001055		0.155	0.00057836		268
B6	09/10/2016	254428.947	2983481.12	691.644	0.001221	0.00000296	0.001414	-0.637	-0.00154237	1.007	413
B6	03/06/2017	254428.945	2983481.116	690.155	0.004214	0.0000159		1.489	0.00561887		265

Table 5. Summary of movement of tension cracks

Tension cracks at Tsimasham

Sl. No.	Lat	Long	Elevation (m)	Dimension of tension crack in September, 2015(m)	Dimension of tension crack in May 2016 (m)	Dimension of tension crack in May 2017 (m)	dM	Remarks
1	27.10250˚	89.53556˚˚	2229	No tension crack has been observed	L=30	The tension crack has been displaced by 2m		Crack has been placed displaced
					W=0.30			
					D=1.36			
2	27.10251˚	89.53541˚	2240	No tension has been observed	L=20	L=20	0	Tension crack is located on the crown.
					W=1	W=1.5	0.5	
					D= 2.30	D=2.5	0.2	
3	27.10247˚	89.53534˚	2225	No tension crack has been observed	L=45	The tension crack has been displaced		Crack has been completely displaced
					W=0.08			
					D=2			

Tension cracks at Reldri

Sl. No.	Lat	Long	Elevation (m)	Dimension of tension crack in September, 2015(m)	Dimension of tension crack in May 2016 (m)	Dimension of tension crack in May 2017 (m)	dM	Remarks
1	N26˚50'52.4"	E89˚24'16"	406	L=10	The cracks have been completely displaced and no crack is seen	No new cracks have been formed		At the crown of the landslide
				W=0.10				
				D=0.36				
2	N26˚50' 52"	E89˚24'16"	405	L=10	The cracks have been completely displaced and no crack is seen	No new cracks have been formed		At the crown of the landslide
				W=0.08				
				D=0.05				
				L=0.55				

3	N26˚50’52.7”	E89˚24’16.1”	411	W=0.15 D=0.07	The cracks have been completely displaced and no crack is seen	No new cracks have been formed		At the crown of the landslide

Tension cracks at Box-Cutting

Sl. No.	Lat	Long	Elevation (m)	Dimension of tension crack in September, 2015(m)	Dimension of tension crack in May 2016 (m)	Dimension of tension crack in May 2017 (m)	dM	Remarks
1	26˚57’01.2”	90˚31’35.6”	2229	L=6 W=0.10 D=0.60	L=6 W=0.30 D=1	The cracks have been displaced making a slip face angle of70˚	0 0.20 0.4	Crack has been placed displaced
2	26˚57’01.3	90˚31’35.2”	2240	L=5 W=0.20 D=0.40	L=8 W=0.08 D= 2.30	The cracks have been displaced making a slip face angle of70	3 0.06 1.9	Tension crack is located on the crown.
3	26˚57’02.3	90˚31’35.2”	2225	L=6 W=1 D=0.50	L=12 W=2 D=2	The tension crack has been displaced	6 1 1.5	Crack has been completely displaced

6. CONCLUSIONS

6.1. MOVEMENT OF GPS POINTS

(1) All monitoring points moved between each set of GPS observations (refer Table 4 for movement data).

(2) In Tsimasham area, not much horizontal movement is observed while the GPS data collected over the time suggest a uniform downward movement of the landmass.

(3) In Box-Cutting area, not much horizontal movement is observed in the mid segment of the slide while the GPS data collected over the time suggest a uniform downward vertical movement of the landmass in the lower and upper segment of the slide. The rate of movement of the landmass is slightly faster in the lower part (i.e. below road) of the slide. Overall, the Box-Cutting landslide is observed to be active since the GPS point B5 and B6 have vertical displacement of 4 m and 1 m respectively.

(4) The summary of horizontal and vertical movement (displacement) and movement rate (velocity) is shown in Table 6.

(5) The net average velocity (movement rate) of 0.296 mm per day at Box-Cutting landslide falls under very slow to slow category of movement rate as per classification of Varnes (1978).

(6) The net average velocity (movement rate) of 0.0008 mm per day at Reldri landslide and 0.007 mm per day at Tsimasham landslide fall under the extremely slow category of movement rate as per classification of Varnes (1978).

(7) The net average movement rates of the Tsimasham and Reldri landslides can be classified as a stable movement (Figure 14) and therefore indicate a normal situation.

(8) The net average movement rate of the Box-Cutting landslides can be classified as large seasonal fluctuations (Figure 14) and therefore indicate an alert situation.

(9) However, since the GPS observations are made only on the surface or near-surface of the landslides with only few control points, therefore, monitoring using integrated monitoring systems approach (both contact and remote) that help determine more representative and accurate movement of these landslides is recommended. This will include but not limited to monitoring using instruments or techniques such as inclinometer, extensometer, piezometer, total stations, and satellite and terrestrial remote sensing.

Table 6. Summary of net horizontal and vertical movement (displacement) and movement rate (velocity).

Description	Boxcutting	Reldri	Tsimasham
Net average horizontal movement	0.0012m	0.38 m	0.003 m
Net average vertical movement	0.856 m	0.007 m	0.031 m
Net average velocity (movement rate)	0.296mm/day	0.0008mm/day	0.0066mm/day

The relationship between the movement rate of landslide and situational or hazard level is shown in Figure 14.

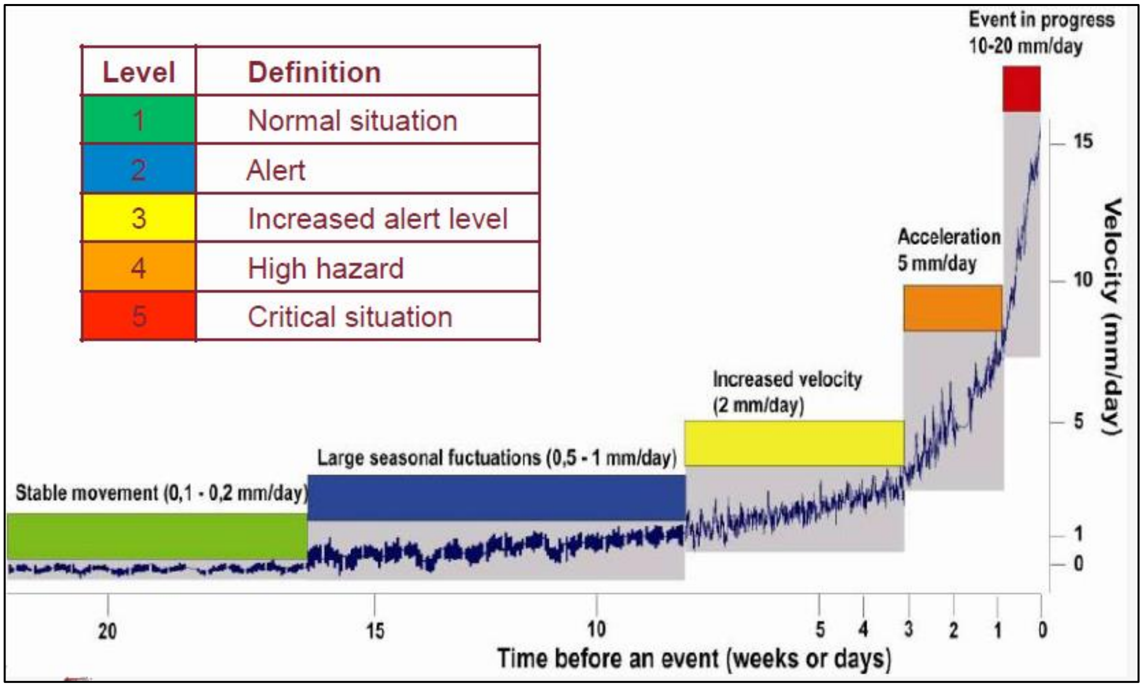

Figure 14. The relationship between landslide movement rate and situational or hazard levels

6.2. TENSION CRACKS

Like monitoring points for GPS all the 9 tension cracks showed movement (see Table 5 for movement data). The change in the length of the tension crack ranges from 0 m to 6 m for tension crack located in Box-cutting landslide. The maximum number of cracks developed has been displaced.

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8. REFERENCES

Althuwaynee, O. & Pradhan, B., 2012, Prediction of Slope Failures Using Bivariate Statistical Based Index of Entropy Model. , (Chuser), pp.8–13.

Anon, 1997. 2 . REVIEW OF LANDSLIDE HAZARD AND RISK ASSESSMENT : , pp.1–56.

Anon, 2000. Seasonal movement of the Slumgullion landslide as determined from Seasonal movement of the Slumgullion landslide as determined from GPS observations , July 1998 - July 1999.

Coe, J.A. & Lidke, D.J., 2003. Seasonal movement of the Slumgullion landslide determined from Global Positioning System surveys and field instrumentation ... Seasonal movement of the Slumgullion landslide determined from Global Positioning System surveys and $ field instrumentation ,. , (August 2017).

Long, S. et al., 2011. Geologic Map of Bhutan. , p.89.

McQuarrie, N. et al., 2013. Documenting basin scale, geometry and provenance through detrital geochemical data: Lessons from the Neoproterozoic to Ordovician Lesser, Greater, and Tethyan Himalayan strata of Bhutan. *Gondwana Research*, 23(4).

Rawat, M.S. et al., 2011. Landslide movement monitoring using GPS technology : A case study of Bakthang landslide , Gangtok , East Sikkim , India. , 3(May), pp.194–200.

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