Extreme hydrological situation and debris flow initiation – Consequences and concern

Sarkar, Niroj Kumar
Superintending Geologist
Geological Survey of India, North Eastern Region, Shillong- 793 003
E-mail: niroj4@gmail.com

Abstract

The relation of extreme hydrological situation and debris flow initiation across the mountain slope of Himalaya, Trans-Himalaya and Western-Ghats were highlighted with recent examples. The significant negative consequences of this long travel short period fluidised mass movement on the people, infrastructure, land-use, forest, etc were highlighted to emphasized the need for debris flow susceptibility mapping. The various predisposing and triggering factors for debris flow initiation in the mountain slope are outlined along with a few revealing factors. Some of the prevalent methodologies used for debris flow susceptibility mapping and run out modelling being used globally are discussed highlighting the complexities and uncertainties associated the same. The need for multi-disciplinary/multi-institutional approach incorporating advance climatic input in regards to identification and delineation of the possible loci of extreme hydrological situations, identification and delineation of the slope morphometry and stream configurations, detailed event based inventory of the debris flow/mudflow and identification of the loci of the paleo debris flow/mud flow situations has been emphasised for preparation of debris flow susceptibility maps, hazard, risk assessment and mitigation of this significant natural hazard.

1. Introduction:

The relation between extreme hydrological situation and debris flow initiation in mountain slope across the globe has been attempted by scientists through understanding of a number of process based physical modeling and data based statistical studies as well. The studies indicate that the long travel fluidised debris flow initiation though largely triggered by extreme and high rainfall, snow fall, snow melting, etc, but the relation between the same is not exactly linear, instead is very complex and found to be both terrain and time dependent. The physico-climatic attributes of the terrain, availability of sediment supply through past erosion process, the configurations and slope of the mountain streams, and other predisposing geo-factors are related to the initiation of extreme hydrology triggered debris/mud flow. The debris flows are the most damaging among various kinds of slope failures and shows an overall increasing frequency in recent times related to the global climatic changes. Because of increasing population and infrastructure development in last few decades along with rapid changes in land-use pattern, it is likely that larger areas of the mountain slopes may now comes under the path of debris flow. The 2010 and 2013 disasters of Ladakh and Uttrakhand related to extreme hydrological situation, large scale debris flow initiation and consequent devastation to a larger part of mountain slope clearly highlights the might of the events and need for an appropriate pre disaster perspective planning in respect to the similar hazard. An attempt, therefore, is being made in this paper to identify all the predisposing factors for the debris flow initiation and physical understanding of such process in different geological and geomorphological domain across the country. The need for debris flow modelling and estimation of susceptibility, hazard and risk of this natural hazard to the population, infra structures and settlement is felt required particularly for mountain slope susceptible to extreme hydrological situation.

2. Recent Debris Flow Events in India:

During the last four years, India experienced two most extreme hydrological situation related disasters namely that of Ladakh, J&K, 2010 and Uttarakhand, 2013. The said extreme climatic situation resulted unguided, unconfined debris/ mud flow initiation consequences of the same to the population, infrastructure and environment was enormous and unmanageable due to the lack of required preparedness. The debris/mud flow were rapid and long travel with a great impact force and did not allow evacuation and destroyed houses, infrastructures and disastrously affect a large area. In India, the main Himalayan range from Kashmir in the west to Arunachal Pradesh in the east have a number of recorded history of such unguided sub aerial debris/ mud flow related with extreme hydrological situation. The devastative consequence of extreme hydrological situation in the cold desert area of Ladakh in 2010 is also an eye opener to the probability of such disasters in diverse geological, geomorphological and climatological set up. During the landslide susceptibility mapping in parts of the Trans Himalayan belt of Lohit river valley in the Eastern Arunachal Pradesh, a number of confined and unconfined debris flows were identified by the author. However, more than identification of a few debris flows, the identification of a number of preparatory factors in this highest seismicaly vulnerable and high rain fall zone, is of great concern since the same at selected stretches during extreme hydrological situation may initiate large scale debris flow. The author and his associates (Sarkar et al, 2014, in press) have identified and documented three prominent recent debris flows at KMC old dumping site, Phesama and Meriema, adjoining to National Highway Corridor, Kohima district of Nagaland. The debris flow along with other kind of slope failures in the said locations are responsible for blockade of road traffic, destruction of agricultural & forest land, partial blockade of river course and therefore, are responsible for consequent economic losses, social concerns and environmental degradations. Further, debris and mud flow of smaller dimension but larger hazard potential is also noted in part of the high rain fall region of the Western Ghats, where shallow translational failures along steep slope followed by high anomalous rainfall reported to have initiated debris flow /mudflow and consequently damaged properties and infrastructures. Therefore, it emerges that rapid and long traveling debris flow of varying dimension and damage potential can be initiated in varying geological and geomorphic situation in India under extreme hydrological condition. Since the damage potential of this kind of slope failures is the maximum, it is felt that debris flow susceptibility mapping for estimation of hazard and risk to the population, infra structures and settlements may be initiated particularly in those areas where reports of past cloud burst and similar extreme hydrological situation were known.

3. Predisposing, Triggering and Revealing Factors for Debris Flow Initiation:

Identification of predisposing, triggering and revealing factors for debris flow initiation in mountain slope is the primary tasks for debris flow susceptibility mapping. In general steep slopes, potentially unstable loose materials and surface run off are considered to be the perquisite for debris flow initiation. The same when acted on by conspicuous hydrometeorologic events (thunderstorm, often in combination with rapid snowmelt, or prolonged rainfall) triggered debris flow of varying dimension. Debris flows reported to be triggered by sudden release of water stored under a glacier or by the breaching of an ice or morainic dam are not uncommon. Apart from the predisposing factors like slope, surficial material and triggering factor like extreme hydrological events, some other factors like drainage configuration, drainage load, neo-tectonic movement and seismic shaking also influenced the debris flow susceptibility in the mountainous slope. The debris flow susceptibility of some mountain slopes can be qualitatively estimated based on some of the revealing factors like nature, frequency and magnitude of past slope failures in the area, signature of recent, past and paleo debris flows. The above said Predisposing, triggering and revealing factors are briefly outlined below:

3.1 Slope:

Although, in general, a steeper slope is more favourable for debris flow initiation, but the same assumption may not be applicable universally. Debris flow is reported to be initiated in very gentle to steep slope and as such the slope amount is not exactly a guiding factor for debris flow initiation. However, the debris flows run out and spread in many observed areas indicate that a steeper zone of initiation with a relatively gentler down slope is favorable for a greater run out and even very gentle near flat slope at the base of the steeper hill is a highly vulnerable zone as the said gentle to flat area comes under the flow path of debris flow initiated in the steeper up-slope. Regarding shape of the slope, a relatively planar upslope is more vulnerable than a concave or convex slope because of lesser total frictional resistance the said slope mass offered against the moving mass. As regards slope aspects, the directional relation of moisture bearing wind to that of the slope face is always significant. In the Himalayas the southerly facing slope in general are always more prone to rain induced translational failure and consequent debris flow initiation.

3.2 Drainage Configuration and Drainage Load:

The drainage configuration in a slope is a deciding factor for mass &length of the debris flow run out and its horizontal spread. A highly incised drainage network will able to carry the debris mass descended from the upslope within its valley while that of a shallower one lead to unconfined debris flow of larger spread. A slope with a relatively lower drainage density and wider valley is more prone to debis flow initiation and longer run out than that of a slope with a dense network of highly incised drainage. This may be explained in terms of rapid transportation of the eroded debris material by relatively dense drainage network which does not allow the said material to settle in the slope. Whereas, debris mass in the relatively less drained slope is prone to triggering of debris flow in the event of anomalous high/ extreme rain fall event. Since the nature and volume of sediments load is related to the erosion rate, which is again dictated by complex geomorphological and recent tectonic processes, the same is also to be considered along with drainage attributes for estimating the availability of material required for generation of a debris flow.

3.3 Surficial Material:

The nature, disposition and thickness of the surficial material covering the slope mass is a very important factors for initiation of a debris flow. It is obvious that a slope with bare competent rock-mass is less prone to debris flow than that of a slope with variable compacted older to younger overburden. It is found that a relatively thin (1-5m) overburden over impermeable bed rock in a steeper slope is a potential area for shallow translational failure due to lubrication along rock-water interface and subsequent debris flow under higher saturation condition. The type of surficial material which are prone to debris flow generation during high rainfall are Colluvium/ slope wash, unconsolidated heterogeneous soil mass deposited by water run-off/down slope creep, accumulated talus at the base of a cliff or steep rock slope, spalling/ravelling and rock falls. Further, fluvial uunconsolidated detrital material laid down by a stream, river or other body of water, glacial uunconsolidated heterogeneous soil mass (clay, silt, sand, gravel, cobbles and boulders) deposits, regolith mantle of unconsolidated rock fragments (gravel, cobble and boulder sized), sand, silt and clay covering bedrock, are also prone to debris flow.

3.4 Magnitude, Frequency and Distribution of Past Landslides:

The magnitude, frequency and distribution of past landslides in a domain of the mountain slope are largely dependent on the event based triggering of a set of inherent predisposing factors. A part of the slope mass which underwent repeated failures during the past may have a zone of accumulation of released debris mass of varying nature and dimension disposed in lower slope. Debris flow initiation in such kind of slope is a strong probability in the event of triggering by high anomalous rainfall or a combination of anthropogenic and natural factors.

3.5 Signature of Past and Paleo Debris Flow:

A detailed field and remote sensing based inventory of the debris flows will able to quantify the frequency and magnitude of the recent, past, historical and paleo-debris flow events in a specified region. The frequency and magnitude distribution of the past events will help in understanding the terrain specific predisposing factors responsible for the debris flow initiation and threshold value for same. It is important to mention that a debris flow is more likely to initiate in the adjoining slope to the past sites of debris flow having similar predisposing factors. The old debris-flow deposits are readily recognizable in the field in the form of alluvial fans and debris cones along steep mountain fronts. Fully exposed deposits commonly have lobate forms with boulder-rich snouts, and the lateral margins of debris-flow deposits and paths are commonly marked by the presence of boulder-rich lateral levees. Lateral levees can confine the paths of ensuing debris flows, and the presence of older levees provides some idea of the magnitudes of previous debris flows in a particular area. Through dating of trees growing on such deposits, the approximate frequency of destructive debris flows can be estimated. Ancient debris-flow deposits that are exposed only in outcrops are more difficult to recognize, but are commonly typified by juxtaposition of grains with greatly differing shapes and sizes. This poor sorting of sediment grains distinguishes debris-flow deposits from most water-laid sediments.

3.6 Signature of Extreme Hydro Meteorological Events:

Extreme hydrological events happen in conducive conditions like development of high vertical cumulo-nimbus clouds, continuous supply of moisture due to off-shore trough and vertical wind shear besides several other factors. An analysis of climatological data for the last three decades in parts of Alps reveals that debris flows linked to rain are likely to be triggered when total rainfall amount over a three-day period exceeds four standard deviations, i.e., a significant extreme precipitation event. The latitude and altitude of different mountain systems determine the relative amount of snow and ice at high elevations and intense rainfall at lower elevations. Because of the amount of precipitation and the nature of the orography, the effect of intense rainfall in low to middle altitude regions is to produce some of the highest global rates of slope erosion (Beniston et al., 1995). Climate change could alter the magnitude and/or frequency of a wide range of geomorphologic processes (Eybergen and Imeson, 1989). In particular, higher precipitation, especially during extreme events, can augment the risk of erosion. Past reports of cloud burst or extreme hydrological situation in the mountain slope need to be chronicled for understanding factors responsible for such localized extreme events. Identification and delineation of areas where such extreme events are probable can be modeled by the meteorologist using state of the art satellite based weather inputs. The consequence of such identified and delineated extreme events on the mountain slope can be further modelled using the slope attributes discussed above. The spatial and temporal variability of extreme rainfall events over India and their long-term trend need to be modeled specially for the region where predisposing and revealing factor for debris flow initiation has already been identified.

3.7 Neo-tectonics:

The recent tectonics largely governs the erosion rate by rejuvenating the hydrological network in the slope mass. A slope mass proximal to regional neo-tectonic discontinuity will therefore is more prone to various kind of mass movement and consequent generation of larger debris mass. The same generated debris mass disposed variably in the slope under favorable triggering input may flow of varying dimension.

3.8 Past Seismicity:

The large scale triggering of landslides both during and after an earthquake of 6.0 magnitudes and above has been reported world wide in the slope mass specially proximal to the epicentral zone. The magnitude, distance from the hypo- centre, topography and material property of slope are the governing factor for the initiation of such seismic induced landslides and their distribution, frequency and magnitude. Therefore, near complete records of the major seismic events (both instrumental and historic) and their effect on slope instability in a region need to be documented to understand the vulnerability of the slope for further distressing. In many areas of the world, the earthquake induced landslides are reported initiate mass movement in the upper reaches of the slope due to topographic effect. Consequently, displaced mass of varying dimension is variable disposed in the slope. Under extreme hydrological situation, the said displaced mass is susceptible to generate debris flow of varying magnitude. Therefore, it emerges that an area in the mountain slope which is reportedly experienced large scale past seismic induced slope failures are also a favourable area for debris flow initiation under extreme hydrological condition.

4.0 Debris Flow Susceptibility and Run out Modelling:

Debris-flow susceptibility in a given area can be defined in terms of likely magnitude and corresponding frequency. Magnitude-frequency characterisation of debris-flow process is an essential element for hazard assessment. Debris flow susceptibility of the mountain slope can be modelled by welding the climatic (triggering factor) and slope inputs (predisposing factors) under varying probable condition. The model may be physical one through duplication of the near identical situation in artificial slopes in the laboratory condition under various induced hydrological triggering or may be statistical one using the input from inventory data. It is important to understand that understanding the slopes where debris flow may be initiated largely depends on judicious identification of a set of predisposing factors which may experience triggering during extreme events. The physics of debris flow generation through mobilisation of the slope mass need to be understood through the various experimental works carried out in this regard. Once the same is understood with respect to the relative role of predisposing and triggering factors, terrain specific numerical modelling may be attempted. The susceptibility of the mountain slope can be brought out by suitable derived maps. The same derived map may form the basis of hazard and risk assessment considering element at risk and their vulnerability. It is important that debris flow susceptibility map should also include probable run out zones and the same also need to be modelled based on physical attributes like water content, sediment size and/or sorting, and on the dynamic interaction between the solid and fluid phases. The modelling of such an interaction still remains a quite difficult task and the currently available computational models inevitably rely on simplifying assumptions. A different and promising approach is that based on the continuum numerical modelling, which allow determination of the flow parameters and deformation of the mass along the entire path, including deposition (e.g. O'Brien et al., 1993; Iverson and Denlinger, 2001; McDougall and Hungr, 2005). The numerical codes based on this last approach are at present largely used by choosing rheological parameter of materials for prediction. The guidelines in choosing rheological parameter may be formulated based on the analysis of the geological and geomorphological settings that characterize a study basin and of the alluvial fans that may exist at its toe.

5.0 Discussions:

The estimation of susceptibility, hazard and risk of the mountain slope associated with this kind of extreme situation is most complex and difficult task due to its relatively low frequency, unpredictability of the extreme climatological events and absence of meaningful data and model to indicate susceptibility of mountain slope to debris flow initiation. Landslide susceptibility mapping through conventional methods as such cannot exactly predict the said hazards based on the available inputs. In similar situation, therefore, all the heuristic modelling for susceptibility and hazard estimation may go wrong. It is important to mention that apart from extreme hydrological situation, large scale initiation of debris flow is also possible in highly seismically vulnerable and neo-tectonically active zones triggered by rainfall above threshold specially in the areas where the preparatory factors like large scale old failures and consequent disposal of displaced mass in steep slope exist. However, when the same highly seismically vulnerable and neo-tectonically active zones with identified preparatory factors experienced or likely to experience extreme hydrological situation the consequent to the mountain slope and adjoining areas will be highly hazardous and a real concern to the administrator since the debris flow initiated in such cases will be rapid and long travel and as such move with a great impact force and does not allow timely evacuation. The destructive track of such unguided aerial debris flow can destroy houses, infrastructures and disastrously affect large areas. Sassa (2004) from the study of Tsukidate landslide in Japan documented that the debris flow moved from a gentle slope of 10 degree and travel a long distance at a speed several metre per second which indicates that even the houses that have been constructed away from steep slope and on gentle slope is destroyed by this phenomena.

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