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Advances in landslide hazard assessment in India

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Abstract

Various methods adopted for Landslide Hazard Assessment in India include heuristic, semi-quantitative, quantitative, probabilistic, etc. However, no single method can be perfectly suitable considering the variety and diversity of landslides. To identify various approaches to Landslide Hazard Assessment, different articles are compared based on landslide type, geo-environmental factors, and approaches to Landslide Hazard Assessment in this review article. The advanced multivariate techniques are effective in the spatial prediction of landslides with a high degree of accuracy. Physical process-based models also proved better in Landslide Hazard Zonation mapping even in the areas with the poor database. The multi-criteria decision-making approach is effectively used in determining the relative importance of landslide causative factors in the slope instability process. Remote Sensing and Geographical Information System (GIS) are powerful tools to assess landslide hazards and are being used extensively in landslide researches since the last decade. After the review of articles, it is found that many scholars admitted that for inaccessible areas, satellite data is the only source in detection, mapping and monitoring of landslide processes. Still, the application of geospatial technology like unmanned aerial vehicle (UAV) in this field of study is lacking in India, particularly when it comes to monitoring the slope failure process and landslide hazard warning system studies. Geospatial technology such as UAV has improved access to inaccessible areas.

Keywords: *landslide hazard zonation, landslide inventory, remote sensing, geographical information system, landslide risk assessment.*

Introduction

Slope failure refers to the downslope movement of slope forming material under gravity and commonly in a relatively dry state (Kale and Gupta, 2018). Landslide is one of the major geological hazards in India that causes damage to the natural and social environment. About 15% of the total land area in (over 0.49 million Km^2 area) India is affected by landslides of different magnitudes. Two of the major landslide-prone regions in SAARC (South Asian Association of Regional Cooperation) countries lie in India viz. Himalayan region and Western Ghats (NDMA, 2009).

India alone accounts for 23% of the fatalities due to landslides in South Asian countries in the year 2010 (SMDC, 2010). Landslides in India have claimed 517 lives in India in just five years between 2007 and 2011 with many economic losses (SMDC 2007, 2008, 2009, 2010 and 2011). Unfortunately, the amount of losses caused by landslides is often underestimated firstly because many times landslides are considered as a secondary disaster.

Landslide Hazard Assessment provides probabilistic expertise on future slope failures to all the stakeholders engaged in land use planning and disaster management (Guzzetti et al. 2006). At least 90% of landslide losses may be avoided if the problems are identified before the event (Brabb, 1993). Hence, there is a need for landslide hazard assessment at various spatial scales. The review of existing literature on landslides is essential for the application of appropriate hazard assessment methods and techniques. Basu et al. (2009) reviewed the progress of landslide research in India about landslide hazard zonation methods and control measures. Pardeshi et al. (2013) took a brief review of recent advances in landslide investigations in different parts of the world regarding methods of landslide hazard zonation, consideration of landslide causative factors and application of Remote Sensing and Geographical Information System in landslide hazard assessment.

This paper is an attempt to review the methods applied and database used and also tries to evaluate the possibilities of applications in landslide hazard studies. The paper also intends to find out gaps in the existing literature and future research directions.

Review

Landslide Studies in India: an overview of landslide hazard assessment methods

Several studies have been reported in recent times to analyze landslide hazards in different parts of the country especially the Himalayan regions and the Western Ghats and Nilgiri hills. The landslide hazard assessment in India covers various dimensions such as geotechnical assessment, landslide inventory, Landslide Hazard Zonation mapping, event-specific analysis and landslide risk assessment.

Landslide Inventory

'Landslide inventory is a simple form of landslide map that records location, landslide type, landslide dimensions and date of landslide occurrence' (Hansen, 1984). Preparation of landslide inventory is an important step in landslide hazard investigation. Landslide inventory map helps in understanding the spatial distribution of landslides in a given area and also in the validation of the Landslide Hazard Zonation (LHZ) methods. Interpretation of multi-temporal landslide inventories helps in landslide hazard and risk assessment (Guzzetti, 2003). Completeness and resolution of landslide inventory determine its reliability in landslide hazard investigations (Guzzetti et al. 2003).

Multi-date high-resolution satellite data (such as SPOT, IKONOS, CARTOSAT - I and II) have been widely used for identification of landslide through image interpretation techniques in different parts of India (Champatiray et al. 2008; Champatiray et al. 2009; Saraf et al. 2009; Gomathi et al. 2013). Landside geometry has also been considered as an important parameter in landslide inventory (Pardeshi et al. 2009; Bodas and Kohli 2009, Sable et al. 2016). Field observations and historical landslide records are proven data sources for complete and reliable landslide inventory (Sah and Mazari 1998; Kuriokose, 2010; Jaiswal, 2011; Karlekar, 2012; Singh and Singh 2013; Tikke et al. 2014; Jaiswal and van Westen 2013, Souisa et al. 2017, Autade et al. 2013). Martha et al. (2017) used high-resolution satellite data for volume estimation of landslides in Zaskar Himalayas.

Several attempts have been made in India to prepare landslide inventories using direct and indirect methods. However, little attention is given to the quantitative assessment of completeness and reliability of landslide inventories. Comparative assessment of existing landslide inventories in India can be useful to determine the most appropriate method of landslide investigation.

Landslide Hazard Zonation

'Landslide Hazard Zonation or Landslide Susceptibility Zonation refers to a division of the land surface based on the actual and potential hazard due to landslide occurrence' (IAEG and Varnes 1984). The accuracy of the landslide hazard zonation map is determined by the completeness of landslide inventory, selection of landslide preparatory and triggering parameters, selection of scheme of rating the parameters, resolution of satellite data inputs, the scale of mapping, mapping unit and experience of the investigator. Several approaches to Landslide Hazard Zonation have been proposed and adopted in different geo-environmental conditions of India. A review of recent researches carried out on Landslide Hazard Zonation in India is briefed as follows.

Heuristic (knowledge-driven) approach

This approach is a knowledge-driven approach that determines the weight of each landslide causative factor based on prior knowledge and experience of the researcher. The most commonly used heuristic method for landslide hazard zonation is the Landslide Hazard Evaluation Factors (LHEF) rating scheme developed by the Bureau of Indian Standards (BIS, 1998). Using LHEF hazard zonation studies are carried out in different parts of India like Garhwal Himalayas, North East India, Kumaun Himalayas and also in hilly tracks of Nilgiri ranges in Tamil Nadu (Champatiray et al. 2007; Naithani 2007; Anbalagan et al. 2008; Singh et al. 2011; De and Jamatia 2011; Roy and Saha 2019). Total Estimated Hazard (THED) is calculated based on maximum LHEF ratings for parameters namely lithology, structure, slope morphometry, relative relief, land use, land cover, and hydrological conditions. However, the LHEF rating scheme may not be applied universally in all parts of India due to the difference in geo-environmental conditions. Ghosh et al. (2009) proposed a quantitative approach to improve the applicability of the BIS method for LHZ at a medium scale. Heuristic methods of the LHZ have recently been used to map landslide susceptibility in Himalayan regions and parts of Nilgiri hills in Tamil Nadu (Sarkar and Kanungo 2004; Patwary et al. 2009; Pareta et al. 2012; Arunkumar et al. 2013; Lalliathanga et al. 2013; Champatiray et al. 2013, Ramesh et al. 2017). It is often difficult to validate the results because it does not take into account the actual 'spatial distribution' of slope failures. Moreover, a high level of subjectivity exists as the accuracy of the LHZ map depends upon the experience and knowledge of the investigator.

Bi-variate statistical methods

The bi-variate approach to LHZ considers the relationship of causative factors with the actual distribution of landslides in a given area. Frequency ratio model, Discriminant analysis, weighted overlay and Information Value Method (IVM) are widely applied for LHZ in India.

The frequency ratio model considers landslide frequency per unit area under each category of the thematic data layer. Finally, frequencies are obtained using the percentage of area under the thematic layer and the percentage of the landslide area. A few studies on LHZ have been carried out recently in parts of Garhwal Himalayas, Nilgiri hills and Western Ghats region of Karnataka (Avinash and Ashamanajri 2010; Martha et al. 2013; Vineetha et al 2019) using the frequency ratio model.

The information Value Model (IVM) is another bi-variate statistical method of LHZ. This method considers the ratio of landslide density in each thematic layer to landslide density within each category of thematic layers. This method has been applied for LHZ mapping in the Himalayan region as well as parts of Western Ghats (Arora et al. 2004; Sarkar et al. 2006; Chakraborty 2008; Vijith et al. 2009; Balsubramani and Kumarswamy 2013; Wagh and Deshpande 2013). Although IVM is of quantitative nature, a certain degree of subjectivity exists in the weight assignment process.

The weighted overlay method involves the subjective assignment of weights to each of the categories of the thematic layer based on the observed relationships between the thematic layer and the landslide occurrence. Balsubramani and Kumarswami (2013) used this method to map landslide susceptibility in the Giri valley of Himachal Pradesh. This approach has also been adopted by few studies in Garhwal Himalayas (Sarkar et al. 1995; Pannikkar and Subramanyan 1997), North East India, Western Ghats region (Biju and Shaji, 2013; Jayanthi et al. 2016; Chawla et al. 2018) and parts of Himachal Pradesh (Ghosh et al. 2009). Naveenraj et al. (2011) used the Relative Effect Method (REM) to map landslide susceptibility in parts of Nilgiri Hills, Tamil Nadu. REM method determines the contribution of each thematic layer in landslide occurrence using Relative Effect Function. Kumar et al. (2017) used Rock Mass Ratings and Factor of Safety for LHZ in Uttarakhand Himalayas. The weight of the Evidence method has also been recently applied by Rana et al. (2017) to map landslide susceptible areas in Mandakini valley. Walde et al. (2017) have recently used the Frequency Ratio model for LHZ in the Malin area, Maharashtra.

The bi-variate statistical analysis is a quantitative approach to LHZ and gives more accurate results as compared to heuristic methods. However, the accuracy of LHZ maps derived from these methods is primarily influenced by the completeness of landslide data input.

Multivariate Statistical Methods

A multivariate statistical approach to LHZ involves the application of multivariate statistical techniques to determine ratings for sub-categories of each thematic layer based on their effect on landslide occurrence. Artificial Neural network (ANN), Multiple Regression analysis, Logistic Regression analysis, and Discriminant analysis are important methods applied for LHZ in India. Nagarajan et al. (2000) demonstrated the application of Discriminant analysis to map landslide susceptibility along the Mumbai-Goa Highway and claimed that this is the most appropriate approach to LHZ in the monsoon climate. Karlekar (2012) used Multiple Regression analysis for LHZ mapping in Raigad District, Maharashtra and emphasized the role of anthropogenic activities in landslide initiation.

Landslides are the results of several preparatory and triggering factors that are complexly interlinked in the Indian environment. Recent studies revealed that these complex non-linear relationships could effectively be modeled by using the Artificial Neural network (Prabhu and Ramakrishnan 2009; Chauhan et al. 2010) method. Application of the Logistic Regression (LR) model in LHZ helps in finding the best-suited model to describe the relationship between the presence or absence of landslides in the independent layer of landslide parameters (Ayalew and Yamagishi 2005). LR model has been applied for LHZ mapping in Garhwal Himalayas (Das 2011; Ghosh, 2011; Das et al. 2012; Onagh et al. 2012) with a high success rate. Support Vector Machine (SVM) has been applied for LHZ by Kumar et al. (2017) in Garhwal Himalayas. (Kumar et al. 2017) applied rainfall threshold analysis for assessment of landslides in Kashmir Himalayas.

Multivariate Statistic analysis is an objective approach to LHZ and is based on complex calculations. Therefore the results obtained from multivariate statistical models are more accurate as they are derived from a huge database. However, these models are difficult to apply in the data-scarce environment of India especially in the Western Ghats.

Probabilistic Approach

A probabilistic approach to LHZ considers a comparison of landslide explanatory (causative) variables to landslide distribution and assignment of weightage based on the degree of relationship within the probabilistic framework (Kanungo et al. 2009). Spatial, temporal and landslide size probability is determined through probabilistic landslide hazard assessment (Guzzetti et al. 2005). Some recent studies have been carried out using probabilistic models in Garhwal Himalayas (Martha et al. 2013), Nilgiri hills (Jaiswal et al. 2011; Sujatha et al. 2012; Jaiswal et al. 2010; Jaiswal et al. 2013), Himachal Pradesh (Chandel et al. 2011) and North East India (Ghosh et al. 2009; Ghosh et al. 2011; Sharma et al. 2009, Dikshit and Satyam, 2017). Although the probabilistic approach to LHZ is proved to be an objective method, some subjectivity enters the weight assignment process. The accuracy of the LHZ map produced using this method depends upon the completeness of landslide inventory.

Physically process-based models

Physically process-based landslide models involve the assessment of transient groundwater response of the slope to rainfall which mostly is an important trigger of landslides (Kuriokose 2010). Kuriokose (2010) claimed that the application of physically process-based models in LHZ is proved to be most appropriate especially in the data-scarce environment.

Analytic hierarchy Process

Landslide is a result of its complex relationship with the preparatory and triggering factors. Therefore, it is essential to determine weightage to the parameters based on the degree of relationships not only the relationship of landslide distribution with these factors but also within landslide affecting factors. Analytic Hierarchy Process (Saaty, 2008) is a multi-criteria decision-making process that provides the framework for objective LHZ through pair-wise comparison. This is a recently adopted approach to LHZ in India (Prabhu and Ramkrishnan 2009; Phukon et al. 2012; Mondal et al. 2012). Geographical Information System (GIS) based Analytic Hierarchy Process (AHP) became an effective tool for LHZ and other applications in recent times. However, defining the problem, determining the criteria, selecting of alternatives and ranking the parameters affect the reliability of the results.

The review of recent approaches to LHZ in India shows several approaches to LHZ including heuristic, statistical, probabilistic and Multi-criteria decision-making process, etc. are being used in different parts of India. However, there is no agreement among the researchers on which common method is suitable for the unique geo-environmental and climatic conditions in India. Although LHZ in India is done using several approaches, very little attention is given to validate and compare the results of these methods to determine the best-suited approach.

Landslide hazard investigations: site-specific analysis, geotechnical investigations

Event-specific landslide investigation provides a detailed description of landslide including geophysical properties of the area, landslide scar geometry, type of material and damage to natural and man-made structures through extensive fieldwork and satellite data (pre and post-event images) interpretations (Basu and De 2003; Thigale and Umrikar 2007; Singh and Champatiray 2009; Bodas and Kohli 2010; Singh and Singh. 2013; Anbalagan et al. 2013, Murali et al. 2016; Martha et al. 2016; Kumar et al. 2019). Geotechnical assessment of slopes involves assessment of geotechnical properties of slope and slope forming material (such as dip angle, fractures, the orientation of joints, joint spacing, wedge formation, etc.). In India, little attention is given to the assessment of geotechnical properties of slopes susceptible to failure (Kumar et al. 2010; Bobade et al. 2012; Kumar et al. 2017).

Landslide Risk Assessment

Landslide risk refers to the expected degree of loss (direct and indirect) to the natural and anthropogenic environment due to landslides (IAEG and Varnes 1984). Thus, landslide risk is a product of (R=H*V) Landslide Hazard (H) and the degree of loss (V=Vulnerability) to a given element at risk due to landslide (IAEG and Varnes 1984). Landslide Risk Assessment (LRA) is of immense importance in policy framing for cost-effective landslide hazard mitigation. A few studies on LRA recently carried out in Garhwal Himalayas (Champatiray et al. 2013; Martha et al. 2013), North East India (Kanungo et al. 2008), Nilgiri Hills (Jaiswal et al. 2010; Ganapathi et al. 2010; Jaiswal 2011) and parts of North Konkan in Maharashtra (Kumar et al. 2008; Pardeshi et al. 2009) have been reviewed.

Pardeshi et al. (2009) adopted the semi-quantitative method to assess landslide risk to people, communication route, vegetation and local geomorphology along Wad-Khodala road, Thane District, Maharashtra. Champatiray et al. (2013) assessed landslide risk to Yamunotri temple near Yamunotri shrine caused due to an increased built-up area using the interpretation of multi-temporal satellite images. Jaiswal et al. (2010) carried out quantitative LRA along transportation corridors in Nilgiri hills using the Gumbel distribution model and probabilistic (temporal and spatial) assessment. Martha et al. (2013) used semi-automatically created multi-temporal landslide inventories for LRA in Darjeeling Himalayas.

There is an increasing need for the application of the quantitative approach to landslide risk assessment using complete and detailed data input to increase the applicability of LRA in framing a policy for adopting suitable mitigation measures.

Consideration of Landslide causative factors

Several inherent (preparatory) and triggering (external) causative factors are responsible for slope failure (IAEG and Varnes 1984). Landslide preliminary factors involve inherent characteristics of the land surface (lithology, lineaments, slope morphometry, soil, vegetation cover, joints and fractures, tectonic setting, etc.) while the external parameters (triggering) include seismicity, rainfall, undercutting by streams and anthropogenic activities. The selection of appropriate thematic layers for landslide hazard assessment is a critical task.

The review of recent literature in India shows that slope morphometry, lithology, land use, land cover, drainage, and landslide distribution are commonly used in most of the landslide investigations in India. However, little emphasis is given to the role of neo-tectonics (Deshpande et al. 2009), seismicity (Saraf et al. 2009; Bodas and Kohli 2010; Champatiray et al. 2013), Weathering (Nagarajan et al. 2000; Sujatha et al. 2012) and Hydrological conditions (Bodas and Kohli 2010; Ghosh, 2011; Anbalagan et al. 2013) in the process of slope instability. This may be due to a lack of other supporting evidence of neo-tectonic activities.

Application of RS and GIS in Landslide Investigation

The advancement in Earth Observation (EO) techniques (Satellite Remote Sensing and Aerial Photography) has facilitated effective landslide detection, mapping, monitoring, hazard and risk assessment. In India, Satellite data products are used more frequently as compared to Aerial Photography. Moderate resolution satellite data such as IRS LISS II, IRS LISS III and LANDSAT have been frequently used for landslide investigations in India (Champatiray et al. 2007; Naithani 2007; Kanungo et al. 2008; Champatiray et al. 2009; Prabhu and Ramakrishnan 2009; Nithya and Prasanna 2010; Phukon et al. 2012). High resolution satellite data (e.g. CARTOSAT 1, RESOURCESAT, SPOT; IRS LISS IV, QuickBird) have recently been used for landslide studies in India (Champatiray et al. 2009; Saraf et al. 2009, Sharma et al. 2009; Chauhan 2010; Das 2011; Das et al. 2012; Lalliathanga et al. 2013; Wagh and Deshpande 2013; Champatiray et al. 2013).

Digital Elevation Model (DEM) has wide applications in landslide studies especially in the extraction of thematic layers (such as slope, aspect, curvature, drainage, etc.), pre and post-event landslide investigations and landslide detection. In India, DEM extracted from topographical maps (Topo DEM) and also used from SRTM and ASTER GDEM are used in several studies (Deshpande et al. 2009; Sarkar et al. 2004; Sharma et al. 2009; Saraf et al. 2009; Chandel et al. 2011; Rawat et al. 2012; Onagh et al. 2012; Balsubramani and Kumarswamy 2013). A brief review of the application of RS data in landslide studies in India reveals its importance in accurate and reliable landslide hazard assessment. However, an extensive field check is also essential to validate the information extracted from remotely sensed data.

Conclusion

The review carried out in this article is not comprehensive. However, this review of the recent studies on landslide hazards in India reveals that the availability of a complete landslide database is a prerequisite for reliable and accurate landslide hazard assessment. Unfortunately, very little effort are made to frame and maintain the landslide inventory system by concerned government authorities and departments. Moreover, there is no uniformity in landslide inventory formats in India which leads to difficulty in tabulating and analyzing landslide data for further investigations. The review of approaches to landslide hazard zonation in India indicates that there is a trend from the conventional heuristic and bi-variate approach to multivariate and probabilistic methods for delineating potential areas susceptible to landslides. However, multi-criteria decision making and rainfall threshold models are proved to be of high predicting power in landslide hazard zonation. Very few studies have been reported using these models in the Indian context.

Landslide risk assessment in India is limited to a qualitative evaluation of 'elements at landslide risk' whereas the very little emphasis is given on quantification of risk caused by landslides. Most of the studies indicate the inherent properties of the land surface (lithology, geomorphology, soil, vegetation, etc.) as well as triggering factors (rainfall, seismicity, tectonic activities, etc.). A significant variation is observed in terms of triggering factors considered for landslide hazard zonation in India. In the Himalayan region, seismicity, neo-tectonics, and rainfall are considered for LHZ whereas rainfall amount and intensity are considered as the important trigger for the slope instability process in the Western Ghats.

Application of high-resolution satellite and elevation data in landslide hazard assessment is the important feature of recent landslide investigations in India. Hence, it can be concluded that landslide hazard assessment in India is undergoing significant developments in recent times regarding landslide inventory systems, methods of landslide hazard zonation, quality of data input and consideration of input parameters. However, still, there is a need for the application of quantitative techniques in landslide hazard assessment for a more accurate and reliable estimation of potential slope failure areas. There is a need to develop an all-inclusive and standard landslide hazard inventory. It is also essential to archive the database of previous studies. Heuristic and bivariate methods of landslide hazard assessment are most commonly used in India. However, due to lack of detailed landslide database, there are limitations in the application of multivariate statistical methods which have high predictability. Since geo-environmental conditions in different parts of the country vary significantly; it is also required to evaluate the applicability of combination of different methods of landslide hazard assessment of landslide hazard assessment for accurate mapping of landslide hazards in different geo-environmental settings.

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