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Seismic Slope Instability Assessment using RS and GIS Techniques: A Case study from Garhwal Himalaya

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Abstract

In the present study an attempt has been made to derive information on causative parameters and preparation of seismic slope instability assessment map using Newmark's method in the seismically active zone around Uttarkashi area of Garhwal Himalaya. Predicting where and in what shaking conditions earthquakes are likely to trigger landslides is a key element in regional Seismic Slope Instability Assessment. Spatial data sets such as lithology, slope gradient, strong-motion records of the main shock and aftershock, 1:25,000-scale geological map of the region, geotechnical properties such as cohesion, friction, unit weight and seismic parameters were integrated using Newmark's method. All of these data sets have been digitized and rasterized at 20-m grid in the ARC GIS environment. Combining these data sets in a dynamic model based on Newmark's permanent-deformation (sliding-block) analysis yields estimates of coseismic landslide displacement in each grid cell from the Uttarkashi earthquake. The modeled displacements are then compared with the inventory of landslides triggered by the Uttarkashi earthquake to compare with the result of analysis. The result shows around 72.89% of known landslides including the Uttarkashi landslide is in the unstable slope condition. The seismic data and the role of seismic activity were also analyzed for initiation of landslide. Final result anticipate that this seismic slope instability maps used for to assist in emergency preparedness planning and in making decisions regarding development activity such as construction of hydro power project and other development activity in areas susceptible to seismic slope failure. The results showed that using Newmark's method to model the dynamic behavior of landslides on natural slopes yields reasonable and useful results.

Introduction

The entire Himalayan region is a part of the active seismic zone, thus being prone to frequent earthquakes. The Uttarkashi and Chamoli earthquakes have caused widespread devastation, claiming large scale destruction of human lives and materials, affecting people for their lives. Uttarakhand being a part of this active prone zone, is not only prone to severe earthquakes, but also to other natural calamities like landslides, flash floods, cloudbursts etc. Largest Instrumented Earthquake in Uttarakhand is 19 October 1991 – Uttarkashi earthquake (30.77°N-78.79°E), Mw 6.8, D=015.0 kms, when 768 people were killed and nearly 5000 injured in this earthquake in Uttarkashi district and some 18000 buildings were destroyed in the Uttarkashi-Chamoli region. Landslides are one of the most damaging collateral hazards associated with earthquakes. Seismically triggered landslides damage and destroy homes and other structures, block roads and streams. Landslides and rockfalls were widespread in the Garhwal Himalaya.

In recent year, regional and medium scale seismic slope instability assessment have become an important topic of interest for specialist of different discipline such as engineering geologist, planner, administration and decision makers. This situation can be considered as a consequence of increases in the interference of earthquake induced

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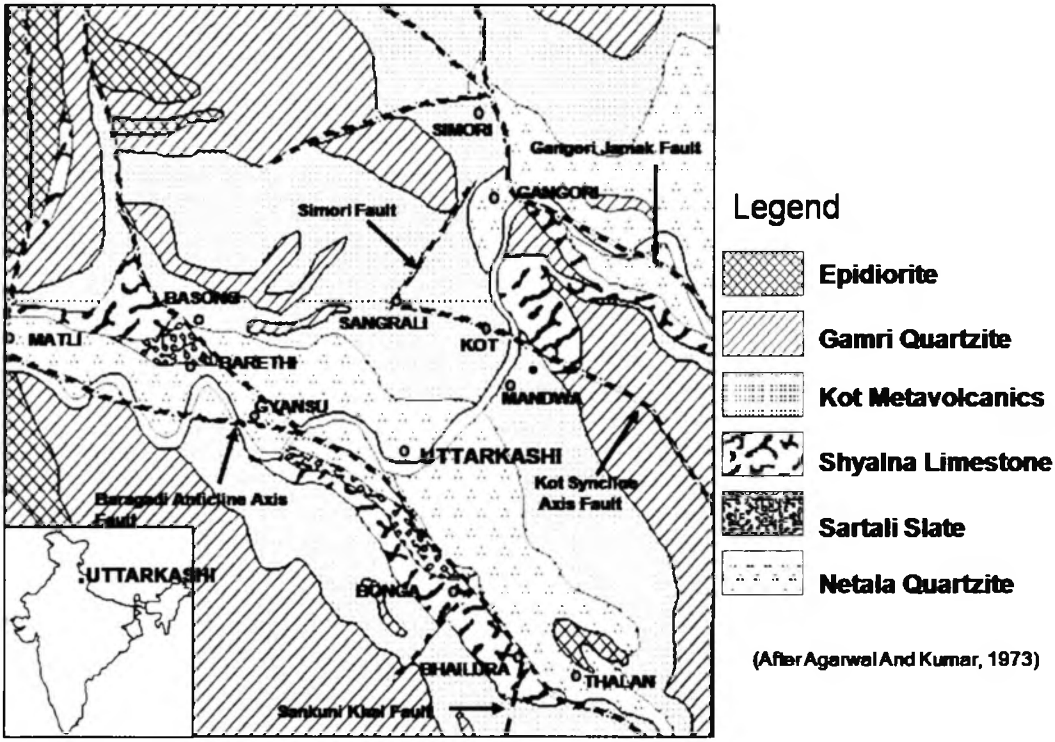

Fig.1: Geological map of the study area

landslides with occurrences with urbanization, engineering activities and other socioeconomic activities in seismic prone area. In this respect production of seismic slope instability map at early stage of the seismic assessment has a crucial importance for safe and economic planning, such as urban activity and engineering structure particularly.

Factors contributing to slope failure at a specific site are generally complex and difficult to assess; therefore, regional analysis of a large group of landslides triggered by earthquake is useful in estimating general conditions related to failure. The 1991 Uttarkashi earthquake presents the ideal case for such an analysis. In present study Newmark (1965) method is apply to map the spatial distribution of probabilities of seismic slope failure in any set of shaking conditions. The method is calibrated using data from the 1991 Uttarkashi earthquake. For the preparation of seismic slope instability map of the region, a detailed geology map (Fig. 1) and landslide inventory map on 1:25,000 scale of the study area were prepared by means of extensive filed survey and available literature and using Satellite image (Fig. 2) and Remote Sensing techniques.

Regional setting

The study area is located 155 km from Rishikesh in the Uttarkashi district of Garhwal Himalaya covered between Latitude 30°41'13.54"N to 30°47'58.38"N and Longitude 78°22' 47.55"E to 78°33'12.50"E and covers approximately 1260 sq km. The terrain and climate of the area provide uncongenial physical environment for human settlement. Physiographically it may be divided into three main parts viz. the mountains and ridges, the sub-mountainous and the valleys. This area has shows a mature topography, which has undergone rejuvenation resulting in a combination of highly dissected topography

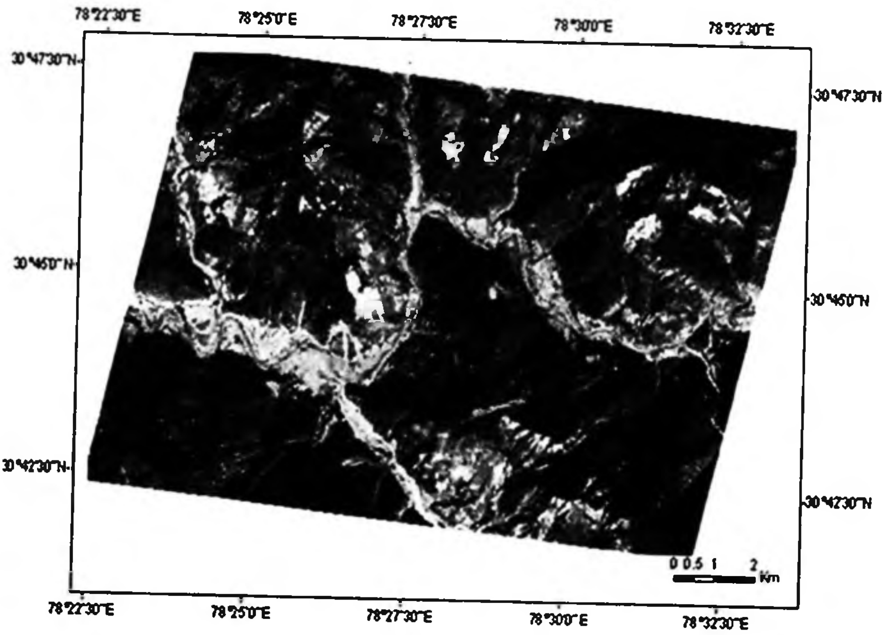

Fig. 2: Satellite image of the study area

with valleys showing vertical walls and scarps in the lower parts and gently sloping concave hill tops in the upper wider parts. It consists of succession of steep mountain ridges ranging from 1100 upto 5000 mts divided from each other by deep valleys which are narrow and precipitous. The inclination of slopes ranges from 0° to 70° and has an average value of 45°. The slope aspects are generally towards the N-S direction. The landuse characteristic changes with respect to elevations and slope conditions. Elevation wise the higher reaches are covered by snow, then the meadows part and at lower elevation the area is covered with oak, pine and cedar forest. Agricultural practices are generally has been carried out in valleys area, at lower elevation. River Bhagirathi and its tributaries not only carried away the weathering products but also erode the toe of the slopes belonging to weak zone through which they flows. The drainage pattern of the area is dendritic type, controlled by the slope aspect and the characteristics of Litho unite and joints patters, which are different in different litho units.

Geology

Geologically the area has been categorized into four unit viz. the Central Crystallines, Martoli Formation, Dudatoli group and Garhwal group, separated from each other by major faults/thrusts. The 'North Almora Thrust' (NAT) and the 'Main Central Thrust' (MCT) separates the Garhwal group from the Dudatoli group in the southwest and from Central Crystallines in the northeast respectively (Saklani, 1972; Agarwal and Kumar, 1973). The Garhwal group is divided into three distinct formations viz. the Uttarkashi, Shyalana and Nagni Thank, which occurs in normal stratigraphic order in the study area. The Uttarkashi Formation includes Netala quartzite, Lower Uttarkashi limestone, Pokhri slate, Upper Uttarkashi Limestone and Bareti Quartzite. The rocks found in the landslide-affected area of Varunavat Parvat comprise thinly bedded quartzites and phyllites which are highly weathered, jointed and fractured. The beds are dipping at 15°–30° towards N35° i.e. inside the hill slope. The rocks of the area have been subjected to at least two tectonic episodes. The NW-SE trending doubly plunging folds, such as Baragadi and Netala anticline and Kot and Punjargaon synclines developed during the first tectonic movements. The axial plane fault such as the Baragadi and Gangori-Jamak faults were developed during the later part of this episode. These folds and faults were refolded into broad NNE-SSW to NE-SW trending folds during the second tectonic phase (Jain, 1971, 1972; Saklani, 1970). MCT is passing through the Sainj, on the northern side of Uttarkashi. Presence of several thrusts and faults indicating that this area have subjected to several tectonic movements. This area is seismotectonically very active and come under the category of seismic zone -V. The MCT zone has witnessed two major earthquakes since 1991. The epicentre of the 1991 Uttarkashi earthquake was in the vicinity of Uttarkashi town.

Seismicity and seismic hazard

Seismotectonically the Uttarakhand area is located in Main Himalayan Seismic Zone demarcated by Main Boundary Thrust (MBT) in South and down dip influence zone of the Main Central Thrust (MCT) in north, demonstrating predominantly thrust type of fault plane mechanism. It has been interpreted by Narula et.al. (1992, 1995) that the strain buildup in different sectors of this domain is taking place at different locales and in Uttarkashi-Chamoli sector, this is concentrated around the MCT as evidenced by the clustering of the seismic events in this subdomain to be around this structural dislocation. As per the Bureau of Indian Standard map (1984) the Uttrakhand state as a whole come under the category of seismic zone IV and Uttarkashi district falls under Zone V. In 1999, the Global Seismic Hazard Assessment Programme (GSHAP) published a map, displaying areas that could expect to have Peak Ground Acceleration (PGA) with 10% probability of exceedence in 50 years. According to this map the entire state of Uttarakhand could expect maximum PGA values in excess of 0.2g. During the last decade two strong earthquakes occurred in the Garhwal Himalaya, namely the 1991 Uttarkashi earthquake, Mw 6.8 (Khattri et al., 1994) and the 1999 Chamoli earthquake, Mw 6.6 (Kayal et. al., 2002, Narula et.al. 2000). The intense aftershock activity after the mainshock implies that the earthquake can influence the seismicity of adjoining region by modifying static stress field. Locations of aftershocks were recorded and the damage pattern suggested that the zone of activity was in the vicinity of Uttarkashi district. This region also showed a maximum intensity of VIII on MSK scale. USGS estimate of the focal depth was 12 km. The earthquake was followed by intense aftershock activity; this included at least 3 events of M >5. Most of the aftershocks were located to the south of Uttarkashi. The fault-plane solution obtained from the USGS indicates a pure thrust mechanism with two nodal planes striking at 332° and 19°. The Uttarkashi earthquake was accompanied by severe ground deformations. Development of ground fissures, landslides and changes in the groundwater flow were reported from several locations. The earthquake also caused changes in ground water regime of the affected area as evidenced by drying out of some springs and increase of discharge in others.

Climatic conditions

70 to 80 percent of the rainfall occurs from June to September and the annual precipitation is about 1000 to 1500 mm. The effectiveness of the rain is among others, related to low temperature which means less evapo-transpiration and less forest or vegetation cover. However, the effectiveness is neither uniform nor even positive in areas where either the vegetational cover is poor or / and has steep slops or the soils have been so denuded that their moisture absorption capacity has become marginal. January is the coldest month after which the temperature begins to rise till June or July. During the winter cold waves in the wake of western disturbances cause the temperature to fall rapidly and this is the time for snow

accumulation on the higher reaches and in the valleys at higher elevation. The temperature record from the meteorological observatories in the district shows that the highest temperature was 35°C and lowest was 0°C, which varies with elevation. The recorded mean maximum and minimum temperatures during the warmest month was 27^0 C and 02^0 C at an altitude of 2000 m and 09^0C and -12^0 C at height of >5000m a.m.s.l. The highest percentage of humidity recorded was 94 and lowest was 32. The average relative humidity is more than 80 percent during monsoon season and in pre-monsoon time humidity drop to 35%. During winter months humidity increases at the afternoon time at certain higher elevations.

Landslides

1991 Uttarkashi earthquake caused damage to built environment and triggered many new landslides and reactivated old ones, developed ground fissures and rock falls in the epicentral areas. Rock fall and debris slide were more prominent as compared to the debris falls, reactivation of existing slides, undermining and road subsidence. Apart from the slope failures numerous ground fractures aligned in NW-SE, N-S and E-W direction along the hill slope were other prominent features which further contributed to the hill slope instability in the region (Narula et.al., 1992). Most of slides were reported along Bhagirathi valley and between Chinayalisaur and Uttarkashi, near Matli two huge landslides were reported. On the Uttarkashi - Gangotri national highway number of rocks and debris slides were reported during field investigation. Most of the rock slides were confined along the MCT zone and numbers of slumping sites were noticed from Gangnani to Gangorti. Cracks were observed in the mountain slopes in the vicinity of Agora, Sangralli and Jamak villages. These cracks in the hill slopes increased the chances of major landslides in future and made some villages situated at the foot of such slopes unsafe.

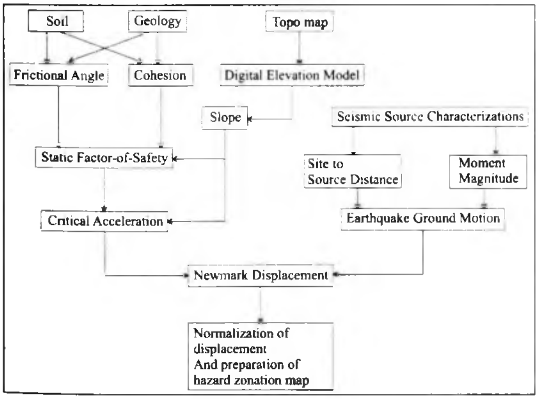

Fig. 3: Flowchart showing the sequential steps involved in instability mapping procedure

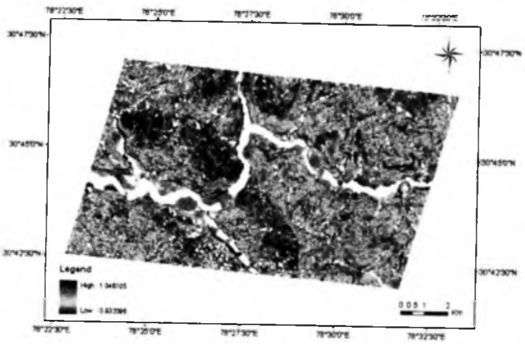

Fig. 4: Critical (Yield) Acceleration map of the study area

Methodology for computing factor of safety and critical acceleration and estimation of Newmark displacement

In present study Newmark method (1965) model used for the dynamic performance of slopes using the permanent-displacement analysis. Wilson and Keefer (1983) showed that using Newmark's method to model the dynamic behavior of landslides on natural slopes yields reasonable and useful results. Wieczorek et.al. (1985) subsequently produced an experimental map showing seismic landslide susceptibility in San Mateo County, California, using classification criteria based on Newmark's method. Wilson and Keefer (1985) also used Newmark's method as a basis for a broad regional assessment of seismic slope stability in the Los Angeles, California, area.

Newmark (1965) noted that the transient motions of an earthquake may lead to deformation of a slope prior to complete failure. In Newmark analysis models a potential landslide function as a rigid friction-block sliding on an inclined plane. The block has a known critical (or yield) acceleration (a_c), which is simply the threshold base acceleration required to overcome basal shear resistance and initiate sliding. The analysis calculates the cumulative permanent displacement of the block relative to its base as it is subjected to the effects of an earthquake acceleration-time history. This is done by double-integrating those parts of the earthquake time-history that exceed the critical acceleration (Wilson and Keefer, 1983). Thus, conducting a conventional Newmark analysis requires selection of an appropriate earthquake record and determination of the critical acceleration of the selected slope.

The data sets for the analysis includes Spatial data sets such as lithology, slope gradient, strong-motion records of the main shock and aftershock, 1:25,000-scale geological map of the region, geotechnical properties such as cohesion, friction, unit weight and seismic parameters were integrated. All of these data sets have been digitized and rasterized at 20-m grid in the ARC GIS environment. Combining these data sets in a dynamic model based on Newmark's permanent-deformation (sliding-block) analysis yields estimates of coseismic landslide displacement in each grid cell from the Uttarkashi earthquake. Fig. 3 is a flowchart showing the steps involved in the instability-mapping procedure. The displacement map is then compared with the inventory of landslides triggered by the Uttarkashi earthquake to compare with the result of analysis.

The first step in the analysis is to determine the critical or yield acceleration of the potential landslide. One way to do this is to use pseudostatic analysis, where critical acceleration is determined by relatively employing different permanent horizontal earthquake accelerations in a static limit-equilibrium analysis until a factor of safety of 1.0 is achieved. Newmark (1965) simplified this approach by showing that the critical acceleration of a potential landslide is a simple function of the static factor of safety and the landslide geometry; it can be expressed as:

$$a_c = (FS - 1)g \sin\alpha \text{ ———— } 1$$

where a_c is the critical acceleration in terms of g, the acceleration due to Earth's gravity; FS is the static factor of safety and α is the angle (herein called the thrust angle) from the horizontal that the center of mass of the potential landslide block first moves. Thus, determining the critical acceleration by this method requires knowing the static factor of safety and the thrust angle, which is typically approximated by the slope angle. Therefore, producing a critical-acceleration grid (Fig. 4) is a simple matter of using equation 1 to combine the slope angle with the calculated factors of safety. Within the context of the Newmark-displacement analysis, critical (or yield) acceleration uniquely describes the dynamic stability of a slope. For a given shaking level, any two slopes that have the same critical acceleration will yield the same Newmark displacement, regardless of how those slopes might differ in geometry or material properties. The critical-acceleration map portrays a measure of intrinsic slope properties independent of any ground-shaking scenario; thus, it is a map of 'seismic landslide susceptibility'.

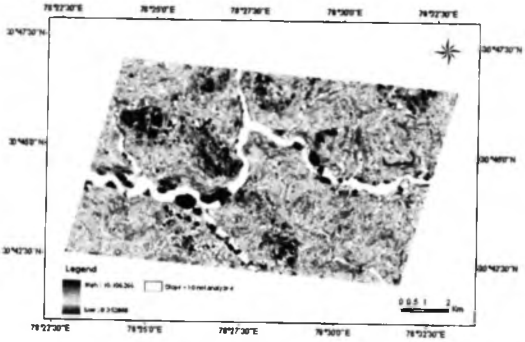

Fig. 5: Static factor-of-safety map of the study area

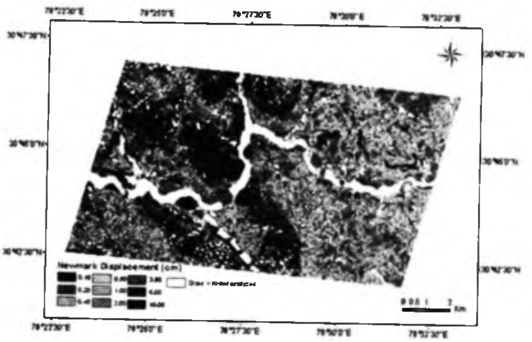

Fig. 6: Map showing predicted Newmark displacement in Uttarkashi area

The result of stability calculations, suitable to introduce an expectation value, is the 'factor-of-safety' (FS). As noted by Newmark (1965), modeling dynamic slope response requires undrained or total shear-strength parameters. During earthquakes, slope materials behave in an undrained manner because excess pore pressures induced by dynamic deformation of the soil column cannot dissipate during the brief duration of the shaking. Undrained strength also is called total strength because the contributions of friction, cohesion, and pore pressure are not differentiated, and the total strength is expressed as a single quantity. The factor of safety can be determined using any appropriate method that uses undrained or total shear strength. In materials whose drained and undrained behaviors are similar, drained or effective shear strengths can be used if undrained strengths are unavailable or difficult to measure. This allows great flexibility for users. For a rough estimate of displacement, a simple factor-of-safety analysis, perhaps of an infinite slope using estimated shear strength could be used. On the other end of the spectrum, a highly detailed site study could be conducted to determine the factor of safety very accurately. Clearly, the accuracy of the safety factor, and the resulting predicted displacement, depends on the quality of the data and analysis, but the user determines what is appropriate. Mass movements under influences of gravity occur as a result of diverse disturbing and destabilizing processes, for example of climatic or anthropological origin. The stability of slopes is determined by the geometry of surfaces and slip-horizons. Contributions are supplied by the pore water pressure, cohesion and friction. All this relevant factors will be integrated in a slope stability model, by measurement, estimations or derived from physical equations. The dynamic stability of a slope, in the context of Newmark's method, is related to its static stability therefore, the static factor of safety for each grid cell must be determined. For purpose of regional analysis, we use a relatively simple limit – equilibrium model of an infinite slope in material having both frictional and cohesive strength. The static factor of safety (FS) in these conditions is:

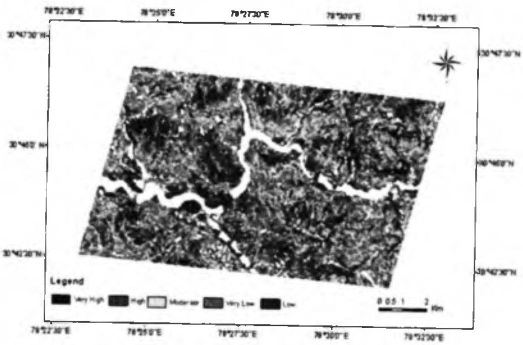

Fig. 7: Seismic slope instability map of the study area

Where is the effective friction angle is the effective cohesion. a is the slope angle of the material, unit weight is the weight of water, t is the slope-normal thickness of the failure slab and m is the proportion of the slab thickness that is saturated. The equation is written so that the first term on the right side accounts for the cohesive component of the strength, the second term accounts for the frictional component, and the third term accounts for the reduction in frictional strength due to pore pressure. In the conditions modeled for this calibration, no pore-water pressure is included (m=0) because it is assumed that almost all of the failures in the Uttarkashi earthquake occurred in dry conditions; thus, the third term drops from the equation. The factor of safety, then, is calculated by inserting values from friction, cohesion, and slope-angle grids into the above equation. Fig. 5 shows a part of the factor-of-safety map resulting from combining these data layers in above equation. The factor-of-safety ranges from 0.35 to 10.10.

To avoid the computational complexity and difficulties of selecting an appropriate earthquake time-history associated with a conventional Newmark analysis, several simplified models for estimating Newmark displacements (Dn) have been developed (Luzi and Pergalani, 1996; Jibson et.al., 1998; Jibson, 1993). A rigorous Newmark analysis is conducted by double integrating the parts of a specific strong-motion record that exceed the critical acceleration. To facilitate using Newmark's method in regional analysis, Jibson (1993) developed a simplified Newmark method wherein an empirical regression equation is used to estimate Newmark displacement as a function of shaking intensity and critical acceleration. We then conducted a Newmark analysis for several values of critical acceleration, ranging from 0.02 g to 0.40g. The resulting Newmark displacements were then regressed on two predictor variables: critical acceleration and Arias intensity. The resulting regression equation is:

$$\text{Log Dn}=1.521 \log \text{Ia}-1.993 \text{ Log ac}-1.546 \quad \text{——} 3$$

where Dn is Newmark displacement in centimeters, Ia is Arias intensity in meters per second, and a_c is critical acceleration in g's. Newmark displacements from the Uttarkashi earthquake were estimated in each grid cell by using equation 3 to combine corresponding grid values of critical acceleration and Arias intensity (Fig. 6). Predicted displacements values range from 0.1 to 10 cm. If we compare the inventory of landslides triggered by the Uttarkashi earthquake with the modeled displacements, it shows that around 72.89 percent of known landslides are in the unstable slope condition. The final seismic slope instability map was prepared and classified into very high, high, moderate, low and very low hazard categories (Fig. 7).

Discussions and Conclusions

Prediction of earthquake triggered landslide displacements is crucial for the design of engineered slopes, seismic hazard analysis and many other applications such as paleoseismic analysis. Analysis of data from Uttarkashi earthquake allows quantitative physical modeling of conditions leading to coseismic slope failure. The distribution of landslides triggered by the Uttarkashi earthquake was used for calibration and validation of the modeling procedure. Newmark's method is useful for characterizing seismic slope response. It presents a viable compromise between simplistic pseudo static analysis and sophisticated finite-element modeling, and it can be applied to a variety of problems in seismic slope stability. The simplified method presented here provides an easy way to estimate ranges of possible displacement in cases where the seismic shaking intensity is known. An attempt is made here to determine the most appropriate Newmark's block-on- plane model to be used in estimating the earthquake –induced displacements. Nearly all of the variability in failure probability occurs in the first few centimeters of displacements greater than about 05 to 10 cm. This is perhaps attributable to the fact that the vast majority of landslides in the database were shallow, disrupted rock falls (mainly in Quartzite) and rock slides, weakly cemented material that fail at relatively small displacements. Even considering all of the caveats and limitations discussed, this analytical mapping procedure provides a simple, systematic, physically based method to estimate seismic slope-failure probability. The linkage of Newmark displacement to a discrete failure probability is an enormously useful tool that will give Newmark's well established method of analysis for more practical utility. Predicted Newmark displacements do not necessarily correspond directly to measurable slope movements in the field; rather, modeled displacements provide an index to correlate with field performance. For the Newmark method to be useful in a predictive sense, modeled displacements must be quantitatively correlated with field performance. In short, do larger predicted displacements relate to greater incidence of slope failure? Comparison of the predicted Newmark displacements with the actually inventory of landslides triggered by the Uttarkashi earthquake allows us to answer the question. It would be better to have actual angle of friction, on site cohesion and unit weight for different rock types present. At many places, unconsolidated sediments are not considered due to lack of information on their thickness, which should be incorporated as these are very vulnerable. It has been observed in Uttarkashi that agricultural land is mainly associated/ spreading with south and south east facing slopes because these slopes are sun facing and good for terrace farming, whereas forest/afforested parts are mainly situated on west and north-west slopes. Perhaps such selective land use practices have played an important role in the case of the Uttarkashi earthquake induced landslides and their specific orientation. The role Main Central Thrust (MCT) and its orientation with reference to the Uttarkashi earthquake induced landslides is being studied by several workers. The cause of this earthquake is a low dipping thrust fault trending NW- SE. Geological structure and lineament mapping is considered as a very important issue in problem solving in engineering, especially, in site selection for construction (dams, bridges, roads etc), seismic landslide risk assessment, hot spring detection etc. In image processing, edge detection treats the localization of significant variations of a gray level image and the identification of the physical and geometrical properties of objects of the scene. The variations in the gray level image commonly include discontinuities (step edges), local extreme (line edges) and junctions. The enhancement of geological line segments with the use of linear and non-linear spatial filters, such as directional gradients, Laplacian filters and the Sobel and Prewitt operators as well as morphological filters. Any idealized model is limited by its simplifying assumptions. The fundamental assumption of Newmark's model is that landslides behave as rigid-plastic materials i.e. no displacement occurs below the critical acceleration, and displacement occurs at constant shearing resistance when the critical acceleration is exceeded. This assumption is reasonable for some types of landslides in some types of materials, but it certainly does not apply universally. Many slopes materials are at least slightly sensitive - they lose some of their peak undrained shear strength as a function of strain. In such a case, Newmark's method would underestimate the actual displacement because; the strength loss during shear would reduce the critical acceleration as displacement occurs. For such materials, the Newmark displacement might be considered a minimum displacement. Some highly plastic, fine-grained soils behave as visco-plastic rather than rigid – plastic materials. The viscous response of these soils results in part from low permeability and high cohesion, and the result can be radically dampened seismic response. Some active, slow moving landslides having factors of safety at or below 1.0 have experienced negligible inertial displacement even during large earthquakes because of viscous energy dissipation. In Newmark's method, displacement depends on the critical acceleration, which, in turn, depends on the static factor-of-safety. Therefore, a landslide at or very near static equilibrium should have a very low critical acceleration (theoretically, $a_c = 0$ if FS =1) and thus should undergo large inertial displacements in virtually any earthquake. Thus, Newmark's method probably overestimates landslide displacements in visco-plastic materials. Generally, Newmark's method has considered static and dynamic shear strength to be the same and has ignored dynamic pore-pressure response; this has permitted use of static shear strengths, which are much more easily determined than dynamic strengths. For many soils, this assumption introduces little error, but static and dynamic strengths differ significantly for some soils. In such cases, dynamic shear testing may be required, or static strengths can be adjusted by an empirical correction factor. Similarly, dynamic pore-pressure response, if considered significant, can be measured in dynamic tests or accounted for empirically by reducing the static shear strength. The GIS based implementation make large numbers of analysis almost trivial, and so the best approach for judging the likely performance of a slope is to select a large number of earthquake records, perhaps 10-50, that have a reasonable range of properties of interest and to then interpret the range of output displacements. Experience indicates that the results tend to be log-normally distributed, with a few records yielding very high displacement forming the right-hand tail of the distribution. Thus, mean displacement a virtually always greater than median displacement, and standard deviation are fairly high.

Newmark's method is useful for characterizing seismic slope response. It presents a viable compromise between simplistic pseudo static analysis and sophisticated finite element modeling, and it can be applied to a variety of problems in seismic slope stability. The simplified method presented here provides an easy way to estimate ranges of possible displacement in cases where the seismic shaking intensity can be estimated. Probability of failure can also be estimated in certain situation on the basis of a model calibrated using data from the Uttarkashi earthquake.

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