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SYNOPSIS: Ground failures in rugged terrain with more that 10,000ft (3000m) elevation above mean sea level in the epicentral tract of 19 January 1975 Kinnaur earthquake in Himachal Pradesh, India, indicate that most of the earthquake generated landslides occur in surficial cover. The collapse of such material on steep slopes often result in cascading rock avalanches obliterating roads and other constructions lying on its way. The accumulated debris during this earthquake dammed Parachu river creating a reservoir behind it. The dislodging, overturning and uplift of boulders on hill tops and scabing and slabing of rocks along joints and other weak zones resulting in loosening, dilation and crumbling of frozen formations indicate that seismic waves incident on rock slope surface and near ground discontinuity surfaces filled with frozen ice on reflection as tensile stress waves shattered the ground. The study indicates the significance and desirability of detailed study of surficial cover on rock slopes in mountainous terrains for evaluation of stability of hill sides during earthquakes. In high altitude frozen ground and rock slopes, seismic stress waves play a significant role in shattering near surface rock mass.

INTRODUCTION

An earthquake, causing severe ground motion in parts of Kinnaur and Lahaul-Spiti districts of Himachal Pradesh in Indian Himalayan Orogenic belt and Tibetan Plateau border region, occurred on January 19, 1975. Preliminary estimates of magnitude and focal depth of the main shock from macroseismic data indicated the magnitude 6.7 and depth 25 km (Singh et al, 1975). The parameters of this event as reported by National Earthquake Information Service of USA are: origin time-08 h 02 m 02.55 (UTC), epicentre-32.45°N; 87.43°E, focal depth-normal, and magnitude-6.8. Figure 1 shows isoseismals of the earthquake in Himachal Pradesh (Singh et al, 1977). In addition to loss of life and damage to various constructions during this earthquake, extensive landslides, rock falls and avalanches in the snow bound and frozen ground in the rugged terrain of the area with more than 10,000ft (3000m) elevation above mean sea level, caused considerable damage to roads and structures. Fissures were developed in the ground. Greater damage to the ground and buildings was noted in north-south trending zone following Parachu and Spiti river valleys and the alignment of major fissures along this zone (Fig. 2) suggest genetic relation with a probable tectonic lineament named as Kaurik-Chango fault by Singh et al (1977). The earthquake provided an apportunity to observe rock slope failures in high altitude mountainous area and study their probable mechanisms.

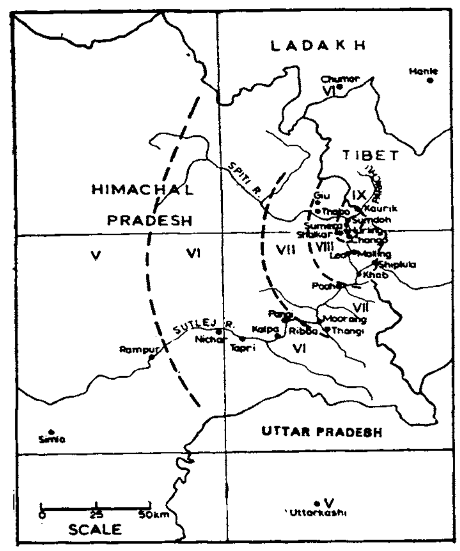

Fig. 1. Isoseismals (MM intensity) of 19 January 1975 Kinnaur Earthquake.

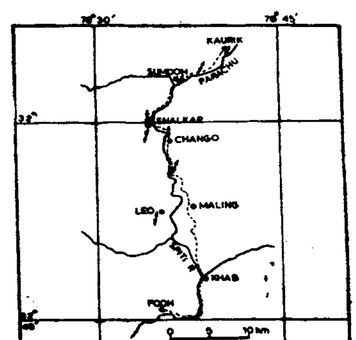

Fig. 2. General trend of ground fissures in area affected by 1975 Kinnaur earthquakes.

ROCK SLOPE STABILITY

Rock slopes with critical stability, when subjected to strong ground motion, can undergo irreversible displacements, which initiate movements leading to catastrophic landslides and slips. The rock mass movement during earthquakes depend on combination of factors governed by the properties and the structure of insitu rock mass and overlying surficial material, inclination and height of the slope, geohydrological conditions, climate and the stage of operative surface geological processes of erosion and denudation affecting their stability. Investigations for rock slope stability evaluation are directed to workout the general geological conditions with reference to spacial distribution of different rock formations and rock defects, assessment of their strength and deformation characteristics, monitoring of their behaviour in the prevailing geomorphological, geological and geohydrological environment, prediction of probable changes in physical and engineering properties as well as induced stress (pressure) conditions in the rock mass during earthquakes and extreme hydrometeorological conditions and workout the failure mechanism.

The geomechanical process leading to sudden failure o f a rock slope consist of separation of volume of rock mass from the bulk of the relatively stable rock, and its outward and downward movement from the hillside. The separated mass may consist of intact rock or slowly (creep) deformed, ruptured, fragmented or dilated rockmass, or overlying sedimentary, glacial or weathered rock cover. Based on the topographic situation, in addition to sliding on the surface of separation (failure) the detatched rock volume may undergo free fall, collapse, tumble down with leaps and bounces, run down slope or form a cascading avalanche. The causative mechanisms, resulting in loss of strength or development of stress to produce rupture and sliding (and or detatchment) of rock mass or tilting, overturning and movement of rock fragments, during earthquakes are effects of reflection and transmission of propagating seismic stress wave at major discontinuities separating intact rock from relatively loose rock mass, alluvial and glacial material or weathered rock cover (or rock-air boundery), and inertia forces induced in the rock mass volume on excitation through interaction of predominant periods of strong ground motion. It is difficult to account for all the possible factors due to scanty geological and geotechnical information. In many cases it is not possible to decipher all the parameters and to reach definite conclusions as the results of geognostic investigations are often open to various interpretations. Thus relative influence of various parameters can be considered in landslide studies. A geologists intuition and an engineering judgment is required in assessment of the probable kinematics of landslides in prevalent geological situations.

Study of stability of various segments of hillsides with high peaks and deep valleys, has to take into account the overall behaviour of the slopes from the top of the mountain to the valley base, as the operative static (and dynamic) forces differ at various elevations. In the upper reaches there is general splitting and loosening of rock along joints and other discontinuity surfaces during extreme climate, without any significant deformation and alteration of rock material. The loosened rock fragments cover the intact rock mass and in high attitude areas such material descend downwards with snow due to gravitational creep, avalanches, high velocity winds or snow storms forming bare rock peaks. The rock scree thus gradually thickens down slope and gets integrated with glacial and glacio-fluvial deposits in the valleys. In the lower parts of the slopes the rock below the scree and talus material and other surficial deposits, remain tightly wedged along discontinuity surfaces. However lateral strain under the vertical load of the mountain range results in outward movement of the rock mass. On being pushed out the rock mass undergoes dilation forming a loose stack of rock units (wedges) bounded by relief joints and openings. Thus even if the hillside is stable, in course of time rock mass may be pushed out to slide or tumble down, along with its overlying surface cover, if any. On exposure to earthquake hill side segments from the valley base to the top would undergo different movements resulting from effects of propagating stress wave and inertia forces induced in the rock mass due to variations in ground motion and characteristic impedence.

WAVE PROPAGATION

The force acting in the rockmass changes rapidly during stress wave propagation and the pressure acting for the particular duration of time at a point creates stress. For a one dimensional propagation in rockmass 'A' the force in the incident wave (P_i) on the interface with another rockmass B, the force in the transmitted wave (P_t) in rockmass B and force in the reflected wave (P_r) in rock mass A can be evaluated from the following relation (Coats, 1987).

$$P_t = 2\,P_i/(1+n) \qquad (1a)$$

$$P_r = P_i\,(1-n)/(1+n) \qquad (1b)$$

where $n = (p_A\ E_A/p_B\ E_B)^{1/2}$ or $(m_A\ K_A/m_B\ K_B)^{1/2}$, p is density and E is modulus of elesticity (m is mass per unit volume or length and k is stiffness) of rockmass A and B. Due to difference in wave velocity in the two rock masses the wave length of the incident and reflected waves are same. However the wave length of the transmitted wave is different. From equation (1) it is noted that when ratio n is greater than 1 wave will be tensile. The transmitted wave will always be compressive. When n is less than 1 the reflected wave will be compressive. When n equals infinity (rock-air boundary) the reflected wave equals the incident wave in magnitude and if the magnitude of the reflected tensile force is greater than about 10 percent of the compressive strength, it will cause tension fractures resulting in scabbing of rock. On such fractures the detached fragments would move in the direction of the incident wave with the velocity of the stress wave. In addition to longitudinal wave (P-waves), there are shear waves (S-waves) with particle motion transverse to the direction of the wave propagation that are transmitted through the rock mass during earthquakes. Besides the P and S waves(SV, SH Love waves), Rayleigh waves (R-wave) are transmitted along the ground surface in which particle vibrate in a plane parallel to the direction of the wave propagation and at right angles to the surface with an up and down and longitudinal motion similar to waves in water. The R-wave affect near surface ground, and the depth of influence can be calculated from their displacement amplitude and frequency records.

DAMAGE TO GROUND

Landslides, rock falls, avalanches, falling boulders and large rock fragments damaged and blocked roads, broke telegraph lines and completely disrupted means of transport and communications in Kinnaur and Lahaul-Spiti district during 1975 Kinnaur earthquake. Most of the affected area lie at an alitude above 10,000ft (3000m). The earthquake is reported to have caused damage across the Indian border in Tibet (China). Eye witnesses on the Indian side stated that they saw Tibetan hillocks crumbling with a deafening sound in heaps of debris. On the Indian side the severely affected zone extended for a distance of 25 miles (40km) from Kaurik towards south covering an approximate area of 300 sq miles (800 sq km) in Parachu and Spiti river valleys.

Fissures

Villages in the area have been located on hill slopes and flat lands over glacial till and moraine and river terra ce

Fig. 3. Kaurik village located on glacial moraines which was completely destroyed large chunks were dislodged and slipped at the crest of upper terrace.

Fig. 4. Buildings constructed on stable ground in Kinnaur.

Fig. 5. Ground fissures which cut accross Kaurik village.

Fig. 6. En echelon ground fissures (partly covered by subsequent snowfall) near Kaurik village.

(Fig. 3 and 4). Extensives fissures were developed in the frozen ground in glacial moraines overlying bed rock. Figure 5 show fissures passing through Kaurik village which was completely destroyed, and individual fissures extended to 50 ft to 100 ft (15-30m) in length trending N 335° to N 35° (Fig. 6). Width of openings varied from fraction of an inch to several feet (few cms to a metre) with down throw towards west. A fracture zone with opening of 4 to 6 in (10-15 cm) with individual en echelon fractures could be traced over 1100 yards (1 km) extending from the edge of the terrace south of Kaurik village, towards hill slopes north of the village. Fissures in the ground transverse to the ridge covered with frozen glacial moraines with openings from a fraction of an inch to 6 in (15 cm) developed between Sumdoh and Kaurik with their general trend along N 25°.

Fig. 7. Step faults accross road between Sumdoh and Kaurik.

Figure 7 show step faults accross India-Tibet road between Sumdoh and Kaurik with fractures trending along N 350° and continuing towards hill side, with openings upto 2 ft (60 cm) width and extending to depths of 10 to 20ft (3 to 6m). At Sumdoh fissures overlapping each other were observed on top of river terrace with openings upto 2 in (5cm) in width extending over 55 yards (50m) length in N 40° to N 60° directions. Carbonaceous shales on left bank of spiti river near Shalkar developed fractures along prexisting north - south trending vertical joints. Similar vertical to steeply dipping fractures trending N 35° to N 5° were observed in lacustrine clay deposits with opening upto 6 in (15 cm) in width, and tabular slabs of clay were dislodged from vertical cliff transverse to such fractures. Similar fractures trending N-S, were observed in limestones at a distance of 2.5 miles (4km) from Shalkar.

Fig. 8 shows fracture trending N 20° with down throw towards east in river bed of Spiti between chango and Malling. Extensive fractures developed in glacial moraines forming flat ridge near Leo, and width of fissures varried upto 2.5 ft (75cm) with their trend towards N 345°. Similar fractures were noted on hill slopes above Leo village with a trend towards N 10°. Figure 2 show the general trend of ground fissures observed at various locations.

ROCK SLIDES

Innumerable instances of sliding and fall of blocks of frozen glacial moraines from the crest of the terraces (Fig. 3) were observed in the macroseismic tract. Major rock slides occurred along hill slopes, which continued for several days during moderate aftershocks. The badly affected regions were beyond Malling, where in rock falls, landslides and rock avalanches damaged roads and disrupted traffic along India-Tibet road and at many locations the road was comp-

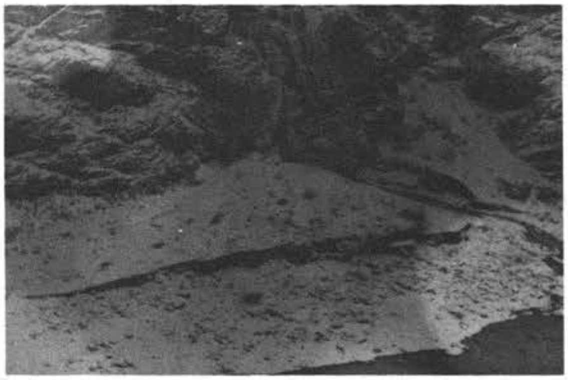

Fig. 8. Ground fissures in Spiti river bed.

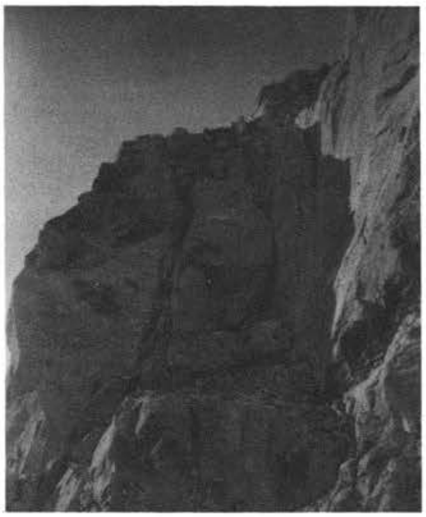

Fig. 9. Widening of pre-existing relief joints in hill slope cutting near Kah.

Fig. 10. Sliding of rock wedge in carbonaccous shales on India-Tibet road between Shalkar and Sumdoh.

Fig. 11. Stoppage of water flow in a spring in limestones near Shalkar village.

Fig. 12. Dislodging and overturning of boulders at the top of the ridge near Leo.

Fig. 13. Overturning and heaving up of large boulders at the crest of hill slope near Leo.

Fig. 14. Bending of telegraph pole resulting from impact of flying rock fragments.

Fig. 15. Large boulder fallen on road pavement between Malling and Chango. Landslide in the back ground has obliterated the road.

letely destroyed. Flat topped hill slopes in glacial moraines developed extensive cracks, indicating initiation of failure of slope towards the valleys. Similar fissures were observed parallel to road pavement on glacial moraines with wide openings upto 20m (50cm) in width. Loosening of rock mass along prexisting joints and fissures was noted on hill slopes. Figure 9 shows separation of rock mass along pre-exting discontinuity surfaces (bedding and joints) and sliding of a rock wedge in carbonaceous shales with rock debris fall at its botton on India-Tibet road between Shalkar and Sumdoh. However such failure were of small size and very few in number and in general insitu rock mass remained stable during the earthquake. Widening of relief joints was observed in cuttings transverse to hill slopes. Figure 10 shows loosening of rock mass and widening of openings during the earthquake along relief joints in hill slope cutting near Kah between Khab and Malling. Loosening and readjustment of rocks resulted in changing the seepage outlets in some of the surface springs in the area. Figure 11 shows the outlet of a spring in limestone near Shalkar village, which ceased to flow due to readjustment along joints. This spring has emerged due to opening of joints at a lower elevation after the earthquake.

Overturning and sliding of boulders and rock blocks at the top of ridges (Fig. 12) and steep slopes took place by development of tension cracks. Seismic stress waves incident at the frozen ground surface on reflection as tensional stress wave shriveled and blighted the frozen ground and rockmass. The resulting scabbing and slabbing of rock mass along joints, partings and other weak planes caused loosening, dilation and crumbling of hill sides, often with deafening sounds in heap of debris. The reflected tensile stress wave caused separation along discontinuity surfaces filled with frozen ice and weathered material, frozen-glacial maraines and fluvio glacial deposits forming flat terraces and mounds along the river valleys developed similar tension fractures resulting in dislodging, overturning and heaving up of large boulders (Fig. 13) and chunks of rock mass. Boulders at hill tops were reported to toss up and down. Fragments from steep rock slopes on rupture flew off with seismic (P-wave) velocity and hit telegraph poles (fig. 14), trees and roof tops and some of the flying fragments pierced through telegraph poles. Large dislodged boulders and chunks of rock at many places fell on road (Fig. 15) disrupting and damaging hillside and roadside houses (fig. 16).

The fragmentation depending on nature and spacing and attitudes of prexisting discontinuity planes in insitu rock and thickness of frozen ice and ground composed of glacial and glaciofluvial material produced loose tabular

Fig. 16. Collapse of check post at Shalkar on India-Tibet road. Big boulder rolling down from hill slope caused collapse of the building.

Fig. 17. Rock avalanche debris in quartzites along India-Tibet road between Chango and Shalkar.

Fig. 18. Catastraphic failure of slopes along India-Tibet road in weathered and jointed grantic gneisses.

Fig. 21. The new path carved out by Parachu river on the left of its original course. Fissures are observed on the right hand side of the photograph.

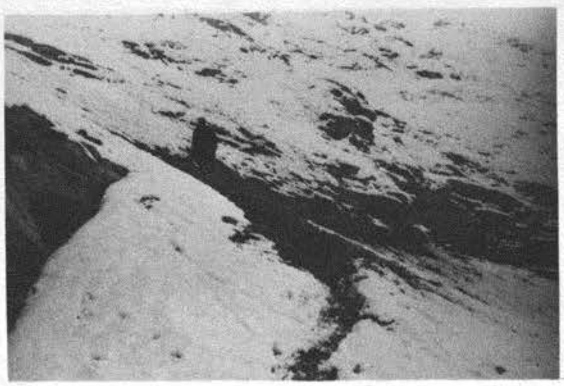

Fig. 19. Landslide in thinly foliated phyllitic schist (covered by subsequent snow fall) on India-Tibet road between Chango and Shalkar.

Fig. 20. Formation of debris dam accross Parachu river between Sumdoh and Kaurik.

and prismatic slabs of clay, carbonaceous shales, phyllites, quartzites, schists, genisses, and unconsolidated materials, which cascaded along the hill slopes (fig. 17) obliterating the roads and other constructions lying on its way. Such surface runs and rock avalanches caused extensive damage to the India-Tibet road, which disrupted rescue and relief operations. There were catastrophic failures and landslides along a four kilometer stretch of the road on the right bank of Spiti river (fig. 18) and in some stretches the road was completely obliterated. Such slopes were composed of variety of thinly bedded carbonaceous shales with close spaced joining, quartzites, phyllitic schists, and granite gneisses. Fig. 19 shows landslide mass in thinly covered folliated phyllitic schists which entombed three ponies and a cow moving on the road which was completely destroyed.

Majority of catastrophic hill side failures were in steep rock slopes with surficial cover of scree material and loose fragmented aggregates, which in general had negligible soil and vegetal cover. Due to the dynamic amplification of ground motion at the hill tops, sliding, overturning and rolling of rock fragments initiated the slip at the higher elevations which gathered momentum in their descent hitting and dislodging other rock pieces and such bombordment gradually grew into a large mass hurling down slope with great speed forming huge rock debris in the valley base. Parachu valley was filled by such a debris from its right bank at a location between Sumdoh and Kaurik (fig. 20). The debris filled the valley upto a height of about 200 ft (60m) and blocked the flow of water creating a reservoir behind it. The debris dam of about 200 ft height and 500 ft (150m) in length was formed. The water started overflowing the debris in about six days and carved out a channel (fig. 21) shifting the course of Parachu by about 200 to 250ft (60-75m) from its original course towards its left bank within the flood plain of the valley. The newly created meander joined the original course of the river at a distance of about 1500ft (450m). Fissures forming linear scarps with up throw of 20-40m (50-100cm) were formed in the river bed (fig. 21).

CONCLUSIONS

Evaluation of rock slope stability during earthquakes is an essential excercise in implementation of development plans in active mountainous regions. Rock slopes carved out by geological processes in general have surficial cover of varying thickness. Steep slopes and narrow valleys with such loose rock overburben undergo mass movements causing extensive rock avalanches, rock falls and slides in which the failure in general is restricted within surficial material and loose rock, and insitu rock forming the bulk of the hill mass remains stable during earthquakes. The nature and extend of such cover controls the loosening of slope material and its movement during earthquakes. In high altitude frozen ground or massive rock slope surface the incident seismic stress wave play a significant role in shattering the near surface rock mass and in detatchment, overturning, uplifting, sliding or fall of boulders or chunks of rock from hill tops, higher reaches of rock slopes and crest of terraces.

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