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Slope Instability in the Fragile Himalaya and Strategy for Development*

by
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Prelude

Between heaven and earth, the Himalaya once stood with scientillating charm as the magic of another world blessed with overflowing Silence, Beauty and Grace. The wicked in human race, 'alas', came very heavy on it through the corridors of time as if to echo what Byron wrote in 1818 to say that 'Man marks the earth with ruin". Indeed one wonders for centuries, how the Himalaya remained outside the world's mainstream, many of it's peaks lay unscaled humbling numerous mountaineering giants and its hinterland was spared locked in mystery !

There was a time when, in the forbidding and awesome terrain of the Himalaya, a robust people did embellish their frugal lives with rich endowments of faith. The Himalaya evoked wonder, praise and veneration. It's towering though fragile mountains, precipices, thousands of peaks and fierce torrents gushing down to the deep valleys seemed permanent and enduring. Then came a time when even whipping winds, fury of avalanches, bullet like fragments of shooting rocks, death traps of crevasses, not even the face of death could deter man from providing a thrilling display of skill and indomitable courage to browbeat the mountains. Edmund Hillary and Tenzing Norkey conquered world's highest and the loftiest peak—Mt. Everest—chiefly because no body did so before! Today Himalayan grandeur and faith live-on but under cloud of doom. It's beauty is stained, purity is soiled and resource is stretched beyond limit in the name of development. Interalia, dams and hydro-electric schemes for harnessing of enormous water potential, exploitation of forest produce, boosting up of agricultural growth, constructions for tourism, defence, communication etc. seem to proceed unabated at a frightening speed subjecting it to harsh treatment at the hands of man in hurry. Let us join Hans Rieger in sounding the alarm: 'There is only one Himalaya to lose ! Build we must but surely there should be ways to build in harmony with nature. One way could be to adjust the pace of change so as to effectively counter its negative impact with strategy of 'regeneration, protection and preservation'. Action need not be a reaction but a creation.

Dynamics of change in the Himalaya is inextricably intertwined with

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factors such as climate, geology, flora, fauna and water resource. Indiscriminiate construction activity compounds the problem that concerns not only over 45 million people in the Himalaya and nearly seven times as many in the plains skirting the mountain chains but in a sense the future of the entire region.

Introduction to the Himalaya

Centuries ago, Sage Nagasena spoke to King Milinda:

The Himalaya, the king of mountains, five and three thousand leagues in extent at the circumference, with it's ranges of eight and forty thousand peaks, the source of five hundred rivers, the dwelling place of a multitude of mighty creatures, the product of manifold perfumes, enriched with hundreds of magical drugs, is seen to rise aloft like a cloud. George Leigh Mallory spoke of it as far higher in the sky than the imagination dared to suggest. Most of those who have visited the Himalaya repeatedly are convinced that a hundred divine epochs would not suffice to describe all its marvels !

The Himalaya are the tallest among mountain chains of the planet earth, almost five and a half mile high (Fig. 1) encompassing an area of half a million square kilometre in its mighty sweep. The great rivers that gush out of snowy mountains cut gorges almost one mile deep to qualify among the deepest cuttings in the world. Nearly 17000 glaciers and snow bodies are the fountain head of the most formidable avalanches which have humbled and sometime killed some of ace mountaineers of the world. To a distant observer the great giant appears more exciting than a rainbow. Sometime it shines like Polished silver, sometime it is seen to be aflame in glow of the setting sun, sometime its crests are hidden behind plumes of clouds (Kazami, 1968). The endless variety it possesses is unequalled. To those who come in their contact, the acquaintance turns rare and the life time of association appears too short.

For more than 22 years I have, as a Geotechnical Engineer, trekked and travelled through the Himalaya and have seen incredibly steep slopes, witnessed deadly fragments of falling rocks exploding on strike into a fusillade, heard horrendous tales of monsoons, rivers in spate, flash floods, cloud bursts, demolished bridges, impossible communication and of sorrow of stranded travellers.

Although my studies have spanned over the entire mountain range, admittedly the bias is on Garhwal, Kumaon and Sikkim Himalaya in which not only that my involvement is much deeper but also that the problems of ecological imbalance due to landsliding and mass wasting are most serious.

The ugly scars on the fragile Himalaya due to slope instability, landslides and other mass movements and strategy for its development are

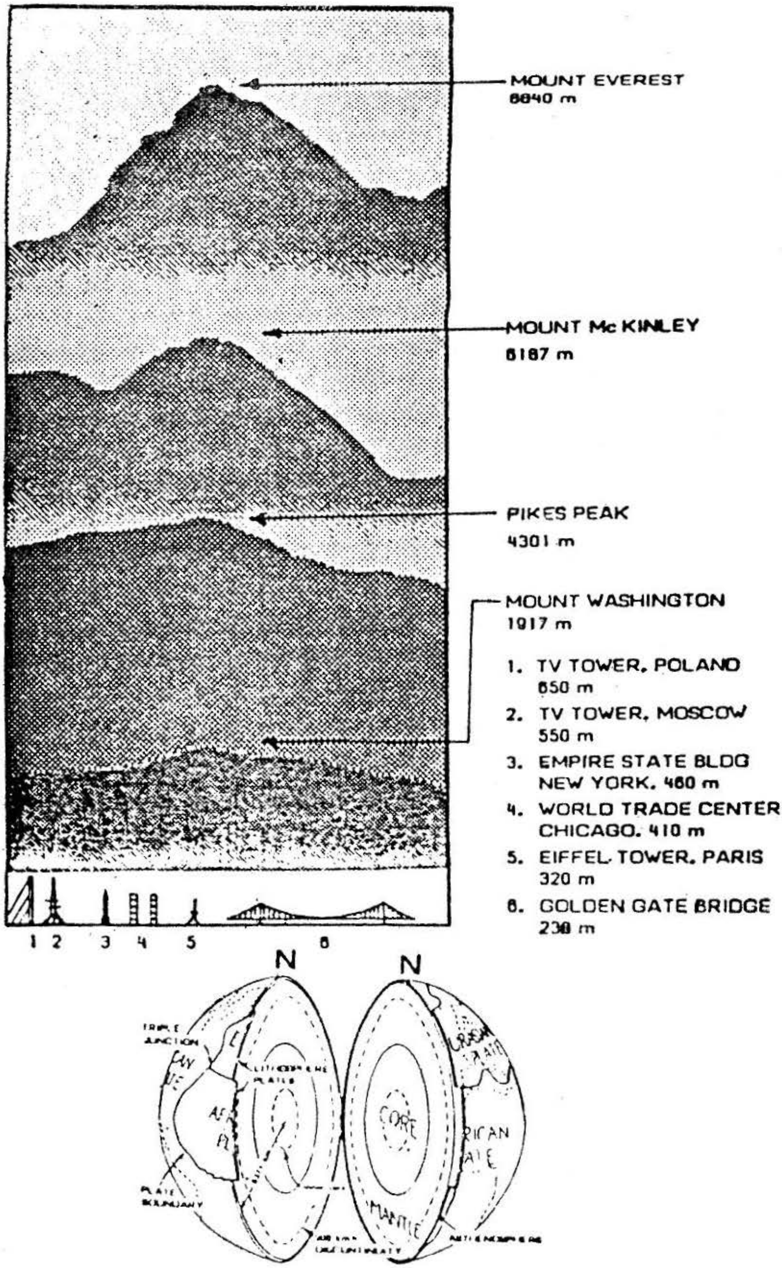


FIGURE 1 Creation of Nature versus Creation of Man

the prime concern of this presentation. Current ideas on the Himalayan Landslides are advanced to suggest an operational strategy to combat their negative impact.

Evolution of Mountain Chains

In the beginning, there was no Himalaya. About 200 million years ago, India was separated from Asia by a vast stretch of shallow sea called the Thethys Sea. About 180 million years ago, the landmass broke up and the plate on which India was located drifted northwards. From about 53 million years ago, it began to push against the Asian mainland. As India and Asia collided, the under water sediments were squeezed up into a mountain chain we call the Himalaya (Fig. 2). During the process, developed a prodigious white fang—an excrescence from the jaw of the world, we call the summit Everest. It looks mighty but the layers of limestone on it are so soft that one can scratch it with ones finger nail.

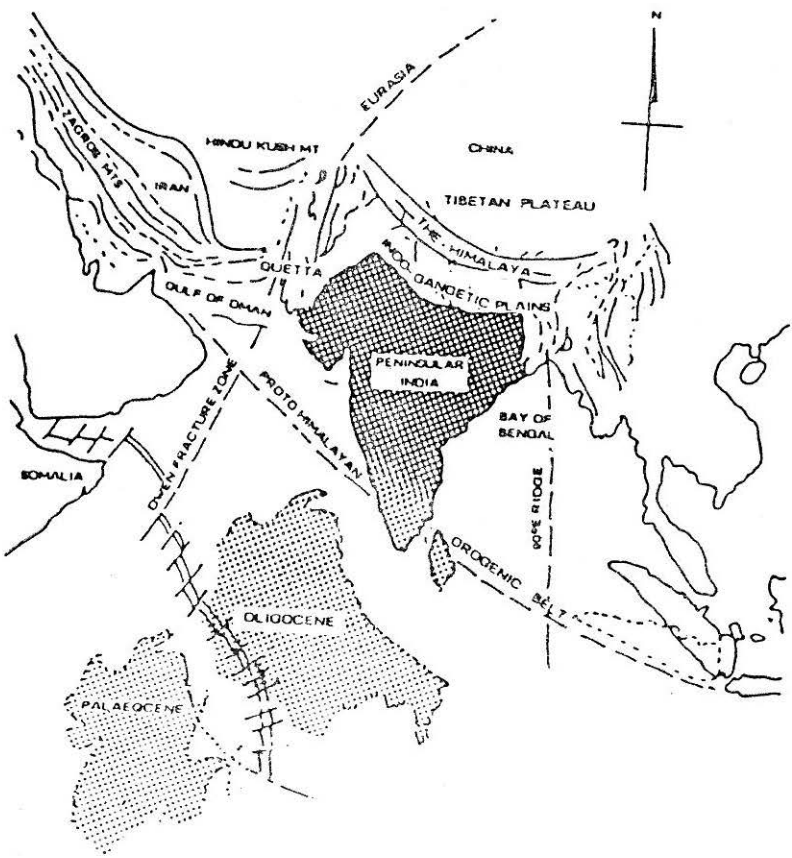


FIGURE 2 Tectonic Movement of Indian Subcontinent and Birth of the Himalaya (after Farooq. Rais and Siddiqui 1981)

The Himalaya abounds in thrusts and faults which have profound effect on slope stability. Siwalik foot hills are separated from the Lesser Himalaya by the Main Boundary Thrust (MBT). Again, Greater Himalya are separated from the Lesser Himalaya by the Main Central Thrust (MCT). (Fig. 3). It has been postulated that the northern boundary of the Indian plate coincides with the southern margin of the Tien Shan-Nan Shan mobile fold belt. In consideration of the parallel Cretaceous and Eocene Indus Tsangpo Suture Zone, Miocene MCT, and recent MBT, the present day northern border of the Indian plate is a structural line that was individualised at the end of Paleozoic, or even earlier, although the western border seems to have attained its final location at a much more recent date, Oligo-Micocene, about 26 million years ago, Farooq (1981).

The Himalaya, like other mountain belts, have roots striking deep into the body of the earth. When it was discovered that the Himalaya fails to exert the gravitational pull which would be expected from its size, some speculated that it is hollow. This myth was soon abandoned in favour of the conclusion that the Himalaya were supported by unusually light material at depth—that is, by masses of Sial penetrating down into the projecting Sima. The principle of isostasy perhaps owes its origin to the concept that world's lands stand high simply because they consist of relatively lighter rocks (density = 2.8) buoyed up by heavier (density=3.0) but weaker material beneath. In general crystalline Sima and Sial combine to form earth's crust, about 64 km thick.

After the subduction of the crust is brought to an end by the buoyancy effects of non-subductible material in the subduction zone, a new line of weakness takes the relay. Mountain building now proceeds indirectly by underthrusting of one continental slab along a deep fracture developed within the colliding plate. This hypothesis explains how one thrust takes the place of another. The role once played by the MCT in the birth of the Himalaya is now being played by the MBT. In a few million years from now a new intracontinental thrust would probably appear further south of the MBT to continue the growth of the mighty Himalaya.

The pressure caused by the collision of the plates is estimated to be so high that if all the folds of the Himalaya were to be stretched out flat, elongation would measure as much as 650 km i.e. nearly a quarter of the length of Himalayan arc. Geotechnical engineers will have to understand the implications of the tremendous locked-in strain energy in relation to the progressive failure of slopes and development of landslides, particularly on cuttings.

Is Himalaya Still Rising ?

The Himalaya and the Alps are reported to be still rising. So far it has

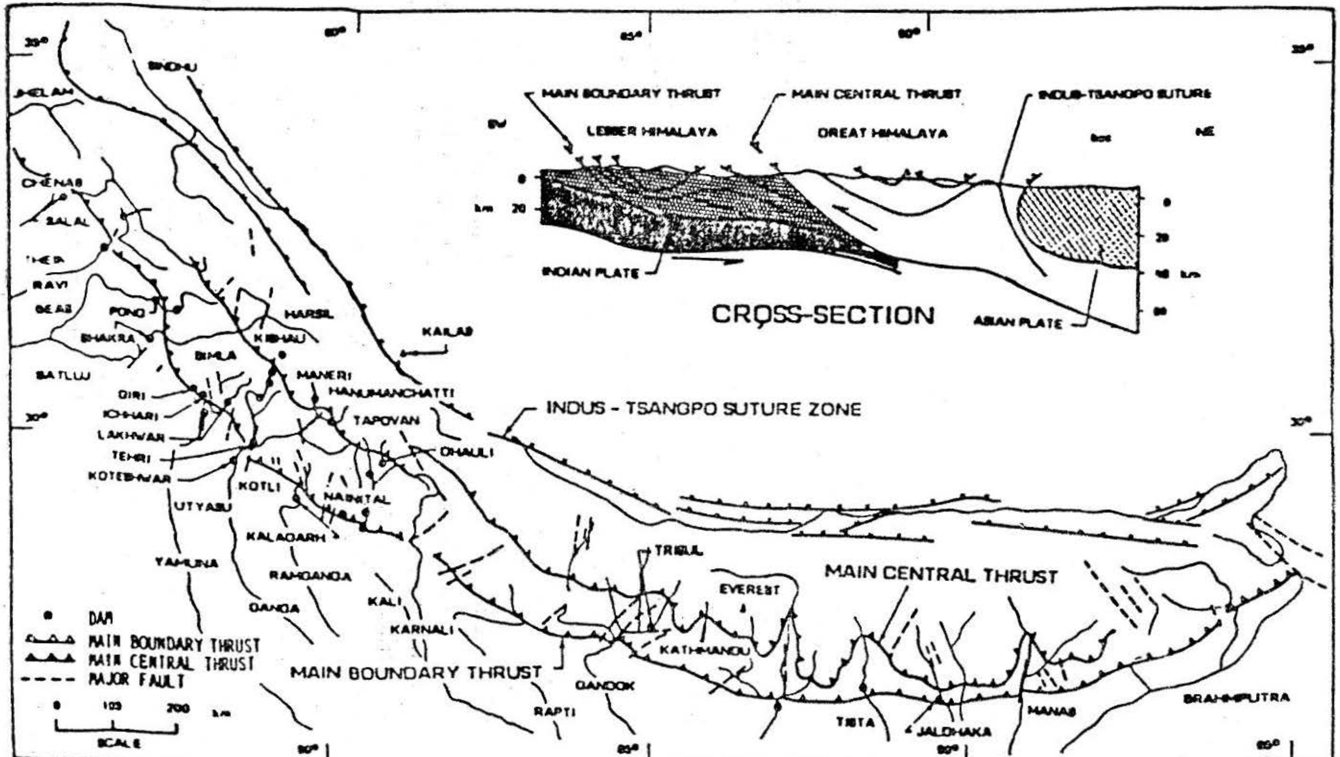


FIGURE 3 Tectionic Map of the Himalaya (Gansser 1974: Valdiya 1985)

not been possible to measure the rate of rise precisely, although it is reported that since the end of the last glacial epoch some twenty thousand years ago, the Himalaya has risen by about 1500 to 2000 m, faster than any other landmass on the earth. The total rise may be well over 3000 m. As the Indian plate pushes the Asian plate, it may further rise. The estimate of the rate of rise is nearly 100 mm per annum, (Nicolson, 1975 and Fukada, 1976). The forces of erosion and creep counter the tendency of uplift and unless accurate measurements are made over long durations of time, the exact rate of rise will always be difficult to predict. Achievable accuracy of measurement made possible by magical advancement of science and technology raises a new hope in that it is now possible to measure length to the accuracy of 4 parts in 10^9; time to the accuracy of 2 parts in 10^{13} and temperature to the accuracy of $\pm 0.0001°$ K.

The Himalayan Geology

Extending over several countries as Pakistan, India, Nepal, Bhutan, China and Burma, the Himalayan system could be classified into (*a*) the Sub Himalaya or Siwaliks (*b*) the middle Himalaya (*c*) the great or high Himalaya and [*d*] the Trans Himalaya [Fig. 4]. From the point of view of slope instability, highlights are presented in Table 1.

The Planning Commission (1982) has divided the Indian Himalaya into three subregions namely the Western Himalya in the States of Jammu and Kashmir, and Himachal ; the Central Himalya consisting of the eight

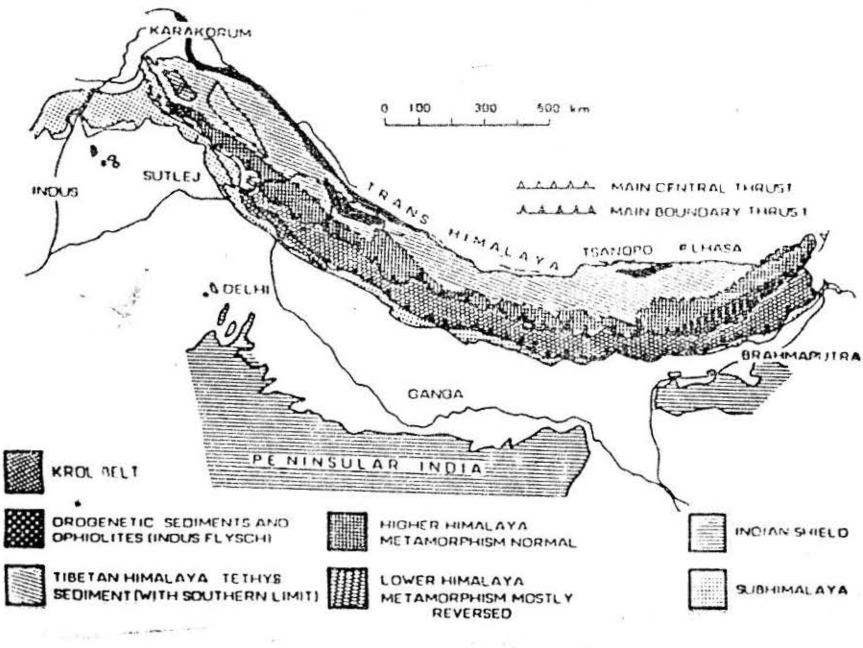


FIGURE 4 Geological Map of the Himalaya

TABLE I

The Himalayan System

Group	Relief	Description
The sub-Himalaya or the Siwaliks (6000 m to 1200 m)	A succession of disrected hills largely with flat summit forming the southern most part of foot hills. They are characterised by zone of intense landslides and mass wasting.	Comprise soft tertiary sediments sandstones, silt stones, shales and clays prone to distintegration. It experiences full force of monsoon season. Siwalik range is still thickly vegetated.
The Middle or Lower Himalaya (1200 m to 3000 m)	It is a tangled mass of ranges and valleys, with major rivers cutting across it, some times in deep gorges. It lies immediately to the north of MBT where Siwalik belt ends and falls in medium to high relief zone.	This is para-autochthonus zone consisting largely of unfossiliferrous rocks. The northern slopes are gentler, densely forested, colder and not much inhabited. The southern slopes are steep, bare and gullied, comprise essentially of sedimentary rocks subject to weathering. Deforestation, over grazing and impact of monsoon are chief causes of denudation and mass wasting.
The Higher Himalaya (average hight= 5200 m−92 peaks over 8000 m high)	Lies north of MCT and is characterised by high relief zone of glaciation.	Is is characterised by serrate nature of mountains with abundant sharp edged features and discordant drainage system. Comprise granitic gneisses and other crystalline rocks. Slopes are mostly bare with debricones and moraine walls at their base. Avalanches are recognised as major hazard.
The *higher* Himalaya (average altitude 4500 m)	*Tibetan marginal land High* altitude passes between India & Tibet are located in this region.	*It is* composed of fossiliferrous sediments of precambrian to cretaceous or even the tertiary periods. The principal rocks include slate, sandstone, conglomerates and limestone.

hill districts of Garhwal and Kumaun Divisions of U.P. ; and North Eastern Himalaya comprising States of Sikkim, Manipur, Nagaland, Tripura, Union Territories of Arunachal Pradesh and Mizoram and hill areas of Assam and West Bengal.

Extremes of Variation

The Himalaya displays fantastic variations of geomorphology, climate and vegetation. The southern side of the Himalaya is humid with luxuriant flora whereas the northern side is arid, barren and wears the look of a desert. If one were to decide to climb up the Himalaya, India would welcome him at start with sweltering heat, then one would encounter rather damp zone with abundance of exotic vegetation, then the grassy highlands with the purest air to breathe. The real climbing would normally begin thereafter at an altitude of 4000 m or so. Thus, after passing through the tropical and the sub-tropical climates, the climbers enter an arctic like region stepping into the world of snow and ice (Fig. 5). The temperature variations are baffling.

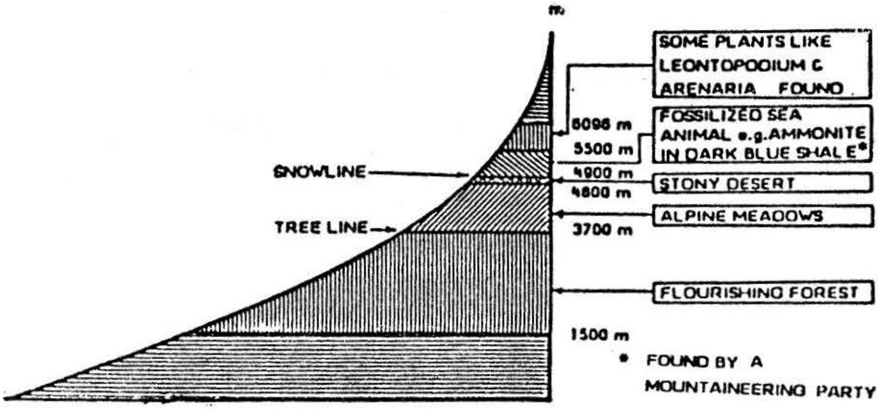


FIGURE 5 Climatic Variation up the Himalaya

In trans Himalaya, including the region of Ladakh, temperature during summer never exceeds 30°C and in winter season, it may fall as low as −43°C as at Dras. The rainfall variations are also astounding. On the one hand, in the eastern Himalaya, rainfall is to be measured in metres whereas on the other hand, in places like Ladakh total annual precipitation seldom exceeds 10 cm and is largely due to glacier melt that irrigates terraced fields (Fig. 6).

Rivers of the Himalaya

The glaciers of the high Himalaya form the headwaters of three of the world's major river systems namely the Indus, the Ganges and the Brahmaputra. The Indus originates in the Indian Himalaya and flows into Pakistan ; The Ganges system also originates and flows in India. The Brahmaputra drains the north side of the Himalaya.

Rivers of the Himalaya also tell the tale that the Himalaya rose from the lowlands. Several rivers having their sources in Tibet for instance, flow between the soaring walls of Himalaya into the great plains of India, a geographic characteristic peculiar to the Himalaya (Fukada, 1976).

Indeed the direction taken by Himalayan rivers is mind boggling. Natural expectation that greatest mountain range on earth should also form

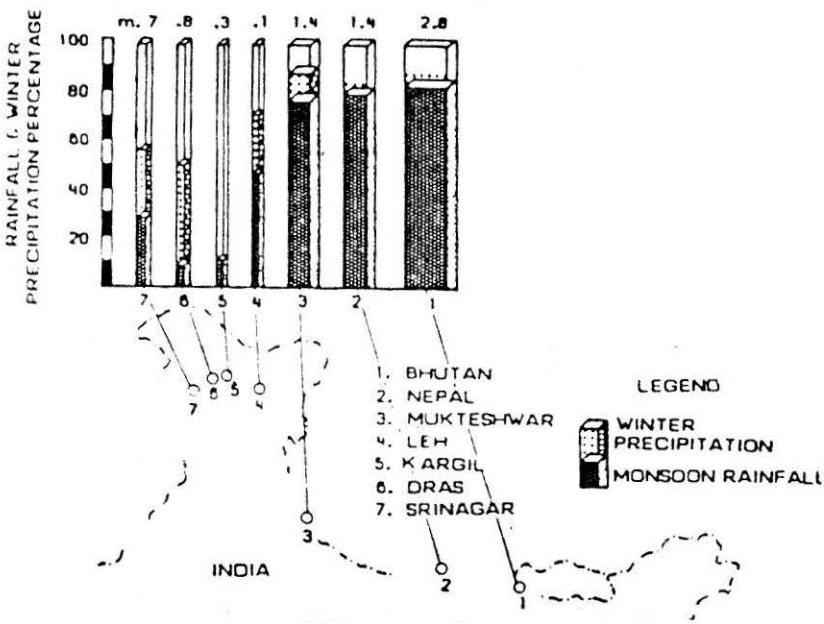


FIGURE 6 (a) Monsoon Rainfall vis-a-vis Mean Annual Rainfall in Sikkim

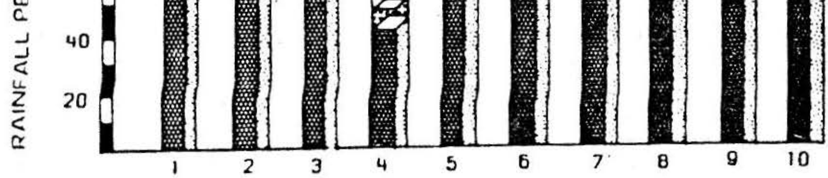


FIGURE 6 (b) Patterns of Monsoon Rainfall and Winter Precipitation from the Eastern to the Western Himalaya

its most impressive watershed is not correct. The rain and melt snow neither flow down the northern slope into Tibet nor down the southern slope into the great Indian Plain. Rather they form rivers that cut through young Himalaya on their way to the lowlands and eventually to the sea. Thus the great water divide is not the crestline of the mountain but the edge of Tibetan Plateau, 160 km north of it and nearly 3000 m lower down. Premier rivers like Brahmaputra and the Indus although born within a few km from each other negotiate nearly 1600 km east and west respectively before cutting through the Himalaya. The only satisfactory explanation seems to be that the rivers must have existed before the Himalaya rose to their present height. They were strong enough to hold their course even when the Himalaya topped and outcast the Tibetan mountains.

The Ganga drainage system supports over 200 million people and accounts for more than a quarter of the geographical area of India. Nearly 10 per cent of the river lies in the Himalayan hills with elevations ranging from 3000 to 6000 metres and remaining 90 per cent in the alluvial plains. The mountainous region consists partly of granitic hard rocks and partly rocks of Siwaliks. *On the whole, in the entire Ganga drainage* system nearly 40 per cent of basin area lies in the Himalaya and balance 60 per cent in plains. Gandak, Ramganga, Yamuna etc. are its major tributaries. Yamuna system accounts for about 40 per cent of the total basin area of Ganga. The studies show that Yamuna system and tributary Gandak alone influence the chemical and sediment erosion in the Ganga basin.

Unlike the flat basins of the Yellow and Missippi Rivers, the Ganga basin is trough shaped, with mountains on eitherside. The river valleys measure 15 to 80 km in width and it's discharge exceeds 7.4 million gallons per second when in full spate. It spreads as much as 30 km into it's flood plain when banks are overtopped.

The Ganga Flood Control Commission and others have worked towards improving the drainage and lessening the impact of floods. Similar effects must continue on all Himalayan rivers to take away the enormous bank slope erosion associated with them.

Glaciers of the Himalaya

It is estimated that 2.15 per cent of the world's total water is frozen in ice as in a glacier. If all this ice was suddenly to melt, the sea level would rise by between 60 and 90 m, flooding many of the world's most thickly populated low lying areas. Although most of the world's ice is locked in two great ice sheets covering Antarctica and Greenland, nearly 17,000 glaciers covering 17 per cent of the Himalayan region claim a fair share. Some of them are tens of hundred metres thick and 3-5 km long. Most of them form above the permanent snowline around 4900 m (Fig. 7). They gouge out cirques and descend from elevations as high as 7, 000 m to 3,500 m. The longest glacier Sianchen gouges 72 km long valley through the eastern Karakoram, where it terminates and exposes a jumble of debris called terminal moraine.

The effect of glacier input and ablation imbalance is significant inasmuch as on it depends the run off. The variation in run off due to glacier imbalance may be as high as 30 per cent of the annual figure particularly

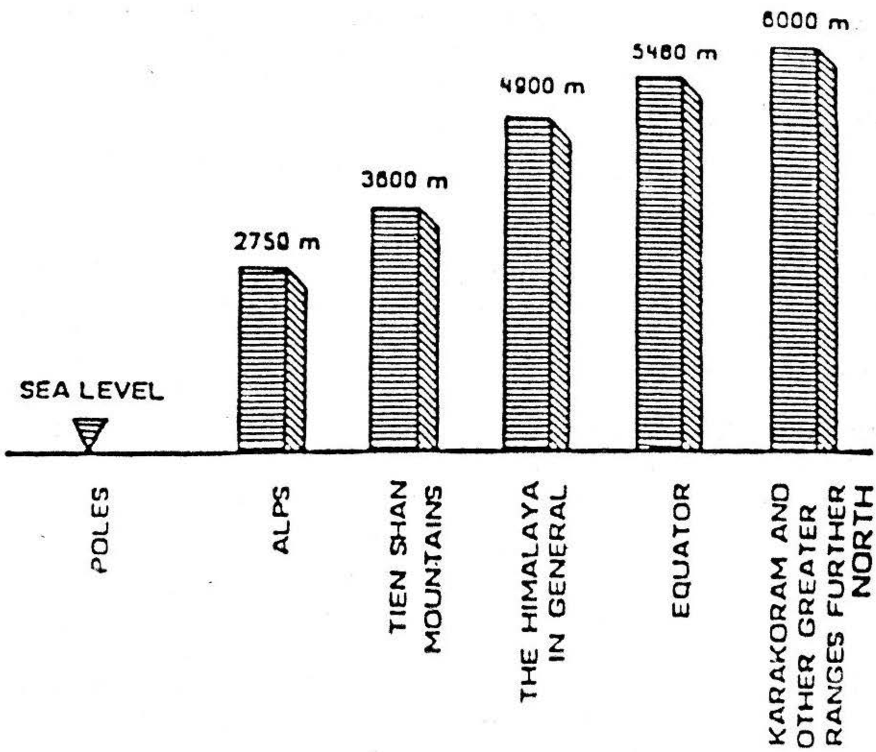


FIGURE 7 Himalayan Snow Line

in streams with high glacierisation. This may well be due to abnormal snowfall, abnormal or subnormal summer temperatures or any other possible combination.

The glaciers move at different rates of flow, almost from zero to 60 m/day, and this is primarily the reason that edges of the glaciers usually split into crevasses.

Our knowledge of glaciers and particularly of associated hazardous avalanches has been greatly enriched by the mountaineers who were either directly involved or did witness the phenomena from a distance. While viewing the summit of Dhaulagiri, Nicolson (1975) saw a mattress of snow 15 m thick on the glacier poised to collapse as an avalanche. It was described as the nature's unique way of restoring equilibrium in that a puff of snow brings down a million ton mass to find new level of stability. Of course then the process begins again. Similarly, warm weather, rain or sudden vibration has been the cause of several monstrous avalanches seen hurtling down the elevations of 7879 m at Nuptse Ridge near Mount Everest.

The snow and ice of the Himalaya are therefore a valuble economic resource. It is important for this resource to be measured, monitored, studied and understood so that maximum use could be made of it.

Why the Himalaya is Fragile ?

Firstly, the geomorphic features are born of tectonically displaced, folded, as well as crumpled rock formations of various nappes, their klippes and numerous oblique and transverse faults. Secondly, the region is subject to periodic earth tremors or seismic phenomena being placed in the orogenic belt of continuous dynamic modifications. (The impact of some of the devastating earthquakes is highlighted in Table 2). Thirdly, some

TABLE 2

Devastating Earthquakes in the Himalayan Region

Place and Epicentre	Date	Richter Magnitude	Damage
Kashmir (34.6° N, 4.4° E)	30 May 1885	7	Felt over 11000 sq. miles; 6000 people were killed.
Assam*	12 Jun 1887	8.7	Felt over 25000 sq. miles; Landslides, flow-slides and ground subsidences were widespread.
Kangra (32.5° N, 76.5° E)	4 Apr 1905	8	Felt over an area of 1.625 million sq. miles; 2000 people were killed.
Quetta (Pakistan) (30.2° N, 67.7° E)	24 Aug 1931	7.8	Many buildings and a railway bridge destroyed.
Nepal (26.6° N, 86.8° E)	15 Jan 1934	8.3	Extensive landslides, collapse of building, lateral ground spreading, ground settlement and sand boils over an area of 4320 sq. miles.
Assam (30.5° N, 91.5° E)	15 Aug 1950	8.5	Felt over 0.42 million sq. miles; caused extensive landslides and rock falls, fissures and sand boils resulting in collapse of buildings, roads, bridges, etc.
Lhasa Tibet (30.5° N, 91.5° E)	17 Aug 1952	7.5	55 people were killed and 157 injured. 850 buildings were destroyed.
Srinagar** (33.9° N, 74.7° E)	2 Sep 1963	5.3	79 people were killed and 400 injured.
Kinnaur	19 Jan 1975	6.8	Huge boulders hurtling down the hill slopes resulting in widespread damage to life, property and communication system,

* Earthquakes also occurred in 1923, 1930, 1947 and 1957.

** Earthquake also occurred in 1921.

parts of the Himalaya are subject to exceptionally heavy rainfall almost certainly associated with huge landslides (Table 3). Fourthly, the Himalaya has been robbed of it's forest cover particularly over the last three decades, as clearly revealed by aeral photographs and satellite pictures and deforestation continues. And, inter alia, most importantly because of large scale constructions of dams, roads, tunnels, buildings, towers, ropeways, tanks and other public utilities, not to speak of indiscriminate mining and quarrying.

TABLE 3

Exceptionally Heavy Rainfall and Devastating Landslides

Place/Area	Date	Consequence of Heavy Rainfall
Darjeeling and Jalpaiguri	3-5 Oct 1968	Widespread landslides and other mass movement caused death and devastation all over.
Uttar Pradesh	July 1970	Alaknada River caused considerable loss of life among pilgrims. Many bridges, houses and an entire village were washed away.
,,	Sep. 1970	Landslides & house collapse killed 223 people.
Jammu and Kashmir	Feb. 1971	Widespread landslides caused disruption of traffic & communication systems.
,,	Aug. 1972	Widespread landslides causing damage to life and property.
,,	March 1973	Landslides cut off Kashmir valley from the rest of the country.
Shimla (H.P.)	July 1973	Landslides cut off Shimla from the rest of the country.
North Bengal	July 1975	Teesta, Jaldhaka and Diana rivers were in spate. Widespread landslids and floods rendered 45,000 people homeless.
Jammu and Kashmir	Sept. 1975	Landslides killed 2 labourers and disrupted transportation system for 3 days.
Darjeeling	June 1976	Teesta in floods triggering many landslides, 3 people were buried alive due to caving in of a hillock.
Jammu and Kashmir	July 1977	Srinagar-Leh road was blocked due to landslides.

All in all, the immature and complex geology, seismic activity, heavy rainfall including cloudbursts and flash floods alarming deforestation, and indiscriminate construction activity combine to create a class of slope instability problems, huge and complex, never witnessed before. A profile of the causative factors, ensuing nature of mass movements, their negative and positive impact and common control measures are presented in Fig. 8.

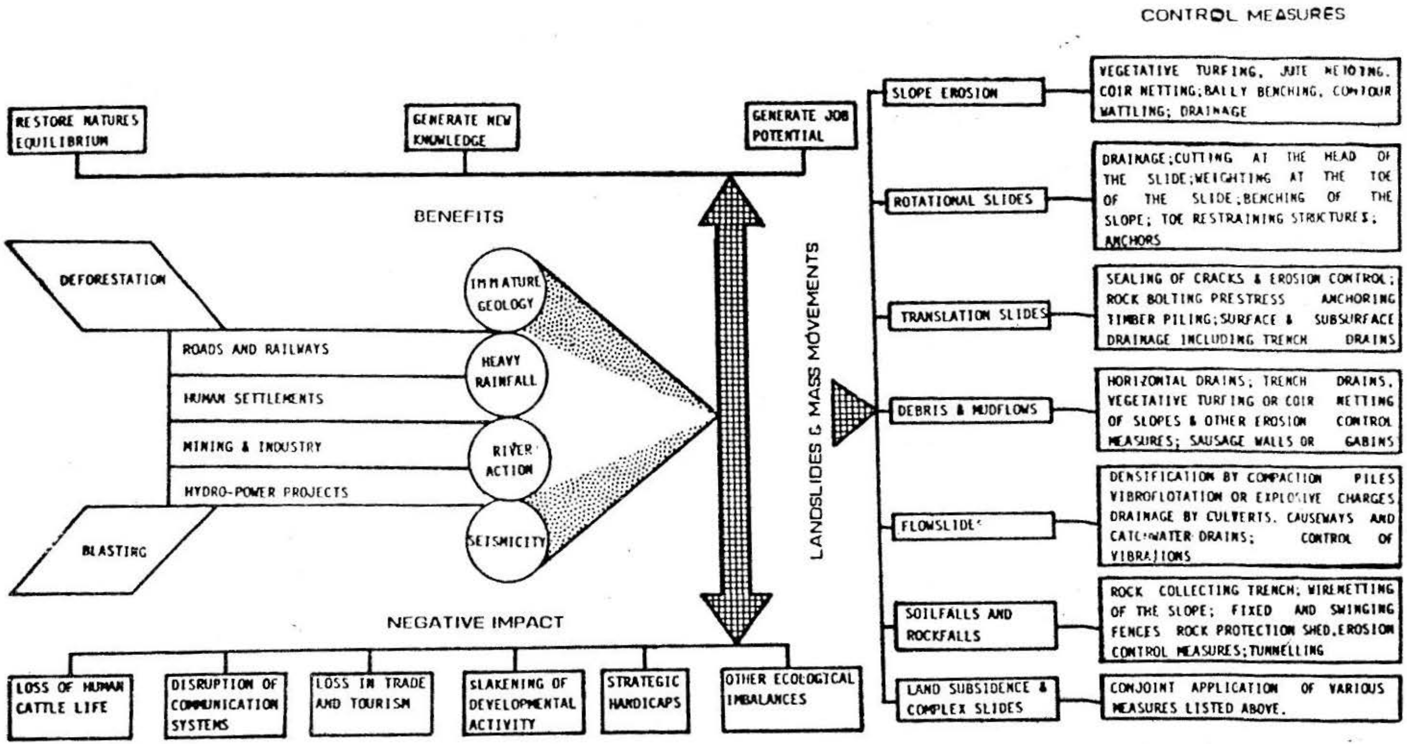


FIGURE 8 Factors Causing Slope Stability Problems and Common Prescription for their Control

Man as the Agent of Change

Who is responsible for the alarm which is rightly being raised as the Himalaya today faces the greatest danger to its stability? Himalya's immature geology, meandering rivers, snow bodies, climatic variations, cloud bursts, flash floods etc. have always been there. For centuries, formidable, snow avalanches did hurtle down the in the higher Himalaya as they do now. If at all, the changes in the basic system have been only marginal.

Then came the man on the scene. Vast areas of Nepal, Western Sikkim, Kumaon, Garhwal, Himachal, Kashmir and several other hilly regions fell to his axe and were robbed of the protective vegetal cover to about 30 per cent as against twice as much considered desirable. Lopping of trees for fuel or fodder, overgrazing, increased domestic and industrial consumptions of timber were chiefly responsible for deforestation. The slopes without vegetation could not be expected to hold soil cover together and widespread erosion was the natural consequence. According to one estimate, nature takes nearly 1000 years to produce a few centimetre of top soil but destablising forces of nature in the Himalaya wipe away millions of cubic metre in just a second! The rate of erosion in the catchment area of Himalayan rivers has increased five-fold in the geological time scale; the present rate being upwards of 1 mm per year (Valdiya, 1985). According to him, rivers are carrying incredibly large amount of sediment at the rate of 16.5 hectare—metre per hundred sq. km of the catchment area per year, leading to rapid siltation of reservoirs and lakes. Satellite photographs taken in 1974 dramatically reveal that eroded debris carried by the Himalayan rivers have created a new land mass about 50,000 sq. km in area extending to about 700 km into the sea.

As the pressure of population grew, more and more of human settlements, roads, dams, tunnels, water reservoirs, towers and other public utilities were added. The network of roads in the Himalayan region is today well over 40,000 km. Some of the roads exist even at altitudes as high as 5,000 metre surrounded by mountain ranges such as Kanchenjunga (8586 m). Khardung La at 5600 m is perhaps the highest motor road in the world. Due to inclement weather and extremely low temperatures (—40°C), it is open for just three months in a year. The 434 km hill road from Srinagar to Leh has although cut down the time of journey from 16 days to 2 days it has created problems of landsliding. A 300 m long stretch of mountain road, 18 km east of Srinagar (Garhwal) in the valley of Alaknanda is also badly affected by landslides involving limy quartzite and slate. North Sikkim highway too is bristling with the landslide problems of a bewildering variety and so are the roads in the J and K.

Construction of roads requires imaginative planning and methodical construction but when engineers work against time, they may not even have the basic data on geological formation, topography, drainage pattern etc., and as a result, some of the hill roads begin to pose chronic landslide problems. Every kilometre of road when constructed may bring a stress relief equivalent to about 1-2 lakh tonne of rock mass and if the cuttings are not properly protected, landslides and rockfalls become imminent adding additional of about 1000 tonne of landloss per km annually. At many major landslide locations, the debris clearance may well be of the order of 4,000—5,000 tonne annually.

Likewise, a number of dams have been built in the Himalaya (Fig. 2) and many more are currently under construction like the mighty Tehri Dam on Bhagirthi. The Dam projects over the Ganga and its tributaries in the hills alone number 22. Apart from the fear of reservoir induced seismicity, the implications of such constructions include mass scale deforestation, huge excavations, resettlement problems, and consequent threats to life and property. A number of tunnels are also being made. The highlights of some of the major Himalayan tunnels are presented in Table 4. Microwave, TV, Transmission Line and other towers are also dotting the hilly areas. Quarrying and mining, for cxample, in Doon Valley, Jhiroli (Almora) and Chandhak (Pithoragarh) have inflicted heavy damages to slopes and to the environment of the area.

Influx of tourists into the hilly region have brought about tremendous pressure on land due to construction of new buildings and tourist complexes including aerial ropeways. For water storage, underground water tanks are being built without any special instructions or precautions despite considerable bad experiences of slope instability from similar tanks as at Mussoorie and Shimla. Some of the constructions are coming up on old landslides without adequate pretreatment and investments on hill side stability, compounding the problem.

The author's experience in North Sikkim and Garhwal clearly reveals that on an average there are 2 landslides every sq. km and we tend to add one more every 6 sq. km. The mean rate of land loss is to the tune of 120 m^2 per km^2 per year and annual loss of land is about 2500 tonne for every sq. km of area, (Bhandari et al. 1985).

The time has come when the planners will have to recognise the problems of hilly regions far beyond the norms of routine practice and the authorities would have to ensure that no plans are cleared unless adequate provision is made for fullest investigation and protective measures. For example, Bhatt. et al. (1985) have raised a number of pertinent issues related to the Vishnuprayag hydro-electric project at Joshimath and it's environmental implications not fully examined prior to launching of the project. Bahuguna (1985) has feared that Tehri dam would cause widespread destruction of the hills, flood the fertile land of the valleys and create rehabilitation problems.

TABLE 4

Tunnels in the Himalaya

Name of project, name of tunnel, length and cross-section	Rock type	Tunnelling problem	Remedial measure
1	2	3	4
Yamuna Project: * Ichari-Chibro tunnel, 6.2 km, 7.0 m dia.	Quartzite, slate and limestone	Poor stand up time, high overbreak, semi-solid flowing conditions	Shotcreting, pre-reinforcement, pregrouting and heading & benching
Chibro-Khodri tunnel* 5.6 km, 7.5 m dia.	Quartzite, slate, limestone, shale, sandstone and clays	High overbreak, tunnel colsures, abnormal rock loads	Shotcreting, perfobolting, forepoling, flexible lining, heading and benching, and multi drift method
Beas Sutej Link* Project: Pandoh-Baggi tunnel, 13.12 km, 7.62 m dia.	Granite with schistose bands and kaolinised pockets and phyllite	Overbreak, cavity formation, flowing ground conditions, squeezing ground with abnormal load, twisting of ribs, heavy water inflows	Forepoling, destressing by drilling advance holes at heading, benching, and draining rock from behind the heading
Sundernagar-* Slapper tunnel, 12.23 km, 8.5 m dia.	Limestone, dolomite	Overbreak, cavity formation, flowing ground, heavy water inflow	Forepoling, draining rock from behind the heading, changing tunnel alignment
Giri Project: Giri* tunnel, 7.0 km, 3.66 m dia.	Slates with boulder beds, phyllite, shale clay, sandstone	Overbreak, tunnel closures with abnormal rock loads, twisting of ribs, occurrence of gases	Shotcreting with perfobolting, flexible lining, excavating larger dia. tunnel to allow closure before supporting, use of gas detectors
Baira-Suil: Headrace* tunnel 7.6 km, 4.5 m dia.	Carb. phyllite, pebbly slates, phyllite	Overbreak, cavity formation, flowing ground, occasional heavy water inflows	Forepoling
Baira-Baledh feeder* tunnel, 7.9 km, 2.5 m dia.	Phyllite	Overbreak, occasional cavity formation	Forepoling

Maneri Bhali: stage** II tunnel, 16.8 km, 6.0 m dia.	Quartzite, basic rock & limestone	Overbreak, cavity formation and heavy water inflows	Forepoling and draining of rocks before drive
Salal: twin tail** race tunnels, 2 km, 11 m dia. each	Limestone & dolomite	Occasional seepage	-do-
Sanjay (Bhaba):** head race tunnel, 8.0 km 5.0 m dia.	Granite, gneiss, amphibolite and schist	Gouy flowing ground	
Banihal: twin traffic* tunnels, 2.25 km, 5.5 m dia. each	Basic flows & limestone	No major problem	
Khara Project: head** race tunnel, 10.2 km	Sandstone, clay and conglomerate	Overbreak and flowing ground conditions where saturated with water	
Umiam Project:* link tunnel, 2.8 km	Granite and gneiss	Montane-stresses, Chlorite/sericite/kaolinised pockets and heavy water	
Jaldhaka Project:* head race tunnel, 4.4 km, 3.0 m dia.	Schist, amphibolite, and gneiss	Heavy overbreak,& cavity formation	Forepoling
Loktak Project:* head race tunnel, 6.25 km, 3.65 m dia.	Sandstone & shale	Squeezing ground, abnormal rock loads and gases	Perfobolting, shotcreting and use of NATM

* Completed!   ** Under execution

Severity of Landslide Problems in the Himalaya

Degree of severity of the Himalayan landslides and other mass movements swing from zero to alarming, and one index of judgement could be the speed of their movements. Statistically speaking creep rates on Eastern Himalayan slopes range from 5 cm in a decade on slopes β less than 35° to as much as 1 m in a decade on slopes $35° \leqslant \beta < 75°$. Typically movements of landslides and mudslides fall in the range 1-4 cm per day. The most hazards are however associated with high speed mudflows and avalanches which acquire speeds as high as 3 to 50 m/s. These invariably take place with heavy rainfall or earthquakes or both. Take for example the devastating debris flow in the year 1880 on the slopes of Sher-Ka-Danda hill in Nainital which travelled 1 km in 30 seconds, killed 150 people and swept away 'Victoria Hotel', 'Naina Temple' and other buildings and filled a part of the lake.

Similarly, the flow slide of Kuekhola trestle point, (Bhandari 1977), generated large movements in a few minutes destroying the huge retaining wall, the road formation and the rope way trestle platform.

A striking example of devastating landslides in eastern Himalaya is provided by Darjeeling floods of 1968. Towards the end of monsoon, vast areas of Sikkim and West Bengal were destroyed by some 20,000 landslides killing 33,000 people. The landslides occurred over a three day period with precipitation ranging 500 to 1000 mm, considered a 100 year event in the area. Most of the landslides were released during the third day. The 60 km mountain highway to Darjeeling was cut off in 92 places leaving behind a trail of devastation and disruption to the communication system.

The author has documented a number of examples of exceptionally large movements. One of the landslides on north Sikkim moved down by 13 m and moved out by about 26 m. Similarly, on National Highway *31 (Mile 9), a stretch of road sank by 5 m* and moved out by 15 m in 1963. Some corrective measures were provided but the road sank again by 18 m, Bhandari (1982). Most of landslides are made more severe when coupled with rockfalls. The genesis of rockfalls in the Himalaya and their methods of control are discussed elsewhere, Bhandari and Sharma (1975). Slope instability problems seem to compound when landslides involve multitier failure involving e.g., debrisflow or mudflow in slope cover, deep seated movement on boundary shears, soil falls usually at the rear scarp of the slide and rockfall directly hitting the road formations, culverts, bridges and the travelling public.

Apart from the problems of landslides and other mass movements, snow avalanches pose formidable problems in Higher Himalaya and many people are killed almost every year, (Bhandari 1982).

A classifiction of the problems of mass wasting is proposed in Table 5.

TABLE 5

Classification of the Problems of Mass Wasting

Class	Problem	Effect	Economics of Control Measures and Efficiency
A Catastrophes	Simultaneous triggering of several landslides & other mass movements following 'cloudbursts', flash-floods' & tectonic activity. Includes fresh slides as well as reactivation of old ones.	Landslides and breaches often create river blockades, landslide dams and lakes. Damages are spectacular and ground movements extensive and large scale.	Problem often faced as it comes. Control measures require very heavy technoeconomic inputs rarely available. Palliative measures are only partially effective.
B Repetive slides and mass movements	Major old landslides, particularly if left neglected, enlarge themselves to assume formidable proportions. The problem is less severe for slides already in treated state before reactivation.	Slope movements are sudden, extremely large and ensuing subsidences usually of a very high order. Drainage of area is severely impaired & susceptibility to erosion increases.	Massive haulage of earth and protection works essential and efficacy of the latter is intimately related to the appropriateness & adequacy of control measurees and their timely execution.
C First time or fresh slides and mass movements	Problems on cuttings are more severe than those on natural slopes. Slides often involve subsidence at 'crown' & heave at the toe. Planer slides are also common in certain geological formations.	Virgin natural slopes usually retain cover of vegetation. Toe, rear scar and side shear boundaries can generally be identified. Mud flows cut across colluvium.	A 'stitch' in time can generally save the slope at a nominal cost. Drainage deserves special emphasis. Vegetation should be restored to certain surface erosion problem.
D Blockslides and Rockfalls	Shooting boulders hurtle down the slopes ensuing noise trigger mass movements.	Destroy bridges, roads and communication systems.	Often require detouring, tunnelling, anchoring etc. which are expensive.
E Creep Movement	Does not pose any serious problem.	Tilt trees, buildings etc.	No attempts are made to arrest creep movements.

River Action, Flash Floods and Landslide Dams

Carrying capacity of moving water increases proportionately with the velocity of flow and correspondingly with its turbulence. A large river flowing on a smooth bed at about 0.8 km per hour can entrain very fine particles, such as sand sized lignite. To transport the heavier grains of quicksand along that bed, the velocity of current must approach nearly 1.6 km per hour. Himalayan rivers with flow velocities far exceeding these limits are seen to perform prodigious feats of transportation taking into their mighty sweep huge boulders that roll, glide and bounce as they travel, adding to the fury of flow by complex compounding of kinetic energy of motion. The power of flowing water is usually quantified in terms of velocity of flow (Table 6).

TABLE 6

Power of Flowing Water

Transported Rock Fragments	Size* (mm)	Velocity of Flowing Water (m/s)
Fine sand	0.425—0.075	0.3
Coarse sand	4.75 —2.0	0.6
Fine gravel	20.0 —4.75	1.0
Coarse gravel	80.0 —20.0	1.2
Cobble	300.0 —80.0	2.4
Boulders	> 300.0	> 3.0

(*IS : 1498-1970)

The devastating effect of flowing water coupled with flash floods is truly, dreadful. River slopes are stripped naked, huge landmasses roll down into rivers damming them temporarily or even permanently, and avalanches of mud and water effortlessly uproot trees on slopes carrying them kilometres away from where they existed.

In Himalayan rivers, broad bed widths alternate with narrow constricted gorges. Occurrence of flash flood, particularly in a narrow river gorge, seems to be one of the much feared causes of some of the major Himalayan Landslides. Accumulation of slipped masses, shooting boulders, charge of river silt and above all, massive rocks transported by the turbulence of flowing water throttle the narrow river passage building up a reservoir of water (pressure) that eventually flushes the obstacles. The resulting draw-down effect triggers slides in the toe region, eventually jeopardising the stability of the hill as a whole. Blockade of river Teesta by massive rocks transported by river current is a common knowledge. Chopra (1977) reports of boulders as big as 1.5 cu.m and sometimes larger. Chaturvedi and Mullick (1981) report boulders up to 100 cum in size carried about 1 km in a single shower. For the New Vong Slide area in Sikkim, Raghuraman (1975) reports falling boulders of sizes ranging up to 6 m diameter which literally bomb the road formation restraining structure and bridges creating vibrational impact that is felt even at a distance of about 300 m. On one occasion in 1966, the author saw the 40 m wide river at this location virtually blocked for about 20 minutes, (Bhandari 1974). Such blockades have also been seen elsewhere in the Himalaya.

Some of the Himalayan rivers display enormous rise of water level in the monsoon season. The rise of water level in the Teesta river to the tune of 22.5 m in 17.5 hours is illustrated by following flood level records of 4th Oct 1968 at Anderson bridge near Teesta Bazar (Chandra, *1975* ; Chaturvedi and Mullick, 1981 ; Government of India Report).

4 Oct 1968	**River Water Level (m)**	**Remarks**
0500	206.04	Danger Level (DL)
0730	208.39	2 m above DL
2300	228.60	22.5 m above DL

The devastating effect of such a high order of water level fluctuation is obvious. Fujita (1977) reports cases of land slides at the sites of Futase dam, Narugo dam and Shimo-rubo dam that occurred due to draw down effect, and the slide at Shingu dam site that occurred as a result of the fluctuation of water level and heavy rain. Chansarkar (1975a) reports that a cloud burst in area Kunwarikhal resulted in flood (July 1970) in Patal Ganga dislodging huge boulders in the catchment area. The narrow constriction of Patal Ganga was choked and a more than 60 m high reservoir was built up, the bursting of which resulted in flood pulse in Alaknanda, consequently triggering a number of landslides in the immediate vicinity of the river. Similar experiences are reported for Birehiganga, a tributary of river Alaknanda, (Chansarkar 1975b). Krishnaswamy (1980) reports a number of similar examples of blockade of several Himalayan rivers in Middle Himalaya of Uttar Pradesh, Nepal and Arunachal Pradesh. History is witness that even in Pleistocene period damming of river beds and subsequent landsliding took place, as evidenced in the Baspa Valley in the Himachal Himalaya. Man's intrusion in the eco-system seems to have added only to both frequency and gravity of the problem.

Landslide Dams are made by nature and are therefore quickest to appear. Nature seldom designs them for stability and therefore they usually bring about world's largest catastrophic failures rarely to be seen in the manmade dams. Examples of some of the major landslide dams in the Himalaya are presented in Table 7. Similar experiences have recently been reported from the US, Canada, Pakistan, Japan and China, (Schuster, 1986). Whereas cloudbursts, flash floods, avalanches and earthquakes

TABLE 7

Examples of Major Landslide Dams in the Himalaya

Event	Reference
1841	
A mass of rock from west side of Nanga Parbat was preeipitated into the Indus, holding back the waters to form a lake 64 km long, and when a few months later the dam burst, the flood was catastrophic drowing an entire Sikh army camped at Attock 160 km lower down.	Nicolson (1975)
October 1983	
Gohana slide which hurtled down from a hight of a few thousand metres into Birehi Ganga, a tributary of Alaknanda, filled up the river bed to a height of 350 m. The lake formed was 5 km + 2 km. On 24 August, 1984, the dam toppled raising water level by 50 m at Srinagar and two days later, the level of river rose by 4 m Hardwar.	Raina et al. (1980) Krishnaswamy (1980)
July 1970	
Floods in Rishi Ganga created 40 m high blockade near village of Reni in U.P. Lake silted up by May 1970 and eventually blockade breached in July 1970.	Raina et al. (1980)
July 1970	
Narrow constriction of Patal Ganga got choked and more than 60 m high reservoir was built up, the bursting of which resulted in flood pulse in Alaknanda triggering many landslides.	Chansarkar (1975a)
Floods in Birehi Ganga near its confluence with Alaknanda triggered landslides causing major blockade of river with 10-12 m afflux. A girder bridge was by-passed and another one was destroyed.	Raina et al. (1980)
August 1978	
The Kanauldhia Gad, a tributary joining Bhagirati River upstream of Uttarkashi in the U.P. Himalaya spread a debris cone across the main river i ıpounding river to a height of 30 m. Breaching caused a havoc due to flash flood. A 1.5 km long, 20 m deep lake was left behind as a result of failure of the landslide dam.	Krishnaswamy (1980)

are the main causes of formation of landslide dams in the Himalaya, according to the analysis carried out by Schuster (1986), volcanic eruptions and other factors have also been responsible for such dams in other parts of the world (Fig. 9). Schuster also presents the distribution of landslide dams by type of landslide, based on 181 cases from the literature (Fig. 10).

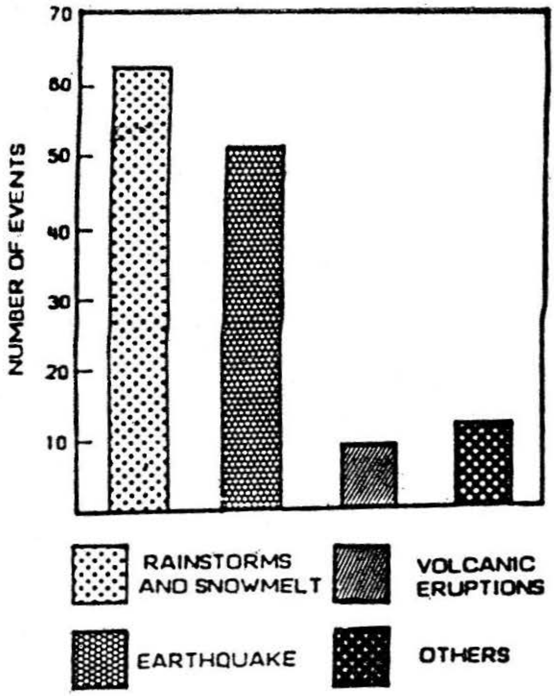


FIGURE 9 Causes of Landslides that have Formed Dams Based on 135 Cases from the Literature (Schuster 1986)

Similar to the experiences in the Himalaya, overtopping, piping and slope failure are identified as the causes of failure of landslide dams (Fig. 11). Other important factor to be considered is the life of a landslide dam which in the Himalayan situation, unlike that elsewhere, depends largely on dynamics of destabilising forces not fully understood at this time. Dimensions of a dam, it's mechanical characteristics, geological setting and support it derives at interface with ambient formation contribute to stability, and magnitude and dynamics of inflow to the impoundment tends to counter that. As the height of such dams is usually seen to increase without corresponding increase of base width or flattening of slopes, failure becomes imminent close on the heels of their formation. The longest life of a landslide dam that ultimately failed in the Himalaya to the author's knowledge, is Gohana Slide Dam of October 1983 which breached on 24 August 1984 after nearly 10 months of its formation. Most others have hardly survived beyond 60 days of their coming into existence. The experience seems similar to the one reported in Fig. 12.

Rainfall, Cloud Bursts and Landsliding

The search for a relationship between 'incidence' of a landslide and 'rainfall' seems practical although it may be more scientific to took for a relationship between piezometric pressure across the critical surface of

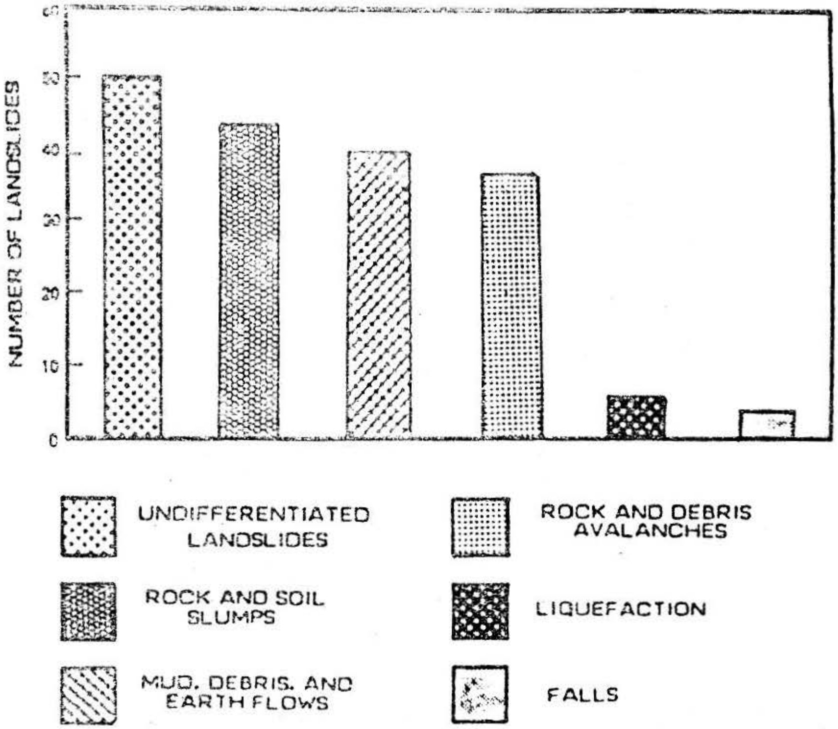


FIGURE 10 Distribution of Landslide Dams by Type of Landslide Based 181 Cases from the Literature (Schuster 1986)

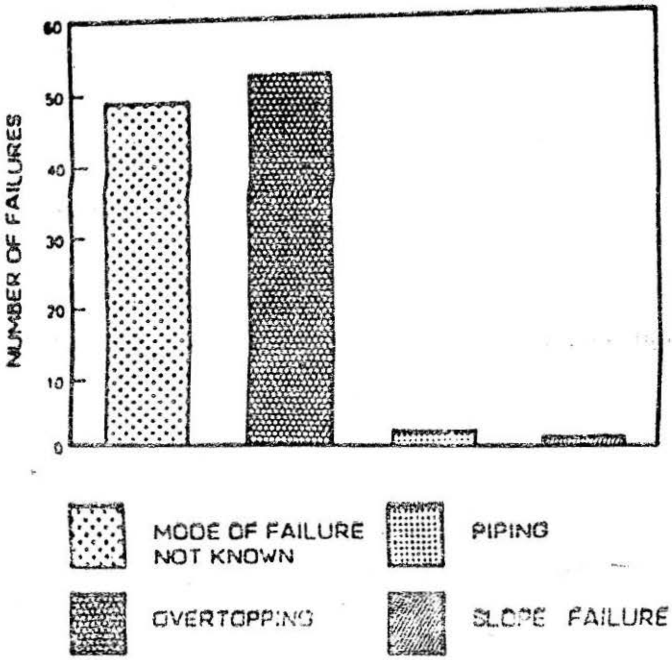


FIGURE 11 Modes of Failure of Landslide Dams Based on 103 Failures from the Literature (Sheduler 1986)

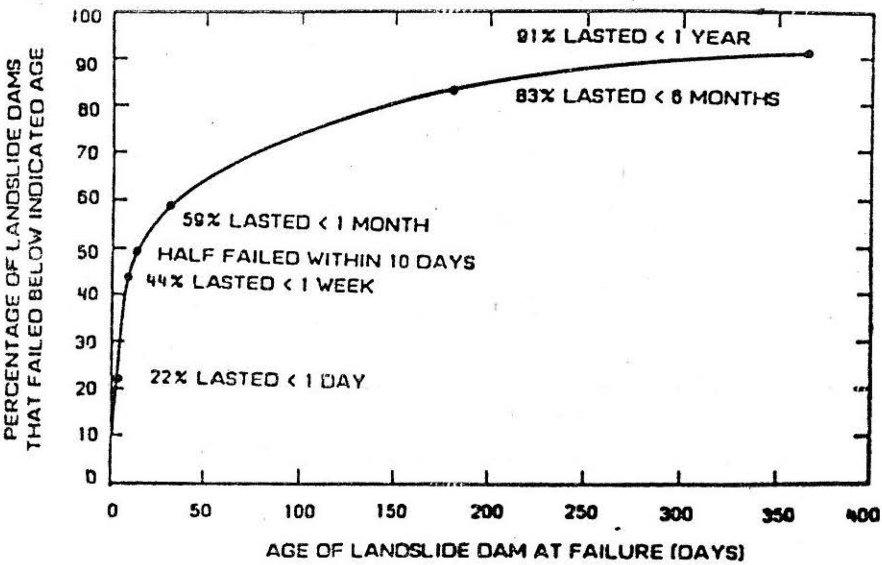


FIGURE 12 Length of the Landslide Dammssurvived Based on 63 Cases from the Literature (Schuster 1986)

sliding and incidence of a landslide. A geotechnical engineer, in a great majority of cases, 'knows' neither the 'critical surface' nor the 'pore-pressures' on it. On the other hand, rainfall observations are inexpensive, simple and common, Bhandari (1984).

The avilable case records suggest that reactivation of old Himalayan landslides invariably takes place following heavy or prolonged rains. For first time slides, however, the action is so long delayed that connection between rainfall and landslide appears tenuous. In such cases it is conclusively established that to name rainfall as 'the cause' would be as wrong as blaming the dynamite that rocked the building as the cause, although the dynamite, the fuse, the match and the man behind the blast must all share the blame as co-partners.

Rainfall particularly in Sikkim Himalaya is often punctuated by flashes of cloudbursts. A cloudbursts comes with the speed of thunder, lasts for a few minutes to as long as three hours at a time, and leaves behind a trail of devastation worse than inflicted by the combind effect of rainfall for the rest of the seasion. Rainfall records of the Teesta Valley for the period 1891-1965 speak of rainfall intensities exceeding 250 mm in 24 hours, repeated more than 40 times! Table 8 would put the range at 310-1800 mm in 24 hours ; rising to as high as 4032 mm in 24 hours in an isolated case. Taking the mean annual precipitation as 5000 mm for the Teesta Valley, the Event Coefficient (Ce) = (precipitation record of the event/mean annual precipitation) ; mean annual precipitation = 5000 mm figures of precipitation for the events (Table 8) are seen to vary between

TABLE 8

Record of Cloud Bursts in the Teesta Valley

Year	Date	Recorded rainfall mm	hrs	Rate mm/hr;	mm/day	Event coefficient*	Reference
1902	Sep 26-27	320	24	12.9	310	6.2	Chandra (1975)
1915	Jun 11-13	690	24	28.8	690	13.8	Chandra (1975)
1950	June 12	546	24	22.8	546	10.9	Chaturvedi and Mullick (1981)
1968	Oct 3-5	1580 (Padamchen)	36	43.9	1044	20.9	Chandra (1973)
	Oct 5-6	465	24	19.4	565	9.3	Chaturvedi and Mullick (1981)
1969	Aug 5	3000 (Labha-Phaperkheti)	72	41.7	1001	20.0	Chandra (1973)
		2970 (Algarah-Gorubathan)	96	30.9	742	14.9	Chandra (1973)
1972	May 17	168	1	168	4032	80.6	Chaturvedi and Mullick (1981)
1977	Jun 10	230	12	19.2	460	9.2	Chaturvedi and Mullick (1981)
1978	May 20	225	3	75	1800	36	Chaturvedi and Mullick (1981)

* Event Coefficient (Ce) = (Precipitation record of the event/mean annual precipitation) ; Mean annual precipitation = 5000 mm.

6.2 and 36 per cent of the mean annual precipitation. Thus event coefficients (Ce), according to Guidicini and Iwasa (1977), would range between 0.06 and 0.36 which are remarkably high values from any standards, and are usually associated with landslides' on the lower side of the scale and 'catastrophes' on the higher. Admittedly, conclusions derived from study of 'event coefficients alone, without cognizanice of rainfall records prior to the event and without knowledge of landslide history of the area may be deceptive but fact remains that 'cloud bursts' of intensities exceeding 1000 mm in 24 hours ($C_e > 0.2$) trigger mass movements practically in any circumstances, and for $0.1 < C_e < 0.2$, probability of mass-movement is pretty high. For $C_e < 0.1$, a biunivocal relationship between rain and slides does not seem to exist. Pichler (1957) Vargas (1971), Barrata (1969), Endo (1977) Guidicini and Iwasa (1977) and Brand (1984) have attempted correlations between, landslides that occurred in Hokkaido between 1955-58 reveals that majority of them occured when daily precipitation was higher than 200 mm.

Constructions on Problematic Slopes and Their Impact

Several case records highlighting the impact of construction particularly on the problematic slopes of the Himalya have been documented. For example, construction of a 100 m high TV tower on the unstable fractured limestone slopes of Laltibba, Mussoorie led to slope failure in foundation trenches resulting into the suspension of construction activity and requiring detailed slope investigations which ordinarily should have been done prior to launching the construction. The slope analyses revealed that the stress relief due to unnecessarily deep excavations for foundations was either comparable or even higher than the total down-ward foundation stress intensity. Advantage was therefore taken of this fact and foundation trenches were backfilled only to the extent necessary for obtaining desired factor of safety against uplifting, Mohan, et al. (1980).

In a yet another case, a microwave antenna tower built on intensely fractured and layered sandstone slopes of the Monkey Hill in Kasauli required prestressed anchoring for stabilisation, Bhandari (1977). The second phase of Snowdon Medical College building at Snowdon in Shimla required a massive counterfort retaining wall to facilitate construction on an active slide, Both the above problems were first identified not as a result of investigation prior to launching of construction but during it.

Even constructions on the slopes known to be highly problematic are also usually handled without adequate investigation due to constraints of time, resource or because of unplanned activity and naturally adhoc control measures applied in piecemeal cannot be expected to be economical & effective. The culture of instrumentation and long range field monitoring of such slopes is also rarely to be seen for lack of budgetary provision. Time delays in implementation of control measures and their poor maintenance are other matters of serious concern.

Two case records, one dealing with construction of an aerial passenger ropeway on the problematic Sher-Ka-Danda Hill at Nainital and the other involving stability of a road and a village called Chhantikhal on Rishikesh-Badrinath route at location Kaliasaur are presented to highlight the importance of scientific investigations in evolving a blue print of control measures for achieving safety consistent with economy. They will also highlight need and importance of instrumentation and field monitoring, desirability of timely implementation of control measures and their proper maintenance.

Aerial Passenger Ropeway at Sher-Ka-Danda Hills, Nainital

A 705 m long aerial passenger ropeway constructed between Poplars and snowview on the south eastern slope of the ropeway (N 71°E-S 71°W) with respect to the ambient area is shown in Fig. 13. It is supported on two-end terminals designated as the Upper Terminal Point (UTP) and the Lower Terminal Point (LTP) at elevations of 1905 m and 2300 m above the mean sea level respectively, passing over two trestle towers (T_1 and T_2) at elevations 1977 m and 2151 m respectively, (Fig. 14). Despite the slide-prone nature of the slopes and its chequered history, a decision was taken to build the aerial ropeway for promotion of tourism. Naturally it was a great challenge to stabilise the slope for safety consistent with economy. The work was executed with success but a number of other control measures must follow in the interest of long range stability.

Geological Conditions and History of Slope

The area is located in seismic zone IV and slope comprises calcareous greyish to greeenish slates, phyllitic in nature with thin bands of limestone.

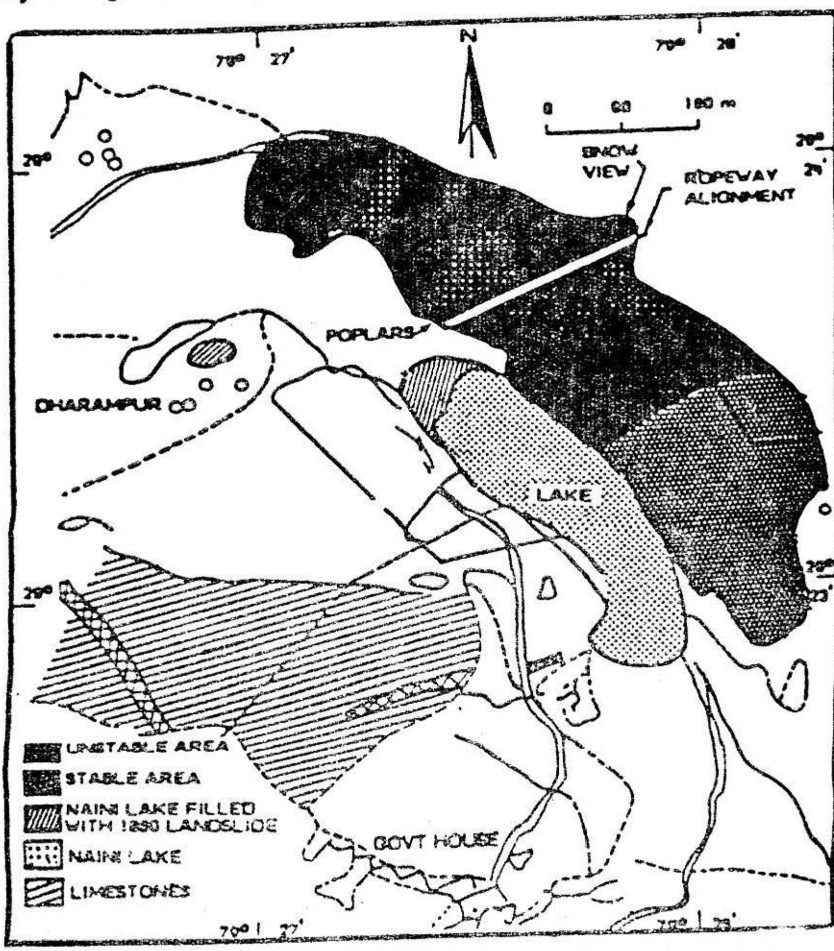
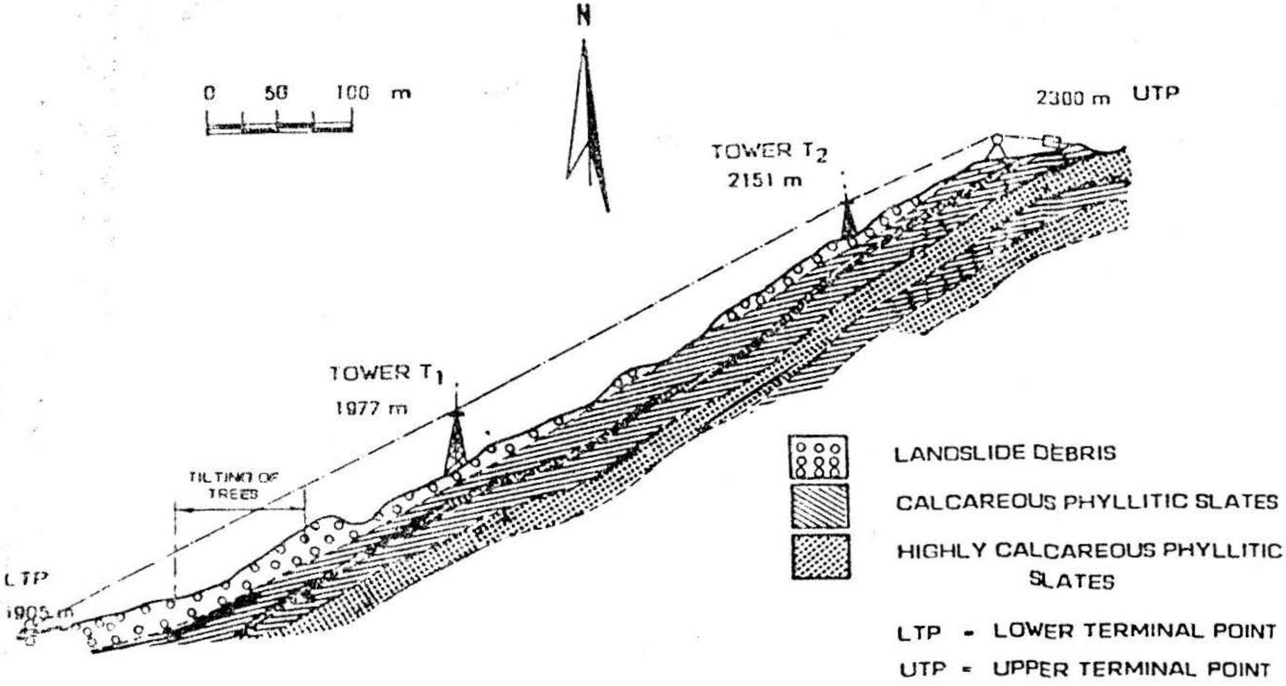


FIGURE 13 Plan Showing Ropeway Alignment on Sher-Ka-Danda Hill



FI GURE 14 Subslope Profile Along the Ropeway Aligrment on the Sher-Ka-Danda Slope Nainital (U.P.)

The cleavage shows a dip 30°—35° parallel to the slope, towards the lake. The rocks belong to lower Krol formation of Permo-Triassic age.

There have been two major landslides on this slope in years 1867 and 1880. It is reported that 1880 landslide took place following heavy rainfall for 3-4 days and an earth tremor. A large portion of north-east range including a number of buildings were swept away in a matter of few minutes and the landslide debris covered the slopes as well as filled a part of the lake. In fact the flat area at the toe of the slope represents the filled up portion of the lake. Oldham (1880) had attributed accumulation of scree material at the base to the occurrence of this slide. The slope cover, inter alia, consists of debris of previous land slides which include shales, slates and limestone embedded in the matrix of silt and clay, the proportion of which is found to increase with depth.

The presence of longitudinal fissure at the top of the Sher-Ka-Danda ridge, running almost over the full length of this ridge is considered to be a tensional opening due to slow gliding of entire slope along deep seated cleavage planes or shear zones dipping towards the lake. The presence of highly puckered, fissile and weathered slates in the slope areas indicates gradual movement of the slope towards the lake. The debris covered areas and the slope steeper than 30° commonly show the presence of tilted trees. The exploratory studies carried out near the base of the slope reveal the presence of thick fluvioglacial upper material, lake sediments and landslide debris resting over the lower Krols. It also shows that there is no toe support of bed rock even at a depth of more than 60 m for this slope.

Observations on the movement of the hill slope for a period of about 70 years conducted by Geological Survey of India have shown that cover of hill has been creeping downhill with gradual diminishing rate of movement reaching an insignificant level, (Fig. 15).

Sub Slope Characteristics

The rock drilling scheme included three drill holes each at both the trestle points upto the depth of 40 m. At the upper terminal point, 5 drill holes were made. All the drill holes failed to indicate and core recovery indicating very poor quality of rock. Three of the drill holes one each at locations T_1, T_2 and UTP, were extended to 60 m, but there was no improvement in core recovery. Microscopic examination of collected samples indicated that the rock cuttings were generally fresh and free from any sign of alteration. These observations were contradictory to the information collected from drilling data. In order to ascertain the quality of rock mass more precisely, the drillling details were carefully scrutinised. Originally TC bit was used for drilling with 80 rpm and water pressure of 1.5 to 2.0 kg/cm^2. In order to improve core recovery, various speeds of drilling were tested at site along with change of water pressure

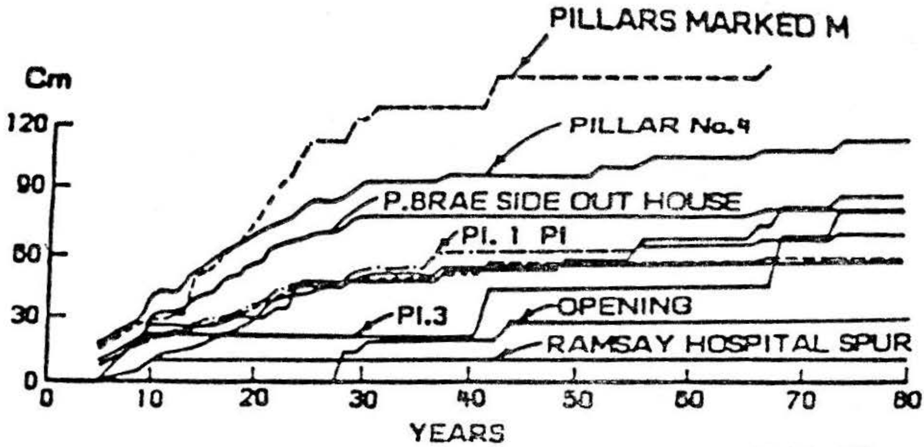


FIGURE 15 Vertical Movement Record of Markers on the Sher-Ka-Danda Hill Nainital

and finally a speed of 100 rpm and water pressure of 2.5 kg/cm^2 were used. Also, drill holes were made slant to suit local geology using diamond bits. With the above revision in drilling procedure, a good recovery of rock core could be achieved restoring the confidence that rock mass was not as poor as the earlier drill holes had indicated. The RQD thus increased from virtually 0 to 24.

The rock sample testing led to shear strength parameters of the material summarised in Table 9.

TABLE 9

Shear Strength Parameters Used in the Stability Analysis

Parameters	Values Assigned
Choesion Intercept	$c' = 10.0$ t/m^2, in the rock mass above the discontinuity.
	$c' = 0$, along the discontinuity.
Shearing Resistance	$\phi' = 40°$, in the rock mass above the continuity.
	$\phi' = 30°$, along the discontinuity.

The unit weight of rocck mass was found to be 2.75 t/m^3 and the slope stability was analysed form pressure ratio (r_u) ranging between 0 and 0.1 and seismic coefficient (μ) ranging from 0 and 0.15. Geology of the slope was suggestive of biplanar failure surface with basal slide boundary coincidant with the discontinuity. Typical failure planes and influence of their orientation on factor of safety are shown in Fig. 16 and Fig. 17,

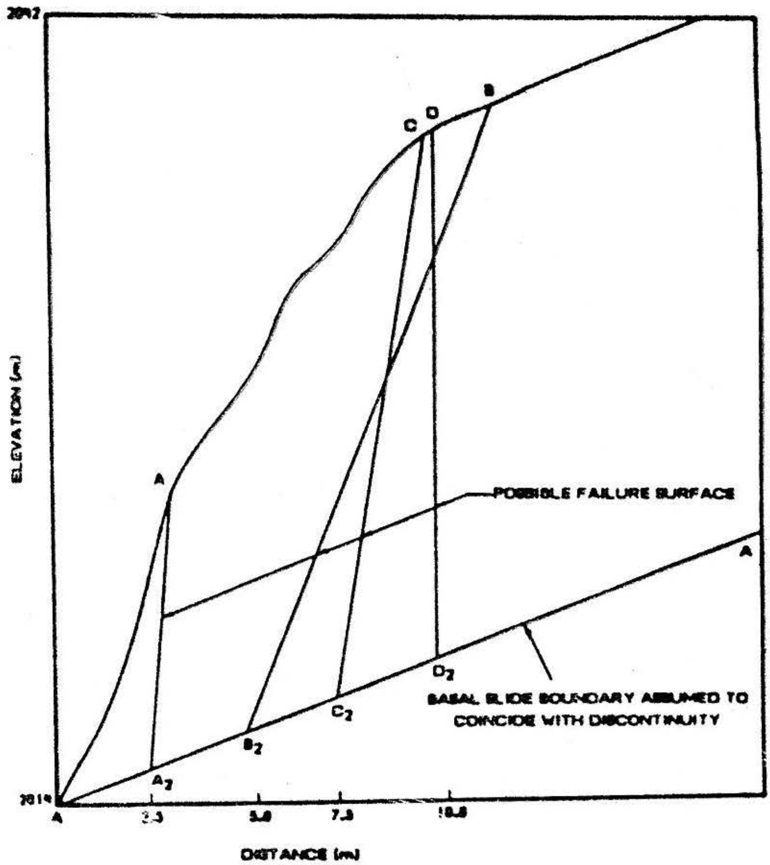
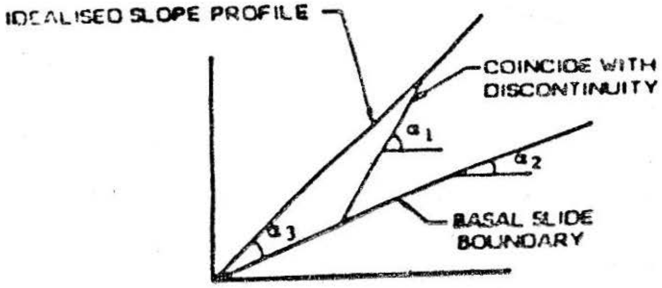


FIGURE 16 A Typical Section at T_1

The minimum factor of safety at the various sections analysed were found to lie in the range 0.85 to 1.4 depending upon the assumptions of *failure surface, shear strength* parameters, pore pressure ratio and seismic coefficient.

Methods to Augment Factor of Safety

Stability can be usually improved by adding to the shearing resistance of the rock mass. This is accomplished either by (*a*) gouting the rock mass chiefly to improve the over all shear strength or (*a*) providing 'Rock Bolts' or 'Anchors' chieflly to add to the effective normal pressure. Grouting is expected to improve both c' and ϕ' values but inhibit natural drainage and rock anchoring is expected to improve σ_n values particularly on the zone of sliding. Grouting was not considered feasible in view of the presence of excessive gouge material and therefore the treatment by prestress rock anchors was adopted,



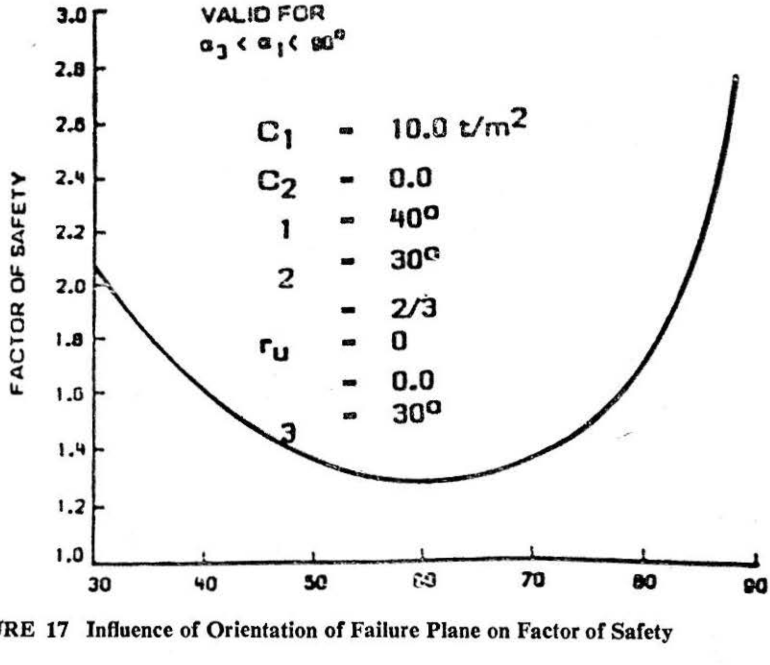


FIGURE 17 Influence of Orientation of Failure Plane on Factor of Safety

Having established the need for prestress anchors to augment the stability of the slope, full scale anchor tests were designed and executed to yield (*a*) scientific assessment of the bond stress and (*b*) relaxation losses as a function of time. In view of the rather poor quality of rock mass, it was decided to limit the magnitude of prestress to 80 tonne only so as to avoid undesirable tension zones around the fixed length of the anchor. The test anchors were designed with fixed lengths of 6 m, 10 m and the 15 m so that at least 2 of the 3 anchors could be expected either to fail or be close to failure. The total anchor lengths were kept about 60 m to take care of the critical surface of sliding, determined by stability analysis.

High tensile steel wires of 7 mm diameter having maximum capacity of 105 kg/mm² were used. Two extra strands were provided to guard against the failure of strands under the maximum applied load. Following Littlejohn (1976), 1.2 times of the designed load was applied at the time of testing. A typical set of timeloss of prestress and time-elongation relationships is shown in Fig. 18. Anchors were designed accordingly and stress relaxation was made up by rastressing after a lapse of time.

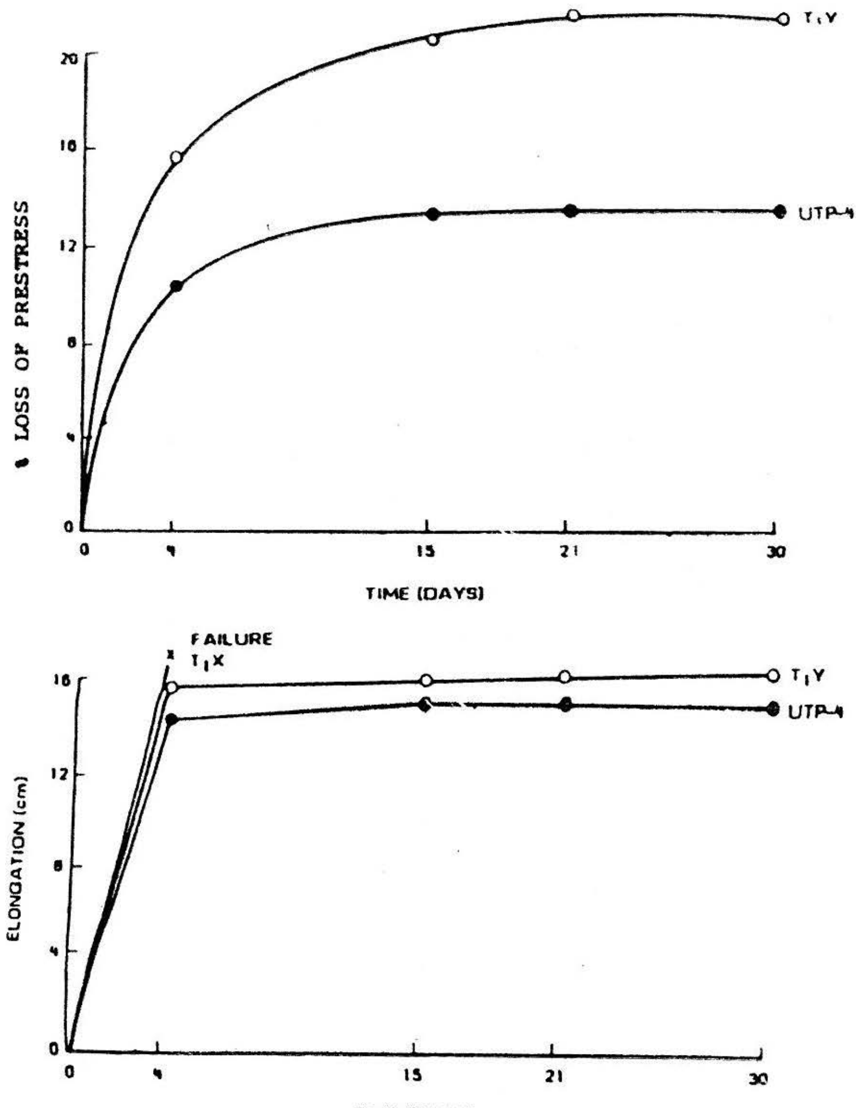


FIGURE 18 Time Vs Percentage Loss of Prestress and Elongation Curves of Test Anchors

Instrumentation

Seven Casagrande open standpipe piezometers were installed at different depths (10 m to 58 m) at location T_1 and T_2. Typical water levels above a piezometer tip level, (Fig. 19) show little variation with time.

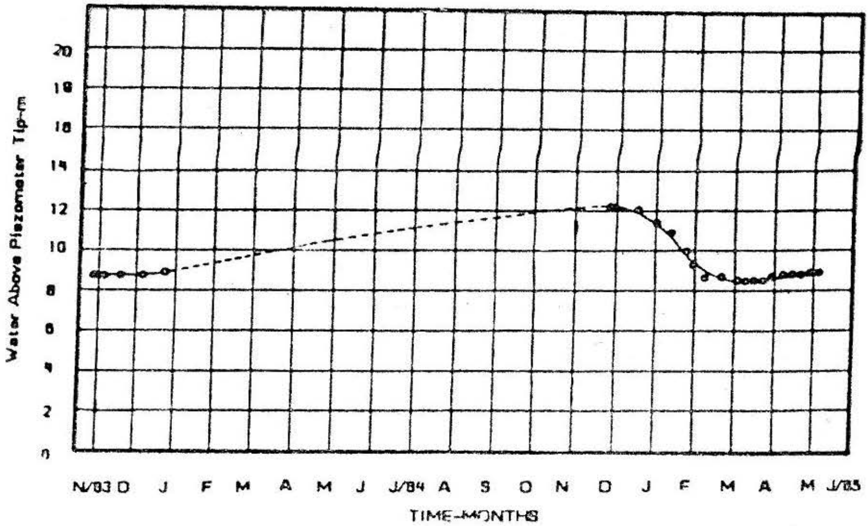


FIGURE 19 Water Level Above Piezometer Tip T_2P_3 at 29.5 m Below Slope Surface

Five, five point rod type borehole extensometers were installed at critical locations on the slope as revealed by measurements of surface movements. Four borehole extensometers T_1E_1, T_1E_2, T_2E_1 and T_2E_2 were installed in April-May 1983. A fifth one, T_1E_3, was installed in June 1984 when T_1E_1 was damaged in a slide which occurred uphill of T_1 while excavating the pit for the foundation of tower T_1.

Measurements on these borehole extensometers yied linear distance of the anchor points in a borehole with respect to a mouthpiece at the top end of borehole. Change in this linear distance between two observations indicates the relative displacement between the mouth piece and anchor point. A typical set of results of measurement related to borehole extensometer T_1E_2 near tower T_1 is shown in Fig. 20. Summary of observations is presented in Table 10.

The movement recorded by extensometers were largely attributed to making of deep excavations which became necessary to install tower foundations. While excuting tower foundation T_1, the excavation suffered three landslides on 25 January 1984, 11 February 1984 and 19 March 1984. The rate of recorded displacements was naturally high. On the basis of the evidence for slope surface instability despite anchoring, the essentiality of vegetative turfing, drainage and restraining structures were highlighted,

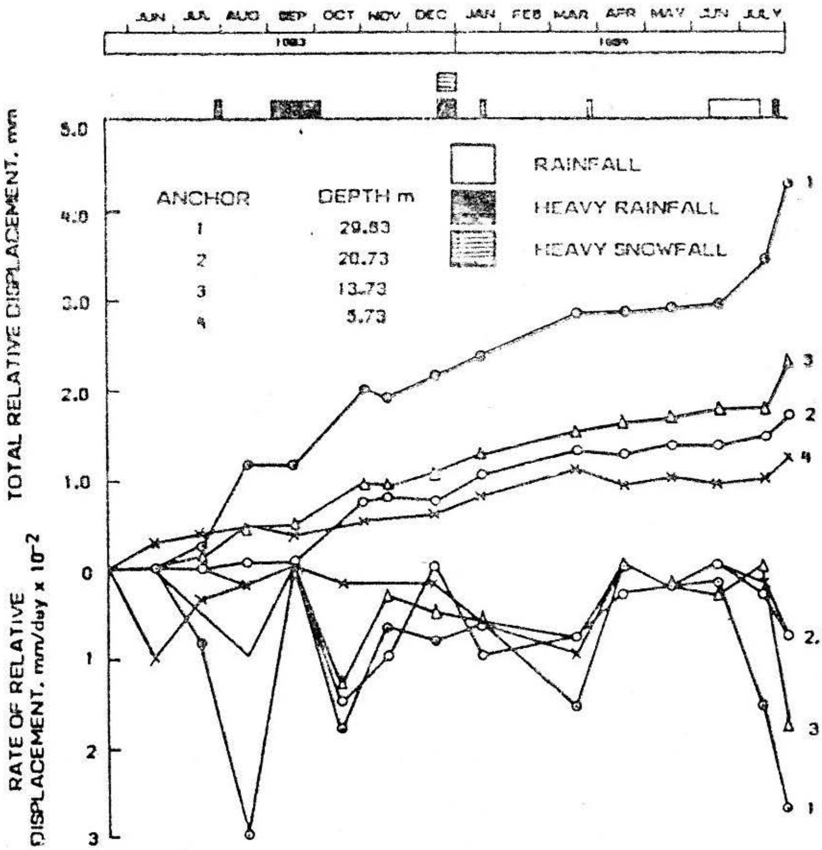


FIGURE 20 Variation of Total Relative Displacement and Rate of Relative Displacement with Time Near Tower T_1

The project stands successfully completed but the question remains whether the project authorities would seriously take the recommendations still unimplemented so that the stability of the ropeway could be ensured at all times !

Landslide at Kaliasaur

For over six decades, Kaliasaur landslide, (Fig. 21) is a nightmare on Rishikesh-Badrinath road. The road is located in sharp bend on the left bank of Alaknanda river, Fig. 22 and Fig. 23. The slide is located at 18 km east of Srinagar (Garhwal) Village. Kaliasaur is located 3 km downstream.

The location has experienced a number of major landslides in 1952, 1963, 1965 and 1969. The slide of 19th September 1969 had blocked 3/4th of the width of the river flowing about 100 m below the road level. The road was badly damaged in a stretch of 300 m. The crown portion of the

TABLE 10

Observations of Rod Type Borehole Extensomers

B.H. no.	Downward angle with horizontal	Anchor no.	Depth of anchor (m)	Period of observation	Total relative displacement (cm)	Max. depth of influence	Max. observed rate of relative displacement (mm/day)		Remarks
							Period	Rate	
		1	34.20		2.765		Oct. 1983	0.36	Dislodged in March 1984 due to a slide. High rate of displacement not indicated in March as observations between 19.1.1984 and 19.3.1984 were not taken.
		2	22.73	16.5.1983	2.805		—do—	—do—	
T_1E_1	10°	3	16.73	to	2.870	< 6.5	—do—	—do—	
		4	8.73	19.3.1984	2.850		—do—	—do—	
		5	4.73		0.840		March 1984	0.125	
		1	29.83		0.430		Aug. 1983	0.03	
T_1E_2	10°	2	20.73	16.5.1983	0.170	Deep Seated	Oct. 1983	0.015	
		3	13.73	to	0.230		July 1984	0.018	
		4	5.73	29.7.1984	0.120		March 1984	0.010	Stable
		1	32.00		2.735		July 1984	0.230	
		2	25.00		2.935		—do—	—do—	
T_1E_3	15°	3	18.00	5.6.1984	2.865	< 3	—do—	—do—	
		4	10.00	to	2.970		—do—	—do—	Unstable, needs immediate remedical measures.
		5	5.00	29.7.1984	2.975		—do—	—do—	
		6	3.00		3.180		—do—	—do—	
		1	37.50	18.4.1983	0.690		March 1984	0.053	
		2	28.18	to	0.740		—do—	0.071	
T_2E_1	10°	3	21.15	29.7.1984	0.375	< 5	Nov. 1983	0.030	Stable
		4	12.16		0.720		March 1984	0.056	
		5	5.11		0.815		—do—	0.083	
		1	37.63		2.320		Nov. 1983	0.250	
T_2E_2	10°	2	28.63	16.5.1983	1.870		July 1984	0.210	Unstable, needs immediate remedical measures.
		3	21.63	to	1.435	Deep Seated	—do—	0.156	
		4	12.63	29.7.1984	1.445		—do—	0.156	
		5	5.63		1.370		—do—	0.140	

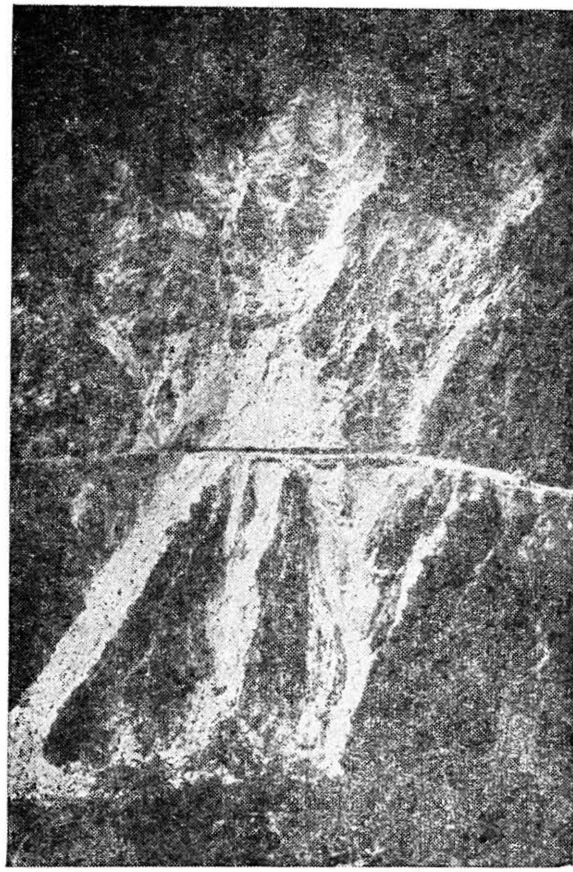


FIGURE 21 Kaliasaur Landslide on Rishikes Badrinath Road

slide extended nearly 120 m above the road level. The slide continued to be active over a period of two weeks. Thereafter, during 1970, 1971 and 1972 the landslides occurred again disrupting the communication system and each time new formation width had to be cut. During August-September 1984, following heavy rainfall, a major landslide occurred and damaged the road considerably, extending the rear scar of the slide retrogressively. The recent slide was in August 1986.

The total area of the slide above and below the road levels together measured 8600 m^2. Every year, the debris added to the river is estimated to be about 5000 tonne.

Geology

The landslide is located in the Garhwal Group of rocks. The main rocks in this area are white and light green quartzites interbedded with maroon shales.

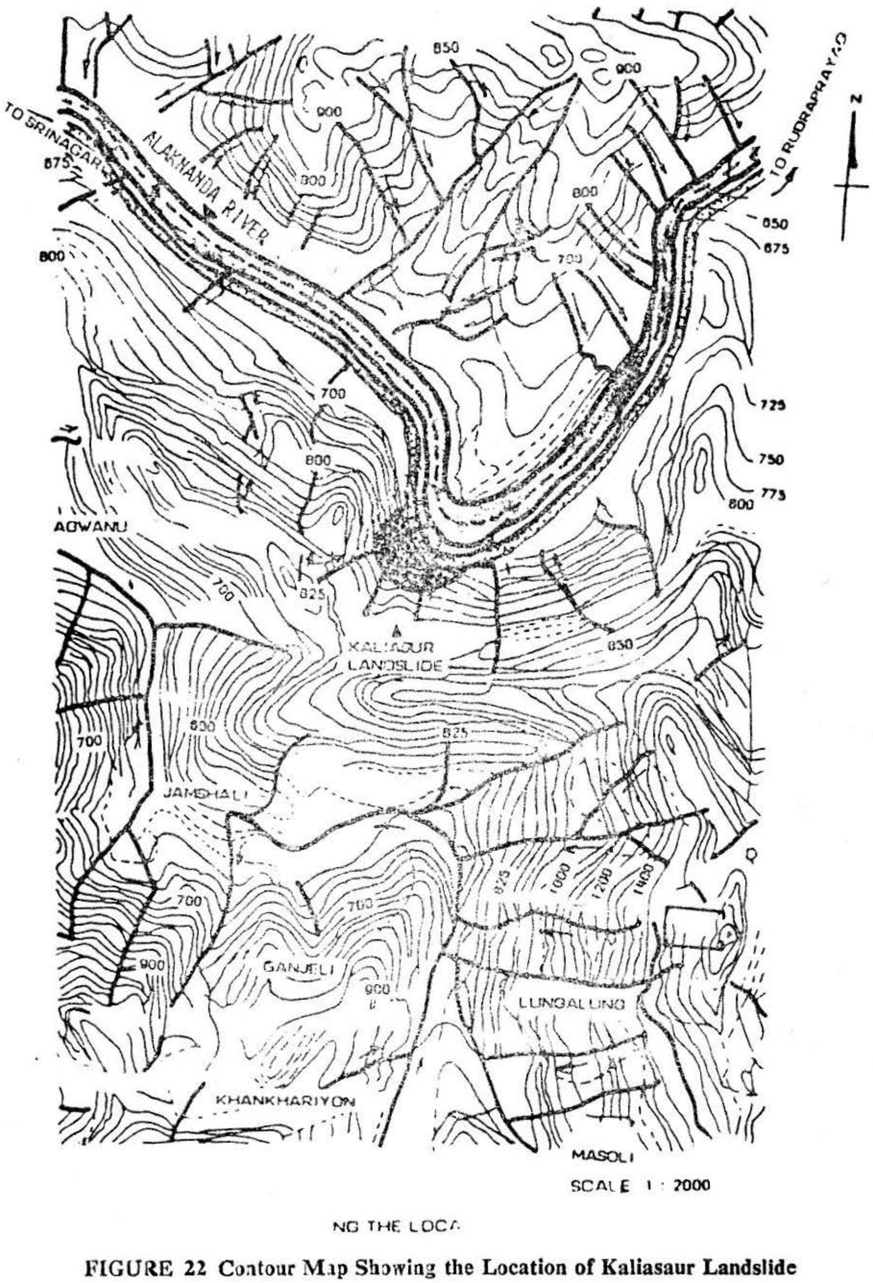


FIGURE 22 Contour Map Showing the Location of Kaliasaur Landslide

Geological mapping was carried out on a 1: 2500 scale and the area included the surroundings of the landslide zone. Three traverses were taken i.e. along the main road, along the river and along the Khankra-Chhantikhal road.

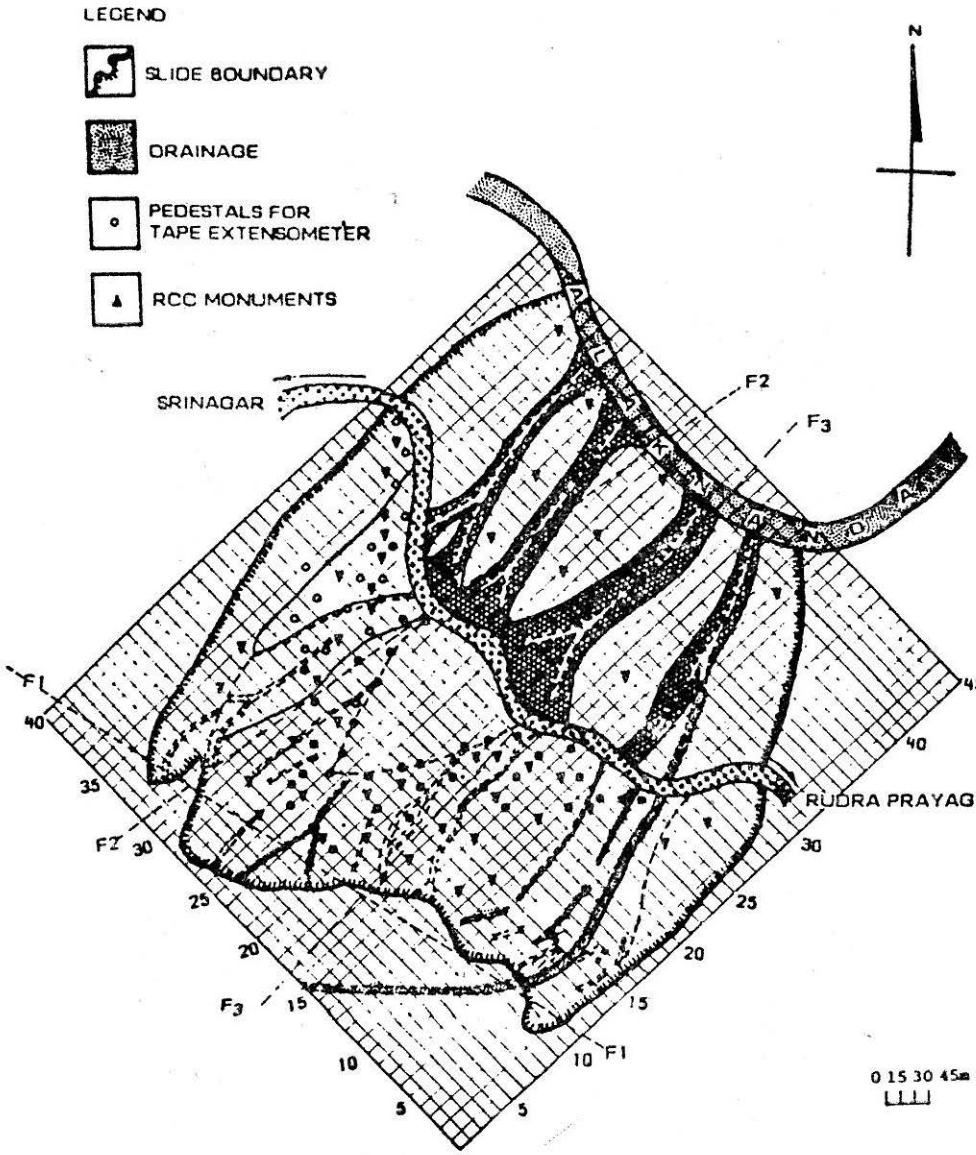


FIGURE 23 Scheme for Monitoring of Surface Movements of Slopes at the Kaliasaur Landslide on Hardwar-Badrinath Road

Observations along the road and long the river suggest the presence of two types of quartzites. One is light green colour with thin beds of maroon shales, and the other is massive and well jointed yellowish white quartzite. On the western side of the slide zone the quartzite are light green with shale bands having a general southward dip with amounts ranging from 25° to 60°. These quartzites end up abruptly along a scree zone beyond which massive yellowish quartzites dipping southeast with amounts 30° to 40°, are exposed. It appears that the scree zone conceals a fault zone trending NE-SW and extending across the river. The massive quartzites continue upto the western flank of the slide zone where they end up against the slide debris.

On the eastern side of the slide zone the quartzities exposed have maroon shales with a south easterly dip and amounts varying from 30° to 60°. These quartzites continue along the river bed. It appears that another fault zone trending NW-SE may be present somewhere within the slide zone.

The traverse *taken along Khankra-Chhantikhal road suggests that the* formations exposed along the main road do not codtinue upto Chhantikhal village. A small and steep escarpment also appears to separate the two sections. On the Chhantikhal road, there are massive quartzites on the eastern side dipping south-east at 20° to 25°. These quartzites are inter-bedded with greyish green metabasics and end up against phyllites having parallel dips. The exposures of dolomitic limestones are found along the road towards south-west of Chhantikhal.

The geological succession in this area appears to be as follows:

Massive yellowish white quartzites

Greenish quartzites interbedded with
maroon shales and Metabasics

Greenish grey phyllites and shales
Dolomitic limestone

The rocks appear to have been folded into a plunging overtuned anticline on the western side of the slide zone with a plunge towards north-east. Another anticline appears to be on the eastern side of the slide zone with plunge towards south. There appears to be a number of fault zones in this area. A major fault appears to be along the Chhantikhal road with a roughly east west trend. This fault zone passses through the crest of the slide zone and separate the metabasics from the quartzites. Two other faults with trends roughly NE-SW exist in this area. They all appear to be high angled and one of these passes through the main slide zone. All these faults merge into the Chhantikhal fault.

Geomorphology

The geomorphological mapping was carried out on scale 1:3125. In this area Alaknanda occupies a deep sinuous gorge with the crest of sinousity located near the slide zone, (Fig. 22).

The slopes on the left side of the river are steep whereas they are rather gentle on the rightside. Slide zone is located on the left side of the river, where the main road is passing through. This area contains a number of smaller scree zones, along with exposures of quartzites. There appears to be a significant escarpment running east-west below the Chhantikhal village. This escarpment continues upto the river bed. The lower part of this escarpment is occupied by colluvium resting nearly at it's angle of repose. The middle part exposes quartzites and on the top there are cultivated fields. Above this escarpment, is a dense forest.

There are a number of small streamlets flowing over the escarpment and meeting the river at high angles. Two such streamlets are reported to pass through the land slide zone. Their implications and morphometric parameters are discussed in detail by Prashad (1985). Tension cracks varying from about 1 m to more than 100 m are present at several locations above the crown of the slide.

Mechanism of Kalisaur Landslide

Kaliasaur landslide is essentially a multi-tier, retrogressive landslide in a complex rock formation with clear evidences of fault planes revealing intense tectonic activity in the geological past. Evidences of sliding at the inter-face of quartzites and maroon shales must presumably have been the starting point. Road construction activity in general and repeated back cutting required for restoring the road width; year after year poor drainage, recurring debris slides in the colluvium cover on the slope robbing it of the vegetative cover and river action at the slope toe have all been responsible to develop the landslide to it's formidable size obtaining today. A typical slide cross-section is shown in Fig. 24.

A very large number of point load tests on quartzite specimes reveal uniaxial compressive strength the order of 1800 kg/cm^2. The samples of maroon shale were however found to be so soft that even undisturbed

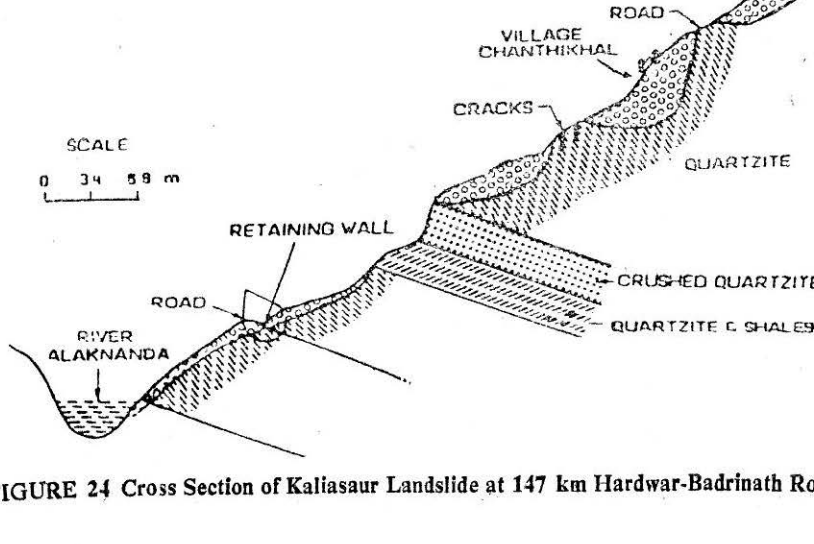


FIGURE 24 Cross Section of Kaliasaur Landslide at 147 km Hardwar-Badrinath Road

sampling was difficult to achieve. During dry weather, samples were found to readily crumble into powder. Large displacements have, however been inferred due to presence of polished surfaces. The characteristics of polished surfaces and genesis of their formation were therefore important factors. The condition of particle breakdown at the shale surface was simulated in the laboratory by subjecting the surface to artificially created abrasion effect for different intervals of them and determining particle size in laser particle analyser. The results, (Fig. 25 and Fig. 26) clearly indicate that initially because of breakdown of bigger particles proportion of the clay size fraction at the boundary tends to decrease but later on clay fraction records marked increases, as could be expected corresponding to large *movements. Well graded character of material at slide boundary* is seen to turn into very nearly a single size fraction. The angle of

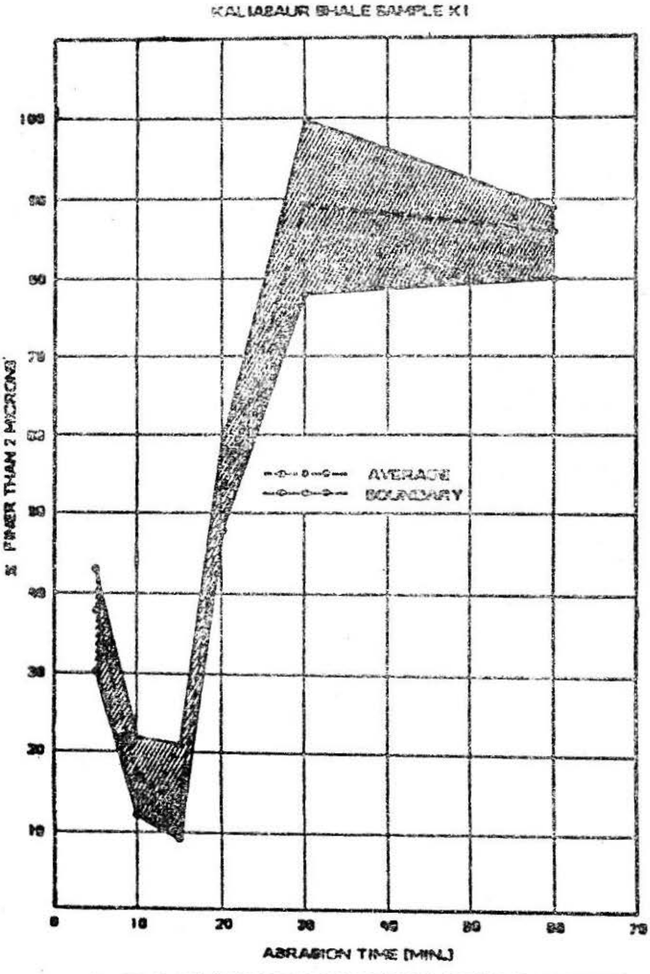
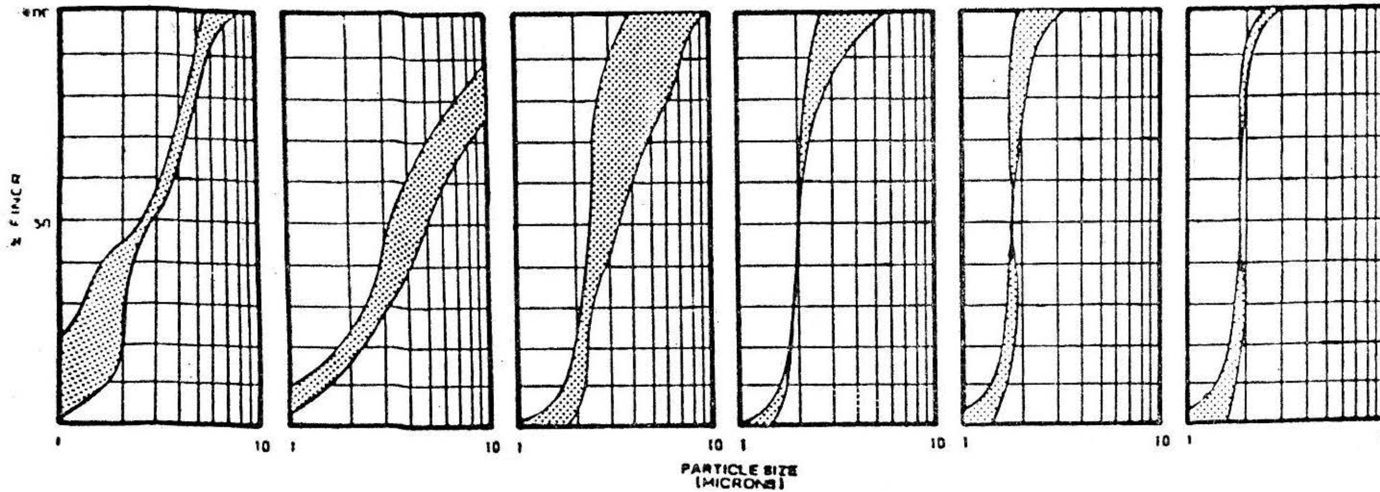


FIG.25. PARTICLE BREAKDOWN DUE TO LARGE DISPLACEMENTS

FIGURE 25 Particle Breakdown due to Large Displacements

KALIASAUR SHALE SAMPLE K1



	5 min	10 min	15 min	20 min	30 min	60 min
Cu	2.1 - 4.4	2.7 - 4.7	1.3 - 2.3	1.2 - 1.3	1.1 - 1.2	1.1 - -
Cc	0.7 - 0.8	0.8 - 1.3	0.6 - 0.9	1.0 - -	0.9 - 1.0	1.0 - -
dm	1.6 - 2.8	2.6 - 3.5	2.4 - 3.0	1.9 - 2.1	1.6 - 1.9	1.6 - 1.8

FIGURE 26 Grain Size Variation on Particle Breakdown due to Larage Displacements

shearing resistance is of the order of 28° but it's residual value corresponding to very large strains is yet to be studied in the light of the above observation though post peak values of shearing resistance may lie in the range 18°-22°.

Debris accumulation on the slope is excessive. Plentiful supply of water during the monsoon season combines with it to cause debris flow. Rockfalls are also very frequent.

Field studies have also shown that outlet of some concealed flow channels below the existing road level is responsible for undercutting of road resulting into subsidence.

Control Measures

Recommended control measures include grading of slope, provision of surface and subsurface drainage system, timber piling for stitching of the debris cover onto the slope, construction of retaining and breast walls, check walls and putting back the vegetation on the slope lost well over last six decades.

The control measures are discussed in detail elsewhere but two of the newly developed concepts in practice are highlighted below :

Stitching of Debris on Slopes

Timber piling or bally cribbing is sometimes being used for arresting surficial movements in the slope cover so that vegetation and drainage facilities are not harmed and hazards due to debris flow could be minimised. Driving of timber piles result in densification of loose and shallow granular slide prone carpet on the slope and provide 'stitch action' that helps to hold the earth mass. Such piles are usually stiffened laterally by horizontal runners of timber. For example some 60,000 ballies of 12.5—15 cm diameter, 3 m long were driven to depths ranging from 1.5 to 2.0 m to stabilise Padamchen Slide in Sikkim. After stiffening the ballies laterally, the space (in between) was filled up and the vertical parts were tied with each other by 8 SWG binding wire. The bally cribbing and terracing were also used to stabilise a shallow landslip at the rear slopes of Idgah substation building in Shimla, Bhandari (1973). After intensive field trials, 20 cm diameter, 3 m long ballies were driven to a depth of about 2 m using a 30 kg hammer, about a metre apart. These ballies were braced on the uphill side by means of 15 cm diameter, 3 m long ballies in three tiers using dogs, nails and 8 SWG wire.

Difficulties of timber piling have now been largely overcome by a new, lowcost portable timber piling machine developed at the Central Building Research Institute, Kaushish and Jain (1986), (Fig. 27). Timber piles 10 cm square from Deodar, Sheesham and Eucalyptus wood were driven in lengths of 1.5 m each suitably spliced, at six locations on the Kaliasaur

FIGURE 27 Stitch of Colluvium on the Slope at Kaliasaur by a Simple Lowcost Timber Piling Machine

slide using the portable machine requiring only one man to operate. The 30 kg hammer used earlier is now being replaced by 50 kg hammer to achieve higher orders of driving energy.

Low Cost Retaining Walls From Slope Waste

One of the novel concepts advanced at the Central Building Research Institute (CBRI) is to make extensive use of slope waste, landslide debris, colluvium, talus and other excavated materials in construction of retaining walls to stabilise slopes. It has been conclusively demonstrated that empty bitumen drums available in abundance through construction agencies *like DGBR can be interconnected vertically and laterally, filled* up with debris to achieve gravitational effect and suitably anchored to obtain desired levels of stability. They could be reasonably designed as anchored diaphragm walls. Cross-section and other details of a nearly 100 m long such wall built by the CBRI at Kaliasaur to stabilise slope immediately uphill on the road is shown in Fig. 28. It's sequence of construction is shown in Fig. 29. A view of the wall after construction, taken in August 1986 at a time when debris flow in the slope cover was at it's peak, is shown in Fig. 30 and a close up is shown in Fig. 31.

The wall has stood well the onslaught of slope movements and the 1986 landslide but could be expected to remain in place in future only when other control measures are simulaneously implemented. Kaliasaur thus provides the best example of need for instrumentation and close monitoring of slopes, implementation of control measures in a single working season for best return on investment and for introduction of innovative techniques such as the drum debris retaining wall to bring down the expenditure on control measures to a minimum. The added advantage is that need for long distance transport of construction material is eliminated and millions of tonnes of wasteful debris in the Himalaya usually lost to rivers could be effectively utilised. Hazards of debris that generate mass movement of a variety particularly in the monson season could also be minimised.

Strategy for Development of the Himalaya

The cry for Integrated Mountain Development on one hand and Eco Vandalism in the Himalaya on the other has brought to focus the need for Eco technology to co-exist with its all powerful and awesome first cousin technology. While for 'technology' the supreme consideration is man, the eco technology seeks to protect and preserve all forms of life in the Himalaya and strongly calls for restoration of interdisciplinary development ethos.

For the fragile Himalaya to be saved from the ever increasing negative impact of slope instability, the experiences of past must be consolidated,

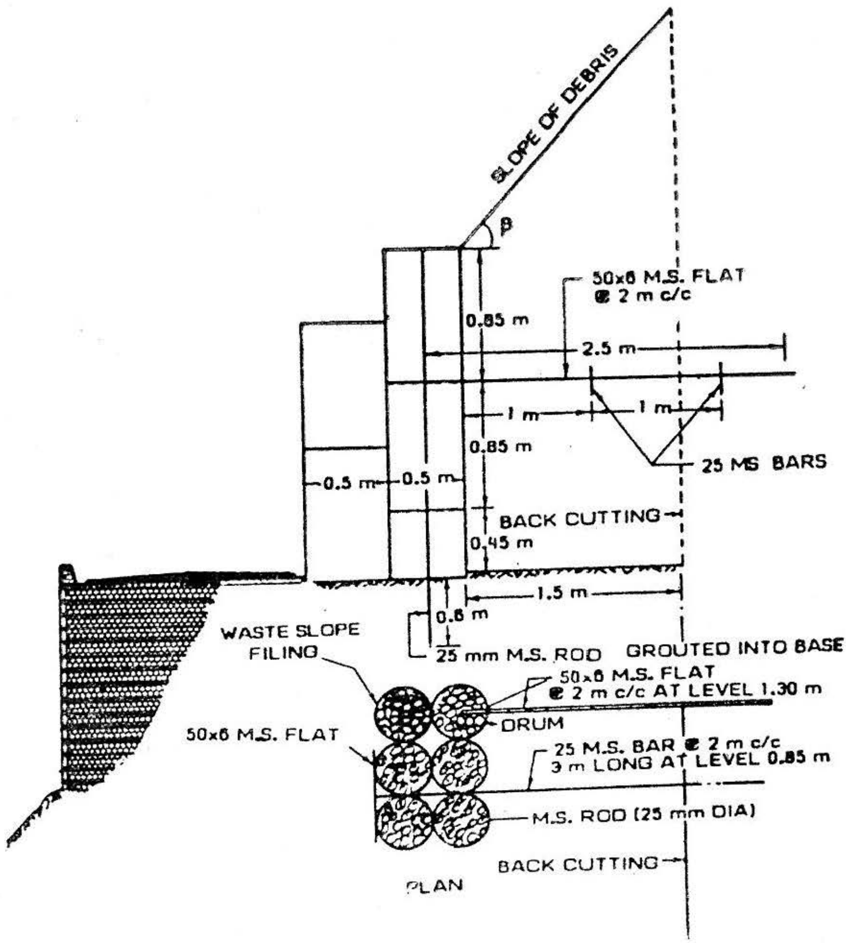


FIGURE 28 Anchored Drum Diaphragm Wall Built of Slope Waste and Empty Bitumen Drums

the available body of information and data should be synthesised, a powerful data base should be created, the entire mountain range in general and the problematic unstable slopes in particular should be mapped and classified to meet diverse land use requirements, construction and development activity should be appropriately regulated with in-built provision for simultaneous implementation of protective measures, short and long term interests should be safeguarded through systematically launched and strictly monitored scientific studies, old constructions should be appropriately strengthened and maintained, forest cover and vegetation should be restored, drainage measures should be augmented and a national network be established not only to give premonition of impending disasters but also to oil the machinery for implementing protective works for relief with speed and efficiency. Although such a massive National

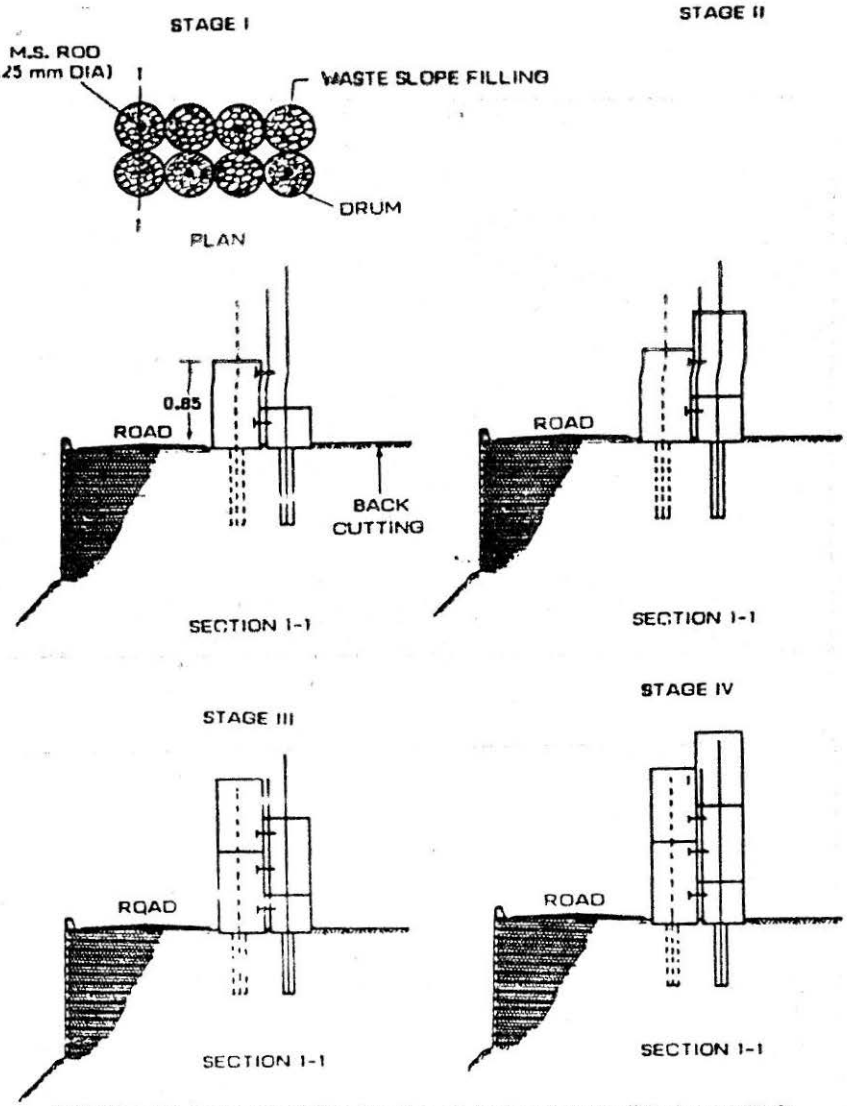


FIGURE 29 Sequence of Construction of Anchored Drum Diaphragm Wall

Programme will have to be launched with multi-institutional, multi-disciplinary inputs, geotechnology of the slope instability in the fragile Himalaya will continue to lie at the heart of the problem. Accordingly, the presentation is restricted in scope.

Establishment of a National Data Base and Mountain Hazard Zonation Mapping

Broadly speaking, the entire Himalaya has been studied for several decades from different angles. Much has already been said and written on the adverse environmental impact of its unstable mountain belts including those located in its highest habitations, coldest deserts, wastelands and

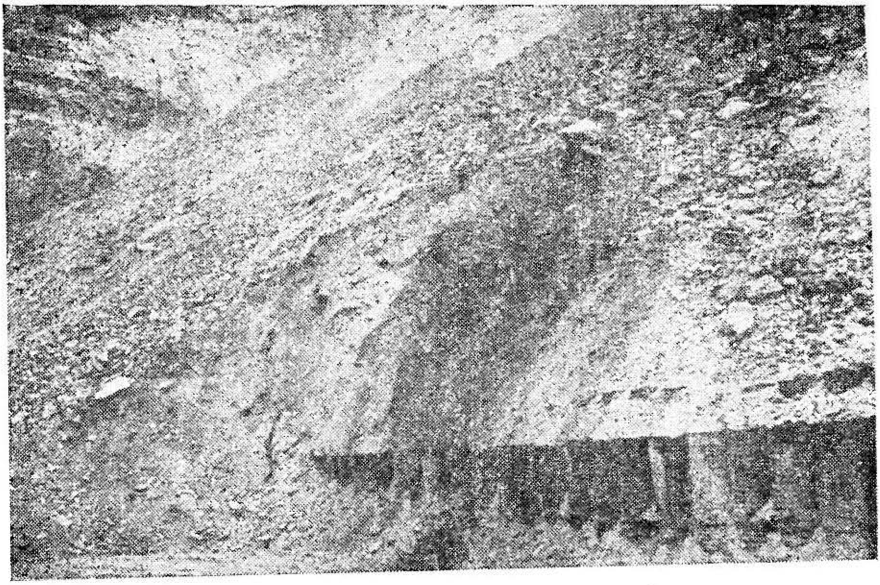


FIGURE 30 Anchored Drum-Debris Diaphragm Wall at Kaliasaur

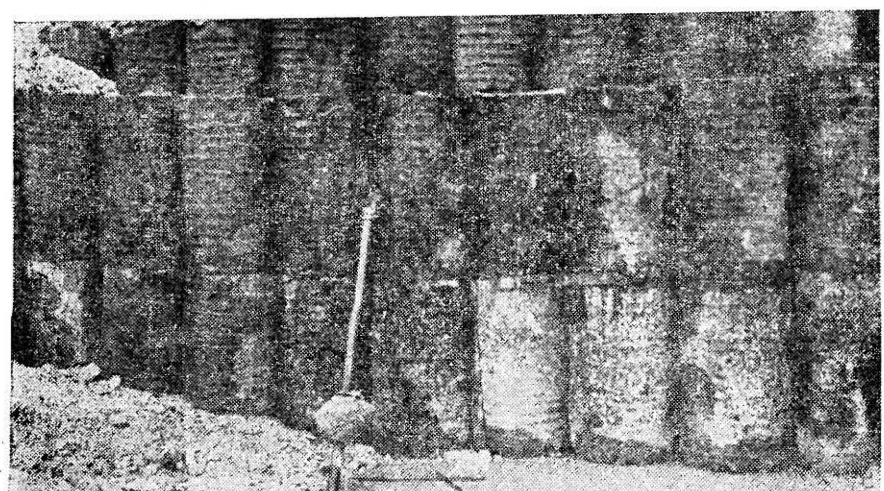


FIGURE 31 A Close up of the Drum-Debris Diaphragm Wall

arid and semiarid zones. Inter alia, geologists, geomorphologists, geotechnical, highway, civil and mining engineers have studied it's defiled, defaced and degraded tracts, slopes or ravines from their own points of view. Elaborate geotechnical investigations, field surveys, mappings and large scale test programmes continue unabated and feed back is constantly pouring in from a number of sources on the reactions of our past actions. The Government of India is getting seized of the problem and researchers are busy taking recourse to satellite imagery and other powerful means of mapping to understand better the magnitude and nature of the problem. We, however, sadly lack an overall national strategy to put all the work together in a usable from, upgrade it from time to time and make it promptly available to the users.

Mountains of USA, USSR, Japan, Switzerland, Hongkong, Czechoslovakia, South America and many other countries have already been mapped for hazard zonation but such maps are yet to be produced for the Himalaya. Thousands of drill holes have been made in the Himalaya but no one knows where is all that information? Many landslides have been investigated, analysed and controlled but we neither have thorough inventory of such slides nor do we have synthesis of even major case records. Several organisations are going ahead with their plans for micro-seismic recording but the question remains whether there is any unified national plan to obtain best return on investment?

Our first task should be to pool together the data and establish a national data base. The mountain hazard zonation mapping of the Himalya should be undertaken on a warfooting and such maps should form the basis of all future planning. The tasks of a national programme are summarised in Table 11. The uses of the information are outlined in Table 12 and users are listed in Table 13.

Since it would be unwieldy to compress all possible information in a single map, the concept of multiple mapping will have to be pursed with specific objectives. Many forms of natural processes may coexist in space and time leading to many types of landslides and mass movements. In the months of winter and spring, avalanche-prone areas may threaten life and property. In the monsoon season, landslides, mud flows and rockfalls may prove hazardous. The concern for multiple hazards has led to geographic or regional approach to mapping of areas subject to mass movement. Two projects, one in the Bernese Oberland, the other in the Colorado Rockies, led to experimentation with the cartographic representation of all natural hazards within a single area. The Swiss approach resulted in the production of a very detailed and highly accurate series of multicoloured maps for the area around Grindelwald on a scale of 1 : 10,000. In the Colorado Rockies the area to be covered was significantly greater and the available topographical base maps were at the reconnaissance scale of 1 : 24,000. This resulted in the production of

TABLE 11

Tasks of a National Programme

Profile of Action Oriented Plan :

* Collection, collation and synthesis of existing body of information flowing out of aerial photographs, geological, seismological, meteorological, taxonomical, pedological, terrain evaluation and water resource management maps and reconnaissance surveys.
* Inventory of major landslides and other mass movements chiefly in selected high priority areas in the first instance. The entire Himalayan region is to be covered eventually.
* Geotechnical study of landslides and other mass movements including exploration, testing, long and short term monitoring, stability analyses so as to pin-point causative factors and quantify risks for delineating hazardous zones.
* Establish guidelines for zoning.
* Make zonation maps for selected high priority areas in the first instance & for the entire Himalayan region eventually.
* Identify areas where catastrophic landslides may occur, study them thoroughly, analyse and map landslide hazard risk in detail, make cost benefit analysis and suggest control measures.
* Develop innovative technologies of landslide correction making optimal use of local materials and abundant human resource available in the country.
* Instrument major landslides particularly in the critical areas for long term monitoring to generate scientific data base.
* Establish appropriate computer software and graphic capabilities to store and manipulate landslide data.
* Suggest areas of future work based on available wealth of data and experience.

two series of maps in black and white (avalanches treated separately as one series). From these beginnings the two groups joined forces and developed a combined natural hazards map at 1 : 24,000 for a test area of the Colorado Front Range, Ives (1982).

The Central Building Research Institute, Roorkee has already made inventory of landslides on Rishikesh-Badrinath and Rishikesh-Kedarnath routes. Their mapping has focussed attention on areas which are unquestionably unstable. The surveying operations, electronic distance meter measurements and tape extensometer observations in some of the areas in the Garhwal region have helped in delineating stable areas from those questionably stable. The criteria for zonation mapping being followed are the same as recommended by Varnes (1984).

Our ultimate objective should be to produce multicolour mountain hazard zonation maps on the scale of 1 : 10,000 and constantly update

TABLE 12

Use of Maps Towards Landslide Hazard Mitigation

Some of the major uses are listed below :

Developmental Plans

* Construction Plans for Housing, Human Settlements, Buildings, Towers, Tunnels, Dams, Ropeways etc.
* General Purpose Plans, Master Plans, Land Use Plans, Open Space Plans, Neighbourhood and Developmental Plans.
* Public and Hillside Safety Plans, Community Facility Plans.
* Roads and Transportation Plans.
* Seismic Safety Plan
* Drainage and Water Supply Plans.

Engineering and Planning Studies

* Environmental Impact Assessments.
* Geological Hazard Inventories.
* Design of Structures and Foundations.
* Site-specific Investigations.
* Early Warning Strategy Plans.

Discouraging New Development in Hazards Areas

* Public Information.
* Recording the Hazard and Sounding of Timely Warning.
* Special Assessments and Tax Credits.
* Funding Incentives and Disincentives.

Regulating Development in Hazards Areas

* Land-use Zoning.
* Special Landslide Area Use Regulations and Developmental Activities on Problematic Slopes.
* Sanitary and Water use Regulations.
* Mining, Quarrying and Grading Regulations.
* Ephemeral Data Collection soon after a Major Landslide Event, Investigation of Selected Major Landslides soon after Failures.
* Computer Analyses of Landslides, Slopes, Cuttings etc. with full Cognizance of Various Geotechnical Factors.

TABLE 13

Users of Landslide Hazard Information

Some of the users of landslide hazard information are :

National Users

* Planning Commission, Departments of Environment, Science and Technology, Tourism and host of other ministries and departments.
* Central Water Commission.
* Directorate General Border Roads, Ministry of Shipping and Transport.
* Central Board of Irrigation and Power, Geological Survey of India, Survey of India.
* Indian Meteorological Department, Departments dealing with Seismological Studies.
* Forest Research Institute and other National Research Institutes.
* Various Institutes and Associations for Himalayan Studies, Institutes for Mountaineering.
* Central Public Works Department.

Regional Users

* State Governments.
* State Public Works Departments, State Highway Departments.
* State Water Source Management and Irrigation Departments.
* State Geology Departments.
* Hill Safety Commissions, Committees etc.
* Power Construction Corporations and other Developmental Agencies.

Community Users

* Municipal Engineers & Planners.
* Schools, Colleges and Universities.
* Tax Assessors.
* Builders.
* Voluntary Agencies.

Private Users

* Construction Companies.
* Consulting Geologists and Engineers.
* Financial Institutions.
* Land Owners, Developers, Estate Agents.
* New Media and Concerned Citizens.

them by collection, callation and incorporation of new data as and when generated. The mapping would involve indepth information on lithology, geological structure, topographical setting, extent and density of vegetal cover, nature of plant canopy and depth of root penetration, ground water condition, drainage, periodicity and intensity of earthquakes and scale and frequency of past landslides, Valdiya (1985).

Forced Regeneration and Afforestation Programme for Enhancement of Slope Stability

As we go up from tarai, sal gives place to pine, the pine to oak, the oak to juniper and rhododendron, and above that comes birch, which marks the treeline. Where trees receive light and soil cover on naked hill slopes is adequate above the treeline, the flowers grow in profusion. Over the period of years, however, the vegetation in the Himalaya has fallen prey to Eco Vandalism. Studies conducted by the National Remote Sensing Agency using satellite imagery during 1972-75 and 1980-82 bear testimony to loss of forest cover which is now only one third of the slope area exposing nearly two-thirds of it to weathering and erosion. The problem of erosion is further aggravated due to overgrazing by an explosively large population of cattle.

For the Himalayan slope surfaces to be stabilised, cover of vegetation must be promptly restored. The role of vegetation through grasses, shrubs and trees in erosion control is primarily reflected in retardation of surface water flow and in the reinforcing effect of the root system. Lopez-Tello (1984) has reported 33 per cent increase of factor of safety for a 10 m high cutslope in clay laid at 1 : 1 when covered with vegetation having root density of 5000 kg/ha. Kassif and Kopelovitz (1968) measured the effect of reinforcement provided by plastic fibre in compacted samples of both clayey sand and loess in direct shear tests. The increase in shear strength was seen to vary directly with the root area ratio defined as the ratio of the area of root system (Ar) to the total area (A). For most soil fibre systems with Ar/A ratio less than 1 to 2 per cent, two and a half fold increase of shear strength was observed over the values for the same soil without fibres.

Manbeian (1973) (in : Gray, 1973) has reportedly studied the effect of roots by means of laboratory shear tests, in samples containing living root system. The peak and the residual resistance were found to increase two and four times respectively due to the presence of roots.

Soares et al. (1975), and Poncano et. al. (1976) have reported occurrences of catastrophic landslides on the slopes of the Serra de Maranguape, in Ceara, in April/May, 1947 due to high rainfall. Records show greater precipitation in 1912, 1917 and 1948, without any record of landslides. Extensive deforestation on those slopes in the sixties and early seventies and destruction of root system were thus responsible for 1974 landslides, Croft and Adams (1950) (in : Gray, 1973), while studying landslides in the mountains of Utah (USA), have also attributed them to the loss of mechanical support formerly supplied by the root system, as a consequence of deforestation and fire. Barker (1986) has summarised the mechanics of the root-soil systam in fair detail.

No such studies have so far been conducted for rejuvenation of the Himalayan slopes with plant species picked to suit different altitudes.

There is a need :

— to evolve and standardise plant culture practices, particularly in the adverse environmental zones, and transform them into an economically viable, readily acceptable, livelihood intensive package technology. New cadres of eco-task forces intimately involving local communities will have to be developed.

— to resort to mass scale outplantation operations on heavily mined and other eco devastated sites and establish new ranges of plant cultural practices for their accelerated colonizing; and for reduction of post outplantation mortality rates.

— to promote forced regeneration and afforestation programme via the Nursery approach. The strategy lays accent on 'natural regeneration' and 'optimised growth' during 'juvenile' stage and forced regeneration serving as backup.

— to give fillip to Humus Gulture Operations for large scale production of high quality humus. This is the single biggest need to make the success of the entire plantation drive which at the same time would cut down drastically on the post plantation expenses and maintenance.

— to promote species such as the "Amada" plant which represents a *superb variety* unmatchable in performance for stabilisation of erosion prone slope cover in the Himalaya. The plant shows a remarkable power of penetrating even into slope strewn with debris, boulders and colluvium. Such high potential but still neglected species must get the recognition they so richly deserve.

Where rainfall is high, additional mechanical support to loose carpet of soil on the slope should be provided by timber piling, jute or coir netting asphalt mulch technique of vegetative turfing, Bhandari (1977). Geotextiles also do find powerful applications.

Modernising the Engineering Practice in India

New Approaches to Surveying and Investigation of Slopes : The earliest surveyors in the Himalaya, men like Nain Singh, Kishan Singh and Kinthup ventured into the vast unknown tracts with little more than beads to tell their paces. We have today come a long way from chaining to plane table; from theodolites to EDMs; from photogrammetry to satellite imagery. Direct mapping of problematic slopes time we can ill afford, apart from providing poor accuracy (±1000 mm). The introduction of theodolite for survey raises the accuracy to± 500 mm. Terrestrial Photogrammetry apart from being less hazardous happens to be considerably more accurate (± 200 mm) with a local accuracy of ± 100 mm for detail and ±50 mm for co-ordinated points. The following relatively new approaches are recommended for promotion in the Himalaya :

Electronic Distance Meter Measurements : The advent of Electronic Distance Measurement Systems has now made surveying quicker, more accurate and much more convenient than ordinary surveying techniques. They require fewer personnel, are light weight, can be used for distance range of 20 m 60 km in visible light range and upto 150 km in microwave range. The extraordinary advantage is that they can be used at any time whether day or night. Poor visibility is of no consequence but rain and drizzle can reduce working range particularly in instruments employing shorter wave lengths. Comparison between various EDM instruments is presented in Table 14.

All current EDM devices used in surveying are based on methods using measurement of phase difference. In fact, distance is measured by determining the transit time of electromagnetic radiation from a transmitting point to a reflector and back. This is achieved indirectly by transmitting a wave, which when returned by the reflector, is detected and converted into an electrical signal. The signal is a replica of the original waveform but is delayed in phase by an amount proportional to the transit time of the carrier wave over the return path.

Measurements of slope movements on a landslide on the Mussoorie Chamba bypass were successfully made by the CBRI Scientists using EDM with an accuracy of ± 5 mm in a 25 km range, (Bhandri, *et al.* 1985). Geological Survey of India and Survey of India have introduced it's use in India but the scale of exploitation of its power deserves a big boost.

Geophysical Tomography : Adits and boreholes particularly in complex rock formations cost considerable amount of money and if structure of rock spanning adits or boreholes could be unfolded through geophysical tomography, engineering interpretation of data could acquire better meaning and higher reliability. It is unfortunate that dams as high as Tehri and tunnels as problematic as Maneri Bhali continue to be designed more on "point data" from adits and boreholes than by generating reliable cross-sectional profiles using seismic, radar and electric tomography techniques singly or in combination, Aki and Lee (1976) ; Petrick *et al.* (1981) ; Itoh *et al.* (1983) & Imai *et al.* (1986). The principles of operation are outlined in Table 15.

TABLE 14

Comparison of Various EDM Instruments

Long radio wave base (λ = hundreds of m)	Micro radio wave based (λ = few cm)	Based on wavelengths of visible spectrum (λ = few microns)
1. Long range of measurement (upto 2000 kms)	Inter-visible range on ground (upto 100 kms)	Short range of a few kms (upto 69 kms)
2. Not as accurate as other instruments	More accurate. Ranges from ± 1.5 cm in 30 m to 50 km range (MRA 3) ± 1.5 m to 40 km range (MRB2)	Most accurate (in mm) Ranges between ± 0.1 mm in 20 km range (LDM2) to ± 6 mm + 1 ppm in 5 to 25 km range (AGA Geodimeter 6A)
3. Not useful for shorter distance measurement	Not much useful for shorter distance measurement	Ideal for measuring shorter distance
4. (*i*) Variations brought about by atmospheric changes are insignificant	(*i*) Range affected by atmospheric conditions. Shorter wavelengths (3 cm) are more Effected than the longer (10 cm) wave-lengths	(*i*) Sensitivity is reduced in the daylight
(*ii*) More accurate over water or in air, well away from the earth's surface	(*ii*) Range increased if installed on aircraft or satellite	(*ii*) More sensitive in night
	(*iii*) Poor visibility do not prevent operation, but rain or drizzle reduces the range. Day or night use.	(*iii*) Mist, fog or light rain restricts range.
5. Major applications in navigation, oceanographics and hydrographic surveying etc.	Recommended for landslide studies. Major applications in mateorological observations, Civil Engineering construction, hydrographic, land and mine surveying etc.	Recommended for landslide studies. Major applications in Civil Engineering Construction, tunnelling and mining, land surveying, meteorology and setting of machinery etc.

TABLE 15

Geophysical Tomography

Tomography	Principle	Remarks
Seismic	Distribution of the seismic wave velocities for the observed area is computer plotted based on travel time.	Imali *et al.* (1986) reports measurements in a granitic formation at a damsite in Japan.
Radar Tomography	*EM wave measurements, taken at an* array of points some distance from source point, are used to determine the distribution of reflectors within the rock formations. Faults & Fracture zones can be identified from these results. (frequency : several tens to several hundreds of MHz ; Wavelength: several metre or less).	*EM waves through rock have* a high rate of attenuation and consequently limited penetrating power. Since higher resistivity means less attenuation, radar suited to high resistivity rocks.
Electrical Tomography	Profile of distribution of resistivity values could be computer drawn based on installation of electrodes in the walls of adits passing of electrical current through one of the electrodes and measurement of electrical potential received by other electrodes.	Harder the rock & fewer the cracks, the greater the resistivity. For intensely jointed, fractured and saturated rock masses, low resistivity is obtained.

Radar as Investigational Tool : The vast Himalayan range can be efficiently exploited for construction, mining, transportation, water utilization, defence, weather forecasting etc. by recourse to radar surveys. The conventional radar operates at frequencies extending from about 25 to 70,000 KHz, but these are not necessarily the limits since radar can be operated at frequencies outside either end of this range. At present ground penetrating radars are operating at frequencies from 5 MHz to 5,000 MHz. Earth materials vary a great deal in their transparency to radar. Useful probing distance could be kilometres in glacier ice, igneous and metamorphic rocks, tens of metres in dune sands, several metres in coarse grained soils and only a few metres in clays even at frequencies as law as 1 MHz.

Major applications of radar include monitoring of avalanche movement, detection of crevasses in geological formations, measuring the thickness of snow on the road to facilitate snow clearance operations and aiding search of avalanche victims (Fig. 32), reported by Bhandari (1981); Bhandari and Pandey (1986) from the work of Fritze (1979).

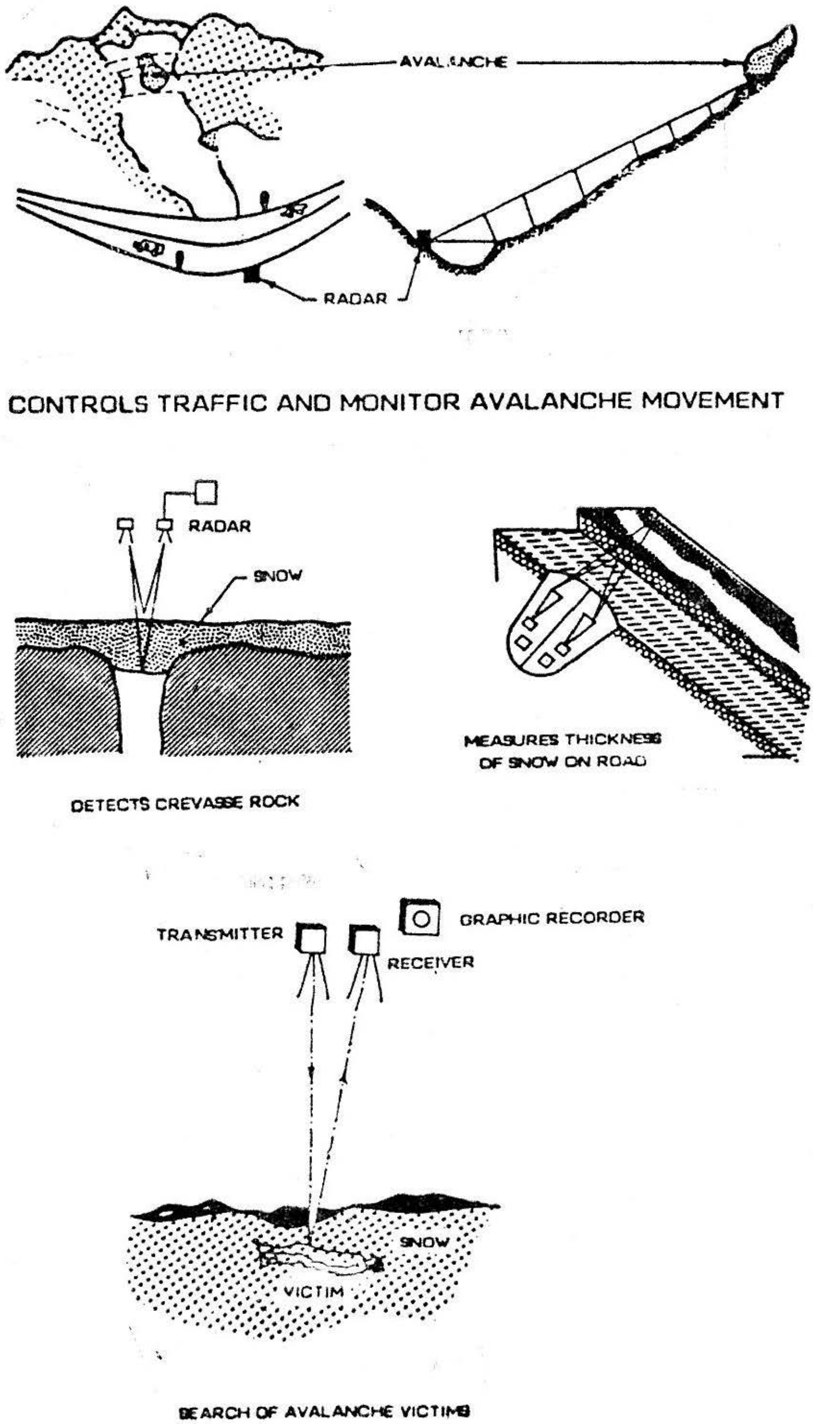


FIGURE 32 Major Application of Radar

Landslide studies particularly involving slopes with limestone formations stand to gain tremendously by introduction of radar surveys in the Himalaya. Limestones, as in the Garhwal Himalaya, are full of cavities seldom detected by drilling or recognised in design despite their profound effect on rock behaviour.

Georadar YL R 2 marketted by OYO Corporation, Tokyo is one of the many types available commercially and are in use in many countries but yet to come to the Himalaya.

Acoustic Emission Technology: *The advent of acoustic emission technology* and its application in evaluation of slopes threatened with instability have demonstrated its vast potential both as an investigational tool and in monitoring of slopes to follow their short and long term behaviour.

The direct measurements have shown that when a slope tends to fail, it generates a set of stress waves which propagate radially from the source location. These stress waves of sub audible level, usually called acoustic emissions, can be sensed by a suitable transducer, Fig. 33. The signal can be easily amplified when received by acoustic emission system so as to quantify the measurement. Quantification parameters imply acoustic emission count, acoustic emission count rate, event rate, amplitude and frequency distribution.

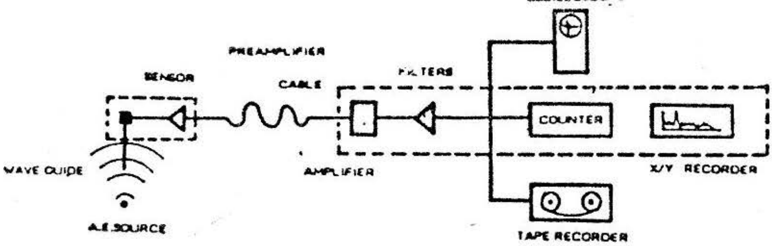


FIGURE 33 Acoustic Emission Monitoring System

The experimental studies have revealed that for a stable slope, acoustic emission counts are low and usually decay with the passage of time. As the slope becomes steep or high, the acoustic emission count tends to rise, shooting up to a high value at failure.

The best illustration is provided by successive cuttings made in a slope and corresponding time decay of acoustic emission count. These are depicted in Fig. 34 and Fig. 35. It is clearly seen that corresponding to the stage of instability at cutting 5, the acoustic emission counts seem to shoot up indicating the instability, Koerner *et al.* (1980).

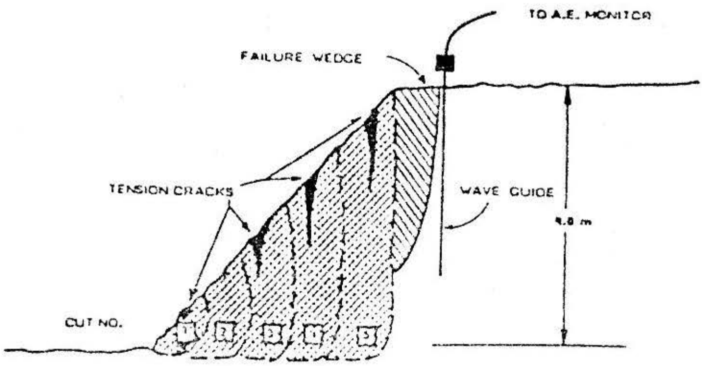


FIGURE 34 Failure of a Cutting by Successive Excavation at its Toe (Koerner. *et al.* 1981).

Broadly speaking the criteria for instability have been summarised as follows :

No or Low AE	**Stable**
10 c/m < AE < 100 c/m	Marginally Stable
100 < AE < 500	Unstable
AE < 500	Failure

The AET can thus provide the best guidance on observational method of construction and help in sounding a note of early warning in the event of impending failure or landsliding.

It is also the most ideal tool to evaluate the efficacy of control measures. It is easy to monitor, provides immediate feedback, represents low investment, low installation cost and is indeed a powerful construction aid as well as a legal and investigative instrument.

Strengthening of Material Testing Practices : The current engineering practice in the Himalaya seldom lays accent on simulation modelling and stress path testing of geological materials. First and the foremost requirement for stability analyses is to locate the slip surface. Although a number of options are available (Philbrick and Cleaves, 1958; Hutchinson and Hughes, 1968; Hutchinson, 1970; Bhandari, 1976) slope investigations in the Himalayan slopes are rarely taken to that stage and need attention. The next comes, recovery of undisturbed samples, particularly from the slide boundaries and shear zones. Hand sampling in blocks from side shear boundaries is fairly reliably accomplished but better mechanical devices and samplers are needed to recover continuous samples from depth. Without such an effort, routine drilling would invariably miss the cores from the basal slide boundary. Samples from shear zones and slide boundaries are very expensive and require meticulous handling and testing under appropriate field conditions. There are a number of laboratories in

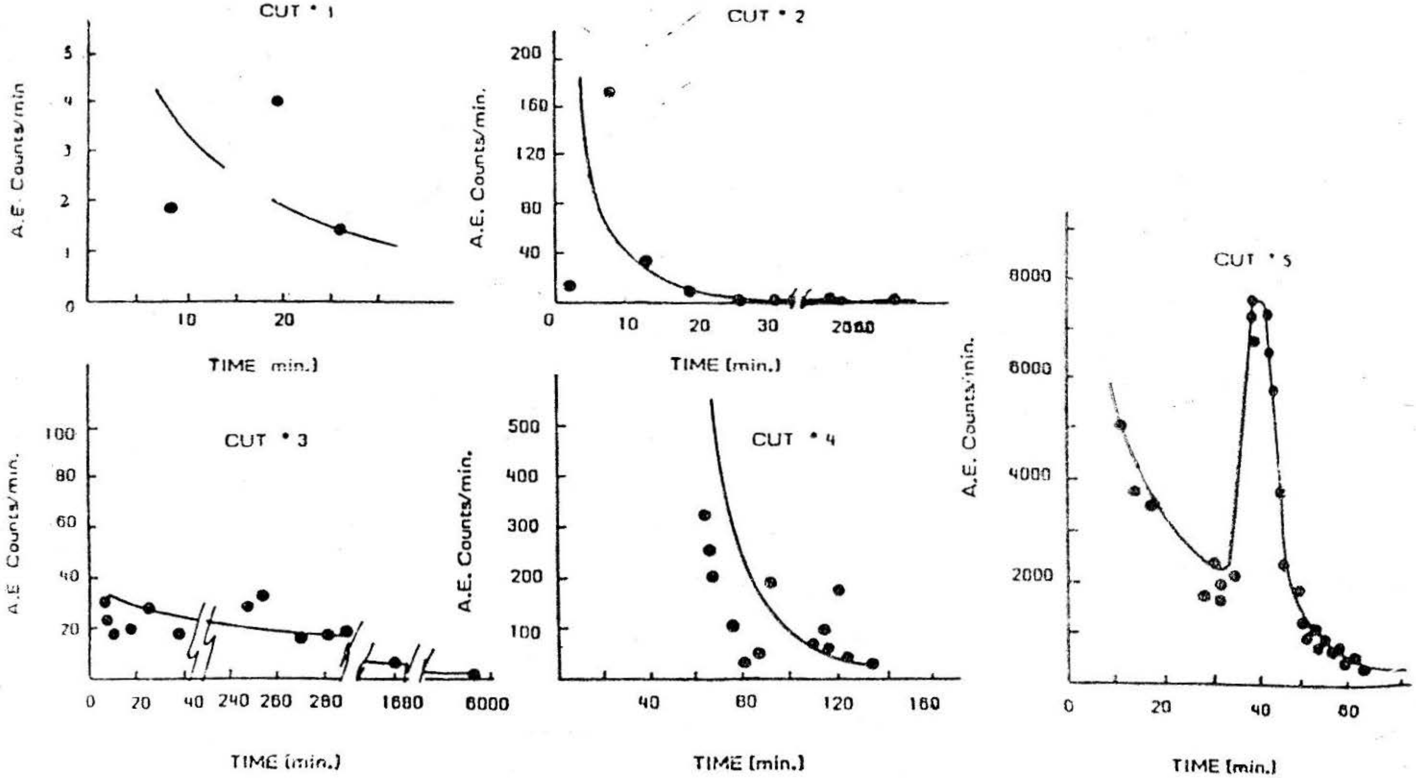


FIGURE 35 Decay of AE Count with Time as Related to Stability (Korener, Mc Cabe & Lord, 1980

India well equipped to accomplish this work. Best check on reliability of results so obtained could be had by back analysis of failed slopes. For all major landslides with well defined boundaries, back analysis should be done.

Difficulties often arise in arriving at the shear strength parameters applicable to stability analysis of repetitive landslides by testing intact samples from the vicinity of slide boundaries. Ring shear apparatus (Garga, 1969) does prove useful to obtain lower bound of strength but results of such tests could be highly conservative, if slide movements are not large, thereby unnecessarily adding to the cost of control measures.

Problematic slopes could then be analysed using either deterministic (Bishop 1955; Janbu, 1973, 1980; Morgenstern and Price 1967) or probabilistic approach (Grivas, 1981; Chowdhury, 1982, 84). Appropriate software packages are now available.

Innovative Landslide Control Measures : Retaining walls of a great variety are commonly constructed as protection against landslide in the Himalaya. Innovations are essential to reduce their cost, improve speed of construction and promote utilisation of slope waste to the extent practicable so that strain on scarce materials and the need for their long distance transportation could be reduced or even eliminated. The drum debris retaining wall developed by the CBRI is a step forward in this direction. Gabions could provide the alternative, if the cost of container material could be brought down.

The otherway out could be to make use of the well known technology of reinforced earth construction. Datye (1986) in his paper on prospects and perspective on reinforced earth application in India, inter alia, discusses slope stabilisation for landslide control and for protection of permanent cuttings and excavations. Bridge abutments and river flood protection works could also be built with considerable economy using the technique. Wooden crib structures of low cost small timbers such as poplar and eucalyptus suitably reinforced with polymer or other forms of reinforcement could also serve to arrest gully erosion on slopes as also for construction of barrier walls on the slope. Portable timber piling machine developed by the CBRI and described earlier could also prove useful in such constructions.

The hazards of landslides and other mass movements in the Himalaya could be significantly reduced by improving slope drainage. There are a number of approaches to effective surface and sub slope drainage for better stability. The choice is governed by geomorphology of the terrain, hydrological conditions including intensity and distribution of rainfall, permeability of the slope forming materials, vegetation, natural drainage, construction activity and sliding mechanism. Catch water drains, trench drains, drainage walls, slope ribs, drainage galleries etc., are commonly adopted to improve slope drainage. The advent of new drilling tools and techniques has, however, brought about a sea change in the approach to draining the slopes with promise of better efficiency, longer life and speedier construction. Geotextiles have opened up new horizons in improving effectiveness of drains.

Wherever high piezometric pressures are found to trigger landslides or situations where rainfall is excessive, slope masses are pervious and water table is beyond the reach of trench drains, sub-surface drainage becomes absolutely essential. One of the effective ways of achieving such a drainage is through drill hole drains or so called horizontal drains. In 1939, such drains were introduced and were widely used in California, Smith and Stafford, (1957); and Root, (1958). Since then, they have found worldwide acceptance and are popular particularly in countries like Japan, Taniguchi and Wateri (1965); Britain, Ayeres (1961); Robinson (1967); Germany, Henke (1968); Czechoslovakia, Zaruba and Mencl (1969); Yugoslavia, Nonveiller (1970); New Zealand, East (1974); Hong Kong, Tong and Maher (1975); Canada, La Rochelle *et al.* (1976) and France, Cambefort (1966) and Rat (1976) Recently, such drains were introduced in India by the Central Road Research Institute, New Delhi, Natrajan *et al.* (1984).

Salient Features of Inclined Hole Drains

Method of drilling	: Helical auger; rotary or hydraulic jacking
Range of diameter	: 5 cm—20 cm
Range of spacing	: 3 m—20 m apart
Depth from the slope surface	: 30 m—100 m
Gradient	: 2 percent—20 percent
Pattern of installation	: Triangular or rectangular; Single or multi-tier
Range of monitored discharge from a single drain	: 175,000 litre/day to negligible
Installation outfit	: Earlier installations deploying perforated steel pipes without filters were prone to both corrosion and siltation. Modern installations deploy plastic pipes with filters formed of porous concrete, Robinson (1967); resin bonded sand Nonveiller, (1970) or synthetic filter fabrics. For top 6 m the installation is kept without filter or perforations to eliminate choking by roots or debris.

The following points deserve foremost attention :

(1) Empirical designs based on quantity of water discharged must give way to evaluating of drainage efficiency in terms of reducing excess pore pressures. Such a methodology of design is yet to be developed.

(2) Influence of minor geological details, such as pervious layers, sand and silt lenses, rock discontinuities and joints, spring points, perched water table or artesian conditions within slopes shoud be studied and recognised in design.

(3) Design of drainage schemes should involve judicious combination of horizontal and vertical drains. Such was the corrective approach followed to tame an active landslide at San Marcos Pass near Santa Barbara, California. Design methodologies should also be developed for horizontal drains constructed in association with drainage galleries.

(4) Appropriate technology needs to be developed for installing drains in an active landslide. Such a development has already taken place and utilised effectively, e.g., to control an active landslide on the Sao Paulo to Santos highway, Teixeira and Kanji (1970), nearly 20 hectares of which did move between 2-5 m every month.

(5) Perfection of technology for simultaneous lowering of drainage outfit with progress of drilling operation to prevent collapse of boreholes is essential.

(6) Development of portable lightweight and yet efficient drilling rigs.

Principle of Synergism and Protection of Existing Structures Against Landslides

The *principle of Synergism underlines that* co-operative active action of discrete agencies yields total effect greater than sum of two or more effects taken independently. This applies as much to correction of landslides as to the effect of drugs in the medical world. Take for example the case of landslide Mile 9 on National highway 31A, Natarajan et al. (1980), Chandra (1975). In 1957, road at this location sank by several metre and was quickly restored to traffic by back cutting the hill and after providing some remedial measures. In 1963, it sank again by 5 m and moved out by about 15 m. Corrective measures such as drains, retaining walls etc. were provided. In July 1966, the road sank yet again by about 18 m calling for repeat of corrective measures. The field authorities could not take up most of the suggested works at a time and only some drains and retaining walls were constructed. Financial constraints, short working season and other pressing obligations forced field authorities to resort to partial implementation which could not be successful. There were unprecedented floods in 1968 and 1972 which substantially enlarged the slide. It was only in 1974 that a conscentious effort was made by the field authorities to implement all important works in a single working season. The measures included lined catchwater drains, a vented causeway and side drains, formation cutting and filling, restraining structures like retaining walls and checkwalls, buttressed toe wall with stone pitched apron, terracing and turfing of slopes. The slide could thus be tamed yielding the most significant lesson that less effective and palliative control measures executed intermittently over a period of several years to suit budgetary allocations could not prove as effective as the total corrective works executed in a single working season. This conclusion is not to suggest that nothing should be done at all, if all that outght to be done cannot be done at once. Nor is it to suggest that efforts should always be mammoth so as to totally control a landslide. On the contrary, a more realistic approach would be to do all that is possible and to see that despite landslides and other mass movements, we are able to construct and preserve our structures by minimising hazards.

Where landslides and avalanches at high altitudes are involved, the engineers face a specturm of additional problems. Rarefied air and reduced oxygen content at high altitudes reduce physical capability, slow down pulse rate, make breathing difficult, induce sleeplessness and loss of appetite. Lips and other parts of the body chafe and crack. In snow bound areas, heat of sun becomes so intense as to cause unbearable glare and serious skin burns. Cold strong winds and low temperatures (—28°C at Leh and —43°C at Dras) create chillblains which are very painful. Metal parts of vehicles become very cold and mere touch would freeze the skin and frost-bite can develop into gangrence, if not treated promptly. Cement takes very long time to set and fresh concrete may crack with alternate freezing and thawing. Bitumen becomes brittle at low temperature. Sand collected from river bed lump making screening and grading difficult. Sand quarries require explosives. All rubber and plastic components of vehicles become stiff and brittle requiring frequent replacements, Ayyar (1980).

The challenge of landslide and avalanche correction works must be viewed in the above backdrop considering the short working season limited to four months in a year. The delivery system deserves to the improved by bringing innovative materials, equipment and technologies to replace the conventional. Speed and quality of construction should also receive the highest considerations because on them depends the ultimate success.

Instrumentation and Field Monitoring of Himalayan Landslides

Bhandari (1984) and Pilot (1984) in two separate recent state-of-the-art report have adequately covered the topic of instrumentation and field monitoring of landslides and other mass movements. The Himalayan situations demand that a new generation of monitoring instruments is introduced to perform multiple functions. For example, a device for surface movement measurements could be such that it monitors precisely low orders of movement (creep) during the period of quiescence and the same device could be adjusted to record higher orders of movement when the slide is active. Similarly, if surface movement measuring devices could also auto record direction of movement and vertical subsidence simultaneously with lateral movements, the need for putting more instruments could be eliminated. There is a need for developing multi-port piezometers which could monitor pore pressures at any desired level with quick response. If simultaneous recording of the vectors of lateral displacements in piezometer casing is made possible, need for additional slope indicator installation is eliminated.

For the control measures to be cost effective, a feedback is necessary of their efficacy through instrumentation and field monitoring. For all major landslides, the scheme of control measures should therefore compulsorily include implementation of appropriate instrumentation scheme. The data so generated would not only help in guarding the stability of the slope at all times, but would also help in advancing the state of the art.

Considerable difficulties arise in instrumenting and monitoring complex landslides which usually in a sense multi-storeyed. On their slope surface one finds flows and falls, at their road side cuttings on the very slope one finds shallow slips and on the whole, the slide advances on discrete, often deep seated, boundary shears. The instruments located in the surface zone have to be rugged and capable of sustaining large displacements. They have to be economical and planted in large numbers because more than half of them not survive very long. On the other hand, movements at slide boundaries may be highly time dependent and slow requiring totally different breed of instruments. Applications of Acoustic Emission Technology seem to hold considerable promise.

For avalanche monitoring in the Himalaya, Snow and Avalanche Study Establishment (SASE) has already established a chain of high altitude (5000 m) observatories particularly in the Western and Central Himalaya. The telemetric information from the automatic weather stations includes monitoring of snow cover properties, solar radiation, wind direction and speed, the forest cover and depth of glaciated deposits. Satellite pictures are also obtained. There is a further need to strengthen ground observatories with remote sensing. The electromagnetic beams from a satellite should be able to provide precise data about the depth of snow and occurrence of avalanches.

Warning Systems

The victims of landslides and avalanches in the Himalaya being on an increase, it is imperative that warning systems are installed on all major landslides for early warning. Simple warning systems are described elsewhere, Bhandari (1984).

The researches done at the Central Building Research Institute show that the warnings flashed on the basis of a single and elsewhere point observation could be deceptive. It is considered appropriate to monitor slope surface and sub slope movements and pore water pressures at a number of critical locations on the slope and go by the statistical behaviour vis-a-vis *dangerous levels stipulated through scientific assessment. There* is a need to develop instrumentation through which the observations on slope surface movement, sub slope movement and pore pressures be integrated to arrive at a decision on criticality or otherwise of the slope. Better still, if monitoring is also done on the foundations of the structure in the area and decision to evacuate the people is taken only if sufficient evidence of slope instability is gathered from the objective interpretation of the field observations.

Concluding Remarks

The impact of human activity on the slope instability and landslides in the fragile Himalaya and the impact of landslides on the human activity and quality of life the Himalaya supports are inextricably interrelated. Optimisation of the welfare of all forms of life in the Himalaya being our ultimate objective, the strategy of development pursued through the concept of Eco technology presented in the paper and through concerted effort of Government departments, expert agencies, universities etc. and the people at large should eventually lead to the much needed regeneration, protection and development in the Himalaya. The problems of Himalayan landslides and other mass movements can be effectively tackled only by recourse to a holistic approach.

The action plan should be vigorously launched in a phased manner in the background of the suggested strategy for development. Scientific reappraisal of the major engineering works and developmental activities on the card should be done from both short and long range views. All such projects should necessarily and adequately provide, say at least about 5 per cent of their budgets, to ensure environmental impact assessment and timely implementation of appropriate remedial measures.

In the end I am reminded of T.S. Elliot's famous couplet :

River flows, season turns,
Sparrow and Starling
have no time to waste,
If man does not build
where shall he live !

Build he must but in harmony with nature. Man and nature have co-existed for centuries and friendship with nature is the only path to enduring relationship.

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