Control Measures

In the past, control measures for landslides were essentially based on individualistic approaches for the qualitative assessment of the situation and experience. In India, in recent years, a more professional and multidisciplinary approach has been followed in terms of control measures involving proper analysis, both in the field and laboratories, of geological conditions, engineering characteristics of soil and rocks, and geomorphological and hydrological statuses. The highly heterogeneous nature of these parameters makes it difficult to obtain a high degree of standardisation in landslide control measures.

The Central Road Research Institute (1992) and the Central Soil and Materials Research Station (1993) have prepared state-of-the-art reports on landslide control or corrective measures currently commonly practised in India. The control measures and case history of some landslides in India, as given in these reports, are described here. The landslide control measures can be classified as: drainage measure, surface treatment, soil stabilisation, positive and self-supporting measures, and geometric methods.

Drainage Measures

Drainage can be surface or sub-surface, both contributing to the destabilisation of slopes. A proper survey of the geohydrological regimes of affected hillsides is a prerequisite for deciding the type and method of drainage to be used. There are several methods available for reducing the potentiality factor for slope stability.

Surface Drainage

The control of surface runoff is the most important factor in stabilising slopes. Surface runoff causes erosion and its percolation through the ground increases porewater pressure within the slope material, both contributing to instability of hillside slopes. Surface drainage is controlled by maximising the runoff from unstable areas and constructing drains. There are several types of drains for collecting and diverting surface runoff, e.g., a) catchwater drains, b) roadside drains, and c) cross drains.

Catchwater Drains

The surface water flowing from hill slopes towards potential unstable areas is the main problem in the drainage of hill slopes during heavy rains. Catchwater drains are constructed to collect and divert the water from the hill slope. The locations of the drains should be decided after studying the geomorphological conditions of the slopes. In the case of large slide areas, a number of interconnecting water drains is more effective. The water from catchwater drains should be diverted into chutes or natural hillside drains. Catchwater drains should be lined and properly maintained, and they can be given a gradient of from one in 50 to one in 33.

Roadside Drains

Roadside drains are provided on the roadsides at the foot of hill slopes to drain out water from the road surface as well as the portion of the hill slopes below the catchwater drains. In the hilly region, where the road is not adequately wide, roadside drains can be built in such a way that they function as drains as well as part of the road surface. Roadside drains are constructed of dry rubble stone masonry and they can be square, semicircular, trapezoidal, triangular, or V-shaped in sections.

Cross Drains

Cross drains are provided where streams cross the roadway. The water from the side drains is taken across by cross drains to divert the water from the road to a water course or valley. Cross drainage should be provided at frequent intervals in order to reduce the volume of water in catchwater and side drains. The number of cross drains, including scuppers, varies from four to eight per kilometre depending upon the nature of the terrain. Cross drains should be provided at every crossing point of natural *nullah*(s) (stream) and water. The cross drainage structures normally used are culverts, scuppers, causeways, and minor or major bridges.

Subsurface Drainage

Subsurface water increases the porewater pressure in subsoil rock material and weakens the fractures and bedding/foliation planes, thereby reducing the stability of the slope mass. Several landslides in the Himalayan region take place as a result of the circulation of subsurface water during the monsoons. Although the removal of water from within a slope by subsurface drainage incurs more expenditure than surface drainage, subsurface drainage is more effective in reducing porewater pressure along weak failure planes. The removal of subsurface water tends to bring about a more stable condition by way of decrease in seepage forces, increase in shear strength, and reduction in pore pressure and driving forces. In dealing with subsurface water, the foremost task is to intercept the subsurface flows above the sliding mass. Subsurface drainage is also useful for slope cuttings and under proposed embankments. Subsurface drainage is carried out by installing horizontal drains, vertical wells, deep trench drains, and drainage tunnels. These drains are meant to remove excess subsurface water and reduce the saturation within hillside slopes.

Horizontal Drains

Horizontal drains are constructed of perforated PVC pipes, 50mm in diameter. The pipes are installed at a negative of 5° to 15° to the horizontal, into a hill or embankment, to drain out the groundwater. These drains serve as additional drainage channels for the hill slopes and facilitate the removal of water from subsoil with poor permeability.

The upper two thirds of the pipe section is perforated or slotted. A lightweight conventional rotary drill is used to make horizontal boreholes into which the slotted PVC pipes are inserted. The groundwater flows into the pipes through perforations/slots. Water drained out from each row of drains is collected in a lined catchwater drain and discharged at a suitable surface-drainage point.

Deep Trench Drains

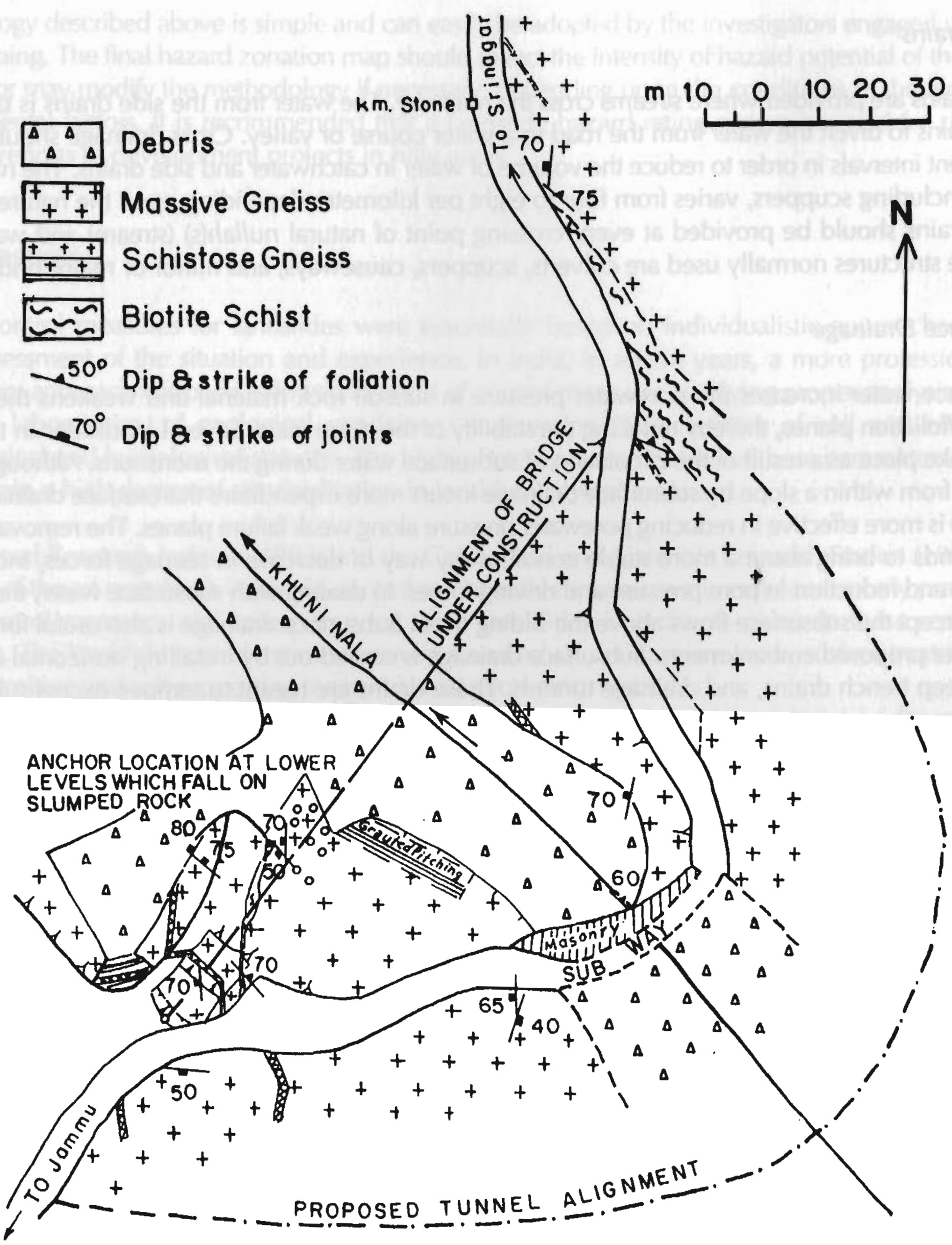
Deep trench drains have limitations in those locations where the subsurface drainage has to be intercepted at depths of less than five to eight metres. Trench drains are normally used where horizontal drilling is not feasible. Deep subsurface trench drains, consisting of a number of interconnected trenches dug into the slope and backfilled with rubble which has good draining properties, can be highly effective in quickly draining saturated slopes.

Filter fabric is an effective means of drainage for landslide control. Clog-proof filter fabric covered drains consist of a permeable gravel core, surrounded by a filter fabric to prevent clogging. The gravel size is either 16-32mm or 35-70mm to ensure a sufficiently high void ratio. The average amount of material needed per metre of drain length is about one cubic metre of gravel and five square metres of filter fabric.

Retaining Walls

Retaining walls are generally erected to stabilise unstable slopes or to support existing landslides (Fig. 11). A substantial amount of manual and skilled work is required to construct retaining walls.

Figure 11: Geological framework of the Khuni Nala landslide and control measures undertaken, including alignment of the bridge along the Jammu-Kashmir highway (CRRI Report 1992)



The foundation of the retaining walls should lie on the hard strata or rock and should be free from scour, frost, and surface water. The base of the foundation must be wide enough to distribute the pressure over the foundation. The stone to be used should be more than 0.14 cubic metres in size, and the width of each stone should be more than 1.5 times its height. The backfill layer immediately behind the wall should be made of stone or some granular material. The soil or granular material between the backfill layer and the hill slope should be rammed and compacted in 150mm layers sloping away and downwards from the back of the wall. Proper drainage facilities should be provided to prevent water from accumulating behind the wall, and an adequate number of weepholes of more than 75mm^2 should be maintained.

Masonry Walls

In the present practice, retaining walls of up to four metres in height are constructed in random rubble-dry stone masonry. Retaining walls above four metres in height are built either in lime or cement mortar masonry or in drystone masonry with 0.6m-wide mortar masonry bands three to four metres apart, laid both in horizontal and vertical directions. The top thickness is usually 0.6m, the front batter one to four, and the back face vertical. Masonry courses are made normal to face batter and the back of the wall can be finished rough.

Sausage Walls/Gabion Walls (SWG)

Timber walls or concrete crib walls and sausage walls are also used as restraining structures. A crib wall is made in a wooden mesh in which drystone masonry is built. Sausage walls are made by forming sausages of steel wire netting of eight SWG with 10cm square or hexagonal holes. The sausages are filled with hard local boulders/stones, and the wire-net is wrapped at the top. This process is carried out on the site where the sausage walls are to be installed. Over the past 25 years, sausage walls have been used extensively on Himalayan slopes. It has been found that sausage walls can withstand a greater amount of deformation than stone masonry, without cracking. They also allow free passage of water.

In the USA and Europe, sausage walls, more commonly called gabions, are assembled from prefabricated geogrids. Geogrids, made of polypropylene, have high resistance to impact and weathering and also possess good strength and elongation characteristics.

Pile Walls

Pile walls are used in place of retaining walls. The main advantage of piles is that they can be installed prior to excavation. Little space is needed and, therefore, less excavation work is required. Piles reduce the danger of slope movements in cuttings and provide an effective means of stabilising existing landslides. Pile walls have some limitations, however, as they are not strong enough to hold back the bottoms of deep cuttings where large horizontal stresses are present.

Anchored Walls

The stability of retaining walls can also be enhanced by using ground anchors (Fig. 12). Gravity walls have limitations where the surface area and the depths of the landslides are large. It has been found that anchored walls are effective where the surface failure is deep.

A deep, pre-stressed anchor is also applied for stabilising soil slopes. Walls with pre-stressed anchors have a major advantage because they actively oppose the movement of the soil mass, rather than behaving passively as in the case of unstressed anchors and gravity structures. Pre-stressed anchors are employed either in combination with retaining structures, or alone, to reduce the driving forces of a landslide and to increase the normal effective stresses on its slip surface.

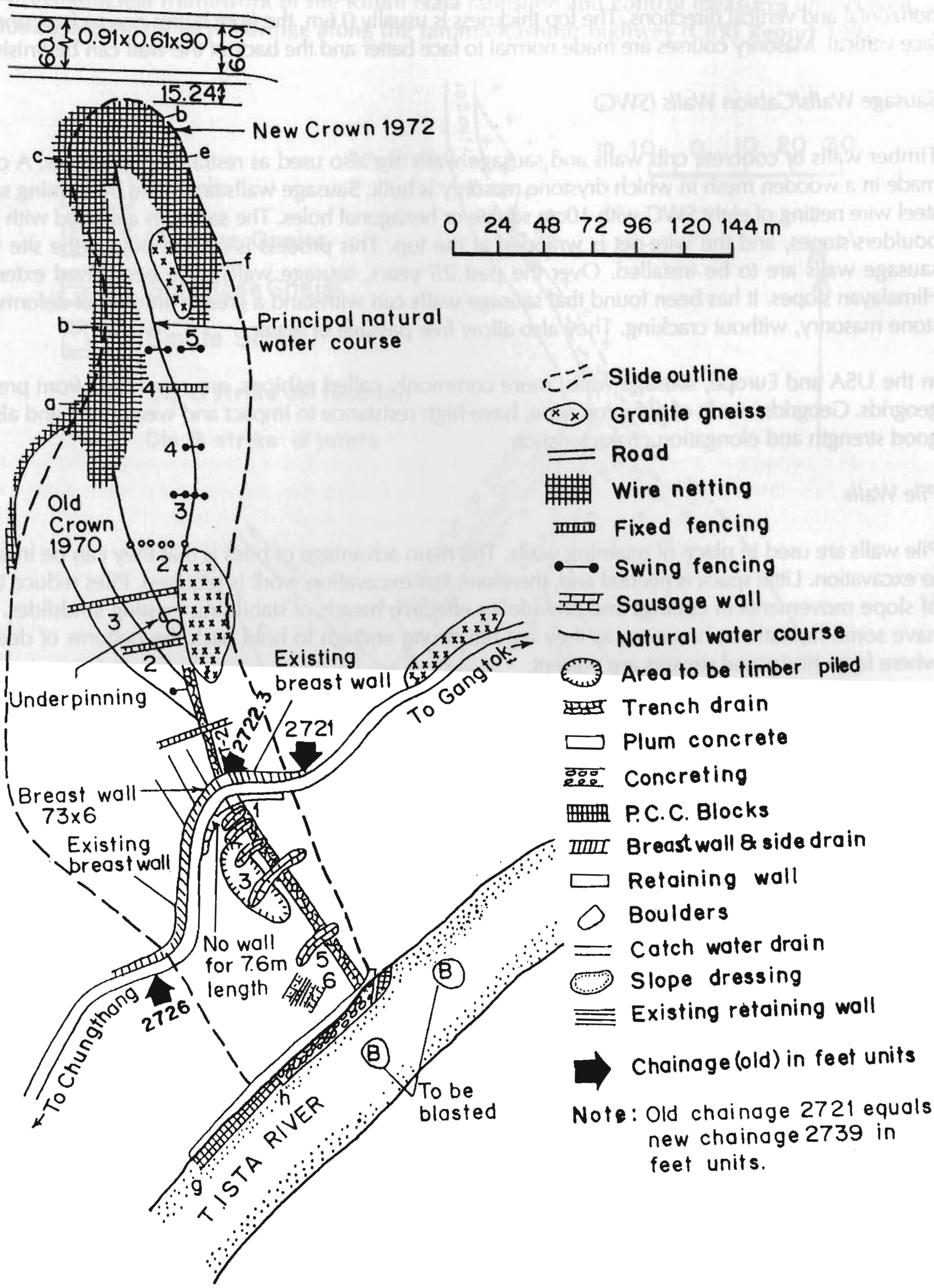
Buttress Walls

Buttresses are often used as retaining devices on landslides and creep movements on hill roads. Failure of the structure can take place due to foundation failure, shear between the structure and the foundation, and shear through the structure itself. Therefore, rock buttresses are constructed, preferably on solid foundations, to avoid foundation failure. The buttress is constructed with the upper face vertical and the lower face with a slope of 1.5:1.

Concrete Retaining Walls

Concrete gravity walls are very expensive and are used for important structures and in urban areas. These walls have a foundation in the bedrock or good soil below the slip surface. The stability of the whole body of the walls and the stem is considered in the design. The body of the walls is taken to include the mass of soil directly above the heel of the cantilevered wall and earth pressure. Weepholes are generally kept in the wall.

Figure 12: Extensive control measures undertaken to mitigate landslide hazards in the Tista Valley, Sikkim (Bhandari and Gupta 1985)



Self-supporting Measures

Self-supporting methods of landslide control are used primarily to improve the shear strength of the soil. The most commonly-employed techniques are rock bolts, rock anchors, anchored beams and cable lashing, shotcreting, and soil nailing.

Rock bolts are shallow fitting elements and anchors are fixed deep into the slope. A rock bolt helps to stabilise the slope face by exerting force which compresses the joints and prevents loosening by freezing. It also ensures greater stability by functioning as a dowel and increasing the shear resistance along the joints. Bolts are usually grouted along their entire length with cement or other chemical agents.

Anchors are used to control a much larger volume of rock than in the case of rock bolts. Anchors can be used to replace retaining walls and other supporting structures. Tendon and cable anchors are used to provide pre-stressing force. Pre-stressed anchors are used to stabilise a rock slope against the possibility of deep- seated failure. Pre-stressed rock anchors consist of high tensile steel wires or groups of wires inserted into the boreholes drilled into the slope. Pre-stressing force can be applied to the slope through the wire, and this makes the slope stable.

Anchored Beam and Cable Lashing

An anchored beam, made of concrete or steel, is used in any direction across the rock face. Anchored beams minimise the number of bolts required by distributing the support of rock bolts over a wide area of the slope. Cable lashing involves tying or wrapping huge unstable rock blocks with individual cable strands and anchoring these into sound rock slopes on each side.

Shotcreting

Shotcrete is concrete consisting of cement mortar with an aggregate of up to 20mm. Shotcrete is applied by air jet directly to the unstable sections of rock slopes to prevent weathering and spalling of rock surfaces and to provide surface reinforcement between rock blocks. Prior to the application of shotcrete, the slope should be thoroughly scaled of loose rock pieces. Shotcrete is applied in 70mm to 100mm thick layers, and each layer is allowed to set before successive layers are applied. A steel mesh is sometimes bolted to the slope face before shotcreting is carried out. Shotcrete provides a rapid and mechanised solution to rockfall problems. It is very commonly used to stabilise rock slopes in hydroelectric projects.

Soil Nailing

Soil Nailing is a method of reinforcing the ground *in situ* and is applied to retaining structures and natural slope stabilisation. It is primarily a combination of the principles of the New Austrian Tunnelling Method and the Reinforced Earth Method.

Soil nailing is employed in alluvial silts, fine sand, cemented sand, weathered rock material, moraine, and so on, to stabilise cuts ,to improve the safety of existing cuts, and to restore failed slopes/walls.

Geometry Alteration Measures

Altering the geometry of a slope can improve the stability of deep-seated slopes. This can be achieved by removing all unstable materials and, if necessary, replacing them with stronger materials. The common approach is to either remove some of the material from near the top of the unstable zone or to add material at the toe.

This method is used occasionally to control potential landslides but is more suitable for existing landslides. It involves designing a suitable slope, followed by proper surface drainage measures. It is best suited for slides moving downslope towards a road and not for slides that undermine a road on its downward slope.

Surface Protection Measures

Surface protection measures may include planting, turfing, coir netting, and rock revetment, which are effective in preventing soil erosion and, in turn, stabilising the slope.

Planting

Afforestation is more effective for stabilising shallow sheet slides than landslides with deep-lying slide surfaces. It is generally accepted that forest growth helps to dry out the surface layers, and that ramification of the root systems assists the consolidation process. Since trees draw water from the surface beds, the most suitable species for planting on sliding slopes are those that have the highest consumption of water and the highest transpiration rates. Experience has shown that a mixed forest of broad-leaved trees, such as oak, hornbeam, ash, and alder, which may also be grown as coppice in a 30 to 40 years' rotation, is most appropriate for the afforestation of sliding areas. In the absence of binding material in the soil, such as silt or sand, reinforcing material is used to strengthen the root mat system.

Reinforced Vegetation Using Geogrids

'Geogrids' (such as Netlon and Tensar) are extremely flexible, extruded polymer meshes of high tensile strength. They are used for earth reinforcement applications. Forced vegetation, regeneration, and afforestation programmes for enhancement of slope stability are proven methods and are practised widely. Normally, the vegetation growth on a slope depends upon several factors, e.g., retention of soil moisture, slope angle, constituent soil particle size, velocity of surface runoff, type of soil cover, and so on.

Vegetative Turfing

This method consists of preparing a slope area into seed beds by grading it to the extent possible and then broadcasting seeds or planting root strips of locally-available creeping grass with a good network of roots. The vegetation network of a root system penetrates 50-75cm deep into the slope, thereby serving as a soil anchor and providing added resistance to erosion.

Coir Netting

Processed coir yarn is made of coconut husk and is generally woven in meshes of 1", 3/4", and 1/2". If a heavy mesh fabric is firmly laid on graded earth and sown with suitable grass seeds, it gives maximum protection to the soil until the grass takes root and provides a permanent coverage. After the soil is stabilised, the netting decomposes and provides nourishment to the grass growing on the soil medium.

Soil Stabilisation

Lime columns, grouting electro-osmosis, and soil nailing are the methods commonly employed for slope stabilisation.

Grouting

Grouting is used to improve weathered slopes from which rock or boulders may be falling. Proper types of grout and acceptable injection pressure is determined before applying the grout. Strict quality control is required for mixing proportions, water content, grout pressures, and so on during grouting operations. Grouting is a costly remedial measure and is recommended for use only in exceptional situations.

Chemical Stabilisation

Landslides in the case of sensitive clays can be effectively controlled by using chemical methods. The shear strength of sensitive clays is increased by the diffusion of different salts placed in holes drilled in the clay. Lime is mixed with clay using a tool shaped like a giant dough mixer or egg beater.

Case Histories of Landslide Control

The Border Road Organisation and Public Works' Department maintain the main arteries of the road system in the Himalayas. They consult other technical organisations, such as the Geological Survey of India, the Central Road Research Institute, and the Central Water Commission, to devise landslide control and management measures (Fig. 11). Two examples of landslide management are described below (after Soin1980).

Landslide 'A'

The slide 'A' area covers a road length of 550m and extends 245m above and 240m below the road. The main causes of the slide were percolation of water, absence of vegetation on the slope, and undercutting at the toe of the slope due to a meandering river. The slide has been controlled by providing proper drainage and carrying out river training measures. Drains have been constructed to lead the water outside the slide area, chutes on the downstream side to drain out water, and check-walls between the river and the road. The river training works include three spurs and a toe wall with an apron. A breast wall has been erected all along the slide. These measures have helped to stabilise the area affected by the landslide.

Slide 'B'

This slide has affected a road length of 700m; it extends 200m above and 37m below the road level. The slide area is located at the river bend, and sliding has resulted in soil-mass movement in wet conditions, subsidence, and toe erosion. The slide took place after the 1968 floods when one kilometre of the road was breached, damaging the retaining walls and breast walls.

Based on studies carried out by the Geological Survey of India, the Central Road Research Institute, and the Central Power Commission, a new formation was cut and drains were built; benching on slopes was provided; and river training works, spurs, and aprons were constructed at river level. During the 1973 floods, the spurs were heavily damaged. The slide has been controlled by providing drainage above the road, river training works, and restraining structures. Water from above the crown of the slide has been drained out outside the slide area through a drain towards the downstream side. Flow through the *nullah* is channelised to pass over the chutes. The denuded portion of slide is cut into steps and a drain provided over the old step. The intervening step is drained through the perforated bamboo placed three metres inside by excavation and backfilling. To prevent attacks from the flow of the river water, three spurs of crated boulders with heavy toe protection, rising one metre above the highest flood level and with an apron in front, have been provided. These measures have stabilised the slide-affected area.