Slope Stability- Problems and Remedies in River Valley Projects of NW Himalayas, India - A Review

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Abstract

The paper deals with the slope instability problems and remedial measures adopted for stabilizing the hill slopes and cut slopes at various river valley projects of NW Himalayas. Geologically the area is represented by the formations ranging from Recent to Sub-Recent Quaternary sediments, soft and friable Siwalik sand-rock and clay-shale in the foothill zone to Central Crystalline Rocks of Archean age in the higher reaches. Due to repeated folding, faulting and thrusting the rock condition has considerably deteriorated, particularly near the tectonic contacts. The entire Himalayan belt is located in high seismic zone hence the area experiences frequent earthquakes of high magnitude. The author has reviewed the case histories of some of the river valley projects located in NW Himalayas. He has come to the conclusion that in most of the cases slope failures have been due to the presence of adversely oriented planes of discontinuities, loss of cohesion and angle of internal friction on saturation, removal of toe support and poor rock strength due to crushing near the tectonic contacts.

Introduction

The author has been associated with geological investigations of several river valley projects located in the NW Himalayas. The perpetual problem faced at all the project sites is slope failure during construction/ excavation or operation, which results in suspension of work, loss of men and material causing considerable delay in construction schedule and cost escalation. The result of slope failure can often be catastrophic hence it needs due attention. It is a normal practice that, the physical and geo-mechanical properties of foundation, as well as, slope forming materials are determined well in advance, hence their behavior under different conditions is very well known. Seismic status of the area is also taken into consideration. Design of safe cut slopes providing a suitable factor of safety is worked out during pre-construction period. Forecast geological sections and plans are prepared at different excavation grades for the overall safety and economy of the project. Case histories of few projects furnished below clearly indicate that the slope failures have been in the form of planer failure, wedge failure, rotational slump slide, debris flow or sloughing on saturation mainly because of under cutting or removal of toe support due to natural processes or human interference. Proper planning, scientific approach and regular monitoring during excavation, as well as, during post construction period can greatly help in preventing such problems.

Case Histories

Ramganga River Project, U.P. (Uttrakhand)

A 125.6 m high earth and rock fill dam has been constructed near Kalagarh in Garhwal district of Uttrakhand. The dam site is represented by gently dipping sequence of alternate beds of poorly consolidated sand-rock and clay-shale of Middle Siwalik Group. Hill slope stability problems were encountered in the vicinity of tunnel inlets and stilling basin where repeated rock slides took place. The bedrock sequence, which has a bearing on the slopes around the tunnel portals and intake shafts between the riverbed

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and elev. 372 m, are clay-shale beds nos. 7, 9 & 11 and sand-rock beds nos. 8 & 10. The clay-shale beds have regular plastic clay gouge seams of 5-25 cm thickness. These seams have very low 'C' and 'Phi' values and act as potential slide planes for planer failures, particularly in the presence of moisture. There were also sufficient indications about the zones with inherently low shear strength of the material in sand-rock members. In the area above elev. 372 m the bedrock sequence that has a bearing on the slope stability are sand-rock bed nos. 14, 16, 18 & 20 and intervening clay-shale bed nos. 15, 17 & 19. The beds are dipping at 38° to 42° in the NE direction, i.e., towards upstream side. The over all stability had been undermined by excavations carried out towards the east for chute spillway, towards the western side by a nala course and at its toe by constructing a berm at elev. 372m. Seepage of rainwater further deteriorated the stability of slopes, causing slides along the clay gouge seams in clay-shale bed no.15. In fact the hill slopes in this area should not have been cut steeper than the prevailing bedding dips (38°). The clay-shale members which are known to have poor 'C' and 'phi' values should not have been exposed on the slopes and should have been taken on the berms with adequate cover of sand-rock over them. During the course of excavation of 15m wide permanent approach road at elev. 335m, a part of the right abutment slope, over-looking the chute spillway and stilling basin, experienced large-scale slide between elev. 335m. and 420m. The slide area waslocated in the weathered and jointed sand-rock sequence 40-42. Besides the bedding planes, the bedrock was traversed by closely spaced, prominent transverse joints trending in NNE-SSW direction and dipping at 65° to 70° in the SE direction, i.e., towards the free face, and a set of stained, oblique joints striking N50° E-S50° W and dipping at 40° to 45° in the SE direction. The transverse joints were at places 10 to 15 cm open on the surface due to which the bedrock had been split into slices of varying thickness. The slide scar was trending more or less parallel and along the transverse joint planes and passing along the oblique joints at lower levels. The slide had been triggered off by the steep cut made during the road excavation and day lighting of the open transverse joints along which the loose rock mass moved down under its own gravity because of poor friction along the joint planes. Flattening of slopes and provision of berms at 15 m height interval, along with proper surface drainage had been recommended (Mandwal N.K., 1975) as the remedial measure for stabilizing the hill slopes in the effected reach

Tehri Dam Project, Uttrakhand

A 260.5 m high earth and rock fill dam / with upstream inclined clay core has been constructed across river Bhagirathi at Tehri. The area is represented by Chandpur phyllites belonging to Tehri Formation of Ordovician-Silurian age. Strike of foliation varies from N55° W – S 55°E to N 80° W – S 80° E and dip varies from 35° to 65° in the southerly direction. Its reservoir extends for 44 km in Bhagirathi valley and nearly 25 km in Bhilangana valley. During the construction period, wedge failures were noticed (Navani, et.al., 1992) on the dam abutments due to the presence of more than five sets of joints

Preliminary surveys carried out to assess the instability risk of the reservoir rim (Navani, et.al., 1992) have revealed that there are some zones above FRL (835m) where slopes consisting of overburden/river borne material either bear clear manifestation of instability in the form of subsidence, extensive tensional cracks, tilting of surfaces, tilting of trees and active slides, or are in the critical state of equilibrium. Instability problems are also anticipated, particularly during the reservoir operation, in the areas where, dwellings are perched on river terrace deposits. Constant monitoring of hill slopes in such vulnerable areas is very necessary. Near Tehri town, on the right bank of river Bhagirathi, frequent slope failures took place in the moderately inclined SE facing slopes consisting of

Chandpur phyllites and phyllitic quartzites, during the construction of roads and buildings. The causative factor is attributed to large-scale excavation at the toe for developing the roads and excessive head-ward loading at the top for constructing the buildings. Infiltration of rainwater and domestic water discharge through the joints and crevices into the slope forming material further worsened the situation (Nawani, et.al., 1992). Remedial measures including better land use management were suggested to tackle the instability problem.

Pong (Beas) Dam Project, Punjab

A 133m high earth core-cum-gravel shell dam has been constructed near village Pong, across river Beas. The dam site is located on gently folded alternate beds of sand-rock and clay-shale belonging to Upper Siwalik Formation. The clay-shale beds generally contain 2 cm to 15 cm thick sheared plastic clay seams nearly parallel to bedding plane, which are dipping at 8-10°in N.N.E. direction, i.e., towards the river. These clay seams were presumably formed as a result of inter layer movement during folding. The angle of shearing resistance {phi) of the plastic-clay material is about 18°. Where ever, the plastic clay seams have been day lighted in the dip direction by topographic cuts, the low 'phi' value of these seams in conjunction with the poor tensile strength of poorly cemented and jointed sand-rock overlying these plastic-clay seams have given rise to block gliding. Some of the sand-rock beds have artesian conditions.

Slope stability problem was encountered at the tunnel intake site, where the cliff face is in the form of a semi-circular slide scar, developed due to a major slide in the past, possibly along the plastic clay seam, that had worsened the situation with the rock formations getting saturated due to impounding of the reservoir Further cyclic effects of drawdown and filling of reservoir facilitated block gliding along the plastic clay seams, there by endangering the safety of tunnel intake structures. The remedial measure adopted was, removal of a portion of the hillock on the back of the tunnel intake structures (Jalote & Tikku, 1975). In addition, toe support has also been provided to the hill face by the gravel pack, in the area below the intake bench.

Ranjit Sagar (Thein) Dam Project, Punjab

A 160 m high earth and rock fill dam has been constructed across river Ravi in Gurdaspur district, Punjab. The project area is located within Lower Siwalik Formations (Middle Miocene) comprising alternate sequence of sandstone, claystone/siltstone having gradational contacts. The dam site is located on the southern limb of Mastgarh anticline. General strike of the formations is N 60° W – S 60° E and the dip varies from 65° to 75° towards SW. However, in the tunnel inlet area slightly gentler dips of the order of 35° to 50° towards the valley side and a low angle fault with deep weathering have been observed. Two major joint sets, i.e., bedding joints and transverse joints with vertical to sub-vertical dips have also been recorded. These adverse features created the slope instability problem in the tunnel inlet area when the excavation for constructing the tunnel portals was proceeding. The remedial measures initially suggested (Andotra, et.al., 1992) were in the form of providing 1:1 slope cuts with berms at every 15m vertical intervals. Further, protection of clay-shale and sandstone against weathering was ensured by means of slabs and shotcreting respectively. The inlet portal reaches of tunnels P-2 and T-1 collapsed up to a length of 45m. The collapsed material was removed around tunnel P-2 from top downwards to expose the interface of the slipped and intact rock. Some tension cracks were observed around elevation 423m on the intake bench, as well as, shotcreted side slope, due to day lighting of adversely oriented joint planes in the deep slope cuts. It appears that the nearby heavy blasting induced large scale ground vibration, which triggered the failure. The stabilization measures recommended were in the form of installation of 5-15m deep inclined and vertical grouted anchors from the intake bench slope cuts, stopping nearby blasting, regular monitoring of slope movement, installation of support system in stages of 3m at a time and back filling of the space above the cut and cover section by RBM. The final benches, on the left side slope cuts of the spillway, between elevation 545m and 515m, also failed in clay-stone reaches along the bedding plane. The causative factors leading to slope failure are day lighting of bedding planes, considerable time lag between excavation and protection measure, induced ground vibrations due to heavy blasting etc. Remedial measure adopted was that the vulnerable slope cuts were protected concurrently with the excavation and it has been very affective in arresting the slope failure in this area.

Yamuna Hydel Scheme, Uttrakhand

A 55 m high concrete dam has been constructed across river Tons, at Ichari near village Koti, power tunnels and an underground power house at Chibro and a surface power house at Khodri in Uttarakhand. Project area is represented by Jaunsar slates, quartzites and limestone; Subathu Dagshai shales and Nahan sandstones and claystone with thrust contacts.

At Ichari dam site, presence of excessive overburden on the left abutment overlying a deep zone of weathered and disturbed rock with glide cracks between 33m and 63m depth pose slope stability problems. In order to stabilize the left abutment, as per recommendation of G.S.I. (Jalote, et.al, 1975) re-enforced concrete wall anchored to a sound quartzite band by means of reinforced concrete anchors has been provided. On the steep right abutment of the dam, local overhangs have been supported, by concrete buttresses raised from top of the dam. The hill face downstream of the dam axis has been provided with 40 mm diameter and 7m deep anchors at 2.5m centers, in order to stabilize the abutment. In addition, drainage galleries have also been provided at suitable locations in side the hill, both upstream and downstream of the dam axis. Slope stability problems were also encountered at Khodri surface powerhouse site. The problem became more acute due to slope cuts required for accommodating the pressure shafts. Any rock fall or slide would damage the powerhouse and would also reduce the lateral cover for the main surge shaft and the adit portal located on this slope. For stabilizing the hill slopes, 5 m deep perfobolts or rock bolts at 3m spacing, covering the entire hill face with chain link fabric and shotcreting has been provided. Surface catch drains and sub-surface drainage holes through drainage galleries have also been provided to keep the hill face freely drained.

Khara Hydel Project, Uttrakhand

Khara hydel scheme envisages utilization of the tail waters of Kulhal power house, by constructing a 17.7 km long water conductor system (12.3 km long power channel, 1.3 km long power tunnel & 4.1 km long tail race channel) and a 72 MW capacity surface power house, on the left bank of Yamuna river in Garhwal district of U.K. Geologically the area is represented by soft and friable Upper and Middle Siwalik sandrock, siltstone and boulder conglomerates and Quaternary sediments. Neotectonic activity has also been recorded (Shome & Mandwal, 1979) across Yamuna tear. The rock formations generally trend in NW-SE direction with variable dips due to folding and faulting. Two prominent tectonic features, viz., Foot Hill Thrust and Yamuna Tear, were picked up (Rawat, et.al., 2002) during the construction stage geological investigations of the project. The significant geotechnical problem faced at this project was, the instability of cut slopes along the left flank of the channel. The causative factor was attributed to the presence of adversely oriented discontinuities and low dipping claystone & clayey siltstone beds. These beds acted as lubricants in the presence of moisture. Presence of old slide debris, which got reactivated, also posed the slope stability problem along the channel alignment. Besides this, instability of steeper slopes in conglomerate beds in the tunnel inlet area posed the problem for establishing the tunnel inlet portal. The remedial measures adopted for stabilizing the slopes at various component sites, included removal of clayey zones, flexible channel lining with proper drainage arrangements, construction of false tunnel portal, provision of berms at 10m vertical intervals and shotcreting with wire mesh in the vulnerable reaches.

Garhwal-Rishikesh-Chilla Hydel Scheme, Uttrakhand

A barrage has been constructed across river Ganges, nearly 4km downstream of Rishikesh, a 14km long power channel and a surface power house at Chilla, on the left bank of the river. Geologically the area is represented by rock formations belonging to Upper Siwaliks. The power channel lies in a rugged terrain comprising Recent to sub-Recent river borne deposits and fan deposits. Construction of the canal necessitated 30-35 m deep cutting and filling in these deposits between R.D. 00 and 10.20 km. Beyond R.D. 10.20, up to the power house, the power channel passes through alternate bands of clay-shale and sand-rock of Upper Siwalik formation. Contact between clay-shale and sand-rock is invariably sheared with 2-40cm thick plastic clay seams. These seams have very low shear strength and have played a very significant role in the stability of cut slopes in certain reaches of power channel and powerhouse area.

Between R.D. 11.00 and 11.50 km. the power channel experienced repeated slope failures during excavation. Detailed geological evaluation revealed that in this reach the channel is located in an old slip area and the plastic clay gouge seams are mainly responsible for such failures. For stability of cut slopes in this reach 5:1 (H:V) slopes were provided on the left flank, higher up toe supports were provided with adequate filter arrangements at each break in slope.

In the power house pit, to achieve the foundation grade at elev. 227.50 m, side slopes of ½:1 (H:V) were provided. However, during the monsoon period a part of the slope, upstream of the powerhouse between elev. 295.00 and 310.00m slided and filled the pit. During the excavation of intake blocks of Unit I and II another slide took place which, got further enlarged while clearing the muck. Geo-technical assessment revealed that the instability was caused by the under cutting of the highly sheared plastic clay seams dipping at low angle towards the free face existing along the contact of clay-shale and sand-rock bands. Stability analysis of the slope carried out indicated that for obtaining a factor of safety of 1.5, the slope in the non-overflow portion should be covered by a minimum of 2 m thick concrete with efficient drainage arrangements comprising vertical sand drains of about 12.5 cm diameter and about 1.5 m center to center in the overflow section and 3 m center to center in non-flow section. At the top of the vertical sand drains, cross and longitudinal drains in the flow section and about 300 mm thick filter in the entire non-flow section have been provided. To ensure further stability of penstock slopes, RCC retaining wall with steel anchors has been provided.

Giri Hydel Project, H.P.

A 23m high barrage across river Giri at Jateon, 7.1 km long head race tunnel and 60 MW capacity power house near Majri in Bata valley have been constructed in H.P. Blaini slates and phyllites (Infra-Krol), purple and green shales with dolomites (Dadahu), black slates and limestone (Tarwali), olive green and red shale with limestone and basic rock (Subathu) and sandstone, claystone/siltstone (Nahan) are exposed in the project area. Slope stability problems were encountered at the powerhouse site, which is located in a deep pit. In this area alternate beds of Nahan sandstone and claystone/siltstone, pseudo-conglomerate and graywacke are exposed. The sandstones are generally soft and friable.

The formations trend in N.- S. to N. 10° E.-

S. 10° W. direction and the amount of dip varies between 15° and 25° towards west. An anticlinal axis passes NE of the power house site and a nearly 5 m thick shear zone runs about 5° to 10° askew to the fold axis. Powerhouse is located on the westerly dipping limb of the anticlinal fold. The hill slopes are steeper than the dip of the beds rendering it unstable. During deepening of the powerhouse pit, a number of slips occurred on the eastern slope. On account of adverse orientation of discontinuity planes it had been recommended (Dayal, et.al., 1973) that the slope cuts be kept at ½:1 with benches at suitable intervals, along with shotcreting, rock bolting and proper surface and sub-surface drainage arrangements.

Shanan Extension Hydel Scheme, H.P.

Shanan hydel scheme was commissioned in the year 1932, as a part of first stage of development of Uhl River Project. Later on, it was noticed that the steep penstock slopes above the valve house level up to anchor block 5-B, are showing signs of distress in the form of shearing of 110 cm diameter penstock pipe inside anchor block-1, cracking of saddle supports in the valve house, cracking of tunnel lining, tilting and subsidence of haulage track and development of eccentric gaps in saddle supports. The project area is represented by Chail Group of rocks, comprising highly folded phyllites, schists and gneisses.

The intake structure is located on the northern limb of a major syncline, while the penstocks and the outlet works are located on its southern side. Chail rocks have come in juxtaposition with the infra-Shali quartzite, phyllites and basic rocks on the southern limb. The tectonic contact between these rocks is Chail thrust, which is located towards north of surge shaft. An intra-formational reverse fault, the Gaira thrust along which the infra-Shali rocks have overridden the Shali dolomites and phyllites, are exposed towards west of penstock route. Shali thrust along which Shali Group of rocks have come in juxtaposition with the Tertiary sandstone and claystone (Draramshala Formation) is exposed on either side of the penstock alignment. It is supposed to cross the alignment between anchor block nos. 5-A & 5-B. The Gaira thrust and the Shali thrust have intersected each other along the penstock route. A number of transverse faults cutting across the major tectonic contacts have also been observed. Neotectonic activity has also been observed along the Shali thrust and Gaira thrust. Both these lineaments have overridden the debris material. Thus the area is tectonically highly disturbed. It has been conjectured that the tectonic movements possibly disturbed the stability of slopes, which resulted in block gliding along adversely disposed shear zones between valve house and anchor block no. 5-B. Past studies also revealed, that the stability of the slope was influenced by the ground water pressure. On the basis of the shear parameters of the slope forming materials, the design engineers carried out the stability analyses on the assumed factor of safety of the order of 1.2 for fluctuating ground water table and creep type of movement. Based on the geo-technical studies, it was recommended (Narula, 1988) that material above the valve house should be unloaded and pre-stressed anchors should be provided in the toe region with effective drainage of the slope. Provision of flexible couplings has also been made in the penstocks to accommodate tectonic creep along Shali/ Gaira thrust.

Upper Sind Hydel Project Stage-II, Jammu & Kashmir

This project involves the construction of two weirs, one across river Sind near Sumbal and the other across Wangath stream near Wangath, 16.5 km and 6.7 km long water conductor systems, a forebay, penstock and an underground power house at Kangan. The rocks exposed in the area are Cambro-Silurian phyllite and phyllitic quartzite with occasional shale beds. Strike of formations varies from N20°E – S20°W to N40°W – S40 °E and the dip varies from 25° to 45 ° in the northerly direction.

The forebay is located in medium to coarse-grained granites, however a greater part of the area is covered with debris and fluvio-glacial deposits. The area is prone to sliding hence, the forebay has been designed as a cut and cover section. Along the Sumbal link channel between RD 5710m and 5825m, rock slide was observed in the highly jointed phyllitic quartzite, resulting due to day lighting of bedding plane dipping at 38° towards the free face, on a steep slope cut. The corrective measures suggested include rock bolting with proper surface drainage arrangements. Another slide also took place between RD 5100m and 5200m along the Sumbal link channel. This slide was in the form of rotational slump failure in the overburden material, due to the removal of toe support during the excavation. Remedial measures suggested include dressing of slopes, construction of toe wall and proper drainage arrangements, in order to ensure stability.

Anandpur Sahib Hydel Scheme, Punjab

Anandpur Sahib hydel scheme comprises a diversion weir across river Satluj near Nangal, nearly 34 km long hydel channel for conducting the water to two powerhouses located at Ganguwal and Makkian in Ropar district of Punjab. Geologically the area is represented by alternate bands of sand-rock and clay-shale belonging to Upper Siwalik Formation. Strike of beds generally trend in N30° to 60°W-S30°- to 60° E with 40° to 60° dips towards SW, i.e., towards the channel. Shallowing of dips up to 5° has also been observed (Sinha & Sharda, 1990) in tail reaches of the channel, which appears to be due to folding. Slope instability problems were observed along the left bank of the channel for which, bed level was achieved after deep(+_ 22m) excavation. During heavy rainfall the canal lining got damaged between R.D.1785 and 1888m. Detailed examination of the area revealed that a large chunk of rock mass overlying a 5 to 7m thick clay-shale band slipped and subsided, resulting in heaving and displacement of the lining up to 2.6m in the toe region of the channel. The cut slopes were steeper than 0.5:1 with a 3m wide berm nearly 20m above the channel bank, without any proper drainage arrangement. In fact, during heavy rains the sand-rock got saturated which resulted in the development of pore water pressure. The impervious clay-shale band behind the sand-rock also got saturated near the contact and lost the shear strength, it rather acted as a lubricant and planer failure took place involving the movement of nearly 25,000 m³ of material.

Satluj-Yamuna Link Canal, Punjab

Satluj-Yamuna link canal takes off from Lohand head works near Kiratpur, picking up the tail water of Anandpur hydel channel. Total length of canal in Punjab state is about 121 kms and its base width in nearly 15m. About 20-40m deep excavation through soft and friable, very low dipping alternating sequence of sand rock and clay shale belonging to Upper Siwalik Formation has to be carried out to achieve the canal bad level. Serious slope instability problems were observed on the left flanks of canal particularly during the rainy season. Presence of nearly horizontally bedded yellow coloured silty-clay shale band is very conspicuous in the problematic reaches. The instability of slope cuts is restricted to the saturated left bank slopes of the canal while the dry right bank slopes are stable. The highly erodible Upper Siwalik sand rock and clay shale units, as well as, Quaternary sediments have disintegrated and slumped during heavy rains. The slumped material was deposited in the canal as fans, thereby choking the canal and also caused heaving of the canal bed at places. The remedial measures suggested were easing of the slopes to 2:1, provision of benches at 6m height intervals with proper drainage arrangements and turfing of the slopes.

Conclusions

In the design and construction of any river valley project, slope stability is an extremely important consideration. In hilly areas infinite slopes are formed over a prolonged period by the natural processes. When efforts are made to dress or cut these slopes according to the project requirements then their equilibrium gets disturbed and slope instability problem arises. A review of such problems at various river valley projects located in NW Himalayas has brought to light that soft and friable incompetent rocks belonging to Siwalik Formation and phyllite and schist (Cambrian-Ordovician-Silurian age) are much more prone to sliding than the hard and competent crystalline rocks like granite and quartzite. Tectonic movement and shearing of rocks near the tectonic boundaries has also played a significant role in inducing instability to the slopes. The movement is generally gravitational, however, rotational or wedge failures due to removal of toe support, debris flows and sloughing due to saturation and development of pore water pressure have also been observed. According to Seismic Zoning Map of India prepared by BIS the entire Himalayan belt is the zone of high seismicity (Zone IV & Zone V). Frequent earthquakes of high magnitude have been recorded in the region and they are also one of the causative factors for triggering the slides. Proper understanding and analysis of the slope stability combined with scientific approach during the excavation can obviate such problems.

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