Engineering geology for high dams

Bhardwaj, Sunil
Chief Manager (Civil), SJVNLimited, Shimla-171009, H.P., India
Thakur, Vinod
Manager (Civil), SJVN Limited, Shimla-171009, (HP),India

Abstract

Engineering geological investigation of a dam site is essential to evaluate its precise geological conditions before the site is taken up for construction. Such investigation is generally done in different stages. Engineering geological mapping of the site is prepared to identify and record the lithological and structural set-up including all the visible geologic defects at the surface, in the subsequent stages, exploratory drilling and sometimes geophysical works are done to identify the subsurface weakness of the site. Geology of high dam construction are associated with adverse geological conditions of the dam site like soft rock, fault, shear zone Joints weathering permeable boulder deposit, soluble rocks, ancient slide etc. The geological set-up of dam sites and associated geotechnical problems are variable from place to place. Thick mantle of overburden and weathered rock, presence of soft layered strata, structural defects like fault, thrust, shear zones and joints are some of the common geotechnical problems faced during dam construction. Old slides, deep zones of kaolinisation, permeable boulder bed, buried channel and karstic condition are adverse geological features of a dam site. To construct a dam in such a geologically adverse situation, it may involve expensive foundation treatment. In spite of the presence of adverse geological features under varied geological set-up, numerous dams have been constructed in India including a part of the Himalayas for the purpose of irrigation, hydel power-generation, flood moderation etc. Of these, only some typical cases are presented in this paper to highlight the various types of geotechnical problems faced in the high dam building history of north India and to show how these problems were solved.

1. Introduction:

A Dam is an engineering structure constructed on a river or stream to divert, or store water for the purpose of water supply, energy generation, irrigation, flood control, ground water recharge, conservation storage and recreation among others. They are required forcreating storages of water, not only for irrigation, hydro electric power generation and watersupply, but also-for thermal power stations, industries etc. They control floods-and increasedry weather flows, and provide the basis of a fishing industry. They also give opportunitiesfor various recreational activities and can maintain a wetland environment that is favorable tobiodiversity. Dams are thus a great source of wealth, and if they disappeared, the livingconditions of one-sixth of humankind would become untenable. But besides being a source of wealth, dams can also be a source of accidents, albeit it few innumber: an average of less than 1% of dams has suffered accidents over a long period of time.Yet the resulting damage and loss of life mean that all such accidents are unacceptable. A damprevents the flow of water on surface, but if water is to be stored, it has also to be seen thatthere is not a flow below the surface either. This means that the foundation rocks must bewatertight, and if they are not naturally so, suitable steps have to be taken to prevent loss ofwater through them. Also, to avoid the disastrous effects of dam failure safety and stability ofa dam have to be assured. These will depend among other things on the strength andsoundness of foundation rocks, which in turn will depend on the nature and structure of theserocks. An analysis of dam failures of the past has shown that failure to recognize or to treatproperly defects in foundation rocks was responsible for a substantial number of them. Thesafety, stability and effectiveness of a dam therefore will depend largely on the geologicalconditions at the foundation and these must be known with accuracy and in sufficient detailbefore the work on a dam is undertaken. Detailed geological investigations have therefore tobe carried out for obtaining the necessary information about rocks at the dam site and in thereservoir area.

2. Dam site Investigations

2.1 Preliminary Investigation:

Preliminary investigation is done on the site to collect the information about the disadvantages or advantages of the site. This is more flexible because the detailed investigation will be more expensive, extensive and laborious. The important information collected at this stage is based on the factors as followed:

- i) Lithology
- ii) Structure
- iii) Physiography (Topography)
- iv) Ground water Conditions.

i) **Lithology** provides the details of rocks types occurring in the dam site. The details include the types of rock present, their nature and extent of weathering, the occurrence of soil, rock debris, etc. Lithology also gives a broad idea of the presence or absence of competent rocks, the weathering it has undergone and other related information.

ii) **Structural** gives information on the strike and dip of the beds. It also reveals the occurrence of geological structures like folds, faults, joints, unconformities and foliation. Details of these features are very important because they have a great influence on the suitability of site for dam.

iii) **Topography** (Physiography) gives information about important surface features like valleys, hills, the trend of the river course, slopes and terraces present in the area. These details indicate the stability of the slope and the slope of the occurrence of landslides. Topographic studies also help in rough assessment of the depth of the bedrock at the site. The nature of seismic activity in the region can also be known by suitable studies.

iv) **Groundwater conditions** are related to the study of occurrence of springs, seepages, swamps, wells etc. present in the selected area. This type of study indicates the water table position and the scope for leakage of water from the associated reservoir. This also indicates the occurrence of solution cavities, if any, in the area.

2.2 Detailed Investigation:

If the Dam Sites is found to be good in the preliminary investigations, then it is taken up for detailed investigation. This process comprises of surface and subsurface investigations. The surface investigations include closer examination of lithology, structure, physiography and groundwater conditions. The thorough investigation of the above factors, with the support of laboratory studies of the materials at the dam site will reveal the conditions of outcrops, faults, joints, folds, & their attitudes, weathering details, soil occurrences, engineering properties like compressive strength, tensile strength, porosity, permeability and durability. These also include the factors of investigations as said above. But the studies include the study of deeper layers of the dam site for ensuring the standards and safety of the dam.

3. Engineering Geology for High Dams:

3.1 General

Dam having height more than 100m is called a high dam. Many high dams have been constructed in the Himalayas and other parts of India. Special care is required before finalizing the site for such dams. Many times high dam construction are associated with adverse geological conditions of the dam site like soft rock, fault, shear zone Joints weathering permeable boulder deposit, soluble rocks, ancient slide etc. The geological set-up of dam sites and associated geotechnical problems are variable from place to place. The construction of dams to create storage reservoirs, and the location and design of major dams are invariably influenced to some extent by geological features. In many cases, geological factors such as foundation conditions and the proximity of construction materials are of overriding importance in determining the type of dam constructed at a given site.It therefore follows that a detailed knowledge of the geology of a prospective dam site and its environs isnecessary before an informed decision can be made on the most suitable dam design and the estimated cost of construction.The most important basic geological data required are the distribution and nature of the various rock types present in the area, the weathering profile, and details of the structural geology. These data are obtained by a site investigation program which uses a wide range of data-gathering techniques, such as outcrop mapping, bulldozed trenching to expose bedrock below overburden, diamond core drilling, water pressure testing, geophysical surveys, joint surveys, and laboratory testing of rock samples. The geological and physical data so obtained are then integrated to form ageomechanical model of the site, which provides the design engineer with a reasonably realistic and quantitative basis on which to design the dam and itsassociated structures. This process of collecting relevant geological data and presenting them in a formwhich is useful to the engineer is the main function ofthe engineering geologist.A high dam has two essential requirements:

(i) It must be reasonably watertight. To achieve this,the dam is either constructed of impermeable material (e.g. concrete) or it incorporates an impermeable membrane in its structure (e.g. an earth core); also, the dam foundations must be made watertight by grouting or other means ifnecessary.

(ii) It must be stable. Movement and deformation of the dam and its foundations cannot be eliminated,but they must be predicted and allowed for in the design.

3.2 Geological Considerations in the Selection of High Dam Site:

Careful geological studies bring out the inherent advantages of any site selected for the dam, and it also reduce the cost of the dam considerably. The important geological requirements that should be considered in the selection of a dam site are as followed.

(i) Narrow River Valley.
(ii) Occurrence of the bedrock at a shallow depth.
(iii) Competent rocks to offer a stable foundation.
(iv) Proper geological structures.

(i) Narrow River Valley:

If the proposed site contains a narrow river valley, only a small dam is required, which means the cost of the dam construction is also will be less. On the other hand if the valley is wider, construction cost will be very high and maintenance of the dam will also be high. Yet if the valley is narrow, following considerations should be taken in to account.

a) Deceptive narrowing of a valley due to the occurrence of thick superficial deposits such as residual soil and talus, in recently glaciated regions, moraine, boulder clay, sand, gravel and river alluvium.
b) Narrow valley due to deceptive rock outcrops which are the result of land slip, rock creep and rock fracturing.
c) The occurrence of buried river channels crossing the site, either below the bed or adjacent to it.
d) Unsuitability of rocks in some places due to the presence of soluble materials like gypsum or due to faulting (i.e., when the river flows along a fault) which may be concealed beneath sediments.

(ii) Occurrence of bed rock at shallow depths:

If the dam rest on very strong and stable rocks, the stability and safety of the dam will be very high. This also reduces the cost of the dam. On the other hand the dam cost will be high and the work of excavation will be more. This also requires heavy concrete refilling. For example, at the site of Bhakra dam on Sutlej river, the sound bedrocks were at a great depth below the ground and, as a consequence, excavation for the foundation was one of the major items of work of that project. In the case of deposition along the river valley depends on the stage of river. If the river is in young stage, the erosion might have exposed the strong bed rocks that may occur at the surface this would be competent for the dam construction. Yet some of the points are to be considered while selecting the dam site at such a location. This is because the hilly terrain which occurs in these stages may not provide a suitable topography for the occurrence of a large reservoir basin and the flow of water itself may not be high in such developing rivers for obvious reasons. In older stage, the deposition will be resulting in overburden. This means that suitable bedrock may lie at a considerable depth and hence proves uneconomical. The general occurrence of material like clay, silt, sand and gravel along the river bed, naturally makes it difficult to assess the thickness of loose overburden by mere surficial studies.

Therefore, to know the bedrock profile in the river valley along the axis of the proposed dam, geophysical investigations such as "electrical resistivity studies" or seismic refraction studies" are carried out carefully. The data recorded in the field during investigations are interpreted and the required bedrock profile is visualized. Such a result gives scope for estimating the amount of excavation work of loose material and concrete refilling required upon only after necessary checks and scrutiny.

(iii) Competent rocks for Safe Dam:

If the dam site consists of igneous rocks, they will offer a safe basis. If sedimentary rocks, particularly shales, poorly cemented sandstones and cavernous limestones, they are undesirable. Even though igneous and metamorphic rocks occupy 95% of the earth's crust, but on the surface only 30% igneous rock occur. Among them granite and basaltare most common ones.A dam site comprising of granite and basalt shall be much competent. Yet another point of care should be taken that, if the granites and basalts occur with the sedimentary formations like shales, sandstones and limestones. If the percentage of sedimentary formations is more, thorough investigation is needed and this will increase the dam construction cost, including excavation.

The suitability of the site for the dam construction can be estimated by the following factors:

a) The existing rock type at the dam.
b) The extent of weathering it has undergone.
c) The occurrence of intrusions.
d) The extent of fracturing.
e) The occurrence of geological structures.
f) The mode and number of rock types.

(iv) Proper Geological Structures:

Details of geological features are very important as they have a great influence on the suitability of site for high dam. The dam located on rocks dipping upstream represents ideal foundation conditions.They are the most capable of supporting the weight of dams and pressure of the reservoir because the resultant of the two forces acts nearly at right angles to the bedding planes of rocks. Further the upstream of rocks does not allow the water in the reservoir to percolate below the dam. As a result the leakage of water and the development of uplift pressure will be minimum.The dam located on rocks dipping downstream may not be safe as the resultant of forces acts parallel to the bedding planes and endanger the stability of the dam. The dam built on jointed and permeable rocks, not only causes leakage of water, but also build uplift pressure at the base of the dam. The uplift pressure acts opposite to the weight of the structure and it may cause sliding. Such rocks may be consolidated by grouting. Faults are most troublesome if they are encountered across the length of the dam. It is better to avoid fault zones for the construction of dams as it is difficult to seal the fault zones and prevent the leakage of water from the reservoir at a reasonable cost.Also careful attention must be given to the orientation of joints, bedding planes, foliations and weak zones that are present in the abutment rocks. If such zones lie parallel to the thrust of the water in the reservoir, the stability of structure may be endangered. The rocks that exist in the abutment of an arch dam should be strong enough to resist the pressure without being crushed.

4. Case Histories of High damsbuilt in North Indian:

Case history of few high dams in North India such as Bhakra dam, Tehri dam and Kol dam have been discussed as below:

Table 1
Engineering Geologic Evaluation of North Indian high dams

S.N	Name of Dam	Main Rock Types	Engineering Evaluation
1.	Bhakra Dam (226.0m high)	Sandstone, siltstone, boulder conglomerate	Low to moderate strength, wide jointing
2.	Tehri Dam (260.5m high)	ChandpurPhylite type are folded and grayish in colour	Low to moderate strength, narrow jointing
3.	Kol Dam (167.0m high)	Lime stone and dolomite	Moderate strength, wide jointing

4.1 BhakraNangal Dam:

Engineering geological knowledge played a key role in thesuccessful completion of many high dams in India. BhakraNangal Dam is verygood Indian example in which, geological considerations at the time of construction weretaken care of, which played a vitalrole in its stability and durability. Bhakra Dam is astraight high gravity dam founded on the soft rocks and medium hard rocks belonging toSiwalik supergroup, with fault zones cutting across the foundations and abutment in differentattitudes (Krishnawami, 1982). The preventive measures carried out comprised excavation ofthe heel clay stones and excavations of the spillway apron, which was tied down to thesandstone member overlying the downstream claystone band to prevent erosion. Beside thesespecial treatments, the cross shear zones on the abutments were treated by providing concretetunnel plugs and the entire foundation area of the Dam was grouted. Grouting and drainagecurtains were further provided from foundation galleries in the dam and through drainage andgrouting, tunnels were provided in the abutments. No major problems have been faced duringthe post construction period of the dam. except for cracks in the upstream (Reddy, 1995).


Picture 1 Bhakra Dam (H.P.), 226m high straight –gravity concrete dam.

4.2 Tehri Dam

Tehri Dam is an earth core rock fill dam (260.5 m high) built on Bhagirathi River at Tehri (Uttarakhand) This dam is highest in Asia. The Dam is situated in Lesser Himalayan geo-tectonic block which is bound by Main Central Thrust (MCT) in the south. The rock exposed in the area isChandpur phyllite, having variable proportions of argillaceous and arenaceous constituents. These rocks are classified into four sub-classes as Phyllitic Quartzite Massive (PQM), Quartzite Phyllite (QP) and Speared Phyllite (SP). The over burden is 10 to 15 m thick below the river bed level at the Dam site. The bed rock is traversed by numerous major and minor shears classified as diagonal (D) and longitudinal (l) shears depending upon their geometric relationship with bedding and foliation of rocks, thickness of clay gouge and the width of the affected zone. These shears have affected the Geotechnical behavior of rocks as revealed by detailed geological exploration. During the execution of large hydro-power project civil works, numerous construction problem of different magnitudes arise due to adverse geological strata. Every geological problem is unique and, therefore, to tackle the same for achieving the target of construction needs patient tackling. Any desperate effort to expedite the construction works in adverse geological condition may create problems, hence be avoided. Spillway structure in large dam all over the world reported failure. There is thus a need to take into account the geological complexities. Tehri Dam has one chute spillway and two shaft spillways. The Dam has been designed to a maximum flood of 15, 540 cumecs corresponding to a flood frequency of 1 in 10,000 years. Detailed investigations were therefore needed in the spill way area during construction of dam. The investigation of the Dam had been divided in to two phases. One before the construction and the other during construction. The pre- construction phase geological investigations were aimed at deciphering the following anticipated problems:

(i) Major river bed shear zones/ faults
(ii) Disposition of bed rock and deep weathering of abutment rocks.
(iii) Huge slide mass on the right abutment
(iv) Lugeon value of rock mass permeability
(v) Seepage through shear/ weak zones.

The investigations led to the following important Geotechnical assessments.

i) The fear of encountering major river bed fault was disposed off through extensive drilling/ drifting in the dam area. It was supplemented by electrical logging. The dam foundations excavations done in 1991 also supported the view of absence of any river bed shears.

ii) The rocks dipped 40º-67º down-stream of dam. This posed no stability problem.

iii) The thickness of overburden was estimated to be 15-30 metres, hence needed stripping before the foundation treatment.

iv) The average thickness of weathered rock in the river section was found to be 1 meter, based on geophysical logging.

v) The thickness of huge slide mass was found to be 40-50 metres.

vi) The permeability value of 50 lugeon was mostly in the overburden and highly weathered rocks. The fresh rock in the dam foundation had permeability in the range of 1-2 lugeon.

vii) Two major longitudinal shears were identified, which traverses across the dam seat, for treatment against seepage.

The above geological facts were helpful in deciding placement and design of the dam and its components. The area is highly seismic, hence the design of the dam had been done to prevent any ill effects. The width at crest is 20m and flared to 25m at abutments, 9.5m free board to take care of settlement/ slumping, dam slopes 2.5:1 (upstream) and 2:1 (downstream) and provisions of inspection galleries in the dam body, are some of the special features provided in view of the geological investigations done prior to the construction of the dam.The construction stage investigation is done to ascertain the stipulations made after pre-construction stage investigations. Most of the stipulations were found to be correct and helped in giving adequate treatment to the rocks exposed during construction.

Photograph 2 Tehri Dam (UK), 260.50m high Earth&Rock fill dam.

4.3 Kol Dam:

Engineering geological knowledge played a key role in the successful completion of Kol dam project in India. Kol Dam is very good Indian example in which, geological considerations at the time of construction were taken care off, which played a vital role in its stability and durability.The Kol Dam project is 167 m high andis situated in a Karstic terrain. The rocks belonging to Shali, Shimla, Sundernagar Groupsand Mandi Darla volcanic constitute the area. The dolomite ofTatapani, Limestone of Sorgarwari (Shali Group) andphyllites of Basantpur formation with basic intrusive are themajor lithological units exposed at the locations of majorcomponents of the Kol Dam project (Sanjiv Kumar 2005-06).In addition two generations of terrace materials are alsopresent in the project area one is simple river borne terracematerial composed of loose river borne materials likeboulders of Quartzite including the material coming from therocks present near the dam site and the other one is terracematerial composed of boulders, pebbles and gravel,essentially made of quartzite, limestone, dolomite and basicrock (all the rock materials that present outcrops near the damsite), in a sandy and highly cemented calcareous matrix. Therock encountered at the Dam foundation is Limestone,Dolomite and Limestone-Dolomite transition zone.Detailed geological mapping of the Main Dam foundationarea has been carried out in 1:100 scale. Pink limestone unit(Sorgharwari Formation), transition zone and Upper dolomiteunit (Tatapani Formation) with thin (1 to 10 cm thick) shaleinterbeds are exposed in the Dam foundation and abutments.The general trend of bedding joint recorded is N100W- S100E,which is nearly 200 askew to Dam axis, with 70-80° dip duesouthwest direction. Due to the disposition of bedding thetransition zone crosses the core foundation from left to rightabutment. The Limestone-Dolomite transition zone in theDam base foundation & abutment carries numerous openjoint networks, solution cavities, sand pockets and smallsinkholes. A number of erosional cavities formed partly bysolution activities and may be by churning actions has alsobeen observed while doing the geological mapping. Twoprincipal families of stress relief joints have been observedalong riverbanks near the dam site; both are striking parallelto the river, the first one consists of joints parallel to theabutments slope (dipping 30 to 70° towards the river) and thesecond one consists of joints, dipping perpendicularly to thevalley dipping joints.

4.3.1 Foundation Preparation at Kol Dam:

The foundation preparation practices in Kol Dam Hydroelectric power project has been characterized into threedifferent categories such as Slope modifications, FoundationGrouting and Surface Foundation Treatment.

i) Slope Modifications:

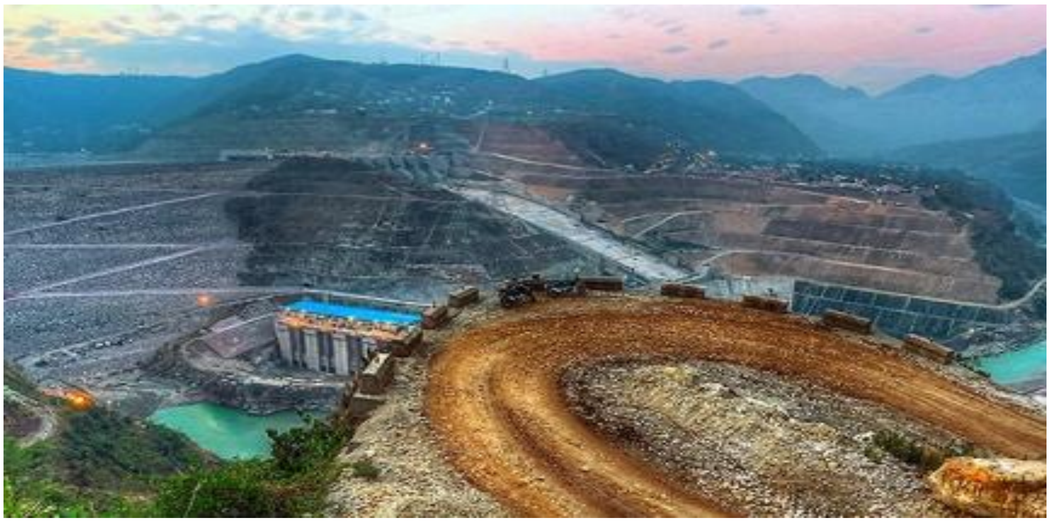
To allow earth fill to be compacted and maintain positivepressure on the abutments, foundation surfaces in bothabutments in Main Dam Clay Core, in particular, has beenflattened to about 0.73:1 to 1.75:1(H:V)in Left abutmentwhile 0.87:1 to 4.45:1(H:V) in the Right abutment (Clay CoreArea) by excavation.

ii) Foundation Grouting:

The principal purpose of grouting is to fill openings in afoundation and render it impervious to percolating water. It isalso used to improve the strength and elastic properties of thefoundation material into which it is injected. Themethodology of grouting given to the foundation materials asa whole has been decided depending upon the availablegeological formations and features in the near vicinity of Damsite. Grouting with normal cement grout is also doubtfulvalue in rocks where permeability value results from a greatnumber of fine cracks. With normal cement grout it is notpossible to seal cracks which have width much finer than0.2mm. In Kol Dam as the carbonate sedimentary rock likelimestone and dolomite are inherited by very fine as well asopen joint networks different fillers/accelerators/admixtureswere incorporated in both curtain and consolidation groutingwith variable C: W ratios. The grout mix for all the groutingoperations in Kol Dam has been designed depending upon theexisting site geology. The grouting operation has been carriedout with a variety of grout mixes starting C/W ratio 0.35:1 to0.6:1 with different admixtures like bentonite, acceleratorslike micro silica etc depending upon the geology encountered.The spacing and the pattern of grout holes has been designedbased on several test sections carried out on the basis ofacceptable permeability of the foundation and the nature ofthe Dam. In the test sections different grout materials withvariable C/W ratio were also analyzed for suitability byobserving the performance in terms of viscosity, decantationand compressive strength. The grout performance in terms oflugeon value, viscosity, decantation, compressive strengthand ground upheaval were analyzed for achieving the designcriteria. The treatments provided as per encountered geologyhas been found satisfactory even during the heavy monsoon.

iii) Surface Foundation Treatment:

Foundation surface preparation practices in Kol Dam includesexcavating overburden; shaping the foundation surface withdental concrete; filling surface irregularities with slush grout(usually a cement/water mixture poured in cracks) or dentalconcrete (conventional concrete used to shape surfaces, fillirregularities, and protect poor rock); providing dentaltreatments for the exposed faults, shears zones/seams, orweak zones as directed by the site geologist prior to caulkingand contact grouting. As the Dam is located on Limestone-Dolomite i.e in Karstic terrain the shear seams/weatheredzones/buried channels/cavities/surface springs were commonin the foundation/abutments. These zones are susceptible todifferential settlement as the in filled material within themajor open joins (>20cm)/shear seams are of different modulicompared to the bed rock. So, special care has been takenwhile doing the dental treatment all through the Damabutments in the Clay core and Filter area. Very often thefaults, shear seams or shattered zones met with afterexcavation extend to such depths that It is impracticable toclean them out entirely.Stress concentrations may occur in the dam due to thepresence of such low modulus zones. Thus for safe, timely and economical execution of earth and rockfill dam construction, adequate foundation treatment isessential to minimize any kind of post construction surprises.(Fell 1992). An understanding of geotechnical characteristicsof the rock mass to be grouted is also very important for asuccessful, economical and timely execution of thefoundation preparation activities in any river valley project.Though unexpected geological features (open jointnetworks/solution cavities/shear seams etc) cannot be ruledout even with adequate investigations in any Karstic terrainbecause of its unpredictable geomorphology, special careshould be taken into the consideration during the design aswell as in the construction stage depending upon theencountered geology which would result in considerablereduction in time and cost over runs.



Picture 3 Kol Dam (H.P.), 167m high earth&rock fill dam.

5. Conclusions:

Engineering geological investigation right from the planning stage to commissioning is very important for high dam construction because large numbers of highdams are located in the fragile Himalayan mountain range.It is thus strongly emphasized to increase the input of geology in decision making process so as to obtain more and accurate information about the high dam site.Not only it is important to carry out detailed geological investigations and testing but it is also equally vital to modify the engineering structures based on geological findings.Engineering geology is thus very important in helping to achieve the engineer's objective of constructing a high dam as economically as possible. There are numbers of case histories of high dams costing much more than the original contract price, and unexpected geological features are often the cause of expensive problems. In many cases, these unexpected problems could have been identified and avoided by a more thorough geological investigation. It is possible to over-investigate a site, but we doubt that it has ever been done. In many cases, high dam sites are under-investigated and the resultant extra cost of construction is far greater than the additional expense that would have been necessary to carry out a thorough investigation. Engineering geology has always had a significant influence on the location, design and construction of high dams. If safe and economic high dams are to be constructed in the future, then recognition of this influence must be increased on the large scale.

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