Subject	Geology
Paper No and Title	**Hydrogeology and Engineering Geology**
Module No and Title	Geotechnical Investigations for Dam and Reservoir Sites
Module Tag	HG & EG XIIIa

Principal Investigator	Co-Principal Investigator	Co-Principal Investigator
Prof. Talat Ahmad ***Vice-Chancellor*** Jamia Millia Islamia Delhi	**Prof. Devesh K Sinha** Department of Geology University of Delhi Delhi	**Prof. P.P. Chakraborty** Department of Geology University of Delhi Delhi
Paper Coordinator	**Content Writer**	**Reviewer**
Dr. Shashank Shekhar Department of Geology University of Delhi Delhi	**Dr. M. Masroor Alam** Department of Civil Engineering Aligarh Muslim University Aligarh	**Prof. Vinay Jhingran** Department of Geology University of Delhi Delhi

Table of Content

1. Learning outcomes

After studying this module, you shall be able to:

- Know different types of dams and their functions.
- Learn about different types of spillways and their utilities.
- Understand importance of geomorphological and geological investigations for the selection of site and type of dams and reservoirs.
- Identify different causes of dam failures and remedial measures.
- Come to know about major dams of India.

2. Introduction

Dams have become an integral part of nations' progress and infrastructure playing pivotal role in the development and management of water in river basins, flood control, irrigation as well as in generating of electricity. In India the history of making dams date back to 11th century when Veeranam Dam, made of carved-rock slabs, more than 15 km long, forming a 250 square mile lake in the then Central India (MP). Another marvel, near erstwhile state of Bhopal, the Mudduk Maur Dam was the highest earth fill embankment dam on earth for three centuries after its construction in 1500. After independence. Many multipurpose dams have come up that include the four-dam Damodar Valley Project in the then West Bengal, Hirakud Dam in Orissa and the most promising and famous Bhakra Dam in Himachal Pradesh. India remains one of the most active dam-building countries and thousands of dams of different sizes have been constructed over the years. However, off late many dam projects got delayed due to inadequate planning, environmental and socio economic issues. The delay in completion of 261m high Tehri Dam in Uttarakhand and 129m high Sardar Sarovar Dam in Gujarat can be cited as example wherein issues related to geo-environmental and socio-economic factors are still not resolved and settled. Tens of major and big dams are under various stages of construction in Uttarakhand, Himachal Pradesh and South Indian States. Hundreds of potential sites are still left and can be tapped after proper investigation to help in river water regulation and hydropower generation.

3. Definition and Classification of Dam

Dams are impervious to semi pervious barriers made across a river in a valley to impound water for slowing down river flow, for moderating flood, raising water level for canalization, hydro power generation etc. Dams are invariably associated with reservoir and depending upon the purpose of dam it may have many other features associated with it such as diversion barrage, canal headwork, guide bunds, access and service roads (Fig. 5.1) etc.

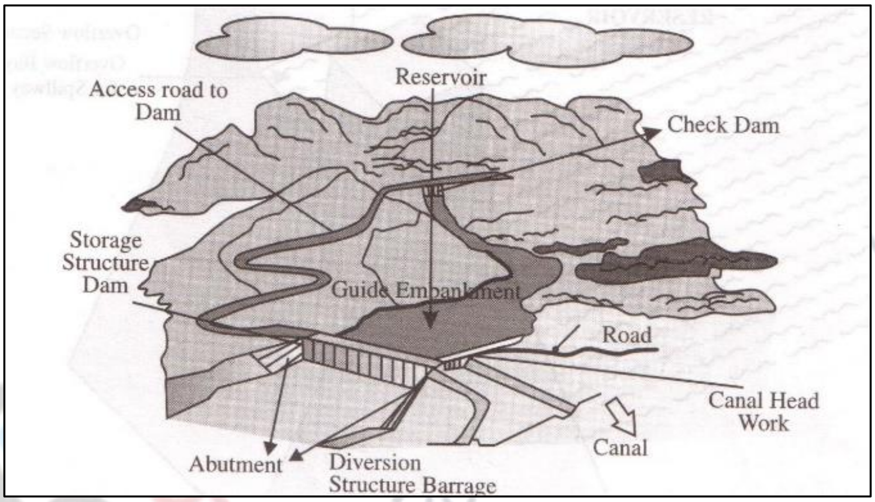

Fig. 5.1 A generalized setting of dam-reservoir and associated structures.

Dams are traditionally made by using earth, rocks and concrete. Wood logs, timber sheets, plastic and steel planks can also be used. The bigness of a dam can be known by its length, and height. The size of the associated reservoir in terms of its areal extent and the amount of water storage can also give an idea of the dam size. The dams are classified on the basis of their size, purpose and the material used in their construction (Table 5.1).

Table 5.1: Classification of Dams

Size (meter)	< 15	15 – 50	50 – 150	>150
Type	*Small Dam*	*Large Dam*	*Major Dam*	*Big Dam*
Purpose of Dam	To Stop Sediments and Mine Tailings	Diverting Water and Canalisation	To Impound Huge Amount of Water for Flood Control and Hydro Power Generation	
Type	*Check Dams*	*Barrage / Weir*	*Multi-Purpose Dams*	
Material	Earth	Rock	Concrete	Mixed
Type	*Earthen Dam*	*Rock Fill Dam*	*Masonry Dam*	*Zoned Dam*

The concrete or masonry dams are further classified as per their shape and size as *Gravity Dam*, *Buttress Dam*, *Single* and *Double Arched Dam*. Site, size and type of dam-reservoir, depend upon the presence of narrow river valley section, suitable foundation geology, availability of construction material and hydrological setup of the river system.

3.1. *Gravity Dam*: It is a huge structure made of either masonry or concrete with dam axis either straight or upstream curved or in combination of the two. Its cross section varies from triangular to trapezoidal shape with upstream side deck having gentler slope as compared to downstream one. The gravity dam owes its stability to its size, but exerts high magnitude stresses on rocks hence; its foundation should be laid on very strong rocks. The gravity dams require huge amount of construction material hence its availability need to be ensured. Gravity dam are generally provided with overflowing spillway in some portion of its length hence make it as two distinct unit as overflow and non-overflow sections (Fig. 5.2). These separate sections are designed separately because of differing load conditions.

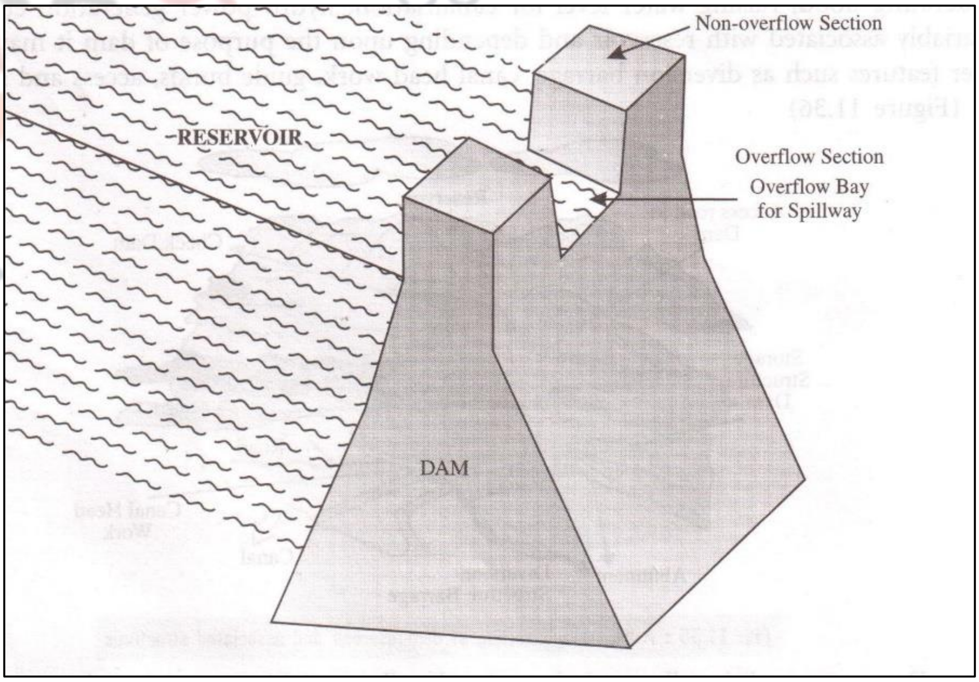

Fig. 5.2 The typical trapezoidal cross section of a gravity dam.

3.2 *Buttress Dam*: In situations where strong and weak rocks are alternatively exposed the main dam is founded on strong rock, supported by perpendicular *buttresses* with a tapered joint called as *corbel*, in downstream direction which in turn are supported by *struts* to make it a complete monotonous unit so that the load is distribute on rocks uniformly. For example in combination of competent and incompetent rocks such as sandstone-shale, quartzite-slate, basalt-tuff whereon the main dam is made on competent rock supported by buttresses and struts spread over incompetent rocks (Fig. 5.3 a & b). The dam can be made of rock masonry or concrete. The amount of construction material required is generally less than what is required in gravity dam; hence, buttress dam is economical.

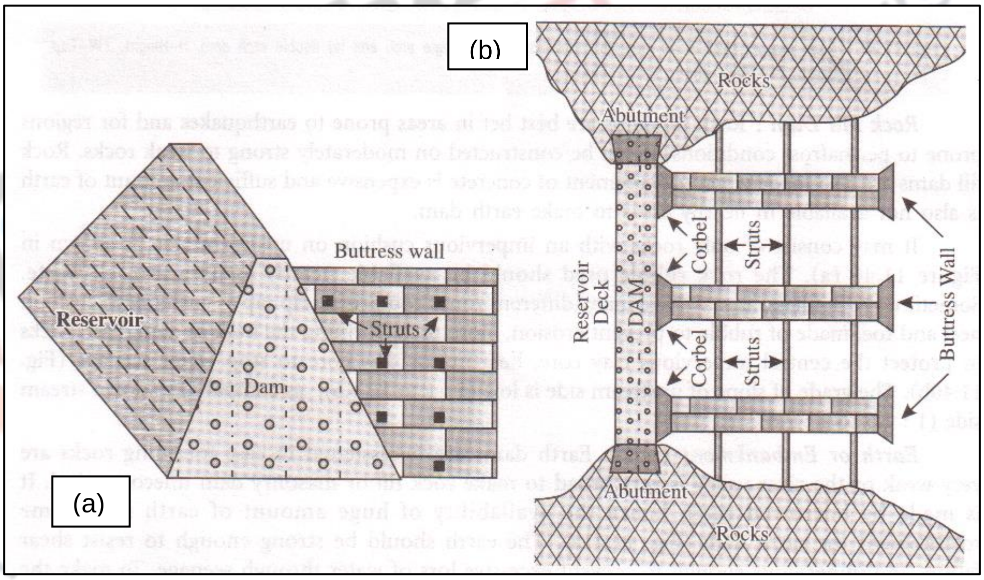

Fig. 5.3 (a) Cross sectional view of a buttress dam showing main dam with deck and buttress wall. (b) Plan of buttress dam, showing main dam with abutment, corbel, buttress walls and struts.

3.3 *Arch Dam*: Arch dams are thin as compared to gravity and buttress dams and require lesser amount of construction material. The arch dams are curved in plan towards upstream and may be of two types, Single or Double Arch Dam depending upon its curved nature only in plan or in plan as well as in elevation (fig.5.4). The arch dams are made when thrust force of water is very high and it needs to be transferred towards abutments apart from foundation. Abutment rocks as well as foundation in this case need to be very strong.

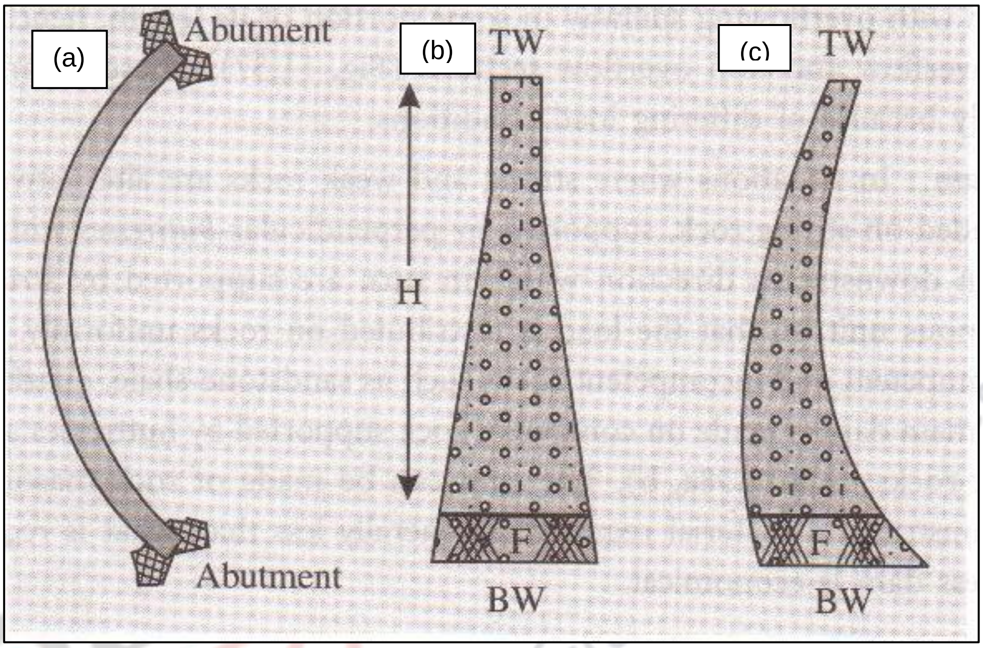

Fig. 5.4 Arch dam as seen in (a) plan, (b) cross section of single arch and (c) double arch dam. H – Height, TW - Top Width, BW - Base Width, F – Foundation.

3.4 *Rock Fill Dam*: Rock fill dams are made when procurement of concrete is expensive and sufficient amount of earth is also not available in nearby areas to make earth dam. Rock fill dams are best bet in areas prone to earthquakes and for regions prone to permafrost conditions. It can be constructed on moderately strong to weak rocks.

It may consist of only rocks with an impervious cushion on upstream side as shown in Fig. 5.5a. The rock rubble used should be available nearby as natural rock waste. Sometimes rock fill dams may have many different zones comprising rip rap as cushion, cushion to heel and toe made of rubble to prevent erosion, loose rocks forming the bulk of dam, hard rocks to protect the central impervious clay core, hearting or clay core to stop water seepage (Fig. 5.5b). The grade of slope of upstream side is low (1:1 to 1:1.5), as compared to downstream side (1:1.5 to 1:2.5).

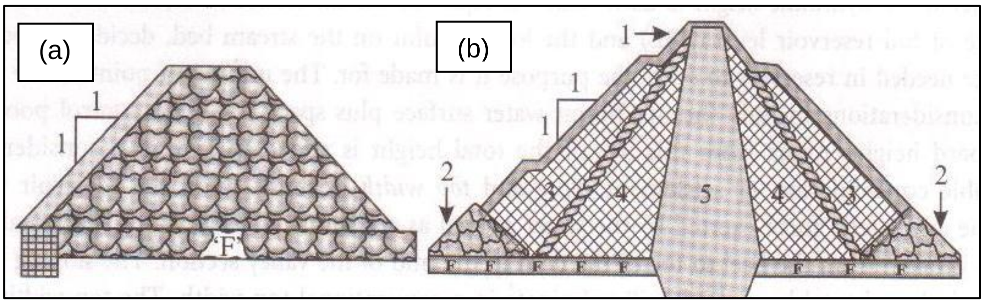

Fig. 5.5 (a) Simple rock fill dam with upstream cushion and cut off wall. (b) Zoned rock fill dam with (1) riprap, (2) Heel and toe cushion, (3) Well graded rock rubble, (4) tough rock rubble and (5) impervious clay core or 'hearting'.

3.5 ***Earth or Embankment Dam*****:** Earth dams are necessitated in case founding rocks are very weak or the river valley is very broad to make rock fill or masonry dam uneconomical. It is made by borrowed earth hence the availability of huge amount of earth is a prime requirement for earth dam (Fig. 5.6 a). The earth should be strong enough to resist shear failure and impervious enough to prevent excessive loss of water through seepage. To make the dam stable the grade of slope should not be more than 2:1 in upstream side, it may be kept 1:1 to 1: 1.5 in downstream side. An impervious clay core in the middle of the dam is necessary to prevent water loss and rock or masonry lining in upstream face as a protection from erosion by reservoir water (fig. 5.6 b). Similarly proper compaction of earth on its *optimum moisture content* (OMC) is one of the prerequisite for a successful earth dam. Sufficient bond between foundation and abutment is of paramount importance to prevent piping and washouts. Post construction maintenance is a big issue in the case of earth dams because of settlement in crestal part, shear failure of upstream and downstream face, piping through the dam and development of cracks due to earthquakes.

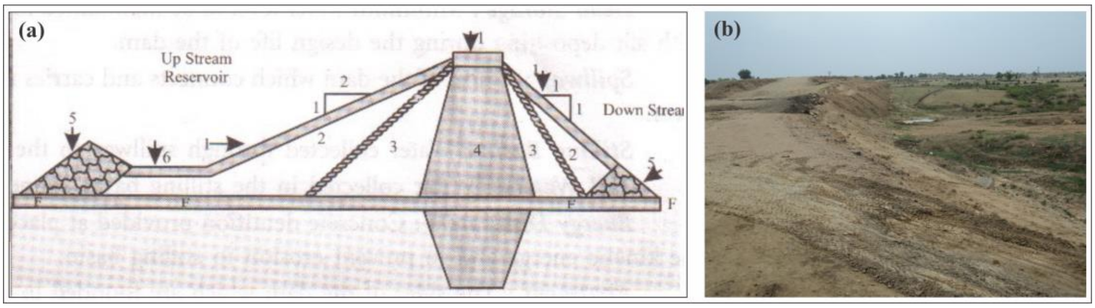

Fig. 5.6 (a) Parts of an earth dam: 1- Riprap as cushion, 2- Bulk earth used for raising the dam, 3- Compacted earth, 4-Impervious clay core, 5- Rock cushion, 6- Berm. (b) An earth dam under construction.

4. Parts of Dam

Different types of dam may have different units or parts depending up on the purpose of the dam. For example, a simple earth embankment may only have foundation base, berm, sloping deck and top crown. Foundation base, depend upon the reservoir size and bearing capacity of the foundation ground. Berm, is made to protect main dam from the erosive action of water and also to provide extra width to the base of the dam (Fig. 5.6 a). Deck, the reservoir facing part of the dam usually made sloping and is cladded by rock or by concrete to protect it from erosion by reservoir water, rainwater, wind and permafrost conditions. Dam alignment is kept straight unless and until some economical or topographical factors or foundation conditions are such that they require variance from straight line. Upstream curve with radius 300 to 1000m can be provided to induce deflection of water towards abutments. Sharp bends or curves with radius less than 250m should be avoided. The upstream edge of the crown or top of the dam is termed as dam axis, which may be straight or curved depending upon the alignment of the dam. Dam length is the distance from right to left abutment. Dam elevation is the structural height of the dam, which starts from lowest part of the foundation to the top. Another term, hydraulic height is used which is equal to the difference in elevation of the water surface of full reservoir level (FRL) and the lowest point on the streambed, decided as per the storage needed in reservoir to serve the purpose(s) it is made for. The important points to be taken into considerations include the maximum water surface plus space for flood control pool and freeboard height. Apart from this 3% of the total height is added to take into consideration probable consolidation or settlement. Base and top width depends upon the reservoir water volume and lateral force exerted by the water as well as economic considerations. The total base width is taken from the heel to toe of the dam in the mid of the valley section. The sloping grade of the deck and total base width will culminate in a conventional top width. The top width may also be governed by the purpose the top most surface is to serve, such as service or transport road, railways etc.

As compared to simple earth dam, concrete dams have many different parts especially if it is a multipurpose dam. Some important parts shown in figure 5.7 and 5.8 are as follows:

Head Waters: Reservoir water impounded in the upstream side.

Dead Storage**:** Minimum water level to be maintained in the reservoir going to be replaced with silt in the design life of the dam.

Spillway: A unit of the dam, which connects and carries reservoir water to the downstream river.

Stilling Basin: Water collected through spillway in the downstream side.

Tail Waters: Water collected in the stilling basin connected to downstream river.

Energy Dissipaters**:** Concrete dentition provided at place spillway waterfall to lower down the kinetic energy and to prevent erosion in stilling basin.

Abutment**:** The sides of the dam, which are founded in rocks on both the sides.

Crest or Crown**:** The upper most part of the dam may or may not have parapet wall, road or railroad. Also hosts the dam axis.

Freeboard**:** The vertical space above maximum water level up to dam crest. It is based on spillway-designed flood, to prevent overtopping due to excessive ingress of water during storm, wave action created by wind, or sudden water level rise due to occasional minor landslide and earthquake effect.

Deck**:** The sloping face of the dam. May have different angle of slope on up and downstream sides.

Sluices: To take out water when reservoir level is at its lowest level i.e. just above the dead storage level. Also used in emergency conditions to withdraw waters when spillway are not able to discharge water to maintain the maximum water level.

Heel and Toe: Lower part of the dam in upstream and downstream side respectively.

Cut Off Wall: An upstream wall provided along the dam length to prevent water seepage in foundation.

Anchor: A masonry structure provided in upstream side as an extra measure to increase the resistance against sliding in the foundation in upstream direction.

Gallery: A tunnel like structure within the dam to inspect dam and to install various instruments to monitor the functioning of the dam including earthquake monitoring device, accelerograph.

Glory Hole: A rarely made device acting as underground tunnel to take water from the reservoir bed and to empty in downstream away from the dam.

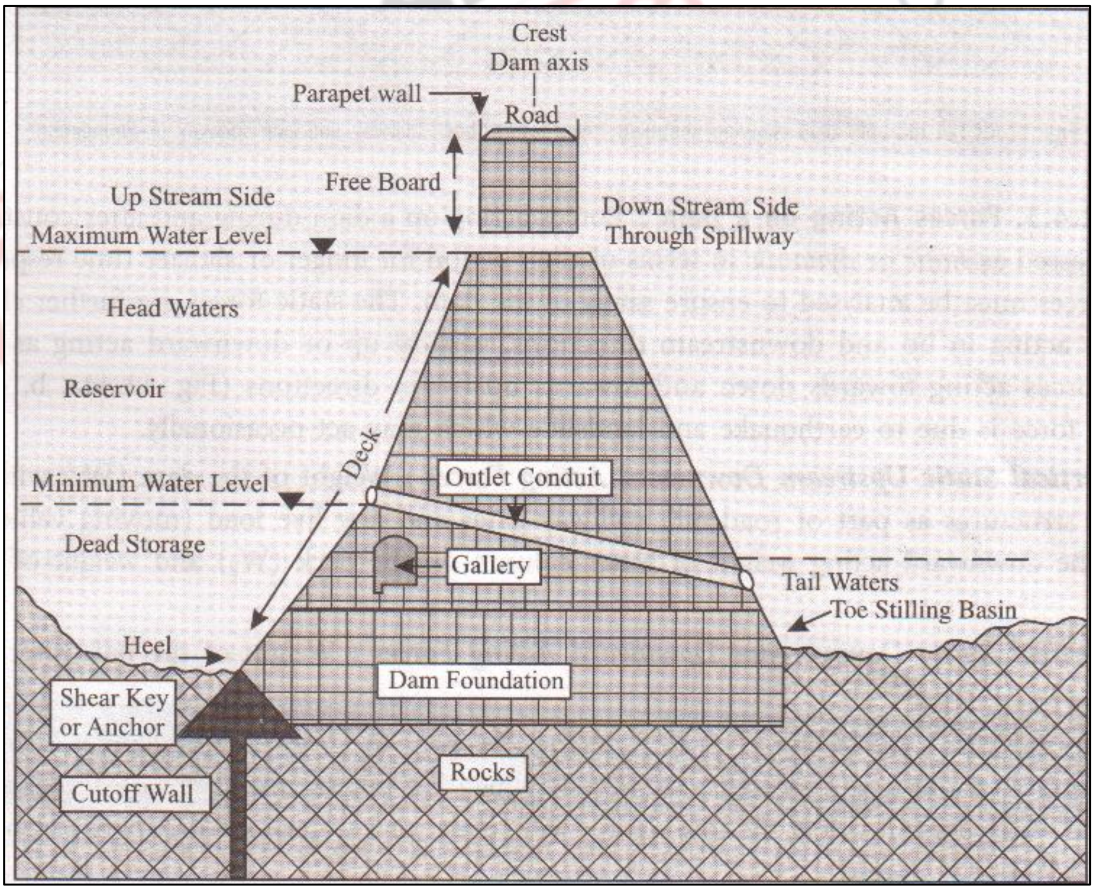

Fig. 5.7 Different parts of a concrete or masonry dam. The spillway shown in diagram is through spillway.

The spillway may be in different numbers and of different types. In small dams, only one spill way may suffice which may be even non gated, termed as run off the river dam. However, in large dams multiple spillways lying side by side are gated to regulate water discharge from the reservoir. Some spillways run through the gates made over the dam, some run through the dam and some are from the sides of the dam (Fig. 5.8).

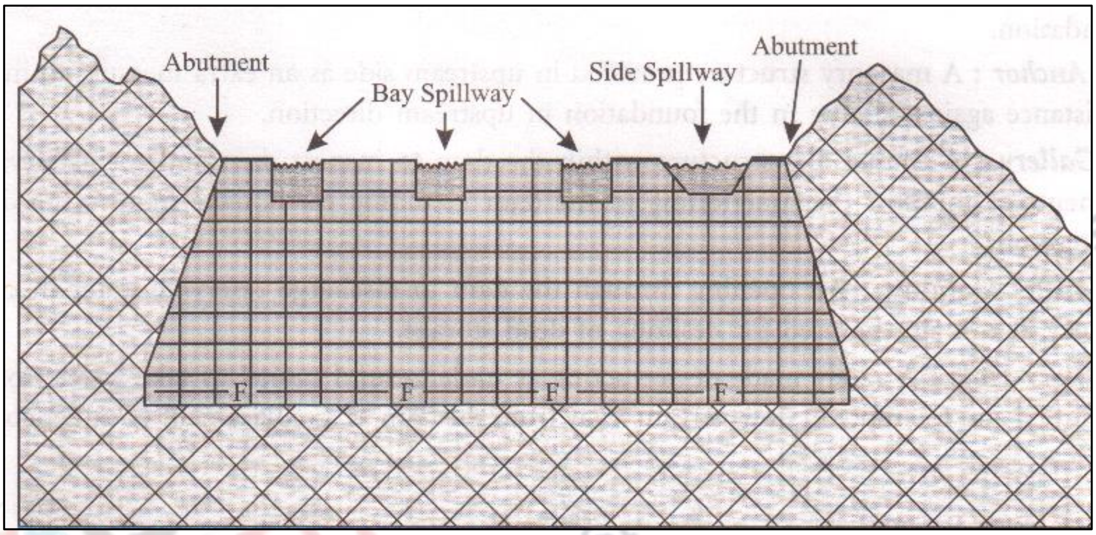

Fig. 5.8 A masonry dam showing abutment, overflowing 'bay' spillway and side spillway.

5. Forces acting on a Dam

Forces acting on a dam during and after construction can be classed as *static* or *dynamic* in terms of their action for longer or shorter time respectively. These forces and must be analyzed to ensure safety of the dam. The static forces are further classified as forces acting in up and downstream directions, vertical up or downward acting as well as lateral forced acting towards down and towards upstream directions (Fig. 5.9 a, b, c). The dynamic force is due to earthquake and landslide, which may take place occasionally.

***Vertical Static Upstream Downward Acting Forces*:** Weight of the dam (W_1) with super imposed structures as part of road/rail, spillway gates and any live load (moving vehicle/bus/train). The downward acting weight of water column on the deck (W_2) and weight of the silt (W_3).

***Vertical Static Downstream Downward Acting Forces*:** Weight of the tail water on the dam (W_4).

***Vertical Static Upstream Upward Acting Forces*:** As large part of dam is submerged under reservoir water, it is subjected to buoyancy, which is equal to the weight of displaced water (W_5). The water present below the foundation will create pore water pressure, part of which will act upward (W_6).

The upward acting forces will nullify part of the forces acting downward and the net vertical force will be:

Net Vertical Forces: $W_N = (W_1 + W_2 + W_3 + W_4) – (W_5 + W_6)$

***Lateral Static Downstream Acting Forces*:** Horizontal pressure exerted by headwater column (L_1) including ice if formed in winters, lateral force exerted by the deposited silt (L_2).

***Lateral Static Upstream Acting Forces*:** Horizontal pressure exerted by tail water column (L_3).

The lateral forces acting in upstream direction will nullify part of the forces acting towards downstream and the net lateral force will be:

Net Lateral Forces: $L_N = (L_1 + L_2) – (L_3)$

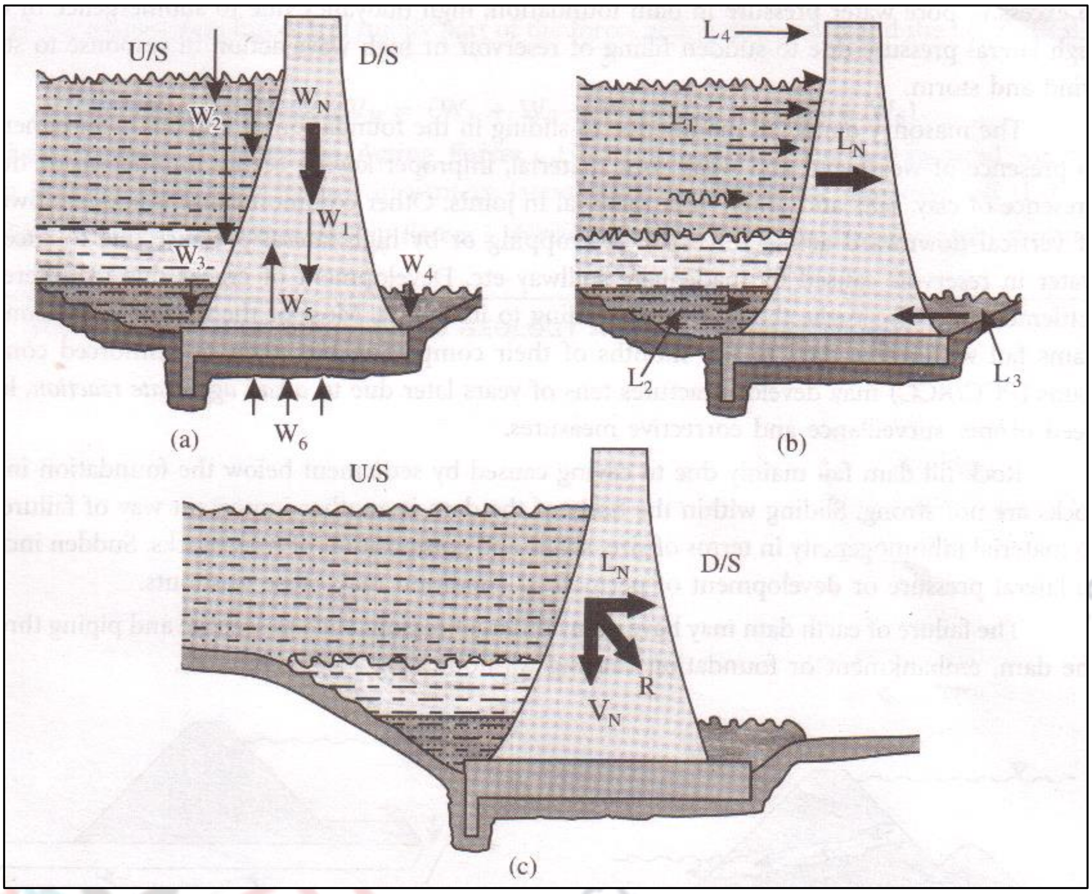

Fig. 5.9 (a) Vertical forces acting down and upward with net vertical force. (b) Lateral forces acting down and upstream side with net lateral force. (c) The resultant force and its direction.

5.1 ***Resultant Forces and Stability of the Dam*****:** The sum of vertical forces acting downward provides stability to the dam while sum of lateral forces acting towards downstream cause instability to the dam. The resultant of vertical and lateral forces is the key of stability if it lies within the foundation, close to the vertical downward acting forces and will bring in instability if it goes out and nears the lateral force (Fig. 5.9c). The dam failures due to sliding has taken place in the aftermath of torrential rain, sudden filling of the reservoir due to inadequate discharge from spillway and overtopping which has not only resulted in development of excessive lateral force but also very high buoyancy thereby leading to sudden drop in vertical forces and shifting of resultant force direction away from the dam foundation causing dam failure by sliding.

The dynamic force will undermine the vertical forces acting downward and will add to lateral forces acting downstream side i.e. will add to overall instability of the dam.

6. Causes of Dam Failures

As mentioned in above section, any force, which undermines the downward acting vertical forces, will lead to the failure of the dam. This can be due to excessive pore water pressure in dam foundation, high buoyancy due to submergence of dam, high lateral pressure due to sudden filling of reservoir or high wave action in response to strong wind and storm.

The masonry dams fail mainly due to sliding in the foundation of embankment due to presence of weathered and weak rock material, improper keying either of the foundation or due to presence of clay, salts and other weak material in joints. Other common cause is sudden lowering of vertical downward acting forces by overtopping or by high lateral pressure due to excessive water in reservoir caused by inadequate spillway is another cause. Development of cracks due to differential settlement will also make the dam weak leading to its failure. Most of the masonry and concrete dams fail within few days to few months of their completion but plain or reinforced concrete dams (PCC / RCC) may develop fractures tens of years later due to *alkali aggregate reaction*, hence need proper surveillance and corrective measures.

Rock fill dam fail mainly due to caving caused by settlement below the foundation in case rocks are not strong. Sliding within the body of the dam is another important way of failure due to material inhomogeneity in terms of size, shape and composition of rock blocks. Sudden increase in lateral pressure or development of permafrost condition may cause washouts. The failure of earth dam may have many different reasons such as seepage and piping through the dam, embankment or foundation-causing washout. (Fig 5.10 a, b, c, d).

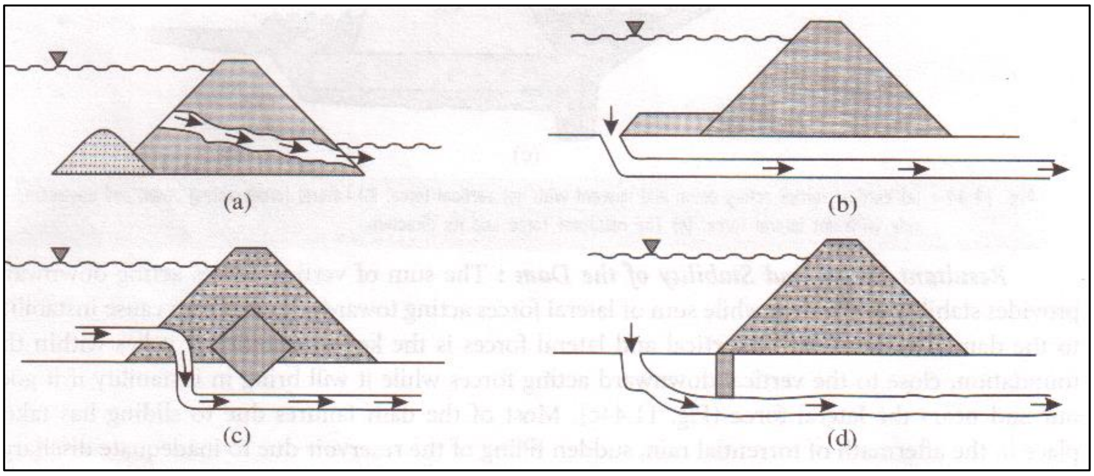

Fig. 5.10 Piping through various part of the earth dam (a) through the main dam, (b) below the berm, (c) below clay core and (d) below cut-off wall.

Seepage of water through slow permeation can make its front as the failure surface similarly permafrost front. Differential compaction of the earth, sudden drawdown and seismic activity may also cause earth dam failure (Fig 5.11 a, b, c, d).

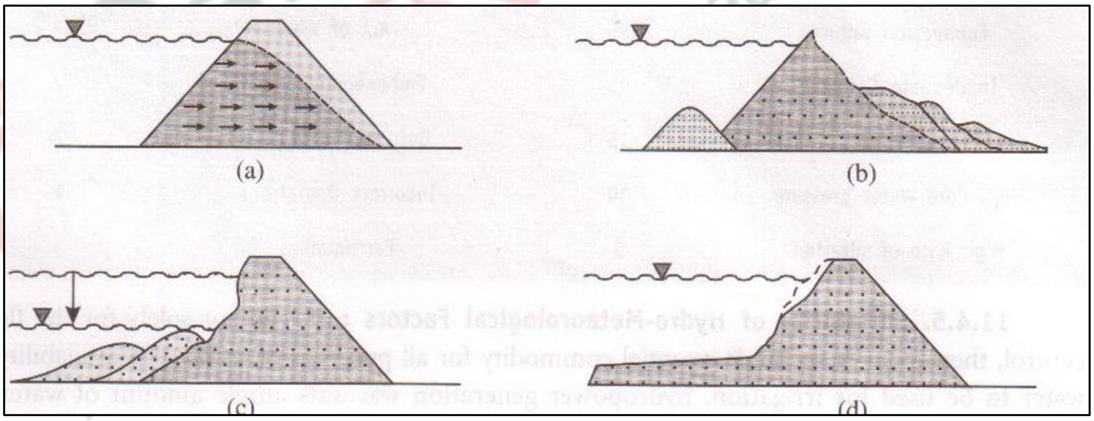

Fig. 5.11 (a) The seepage of water through the earth dam or freezing of moisture in permafrost condition, separates it into wet and dry parts. (b) Downstream shear failure along the seepage or permafrost front. (c) Shear failure due to sudden drawdown of reservoir water in upstream side. (d) Shear failure due to earthquake and liquefaction.

A dam can fail due to many different reasons and shortcomings in geological and geotechnical investigations on one hand and poor design on the other. Presence of Weak rock mass or unfavorable geological conditions if not properly identified and corrected then will seriously affect the stability of the dam. Engineering geologists should explore extensively and intensively to ensure proper geological investigations. Any shortcoming in geotechnical investigations for foundation and abutment will make a dam inherently weak. A geotechnical engineer should not leave any stone unturned to make the very base of the dam strong. Improper design of the dam body will mar the very purpose of the dam. The structural engineers should design the dam with utmost care using state of the art design methods taking in view all the negative and positive points identified during geological and geotechnical investigations.

Table 5.2 Statistics of major causes of dam failures all over the world.

Causes	%	Causes	%
Foundation failure	35	Act of War	3
Inadequate Spillway	25	Embankment Slips	2
Poor Construction	15	Defective Materials	2
High Pore Water pressure	10	Incorrect Operations	2
High Rate of siltation	5	Earthquakes	1

7. Suitability of Hydro-Meteorological Factors

If it is not solely for the flood control, then water is the most essential commodity for all purposes of dams. The availability of water to be used for irrigation, hydropower generation warrants ample amount of water in reservoir and to ensure this adequate study is a must to predict stream flow throughout the designed life of the dam.

7.1. *Climatic Setup and Weather*: The overall availability of water to a river on a large time scale will depend upon the climatic belt, it is flowing into. The weather of that area will control the seasonal and day-to-day variability in the amount of water flowing into a river. Hence, the long and short term database of average annual rainfall/snowfall for last 100 years or more, maximum rainfall and minimum drought stage, periodicity of storm recurrence at 10, 25, 50 and 100 year level, average annual time span of dry season etc. are important meteorological parameters should be known and analyzed prior to selection of river to be tapped or in deciding the size and type of the dam

7.2. ***Hydrological Setup of River***: The database of stream to be damned in terms of average annual discharge, maximum flood level and minimum water flow are very important which apart from meteorology of the area will also depend upon the drainage density, basin shape and stream order. The grade of slope of mainstream as well as of its contributories is also important, as this will decide the rate by which water will come into reservoir. In an event of erratic rainfall the rate at which reservoir is going to fill up has to be taken into account in designing the spillway and the freeboard, to avoid overtopping.

7.3. ***Carrying Capacity*****:** All the rivers carry sediment with them. The total amount of sediment a river is carrying with it at a place is termed as *carrying capacity* of that river. The river distributes the sediment all along its course. When the river is damned, this sediment will now be deposited in the reservoir, termed as *siltation*. The siltation will take place in space provided as dead storage and as and when the total capacity of dead storage is taken over by the sediment then any extra siltation will eat out the space meant for reservoir water, which is unwarranted.

8. Suitability of Geomorphological Factors

Geomorphic setup of a river basin develops in millions of years and attains its dynamic equilibrium. A river gets water in its upper most reaches from snow/ice melt, rainwater through myriads of low order streams, termed as source of a river in its proximal part termed as catchment area. River by lateral, vertical and head ward erosion carves out valleys of different shapes and sizes and drain an area along with its tributaries termed as drainage basin. It empties itself in a lake or sea in its distal part at its mouth (Fig 5.12a), depending upon its being a river with internal or external drainage respectively. The water and sediment collected in catchment area and on its way to mouth are distributed throughout the drainage basin. Depending upon the site of proposed dam the river will be severed from its distal parts, only part of water and only suspended sediment will now go through the spillways while rest of the water and maximum amount of sediment will be held back in the reservoir itself. Now for the river upstream of the dam though original source region may remain intact but it will have new mouth i.e. reservoir while for river downstream of the dam will have the new source i.e. spillway, while it may retain the original mouth (Fig. 5.12b). This change in the dynamic equilibrium of the river may have far reaching consequences and may lead to excessive deposition in upstream and erosion in downstream. Hence, detailed geomorphological investigation of catchment, reservoir and dam site area is a must.

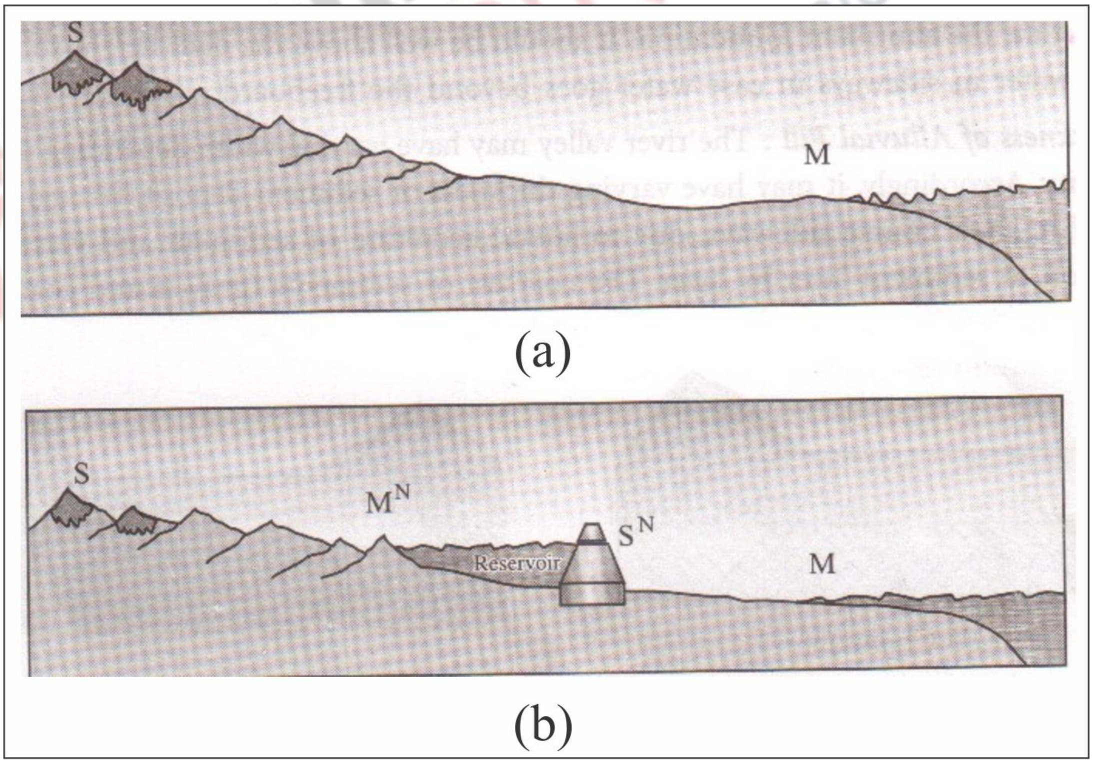

Fig. 5.12 (a) The graded profile of a river showing its source (S) in catchment area and mouth (M) near the sea before the construction of the dam-reservoir. (b) New source and mouth (SN/MN) of the same river after construction of the dam-reservoir.

8.1. *Geomorphology of Catchment Area:* Geomorphology of catchment in terms of slope characteristics apart from shape and size of the catchment area are important in deciding the total amount of water available to a river. The other geomorphic factors such as drainage pattern, drainage density, stream order and sinuosity of river should also be properly worked out as they are going to control the velocity with which available water will come into the reservoir.

8.2. *Geomorphology of Reservoir Area:* The reservoir behind the dam once filled may have different size and shape depending upon the geomorphology of the area as well as the length and height of the dam. The reservoir rim formed by the topography of the area will result into its linear, oval, semi-circular to irregular shapes and will have different pattern of forcing the dam. The danger of landslides in reservoir increases with increasing slope. The scars of previous landslides and slopes showing creeping should be identified and mended. The reservoir water may also lead to increase in groundwater level leading to lowering of frictional resistance along the discontinuity surfaces aggravating landslides.

8.3. *Geomorphology of the Dam Site*: The most important geomorphic consideration at dam site is the narrow river valley section. The narrow is the river valley smaller will be the length of the dam and lower will be the cost. Sometimes this becomes the only criteria for the selection of dam site to economize its construction, leaving (ignoring) other factors as the case is with Tehri Dam (Uttarakhand) wherein the city of Tehri was sacrificed for a site which gave length of the dam only 656m, almost half of its width which is 963 m at its base, a rare case. The height of the shoulder hills is also important, on to which the two sides of dam are going to rest i.e. the abutment foundation. It should be well above the dam height so as to prevent spilling of water in sideways in case water goes beyond the freeboard.

8.4. *Thickness of Alluvial Fill*: The river valley may have varying width depending upon its stage and antiquity. Accordingly, it may have varying thickness of sediment deposit, termed as valley fill. As rivers shift their course sideways, due lateral accretion of sediment and vertically due to deposition of sediment layer by layer. The coarsest of sediments (gravels and coarse sand) are deposited in its channel and are left back as *shoe string* deposits. When dam is made and reservoir filling starts, water percolating downward through sediment deposits find easy to escape through these so called highly porous and permeable zone of sediments termed as *buried channels*, resulting not only loss of stored water but also problem of seepage in foundation leading to solution and development of pore water pressure (Fig. 5.13 a, b). Hence such buried channels are to be explored and identified (geophysical exploration), sealed and be abutted and in no case they should lie below the dam foundation.

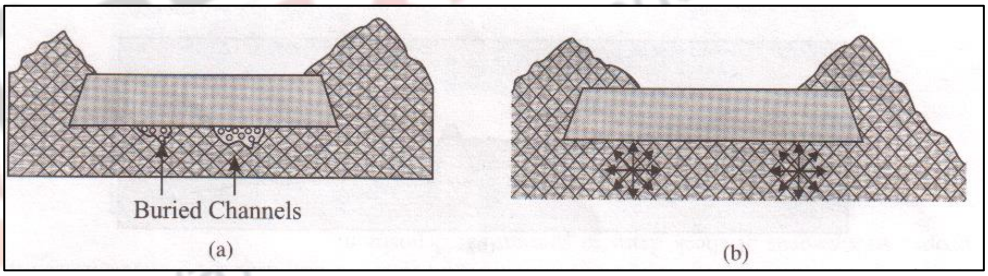

Fig. 5.13 (a) Buried channel deposits acting as conduit for water seepage "*Buried Channel*" below the dam; (b) Pressure created by water in fractures and rock pores causing "*Pore/Fracture Water Pressure*" acting against the vertical loads exerted by dam and reservoir water.

9. Suitability of Geological Factors

As we know that formal application of geological knowledge in civil engineering started after the analysis of many dam failures, took place in USA and Europe. A detailed investigation regarding the geology of the reservoir and dam site have since become mandatory before embarking upon the construction. The important issues to be taken into consideration are related to rock mass properties, their attitude and presence of major deformation structures. As the reservoir and dam setup covers a considerably big area it is likely to bring in as many geological issues. It is also a well-known fact that each site may have its own geological peculiarity hence the elements of uncertainties will always be there. The dam site is especially important and it is only after the excavation for foundation and abutment is completed real picture of geology will emerge to be considered in final design.

The present Navgam Dam site for Sardar Sarowar project in Gujarat proposed by Dr. K. L. Rao was finally selected after considering almost thirty alignments proposed by various organisations, individual scientists and engineers. The rocks included sandstone and limestone of Bagh Formation of Cretaceous age overlain by younger Deccan Volcanics comprising different types of basalts agglomerates traversed by dolerite dykes. All of these rocks are displaced and brecciated by NE-SW trending faults more than ten in numbers. The rocks were found to be deeply weathered in to *red boles* and not only required excavation but also backfilling by concrete and grouting.

9.1. Rock Type: Depending upon the size of a dam its safety increases many fold if there is only one rock type present in its foundation and abutments. Igneous rock bodies being very large three dimensionally, offer such condition more than often.

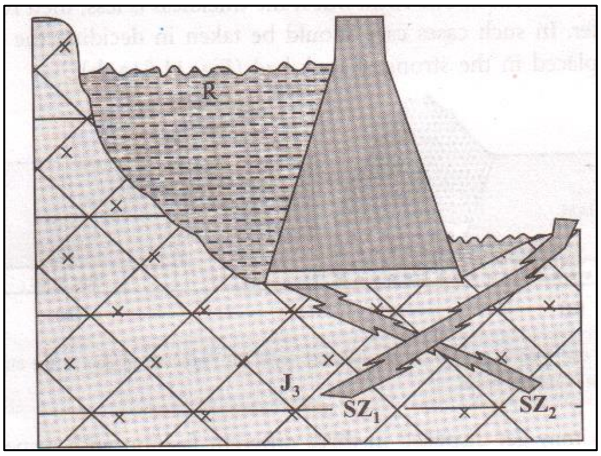

Fig. 5.14 Granite, a plutonic igneous body covering entire dam and reservoir area. Also, see the three sets of joints (J_1, J_2, J_3) and two shear zones (SZ_1, SZ_2).

Metamorphic and sedimentary rock bodies may or may not be large enough to host all elements of dam within a single rock body. The overall strength of rock mass will depend upon its weathering state and other rock mass properties but it is the bearing capacity, which will be an important factor in deciding the type of dam. The gravity dams, being huge in size are only made on very strong rocks. Hence, igneous and non-foliated metamorphic rocks will be most ideal. Volcanic igneous rocks if thick and without intervening ash beds and sandstones with good strength can also host foundation of gravity dams safely. Rock fill dams are ideal for earthquake prone regions and also are the best bet in areas with rocks of moderate strength. Foliated metamorphic rock gneisses, thickly bedded sandstones and strong limestones in comparatively dry regions have been found to perform well. All other rocks, which are thinly layered and weak such as volcanic flows with ash beds, tuff, schist, phyllite, slate, marl, thinly bedded sandstone, limestone etc., are suitable only for earth dams.

9.2. Weathering State: The weathering state of rocks will depend upon its composition, intensity of jointing, climatic setup of the area and geological age. In no case weathered rock be made as foundation ground for any type of dam. In fact for large dams only fresh rock surface (W I) should be taken into consideration and if not naturally available then should be excavated up by scrapping.

9.3. Attitude of Rocks: In the case of stratified rocks the orientation and thickness of rocks in relation to the dam axis and resultant force direction plays a very important role. The *horizontal* rocks or rocks dipping by less than 5^0 do not offer good foundation condition as it may come in parallelism with resultant force direction. If rock beds are thicker than the dam height the whole dam with foundation will remain in one rock. However, if the thickness is less, then rocks in foundation and abutment may differ. In such cases, care should be taken in deciding the foundation of the dam, which should be placed in the strongest rock bed (Fig. 5.15a, b).

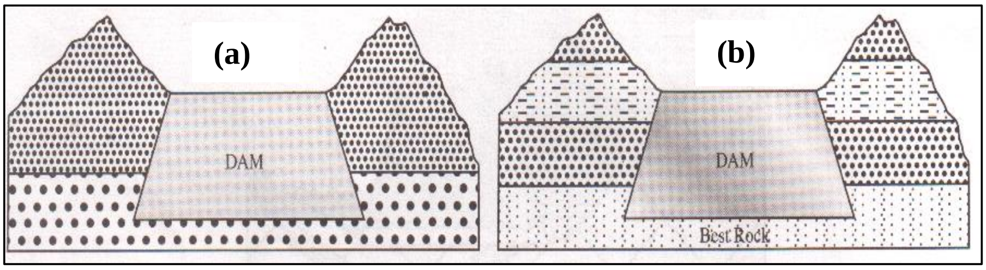

Fig. 5.15 (a) Whole dam unit lying in one horizontally laid rock body. (b) Placement of dam in the strongest rock body in case of multiple horizontal rocks.

The *vertical* rocks may get disposed in three different fashion with respect to dam axis. If striking parallel to dam axis and thickness of rocks are more than the width of dam axis then only one and if less then more than one rock will be encountered in foundation and abutments. The resultant force direction will make high angle to vertically dipping rocks, which is a favorable condition. In case rocks are striking perpendicular to dam axis then there are chances of having more than one rock type will become more due to the fact that rocks may not be as thick as the length of the dam (Fig. 5.16a, b).This situation is also not favorable as resultant force direction will lie in plain of rock contacts. If rocks are striking obliquely then the rocks may be disposed in between these two extreme cases and will give fair foundation conditions.

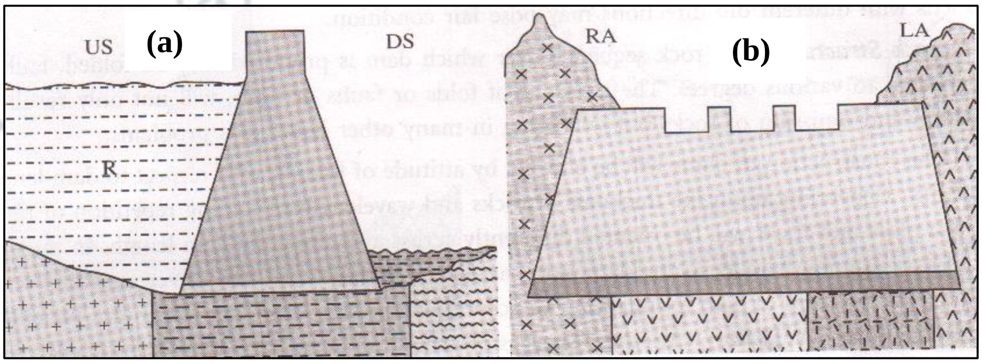

Fig. 5.16 (a) Entire base width of a dam shown resting on a thick vertical rock striking parallel to the dam axis. (b) Multiple vertical rocks lying below the dam in case rocks are striking perpendicular to the dam axis.

The *inclined* rocks will show varied nature of disposition depending upon its strike and dip with respect to dam axis. The rocks if strike parallel to dam axis then it may dip towards up or down stream directions. The rocks dipping upstream will be the most favorable situation as resultant force direction will be perpendicular to the dip directions (Fig. 5.17a). Rocks dipping downstream will result into most unfavorable situation. This may become worst if the rocks are dipping less than 45^0 as resultant force direction will come in parallelism with rocks dip (Fig. 5.17b). The case in which rocks are striking perpendicular to the dam axis and rocks dipping either towards right or left abutment of the dam (Fig. 5.17c) and rocks dipping *obliquely* to the dam axis with different dip directions may pose fair condition.

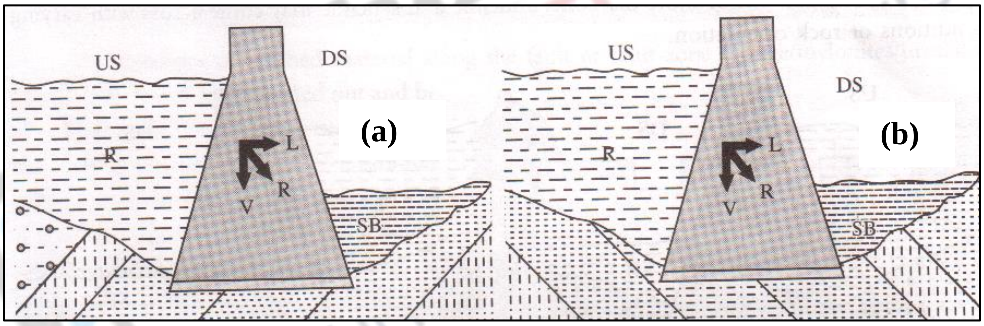

Fig. 5.17 (a) Inclined rocks striking parallel to the dam axis and dipping in upstream direction, see only one rock in foundation due to its thickness more than the foundation base. (b) Inclined rocks striking parallel to the dam axis and dipping in downstream direction, see more than one rock in foundation due to the thickness of rocks less than the foundation base. (c) Inclined rocks striking perpendicular the dam axis and dipping towards right abutment.

9.4. Rock Structure: The rock sequence over which dam is proposed may be folded, faulted and sheared to various degrees. The presence of folds or faults or both, will not only result in repetition and omission of rocks but will bring in many other issues and problems.

The construction of dams will be effected by attitude of folding with respect to tunnel length and width. Depending upon the thickness of rocks and wavelength of folding repetition of rocks will take place and rocks will be oriented differently across and along the dam length. In the case of fold axis running parallel to the dam axis, the dam foundation may run over an anticline or syncline. The position of dam foundation can accordingly be selected to get maximum benefit of rock inclination (Fig. 5.18 a). Another aspect is of groundwater seepage along the folded layers; the water will move away from the dam in case of anticlines and will move into in the case of synclines (Fig. 5.18 b). It is suggested that if the rocks involved in folding are thick enough then the best option is to have dam between the anticline and syncline axis i.e. in the limb dipping in upstream directions. If the fold axis is perpendicular or oblique to the dam axis then depending upon its wavelength one or more than one, anticline and syncline may come across with varying conditions of rock orientation.

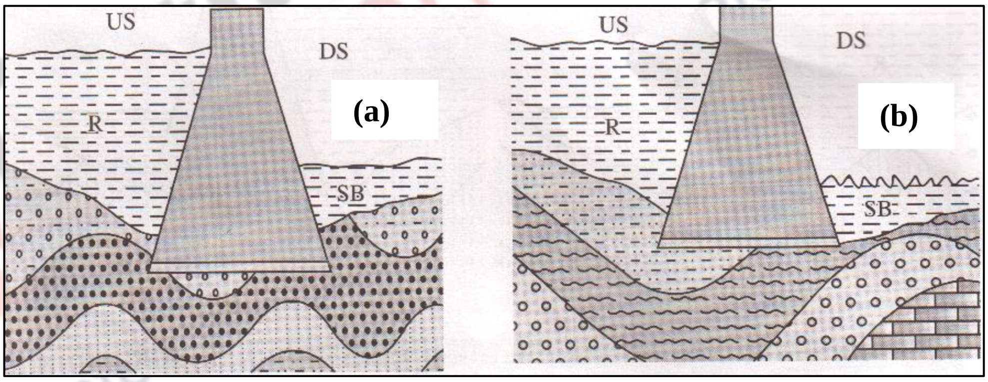

Fig. 5.18 The folding of rocks with fold axis parallel to the dam axis and wave length less (a) and more (b) than the base width of dam and accordingly placement of dam to get upstream dip.

Fault and fault zones should be avoided if it is live. Even if it is a dead fault then too it should be identified in terms of its type and disposition with reference to dam axis and dam should cross a fault in perpendicular fashion to have its run at minimum in dam foundation (Fig. 5.19a, b). Faults lying in regions of Seismic Zone IV to V, such as Himalayan Mountain System should be seen with caution and placing of dam may be decided accordingly.

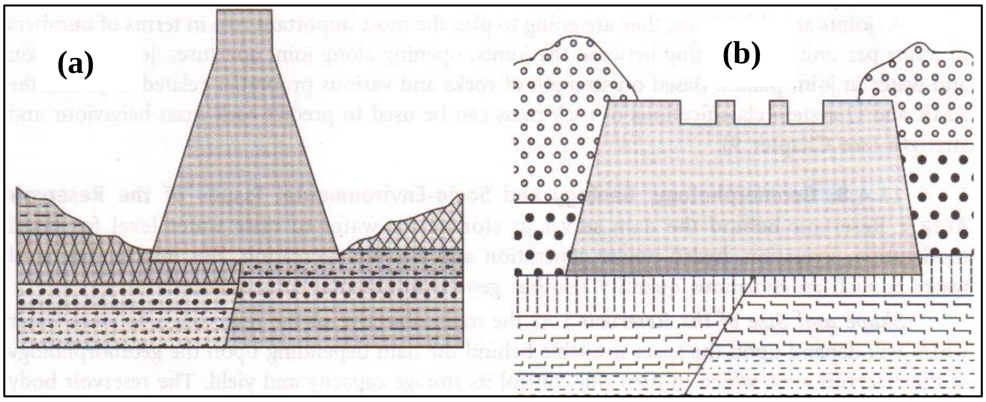

Fig. 5.19 (a) A fault oriented parallel to dam axis will run all along its length, a dangerous situation. (b) A fault-oriented perpendicular to dam axis will run only along the width of dam, somewhat manageable situation.

The presence of crushed material along the fault or fault zone (gouge/mylonites/breccia), being weak should be excavated out and be backfilled by concrete. The crushed zone may also act as medium for groundwater storage and movement. Its extension in reservoir area or exposure to ground surface may lead to percolation of water in to foundation of dam hence it should be identified and sealed. There are other issues related to fault such as repetition and omission of rocks resulting into change of lithology across the dam.

The presence of unconformity will bring in two different sequences of rocks across it. The presence of residual conglomerates and/or palaeosols etc. will make it undesirable at least near or below the foundation dam (Fig. 5.20).

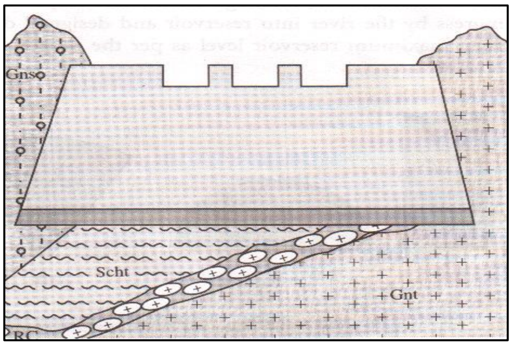

Fig. 5.20 Dam across an unconformity bringing granite (Gnt) and metamorphic rocks comprising granulite (Gnlt) and gneiss (Gns) together. Also, see the residual conglomerate (RC).

The shear zones and Joints being the most important in controlling the overall strength of rock mass, on to which dam is to be constructed, are destined to play the most important role. Shear zones can act as weak zones in rocks along which rocks are sheared and pulverized and need to be excavated out and backfilled by concrete.

As joints are ubiquitous they are going to play the most important role in terms of numbers of joint per unit area, spacing between the joints, opening along joint aperture, joint condition and water in joint planes. Based on strength of rocks and various properties related to joints the RMR and Q system classifications of rock mass can be used to predict rock mass behavior and strength.

10. Geomorphology and Geology of the Reservoir Area

Reservoir behind the dam serves as storage for water to raise water level for flood moderation, irrigation, hydropower generation and also for recreation. However, impoundment of water in such an enormous quantity also has geo-environmental consequences.

***10.1. Shape and Size of the Reservoir*:** As the main objective of the reservoir is to store water, which will depend upon the space available behind the dam depending upon the geomorphology of the reservoir area, which in turn will control its storage capacity and yield? The reservoir body may take different shapes such as irregular, oval, elliptical to linear and accordingly will have varying depths. The maximum possible storage will depend upon the height of the dam while yield will be controlled by annual average inflow of water and losses due to evaporation and seepage. The amount of water supplied to the reservoir will be controlled by the size and shape of the catchment area, drainage density and slope of the river and its tributaries. The rate of water ingress by the river in to reservoir and designed discharge through spillway is very important to keep maximum reservoir level as per the design.

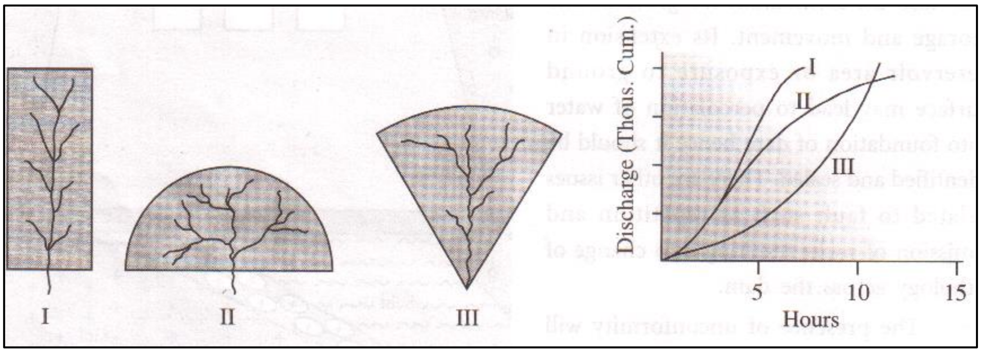

Fig. 5.21 Changing rate of water ingress with time as per the shape of the catchment.

***10.2. Change in Ecosystem*:** A riverine or fluvial system changes to lacustrine system leading to submergence of grassland and forestland causing ecological changes and alteration in biological productivity of various ecosystems. The traditional migration path of animals also get submerged.

10.3. Relocation and Rehabilitation of Human Beings: In many of the cases, submergence of agricultural fields and human habitation takes place. This not only leads to displacement of populace but also loss of livelihood. At the very outset i.e. at planning stage, relocation, rehabilitation and provision of proper livelihood has to be on card for probable displaced populace and need to be executed before starting the project. The very recent example of delay in Tehri Dam project wherein Tehri city was submerged under water. However, New Tehri town was planned well before the inception of the project but still there was resentment, which at many instances leads to unpleasant situations.

***10.4. Leakage and Seepage of Reservoir Water*:** Another pertinent issue is leakage and seepage of water from reservoir which not only undermines the very purpose of reservoir but also cause excessive pore water pressure causing uplift below the dam foundation. Leakage is defined as water loss along the linear openings as stream threads and seepage of water is a loss as diffuse flow through interconnected pores. The causes of leakage can be ascribed to presence of fault and shear zones, high incidence of joints in rocks etc. while seepage may take place along alluvial fill, through the dam and through the foundation material. Another consequence of leakage and seepage of water is groundwater level rise in rocks surrounding the reservoir, which may add to the problem of land sliding. The only positive effect of this rise termed as *bank storage*, is its discharge in reservoir during lean period when reservoir water level is well below the requirement.

The loss of water from reservoir area can be estimated by *Packer's Test* wherein water is pumped in to a borehole and loss are measured in terms of *Lugeon Unit*. One Lugeon unit is defined as loss of water in 10 minutes through a one-meter section of a borehole under 1Ma of pressure. One Lugeon unit equals the coefficient of permeability of 10^{-7} m/sec and a rock having permeability less than this is taken to be practically impervious or water tight. It has been found that Lugeon values correspond very well with the opening of joint planes (Table 5.3).

The protection against leakage and seepage is adopted depending upon worth of investment and value of water going as loss. In case of small and medium size, earth and rock fill dams impervious lining using natural and artificial material are used to prevent water leakage and seepage. If loss of water either undermines the purpose of the reservoir or is deleterious for the foundation of dam, then grouting is the only option as an effective measure.

Table 5.3 Examples of Some Typical Lugeon Values (Houlsby, 1977).

Lugeon Value	**Strong Rocks with Continuous Jointing**	**Weak Heavily Jointed Rocks**
0	Completely tight	Completely tight
1	Occasionally open up to 1 mm	Occasionally open hair cracks < 0.3 mm
2	Opening 1 to 2 mm	Opening 0.3 to < 1 mm
3 to 5	Opening occasionally up to 2.5 mm	Opening occasionally up to 1 mm
20	Opening Frequently up to 1 mm	Opening frequently up to 1 mm
50	Opening Frequently up to 2.5 mm	Opening frequently up to 2.5 mm
100	Opening Frequently up to 6.0 mm	Opening frequently up to 6.0 mm

10.5. Sedimentation in Reservoir: The damming of river will automatically stop the river sediment in reservoir, which were ought to go downstream and get distributed all along its course. Though it is very rare to have rate of sedimentation in reservoir as a decisive factor in deciding the location of the dam but, is a profound factor in deciding the dead storage capacity, as the life of a reservoir is based on this space, which is eventually got to be filled by silt but in designed life of the dam. The decision for height of the dam may also have to take the rate of sedimentation into account, as the total reservoir capacity minus the dead storage will control the total water available for the dam is intended for. Most of the dams in India show, rate of sedimentation twice to ten times more than the assumed one hence, reducing the life of the dam by half to one tenth of its designed life (Table 5.4).

Table 5.4 Rate of Siltation in some Indian Reservoirs.

Reservoir	**River**	**State**	**Assumed** ha m/100km^2/yr	**Observed** ha m/100km^2/yr	**Annual Storage Capacity Loss** (%)
Pong	Beas	HP	4.29	15.10	0.13
Bhakra	Sutluj	Punjab	4.29	6.14	0.65
Kalagarh	Ramganga	Uttarakhand	4.29	17.30	0.25
Mayurkashi	Mahanadi	West Bengal	3.61	20.09	0.50
Matatila	Betwa	UP	1.43	3.50	0.80
Maithon	Barakar	Jharkhand	1.62	13.02	0.50

The cost of sluicing or dredging of sedimentation may be very costly to undertake and may ultimately result in abandonment of the dam-reservoir. Construction of check dams and small run off river dams along the contributing streams and vegetation turfing in catchment area are the best options to mitigate this problem.

***10.6. Reservoir Induced Seismicity*:** If not all but few areas after the construction of dam-reservoir have shown spurt in seismicity termed as Reservoir Induced Seismicity (RIS). The excessive load due to rise in water level on rocks, devoid of such pressure prior to construction of dam-reservoir, start failing, causing seismicity. Shear zones and faults which are seemingly dead and locked at present state of the residual stresses in rock mass may get reactivated due to added load of water as well as seepage of water along them leading to slippage and occurrence of earthquakes. For example in India, Koyna Dam in Maharashtra has shown that whenever the reservoir water level increases to more than 100 m level there is an earthquake. This started in year 1962 with the start of reservoir filling which has increased since then. However, most of these earthquakes are of low magnitude but an earthquake of 6.5 M in December 1967 causing death of 200 people and earthquakes of 5.5 and 5.4 M in 1967 and 1968 are notable ones. Even in year 2010-11, many seismic events of 2.0 to 4.0 M have been recorded. The cause of seismicity in the case of Koyna has been ascribed to presence of a deep-seated fault. The water seeps in case of high water column pressure, leading to wetting and lubrication of gouge/clay, lowering of frictional resistance causing slippage hence, earthquake. Some other dams in India where such kind of RIS is recorded include Idukki Dam (Kerala), Parambikulam Dam (Tamil Nadu), Sholayar Dam (Tamil Nadu), Ukai Dam (Gujarat) etc. but the severity is very low as compared to Koyna Dam (Maharashtra).

Size and shape of the reservoir plays an important role in causing RIS. The fact that larger is the reservoir in terms of area, larger will be the water spread and lesser will be the load exerted by water column on the per unit area of bed rocks as compared to linear reservoirs where thick water column may exert high magnitude loads on bed rocks, an important factor for reservoir induced seismicity. Other important factors include (i) maximum height of the reservoir water level, (ii) rate of increase of water level, (iii) duration to which high water level maintained, (iv) deeper infiltration of impounded water through fractures, joints, shear zones, exposed and concealed faults or fault zones, (v) rocks with chances of undergoing brittle deformation.

11. Spillway

Spillways are that most important part of the dam through which water is discharged from the reservoir to downstream channel. Dams should have an adequate spillway for passing reservoir waters in normal times and floodwater in rainy seasons. The spillways can be *free flowing* or *gated*. In free flowing type, spillway water glides over the crest from guided bays towards the stilling basin. In gated type, water is allowed to move through bays, which have provision of gates to regulate water flow. It has three components (i) entry to spillway, which may be uncontrolled or controlled through gates called as *head structure*. (ii) A channel connecting reservoir to the downstream, termed as *discharge structure* and (iii) mechanism to lower down the kinetic energy of water flowing down the steep spillway known as *terminal structure*. The spillways can be of following types:

***11.1. Normal Spillway*:** It is an ogive type structure with gated or non-gated crest, guided channel termed as chute and terminal part ending into a stilling basin (Fig. 5.22). There can be many numbers of such spillways depending upon the length of the dam and the design discharge.

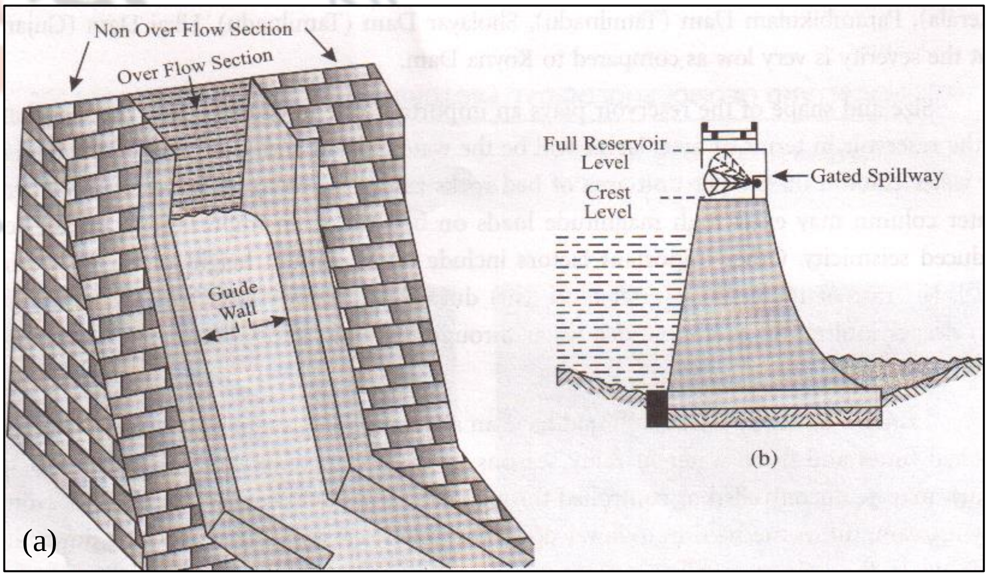

Fig. 5.22 Open and Gated Spillway with related structures.

***11.2. Piped Spillway*:** If water is transferred from the reservoir through the dam to any small power-generating unit using piped structure. Its bigger version is called as *water pressure tunnel* (Fig. 5.23).

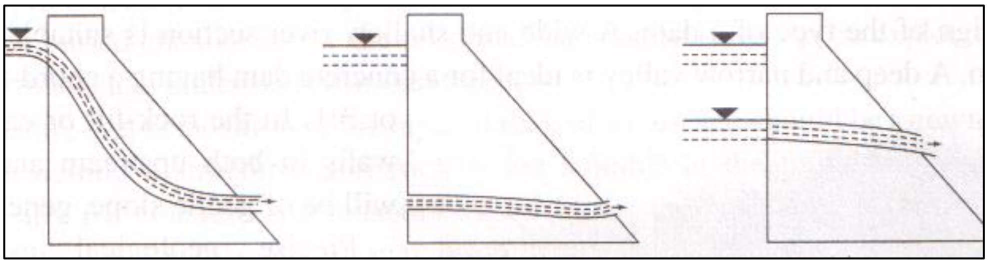

Fig. 5.23 Different ways of piped spillway through the dam body (Gangopadhyay, 2013).

***11.3. Glory Hole Spillway*:** It is formed by creating vertical or steeply inclined shaft in reservoir connected with slightly inclined tunnel to carry water through rocks, well below the dam structure (Fig. 5.24).

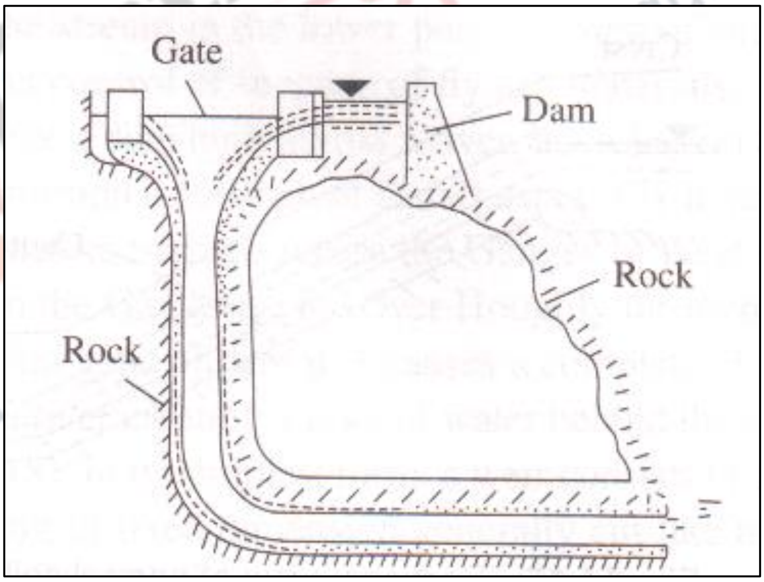

Fig. 5.24 Glory hole spillway transferring water downstream well below the dam body (Gangopadhyay, 2013).

***11.4. Side Spillway*:** A spillway created at the abutment of the dam with a provision of regular flow or controlled flow having all other the parts of normal spillway joining stilling basin or the river directly in the downstream (Fig 5.25).

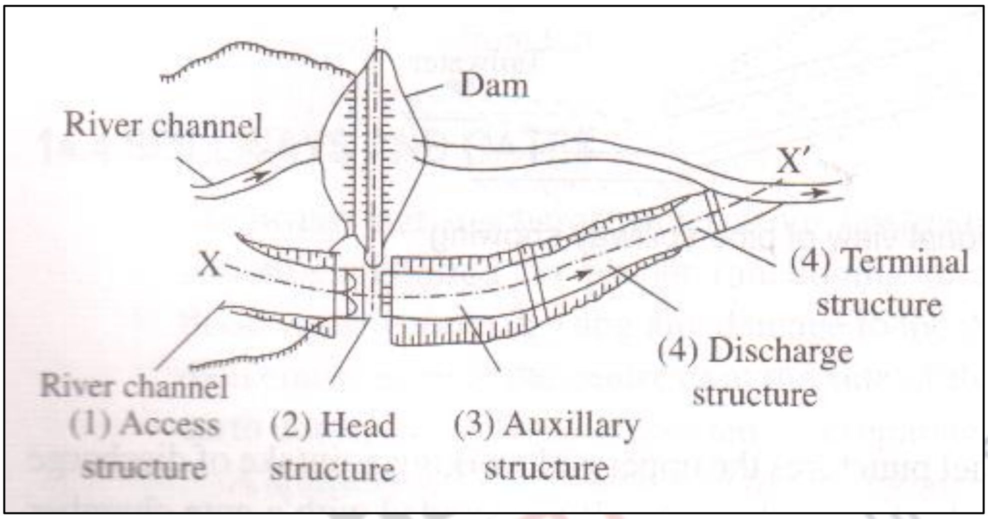

Fig. 5.25 Side spillway carrying water from the flank of the dam (Gangopadhyay, 2013).

In concrete or masonry dam the spillway is made as an intrinsic part but if the dam is rock fill or earth dam then it is made up of concrete or masonry. If the spillway section is of considerable length, width and height as part of any large earth dam then it can be treated as small concrete dam within the earth dam and will need investigations similar to small concrete dam (Fig. 5.26 a and b).

Fig. 5.26 (a) An spillway under construction for a 16m high earth dam, also see the stilling basin. (b) Sides of spillway to act as abutment over which earth will rest.

Following factors should be taken into consideration for designing the spillway.

11.5. ***Strength and Erodability of Foundation Ground:*** The site investigation for spillway should take into account for foundation of its base, chute and guide/training wall. Presence of sound and strong rocks at shallow depth will be of prime importance. The erodability of rocks due to hydraulic and dissolution action has to be taken into account. In case of weak rocks, stilling basin should be lined by concrete.

11.6. ***Vibrations:*** High-speed gushing water and created turbulence generate vibrations all through spillway and in to dam juxtaposed to spillway. It may cause consolidation in case of rock fill and earth dam along abutments and foundation.

11.7. ***High Hydraulic Head:*** Water in and around the spillway lies under high hydraulic head depending upon the maximum reservoir water level. Seepage, piping and uplift of stilling basin are common effect of this problem.

12. The Strategy and Managerial Aspect of Dam Construction

The construction of dam started to block river water during the seasons when there is plenty of water around and to use it in the lean period. The benefits in terms of regulated water supply for irrigation through canalization, generation of electricity to fulfil ever-increasing demand of growing cities and industrialization, stopping and moderation of flood, navigation, recreation, development of fisheries etc. are well known. But at the same time when dam construction and impoundment of water has taken big dimensions and hydropower generation became the prime purpose, bigger and bigger dam-reservoir became order of the day and huge amount of water storage has started taking toll in terms of loss of forest cover, ecological imbalances within the river system, in and around the reservoir, land sliding, displacement of human settlement apart from causing reservoir induced seismicity. This has prompted people to think and compare technological feasibility and economic gains in respect to socio-cultural impact on affected communities. Previously it is used to be said that:

"*You can make dam anywhere you like if you have the money*".

This is because of need of huge amount of material, men and machine to construct dam in olden days. Though technological advancements in the field of construction and invention of heavy earth moving machines, the making of dam has become much easier. However, today due to environmental activism and socio economic factors dam construction has taken a back seat and any proposal of dam at any place is immediately opposed by local populace. No one wants dam in their region due to fear of displacement and also due to their thinking that the benefit will be reaped by others on the cost of their sufferings. The environmental groups and NGOs too are against the dam specially the big dams citing reasons of loss of flora and fauna, change in hydrologic regime and dying of rivers. As most of the dams are made in the hilly regions geomorphological and geological processes make them vulnerable to problems of landslides and earthquakes including reservoir induced seismicity has been cited more than often by anti-dam environmentalists against the dam especially the big dams.

Between the extremes if a rational line is taken given due consideration to welfare of large section of populace and balancing the loss incurred by the people in upstream areas by proper relocation and compensation to minimize their distress.

There are four important variables to be taken into consideration for construction of dam namely, hydro-meteorological, geomorphological, geological and construction related. Out of these first three variables are fixed i.e. they cannot be changed. While the last one, related to construction involves availability of finance, technology, management etc., can be changed as per the need and requirement. There will be very few locations in a river basin, which may have outstanding situations for all the three fixed variables and if at all any such site would have been there it, must have been developed already. Therefore, the future of dam construction may have to come across with more and more non-ideal situations and onus shall lie on the civil engineers to use state of the art technology to confront them in best, economic and safest possible mode. Following aspects should be explored to hilt before embarking upon a dam project to maximize the gains on the cost of minimum environmental and socio-cultural damages.

***12.1. Social Factors*:** Problem of land submergence leading to drowning of residential areas and agricultural fields shall warrant rehabilitation to provide areas not only for living but also to carry out traditional farming.

***12.2. Environmental Factors*:** Submergence of virgin forest, bush or grassland, which cannot be replicated by any scale of afforestation or plantation. Loss, sometimes permanent, leading to extinction of flora and fauna, including those, which have not yet been identified, documented and properly classified.

***12.3. Hazard Sensitivity*:** As most of the dams are made in areas which have topographical edifices, are prone to landslides, geological weakness in terms of shear zone and faults, are indicative of neo-tectonism, earthquakes depending upon the area lying in a particular seismic zone etc. are important issues to be properly addressed. Water is the most important commodity hence hydrological hazards of flash flood in the aftermath of storm or cyclone and farming of glacial lakes due to natural damming by landslides and their probable outburst are very much feared as far as dam-reservoir setup is concerned.

***12.4. Infrastructural Factors*:** As dams are made mostly in remote areas accessibility to the site is very important to haul men, material and machine. Cost involved in up gradation (widening/strengthening) of present road network or in laying road afresh and to buy land for rehabilitation are to be worked out properly. International or/and interstate water sharing issues need to be sorted out.

***12.5. Availability of Construction Material*:** The huge amount of material involved in the construction of dam earth, rocks and concrete should be sequestered from nearby areas. There have been many instances when dam sites were shifted, for want of construction material, as their non-availability in nearby areas would have incurred huge cost in haulage.

12.6. Design Considerations**:** Hydro-meteorological setup of the area to assure water availability as well as to ensure installation of power project or decision for type and size of the dam (length, height, width) to create reservoir water pool enough to moderate flood require lot of planning and geo-engineering acumen. Diversion of river, number and length of tunnels required for it are priori to dam construction.

12.7. Financial Cost and Benefit Analysis**:** Duration of construction and incurred cost should be worked out keeping in mind not only the inflation but also cost escalations due to delay in completion of the project. Source of fund, obligations and standard set by funding agencies should be sorted out and need to be honoured. A proper memorandum of understanding should be in place for return on investment and its sharing between the funding agencies, state and central government.

The sole motto of undertaking the construction of dam and reservoir after the feasibility studies and finalization of detailed project report should be:

"Minimum of socio-cultural, environmental, infrastructural development cost with maximum returns in terms of irrigation, flood control and hydropower generation to ensure optimization of river basin resources."

13. Some Major Dams of India

The construction of dam and reservoirs were started by British Government and given prime importance after independence under the leadership of Pt. Jawaharlal Nehru. The fervour continued and India boasts to have commissioned more than 4300 large dams (table 5.5), making it world's third largest dam maker after USA and China. Construction on many more are in full swing and will be added in near future. Some important features of some major India dams are discussed in following section.

Table 5.5 An approximate distribution of large dams in India as per the height.

Height	**15 – 30**	**30 - 50**	**50 – 100**	**100 – 150**	**150 – 200**	**>200**
No. of Dams	3500	500	100	30	10	2

13.1. Tehri Dam: The Tehri Dam is the highest dam (261m) of India and eight highest in the world made on the confluence of rivers Bhagirathi and Bhilangna, contributories of river Ganga. Made as rock fill earth dam on metamorphic rock stratigraphically known as Chandpur Phyllite, with a downstream dip of 50^0 to 70^0. The dam has the distinction of having base width (963m), almost double of the dam length (570m) solely to increase the loading area for safe foundation, as the rocks are not very strong and are highly jointed. The main dam has a cofferdam juxtaposed to it to thwart direct water thrust and another 103m high, Koteshwar Dam, 20 km downstream as an added measure to thwart any untoward incident as the area lies in *Seismic Zone VI / V*. The reason of having the dam at the very site was a very narrow river valley section resulting into small length and accordingly low cost.

13.2. Idukki Dam: Idukki Dam of Kerala has the distinction of first concrete arch dam (doubly arched) in India and largest of Asia. Made on river Periyar in Idukki district of Kerala for hydropower generation and flood control on Archaean aged rocks comprising high-grade metamorphic rocks gneisses and charnockites. Construction started in 1966 for 169m high and 366m long dam and were completed in record time by 1974 to store 1,996,000,000m^3 of water with a spread at full reservoir level of 60 km^2. Though dam lies in seismic zone II but is known more so for moderate level (II) of reservoir induced seismicity.

***13.3. Bhakra Dam*:** Bhakra Dam located on a narrow valley of Satluj River flowing through Siwalik Hills in Himachal Pradesh, is the first multipurpose dam for flood control, power generation, irrigation and fisheries development. It is the second highest dam with a height of 226m, base length 518m, top length 114m, base width 402m and top width of 8m, hosting second biggest Gobind Sagar reservoir of India. The reservoir can holds 9,621,000,000 m^3 of water spread over 166 km^2 of area, with effective storage of 7,191,000,000 m^3. The founding rocks are thickly bedded sandstones intercalating with siltstone and clay stone, striking NW-SE, slightly inclined to dam axis, with 70^0 to 80^0 downstream dip, representing northern limb of an anticlinal fold. During excavation two very thick bed of claystone were encountered near the heel of the dam and just close to the toe of the dam, which were excavated, and backfilled by concrete for more than 25m of depth below riverbed and almost all the foundation were grouted for the depth of 15m. A 29m high and 305m long subsidiary dam 13 km downstream, located in Punjab, known as Nangal Dam which apart from the natural flow also gets tail water released from power houses situated at right and left bank of the Bhakra Dam.

***13.4. Hirakud Dam*:** Hirakud Dam on Mahanadi River in Orissa is the world's longest dam comprising 3.652 km non overflow masonry section, 1.148 km masonry-concrete spillway section and 20.66 km of earth dam, totaling almost 26 km. Construction started in 1948 and completed in 1957 utilizing 23,700,000 m^3 of earth and 1,400,000 m^3 of masonry-concrete on granite, schist, gneiss and mylonitised slates and shales. The gross reservoir capacity is estimated to be 8,105,000,000 m^3 of which 5,843,000,000 m^3 is the effective storage capacity covering 727 km^2 of area at full reservoir level.

***13.5. Nagarjuna Sagar Dam*:** Nagarjuna Sagar dam is one of the largest masonry dam with a height of 125m and length of 1.45 km of masonry-concrete part hosting spillway flanked by 3.415 km of earth embankment. The gross storage capacity is 11,550,000,000 m with 6,940,000,000 m of effective storage. The bedrocks are mainly granite-gneiss below the main dam section and meta-sedimentary rocks comprising quartzite, arenaceous shale of varying thickness on right and left abutments. The rocks were generally found to weathered and traversed by shear zone and fault zone, which involved lot of excavation and backfilling by concrete.

13.6. ***Sardar Sarovar Dam***: Presently 122 m high and 1.21 km long Sardar Sarovar dam on Narmada River at Navagam in Gujarat is the most controversial dam of the world. The bone of contention is settlement of issues related to the rehabilitation of displaced populace living in the area going to submerged by the reservoir. Its height is increased in piecemeal as per the direction of Supreme Court of India as and when it gets satisfied by rehabilitation done by Sardar Sarovar Hydro Project Authority to be reached to its designed height of 165 m in near future. Its importance lies in irrigation and drinking water through a canal of 458 km, apart from flood control and power generation to the parched lands of Saurashtra and Kachch region of Gujarat. The foundation rocks are assorted mixture of dolerite dikes, Basalt flows, agglomerate beds sandstone and limestone. Numerous faults are traversing through the foundation the main River Bed Fault trending NNE-SSW and dipping by 60^0 in $N10^0E$ direction. The rocks are sheared and weathered to high degree and were subjected to grouting, rock bolting and guniting. The present site proposed by Dr. K. L. Rao was selected amongst 25 different alignments proposed by Geological Survey of India, Public Works Department and many others within one km of stretch from village Limdi in west and Surpan in east.

13.7. ***Indira Sagar Dam:*** It is a 92 m high and 653 m long concrete dam made over Narmada River at Khandwa M. P. The dam hosts biggest reservoir of India with total capacity of 12,200,000,000 m3 of water and second largest hydropower generation (1000 MW) capacity. The construction started in 1984 and completed in 2005. The rocks are mix of Late Archaean-Early Proterozoic Gneisses and Granites, Late Proterozoic and Early Paleozoic sandstones.

Frequently Asked Questions-

Q1. Give a brief classification of dams and describe their important components?

Ans. Dams are impervious to semi pervious barriers constructed across a river in a valley to impound water for slowing down river flow, for moderating flood, raising water level for canalization, hydro power generation etc. Dams are invariably associated with spillways and reservoir. Dams are traditionally made by using earth, rocks and concrete. The bigness of a dam can be known by its length, and height. The size of the associated reservoir in terms of its areal extent and the amount of water storage can also give an idea of the dam size.

The dams are classified on the basis of their size, purpose and the material used in their construction as given in the following table:

Size (meter)	< 15	15 – 50	50 – 150	>150
Type	*Small Dam*	*Large Dam*	*Major Dam*	*Big Dam*
Purpose of Dam	To Stop Sediments and Mine Tailings	Diverting Water and Canalization	To Impound Huge Amount of Water for Flood Control and Hydro Power Generation	
Type	*Check Dams*	*Barrage / Weir*	*Multi-Purpose Dams*	
Material	Earth	Rock	Concrete	Mixed
Type	*Earthen Dam*	*Rock Fill Dam*	*Masonry Dam*	*Zoned Dam*

The important types of dams based on the construction material used are *Earth Dam* also called as *Embankment Dams*, *Rock Fill Dams* and *Concrete Dams*. The concrete or masonry dams are further classified as per their shape and size as *Gravity Dam*, *Buttress Dam*, *Single* and *Double Arched Dam*.

There are some general components of dams but some components are specific to different types and purpose of dams. For example a simple earth embankment may have *foundation base*, depending upon the reservoir size and bearing capacity of the foundation ground and b*erm*, to protect main dam from the erosive action of water and also to provide extra width to the base of the dam, apart from the *Deck*, the reservoir facing part of the dam usually made sloping, cladded with rocks or by concrete to protect it from erosion by reservoir water, rain water, wind and permafrost conditions. As compared to simple earth dam, concrete dams have many different parts especially if it is a multipurpose dam. Some important parts are as follows:

Abutments: The right and left flanks of the dam abutting into rocks i.e. side foundations of dam on the hill shoulders.

Spillway: A unit of the dam, which connects and carries reservoir water to the downstream river.

Crest or Crown**:** The upper most part of the dam may or may not have parapet wall, road or railroad. Also hosts the dam axis.

Freeboard**:** The vertical space above maximum water level up to dam crest. It is based on spillway-designed flood, to prevent overtopping due to excessive ingress of water during storm, wave action created by wind, or sudden water level rise due to occasional minor landslide and earthquake effect.

Sluices**:** To take out water when reservoir level is at its lowest level i.e. just above the dead storage level. Also used in emergency conditions to withdraw waters when spillway are not able to discharge water to maintain the maximum water level.

Dead Storage**:** Minimum water level to be maintained in the reservoir going to be replaced with silt in the design life of the dam.

Stilling Basin: Water collected through spillway in the downstream side.

Tail Waters: Water collected in the stilling basin connected to downstream river.

Energy Dissipaters**:** Concrete dentition provided at place spillway waterfall to lower down the kinetic energy and to prevent erosion in stilling basin.

Heel and Toe**:** Lower part of the dam in upstream and downstream side respectively.

Cut Off Wall**:** An upstream wall provided along the dam length to prevent water seepage in foundation.

Anchor: A masonry structure provided in upstream side as an extra measure to increase the resistance against sliding in the foundation in upstream direction.

Gallery: A tunnel like structure within the dam to inspect dam and to install various instruments to monitor the functioning of the dam including earthquake monitoring device, accelerograph.

Glory Hole: A rarely made device acting as underground tunnel to take water from the reservoir bed and to empty in downstream away from the dam.

The spillway may be in different numbers and of different types. In small dams, only one spill way may suffice which may be even non gated, termed as *run off the river* dam. However, in large dams multiple spillways lying side by side are gated to regulate water discharge from the reservoir. Some spillways run through the gates made over the dam, some run through the dam and some are from the sides of the dam.

Q2. Describe various forces acting on a dam?

Ans. Forces acting on a dam during and after construction can be classed as *static* or *dynamic* in terms of their action for longer or shorter time respectively. These forces and must be analyzed to ensure safety of the dam. The static forces are further classified as forces acting in up and downstream directions, vertical up or downward acting as well as lateral forced acting towards down and towards upstream directions. The dynamic force is due to earthquake and landslide, which may take place occasionally.

Vertical Static, Upstream Downward Acting Forces: Weight of the dam (W_1) with super imposed structures as part of road/rail, spillway gates and any live load (moving vehicle/bus/train). The downward acting weight of water column on the deck (W_2) and weight of the silt (W_3).

Vertical Static, Downstream Downward Acting Forces: Weight of the tail water on the dam (W_4).

Vertical Static, Upstream Upward Acting Forces: As large part of dam is submerged under reservoir water, it is subjected to buoyancy, which is equal to the weight of displaced water (W_5). The water present below the foundation will create pore water pressure, part of which will act upward (W_6).

The upward acting forces will nullify part of the forces acting downward and the net vertical force will be:

$$\text{Net Vertical Forces: } W_N = (W_1 + W_2 + W_3 + W_4) - (W_5 + W_6)$$

Lateral Static Downstream Acting Forces: Horizontal pressure exerted by headwater column (L_1) including ice if formed in winters, lateral force exerted by the deposited silt (L_2).

Lateral Static Upstream Acting Forces: Horizontal pressure exerted by tail water column (L_3).

The lateral forces acting in upstream direction will nullify part of the forces acting towards downstream and the net lateral force will be:

$$\text{Net Lateral Forces: } L_N = (L_1 + L_2) - (L_3)$$

Resultant Forces and Stability of the Dam: The sum of vertical forces acting downward provides stability to the dam while sum of lateral forces acting towards downstream cause instability to the dam. The resultant of vertical and lateral forces is the key of stability if it lies within the foundation, close to the vertical downward acting forces and will bring in instability if it goes out and nears the lateral force. The dam failures due to sliding has taken place in the aftermath of torrential rain, sudden filling of the reservoir due to inadequate discharge from spillway and overtopping which has not only resulted in development of excessive lateral force but also very high buoyancy thereby leading to sudden drop in vertical forces and shifting of resultant force direction away from the dam foundation causing dam failure by sliding.

The dynamic force due to earthquake or large landslide nearby will undermine the vertical forces acting downward and will add to lateral forces acting downstream side i.e. will add to overall instability of the dam.

Q3. Discuss key geomorphological and geological factors in construction of big dams?

Ans. There are various factors involved in the construction of dams specially the big ones. The sole purpose of big dams are to moderate flood and generate hydroelectricity. For this when a site is selected the prime concern is to have availability of water for round the year and for a very long time to come. The hydro-meteorological setup of the area dam is going to be established plays a key role as it is going to ensure adequate amount of water in stream for throughout the designed life of the dam. The weather of that area will control the seasonal and day-to-day variability in the amount of water flowing into a river. Hence, the long and short term database of average annual rainfall/snowfall for last 100 years or more, maximum rainfall and minimum drought stage, periodicity of storm recurrence at 10, 25, 50 and 100 year level, average annual time span of dry season etc. are important meteorological parameters should be known and analyzed prior to selection of river to be tapped or in deciding the size and type of the dam.

The database of stream to be damned in terms of average annual discharge, maximum flood level and minimum water flow are very important which apart from meteorology of the area will also depend upon the drainage density, basin shape and stream order. The grade of slope of mainstream as well as of its contributories is also important, as this will decide the rate by which water will come into reservoir. In an event of erratic rainfall the rate at which reservoir is going to fill up has to be taken into account in designing the spillway and the freeboard, to avoid overtopping. The overall sediment carrying capacity of rivers must be calculated because now this will be deposited in the reservoir, causing *siltation* for which space is provided as dead storage in the reservoir. When the total capacity of dead storage is taken over by the sediment then any extra siltation will eat out the space meant for reservoir water, which is unwarranted and will lead to diminishing of reservoir life unless dredged out. The river valley may have varying width depending upon its stage and antiquity. Accordingly, it may have varying thickness of sediment deposit, termed as valley fill. As rivers shift their course sideways, due lateral accretion of sediment and vertically due to deposition of sediment layer by layer. The coarsest of sediments (gravels and coarse sand) are deposited in its channel and are left back as *shoe string* deposits. When dam is made and reservoir filling starts, water percolating downward through sediment deposits find easy to escape through these so called highly porous and permeable zone of sediments termed as *buried channels*, resulting not only loss of stored water but also problem of seepage in foundation leading to solution and development of pore water pressure. Hence, such buried channels are to be explored and identified, excavated out or sealed so that it should not lie below the dam foundation.

The geomorphological factors in catchment and dam-reservoir area are very important in understanding the hydrological conditions of the river basin. Geomorphology of catchment in terms of slope characteristics apart from shape and size of the catchment area are important in deciding the total amount of water available to a river. The other geomorphic factors such as drainage pattern, drainage density, stream order and sinuosity of river should also be properly worked out as they are going to control the velocity with which available water will come into the reservoir.

The most important geomorphic consideration at dam site is the narrow river valley section. The narrower is the river valley smaller will be the length of the dam and lower will be the cost. Sometimes this becomes the only criteria for the selection of dam site to economise its construction. The height of the shoulder hills is also important on to which the two sides of dam are going to rest i.e. the abutment foundation. It should be well above the dam height so as to prevent spilling of water in sideways in case water goes beyond the freeboard.

The reservoir behind the dam once filled may have different size and shape depending upon the geomorphology of the area as well as the length and height of the dam. The reservoir rim formed by the topography of the area will result into its linear, oval, semi-circular to irregular shapes and will have different pattern of forcing the dam. The danger of landslides in reservoir increases with increasing slope. The scars of previous landslides and slopes showing creeping should be identified and mended. The reservoir water may also lead to increase in groundwater level leading to lowering of frictional resistance along the discontinuity surfaces aggravating landslides.

The maximum possible storage will depend upon the height of the dam while yield will be controlled by annual average inflow of water and losses due to evaporation and seepage.

The amount of water supplied to the reservoir will be controlled by the size and shape of the catchment area, drainage density and slope of the river and its tributaries. The rate of water ingress by the river in to reservoir and designed discharge through spillway is very important to keep maximum reservoir level as per the design.

A detailed investigation regarding the geology of the reservoir and dam site is mandatory before embarking upon the construction. The important issues to be taken into consideration are related to rock mass properties, their attitude and presence of major deformation structures. As the reservoir and dam setup covers a considerably big area it is likely to bring in as many geological issues. It is also a well-known fact that each site may have its own geological peculiarity hence the elements of uncertainties will always be there. The dam site is especially important and it is only after the excavation for foundation and abutment is completed real picture of geology will emerge to be considered in final design. The important factors are as follows:

***Rock Type*:** Depending upon the size of a dam its safety increases many fold if there is only one rock type present in its foundation and abutments. Igneous rock bodies being very large three dimensionally, offer such condition more than often. Metamorphic and sedimentary rock bodies may or may not be large enough to host all elements of dam and reservoir within a single rock type. The gravity dams, being huge in size are only made on very strong rocks. Hence, igneous and non-foliated metamorphic rocks will be most ideal. Volcanic igneous rocks if thick and without intervening ash beds and sandstones with good strength can also host foundation of gravity dams safely. Rock fill dams best bet in areas with rocks of moderate strength. Foliated metamorphic rock gneisses, thickly bedded sandstones and strong limestones in comparatively dry regions have been found to perform well. All other rocks, which are thinly layered and weak such as volcanic flows with ash beds, tuff, schist, phyllite, slate, marl, thinly bedded sandstone, limestone etc., are suitable only for earth dams.

Weathering State of Rocks: In no case weathered rock be made as foundation ground for any type of dam. In fact for large dams only fresh rock surface (W I) should be taken into consideration and if not naturally available then should be excavated up by scrapping.

Attitude of Rocks: In the case of stratified rocks the orientation and thickness of rocks in relation to the dam axis and resultant force direction plays a very important role. The *horizontal* rocks or rocks dipping by less than 5^0 do not offer good foundation condition as it may come in parallelism with resultant force direction. If rock beds are thicker than the dam height the whole dam with foundation will remain in one rock. However, if the thickness is less, then rocks in foundation and abutment may differ. In such cases, care should be taken in deciding the foundation of the dam, which should be placed in the strongest rock bed. The *vertical* rocks may get disposed in three different fashion with respect to dam axis. If striking parallel to dam axis and thickness of rocks are more than the width of dam axis then only one and if less then more than one rock will be encountered in foundation and abutments. The resultant force direction will make high angle to vertically dipping rocks, which is a favorable condition. In case rocks are striking perpendicular to dam axis then there are chances of having more than one rock type will become more due to the fact that rocks may not be as thick as the length of the dam. This situation is also not favorable, as resultant force direction will lie in plain of rock contacts. If rocks are striking obliquely then the rocks may be disposed in between these two extreme cases and will give fair foundation conditions.

The *inclined* rocks will show varied nature of disposition depending upon its strike and dip with respect to dam axis. The rocks if strike parallel to dam axis then it may dip towards up or down stream directions. The rocks dipping upstream will be the most favorable situation as resultant force direction will be perpendicular to the dip directions. Rocks dipping downstream will result into most unfavorable situation. This may become worst if the rocks are dipping less than 45^0 as resultant force direction will come in parallelism with rocks dip. The case in which rocks are striking perpendicular to the dam axis and rocks dipping either towards right or left abutment of the dam and rocks dipping *obliquely* to the dam axis with different dip directions may pose fair condition.

Large Scale Structures**:** The rock sequence over which dam is proposed may be folded, faulted and sheared to various degrees. The presence of folds or faults or both, will not only result in repetition and omission of rocks but will bring in many other issues and problems. The construction of dams will be effected by attitude of folding with respect to tunnel length and width. Depending upon the thickness of rocks and wavelength of folding repetition of rocks will take place and rocks will be oriented differently across and along the dam length. In the case of fold axis running parallel to the dam axis, the dam foundation may run over an anticline or syncline. The position of dam foundation can accordingly be selected to get maximum benefit of rock inclination. Another aspect is of groundwater seepage along the folded layers; the water will move away from the dam in case of anticlines and will move into in the case of synclines. It is suggested that if the rocks involved in folding are thick enough then the best option is to have dam between the anticline and syncline axis i.e. in the limb dipping in upstream directions. If the fold axis is perpendicular or oblique to the dam axis then depending upon its wavelength one or more than one, anticline and syncline may come across with varying conditions of rock orientation.

Fault and fault zones should be avoided if it is live. Even if it is a dead fault then too it should be identified in terms of its type and disposition with reference to dam axis and dam should cross a fault in perpendicular fashion to have its run at minimum in dam foundation. Faults lying in regions of Seismic Zone IV to V, such as Himalayan Mountain System should be seen with caution and placing of dam may be decided accordingly. The presence of crushed material along the fault or fault zone (gouge/mylonites/breccia), being weak should be excavated out and be backfilled by concrete. The crushed zone may also act as medium for groundwater storage and movement. Its extension in reservoir area or exposure to ground surface may lead to percolation of water in to foundation of dam hence it should be identified and sealed. There are other issues related to fault such as repetition and omission of rocks resulting into change of lithology across the dam.

The presence of unconformity will bring in two different sequences of rocks across it. The presence of residual conglomerates and/or palaeosols etc. will make it undesirable at least near or below the foundation dam.

The shear zones and Joints being the most important in controlling the overall strength of rock mass, on to which dam is to be constructed, are destined to play the most important role. Shear zones can act as weak zones in rocks along which rocks are sheared and pulverized and need to be excavated out and backfilled by concrete.

As joints are ubiquitous they are going to play the most important role in terms of numbers of joint per unit area, spacing between the joints, opening along joint aperture, joint condition and water in joint planes. Based on strength of rocks and various properties related to joints the RMR and Q system classifications of rock mass can be used to predict rock mass behavior and strength.

Q4. Enumerate different causes of dam failures?

Ans. Any force that undermines the downward acting vertical forces will lead to the failure of the dam. This can be due to excessive pore water pressure in dam foundation, high buoyancy due to submergence of dam, high lateral pressure due to sudden filling of reservoir or high wave action in response to strong wind and storm. The masonry dams fail mainly due to sliding in the foundation of embankment either due to presence of weathered and weak rock material, improper keying of the foundation or due to presence of clay, salts and other weak material in joints. Other common cause is sudden lowering of vertical downward acting forces by overtopping or by high lateral pressure due to excessive water in reservoir caused by inadequate spillway is another cause. Development of cracks due to differential settlement will also make the dam weak leading to its failure. Most of the masonry and concrete dams fail within few days to few months of their completion but plain or reinforced concrete dams (PCC / RCC) may develop fractures tens of years later due to *alkali aggregate reaction*, hence need proper surveillance and corrective measures.

Rock fill dam fail mainly due to caving caused by settlement below the foundation in case rocks are not strong. Sliding within the body of the dam is another important way of failure due to material inhomogeneity in terms of size, shape and composition of rock blocks. Sudden increase in lateral pressure or development of permafrost condition may cause washouts. The failure of earth dam may have many different reasons such as seepage and piping through the dam, embankment or foundation-causing washout. Seepage of water through slow permeation can make its front as the failure surface similarly permafrost front. Differential compaction of the earth, sudden drawdown and seismic activity may also cause earth dam failure.

Another pertinent issue is leakage and seepage of water from reservoir, which not only undermines the very purpose of reservoir but also cause excessive pore water pressure causing uplift below the dam foundation. The causes of leakage can be ascribed to presence of fault and shear zones, high incidence of joints in rocks etc. while seepage may take place along alluvial fill, through the dam and through the foundation material. Another consequence of leakage and seepage of water is groundwater level rise in rocks surrounding the reservoir, which may add to the problem of land sliding. The only positive effect of this rise termed as *bank storage*, is its discharge in reservoir during lean period when reservoir water level is well below the requirement.

The damming of river will automatically stop the river sediment in reservoir, which were ought to go downstream and get distributed all along its course. Though it is very rare to have rate of sedimentation in reservoir as a decisive factor in deciding the location of the dam but, is a profound factor in deciding the dead storage capacity, as the life of a reservoir is based on this space, which is eventually got to be filled by silt but in designed life of the dam. The decision for height of the dam may also have to take the rate of sedimentation into account, as the total reservoir capacity minus the dead storage will control the total water available for the dam is intended for. Most of the dams in India show, rate of sedimentation twice to ten times more than the assumed one hence, reducing the life of the dam by half to one tenth of its designed life. The cost of sluicing or dredging of sedimentation may be very costly to undertake and may ultimately result in abandonment of the dam-reservoir. Construction of check dams and small run off river dams along the contributing streams and vegetation turning in catchment area are the best options to mitigate this problem.

If not all but few areas after the construction of dam-reservoir have shown spurt in seismicity termed as Reservoir Induced Seismicity (RIS). The excessive load due to rise in water level on rocks, devoid of such pressure prior to construction of dam-reservoir, start failing, causing seismicity. Shear zones and faults which are seemingly dead and locked at present state of the residual stresses in rock mass may get reactivated due to added load of water as well as seepage of water along them leading to slippage and occurrence of earthquakes. For example in India, Koyna Dam in Maharashtra has shown that whenever the reservoir water level increases to more than 100 m level there is an earthquake. The cause of seismicity in the case of Koyna has been ascribed to presence of a deep-seated fault. The water seeps in case of high water column pressure, leading to wetting and lubrication of gouge/clay, lowering of frictional resistance causing slippage hence, earthquake. Some other dams in India where such kind of RIS is recorded include Idukki Dam (Kerala), Parambikulam Dam (Tamil Nadu), Sholayar Dam (Tamil Nadu), Ukai Dam (Gujarat) etc. but the severity is very low as compared to Koyna Dam (Maharashtra).

A dam can fail due to many different reasons and shortcomings in geological and geotechnical investigations on one hand and poor design on the other. Presence of Weak rock mass or unfavorable geological conditions if not properly identified and corrected then will seriously affect the stability of the dam. Engineering geologists should explore extensively and intensively to ensure proper geological investigations. Any shortcoming in geotechnical investigations for foundation and abutment will make a dam inherently weak. A geotechnical engineer should not leave any stone unturned to make the very base of the dam strong. Improper design of the dam body will mar the very purpose of the dam. The structural engineers should design the dam with utmost care using state of the art design methods taking in view all the negative and positive points identified during geological and geotechnical investigations.

Q5. Give an account of different stages and types of investigations for the construction of dams?

Ans. The place where a dam project is envisaged involves usually a very large area-encompassing catchment area, reservoir area and the site where dam structure is to be placed. The premise is to have all the year availability of water, a good founding ground, proper water storage area with minimum of environmental degradation, within proposed budget. Lots of permutations and combinations are to be weighed, in terms of safety and cost benefit analysis before pin pointing the final site. The investigations for a mega dam project can be planned in following three stages:

(i) *Preliminary Stage* (ii) *Main Stage* and (iii) *Concurrent Stage.*

In Preliminary Stage reconnaissance studies are made by going through already available literature in form of topographic maps; aerial photographs satellite imageries, geological maps and reports etc. to work out the area involved, its topography, meteorology and hydrological studies of the river and its contributories going to be damned. The seismic zone in which site is falling, problem of landslides, level of displacement of residents need to be properly worked out. Site visit may then be undertaken for direct assessment of the area and to gather information available with local populace. Once the feasibility of the project is ensured, then a preliminary report can be made to chalk out detailed fieldwork plan, investigations and tests to get information that is more specific.

Environmental Impact Analysis (EIA) is another dimension of investigations for dam and reservoir site as this is the most contentious issue and invariably results in to delay in starting the project. It entails proper identification of the flora and fauna going to be affected by the project.

Once the project gets green signal then multitude of site investigations are undertaken under the *main Stage*, which involves fieldwork to have detailed information about the hydro-meteorological data pertaining to annual rain fall, maximum and minimum rainfall of last 100 years or so, occurrence of storm and drought. Geomorphological studies for collecting data related to the river catchment area, its shape, drainage density, slope characteristic etc. is to be worked out. Fresh surveys are undertaken at small scales for ascertaining the geology of the area to unravel the lithology and structural geology in terms of presence of folds, faults, shear zones and joints. For shallow subsurface information trial pits and trenches, exploratory adits or drifts may be made. For knowing about deep underground conditions drilling, bore hole logging and geophysical surveys can be carried out. The samples of soil and rocks are collected for the laboratory tests and analysis. If some insitu testing is required it is also undertaken at this stage.

Subsurface drilling up to the depth "pressure bulb" is going to be formed is a must not only to work out "rock quality designation" to be used in rock mass classification but also to carry out permeability analysis of rock mass.

After corroborating the data from field and laboratory a final report is prepared. Final report includes detailed topographic and geological maps at scales which can mirror the minute details of the site. Fence diagrams can be made to get three dimensional perspective of the site.

Geophysical studies to work out the depth of overburden, thickness of weathered rock mantle, groundwater level and buried channels should be employed. As the dam foundation is the most important part of the dam it is subjected to greater scrutiny and detailed studies are carried out involving, geo-engineering and rock mechanics. Rock mass classifications are made by incorporating detailed joint analysis to predict its behaviour during loads exerted by dam and reservoir waters.

During the construction or Concurrent Stage, insitu residual stresses need to be measured and monitored during the construction and after. As excavations are done to remove overburden and to expose fresh rocks for laying foundation some new situation may arise which could not be detected in previous investigations should be taken into consideration and changes may be recommended if needed accordingly in the design. These investigations require lot of speciality of geo scientists, geophysicists, engineers etc. All of them have to work in tandem in modelling the site for safety and longevity of the project.

Multiple Choice Questions-

1. Which of the following is not a part of a dam

(a) Crest
(b) Toe
(c) Heel
(d) Portal

2. Which of the following dam is made on very strong rocks

(a) Rock Fill
(b) Weir
(c) Gravity Dam
(d) Embankment

3. The dam made on alternating strong and weak rocks is

(a) Buttress Dam
(b) Earth Dam
(c) Rock Fill Dam
(d) Check Dam

4. The highest Dam of India is

(a) Idukki Dam
(b) Tehri Dam
(c) Bhakra Nangal Dam
(d) Hirakud Dam

5. Which of the following dam is the longest dam of India

(a) Sardar Sarowar Dam
(b) Nagarjun Sagar Dam
(c) Hirakud Dam
(d) Tehri Dam

6. Which of the following dam in India is famous for reservoir-induced seismicity

(a) Sardar Sarowar Dam
(b) Indra Sagar Dam
(c) Koyna Dam
(d) Tehri Dam

Suggested Readings:

1. Subinoy Gangopadhyay (2013), Engineering Geology, Oxford University Press, New Delhi.
2. Krynine, Dmitri P and Judd, William R (2005), Principles of Engineering Geology and Geotechnics, CBS Publishers, New Delhi.
3. Tony Waltham (2009), Foundation of Engineering Geology, 3rd Edition, CRC Press, London.
4. Bell, F G (1983), Fundamentals of Engineering Geology, Butterworths, London.
5. Engineering Geology Field Manual (2001), 2nd Edition, Vol. 1, US Dept. of the Interior Bureau of Reclamation.
6. Alam Masroor M. (2013), Fundamentals of Engineering Geology and Geo-Engineering, Axioe Books, India.