hydroelectric power plants

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HYDROELECTRIC POWER PLANTS

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5. GEOLOGICAL ANALYSIS

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ABSTRACT The construction of hydroelectric power plants is always done using geological information and frequently the whole project is conditioned by the geological nature and characteristics of the site. The importance of geology in the planning, construction and operation of hydroelectric power plants will be presented and discussed. Without trying to be exhaustive, some aspects related to the watertightness of the reservoir, the stability of the reservoir slopes, the watertightness and deformability of the dam foundations, site conditions of the appurtenant structures and availability of construction materials, will be presented.

INTRODUCTION

The construction of dams for hydroelectric production is relatively recent, but the construction of dams began a long time ago. One of the oldest examples dates from 4800 BC and was constructed at Sadd-El-Kafara in Egypt. This dam was 11 m height and 160 m long (Murray, 1965; Hathaway, 1958). Among the civilizations that had an important role in the construction of dams were the Romans with examples in Syria or even in Italy, where in the first century they constructed at Subiaco, 80 km east of Rome, a dam about 40 m hight.

In Europe, the development of industrialization and urban growth generated a great increase in the construction of dams. It is worth mentioning that in Holland, since the 10th century dykes were constructed to prevent tidal flooding.

Suitable places to construct dams are necessary for: - hydroelectric production, - irrigation, - urban and industrial water supply, - flood control, - improvement of landscape or climatic effects.

In most of the countries the best places are already used and it becomes necessary to adapt the design of new dams to the less favourable sites. One example is the Tedori rockfill dam in Japan (Kawashima and Kanazawa,1982). This dam was constructed over a very heterogeneous foundation constituted by deeply weathered gneisses at the higher levels, conglomerates and limestones with small dissolution holes and with a large shear zone 25 m thick, in the left bank.

We can classify the different types of dams (Fig. 1 and 2) as follows.

a) The height of the structure (ICOLD): - large dams (height over 15 m); - small dams (height under 15 m).

b) The materials used in the construction: - concrete dams; - rolled compacted concrete (RCC) dams; - masonry dams; - earth dams; - rockfill dams.

c) The shapes related to the behaviour relative to the foundations: - arch dams; - gravity dams; - buttress dams

"Rigid" dams are: concrete, RCC, masonry and buttress. "Deformable" dams are: embankment (earthfill and rockfill). Composite dams result from the combination of two or more of the basic types.

A rigid foundation does not cause damage on the rigid structure of the dam. Over a rigid foundation a deformable or rigid dam can be constructed. Over a deformable foundation a deformable dam (embankment) is suitable.

Only after the execution of several preliminary studies including: - local survey, -laboratory tests, - engineering and economic analysis, is a decision made on the place and the type of dam to be constructed.

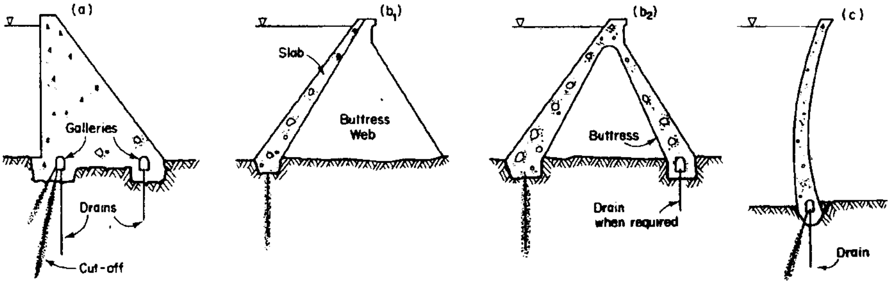


Fig. 1 - Cross-section of (a) gravity dam; (b) butress dams; (c) arch dam (Blyth & Freitas, 1984).

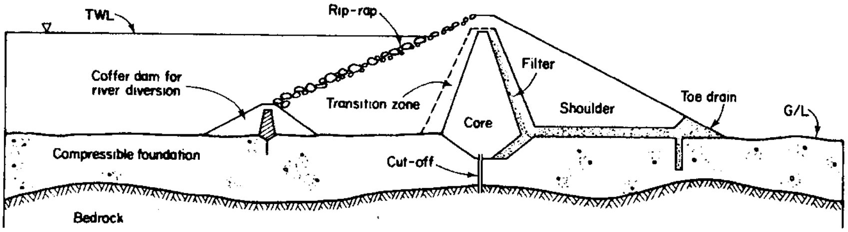


Fig. 2 - Typical Cross-section of an embankment dam (Blyth & Freitas, 1984).

According to Pircher (1982), the most important factors in the selection of the type of dam are the foundation conditions, characterized by site topography and geological structure.

Several important reasons involved in the selection of the type of dam to be constructed are outside the scope of this text and will be referred to elsewhere in this course.

STUDY METHODOLOGY

The contribution of engineering geology to the construction of dams goes from the geological and geotechnical studies of the dam site, the reservoir, quarries and borrow areas to the interpretation of the dam behaviour and its foundations. The sequence of operations necessary to the study of local conditions, in order to construct a hydroelectric power plant, are difficult to summarize because there are a wide range of problems, study methods and techniques that can be used. The extension and detail of a geological study will depend on: the type, height and length of the dam; the dimension and extension of the project; the importance that the designer attributes to the geological conditions.

Despite this, some general considerations can be drawn. The general methodology usually followed during the study of a dam site have been presented by several authors (Neiva, 1957; 1982; Oliveira, 1979; GTAEEA, 1982; Pircher, 1982; Rampon, 1986; Quinta Ferreira, 1990). For simplicity, the study is divided in accordance with the project stages usually considered, and summarized in Table 1.

Table 1 - Main activities of engineering geology during project stages (modified from Oliveira, 1979).

Project stages	Main activities of engineering geology	Document
Feasibility	- Study of existent geological documents - Interpretation of aerial photograph and remote sensing imagery - Preliminary geological reconnaissance of the site - Preliminary geotechnical exploration	Preliminary report
Pre-design	- Surface geological reconnaissance (continuation) - Geophysical exploration (mainly resistivity and seismic refraction) - Mechanical exploration (trenches, adits and boreholes) - Laboratory tests - Selection and preliminary characterization of the materials to be used in the dam construction - Geotechnical zoning of the foundation and preparation of the complementary exploration program	Interim report
Design	- Mechanical exploration (continuation) - Syntheses geological mapping - Large scale in situ tests (dynamic; deformability; shear; hydraulic) - Complementary laboratory tests - Foundation grouting tests	Final Report
Construction	- Geological mapping of excavation surfaces - Foundation treatment - Control tests	Supplementary report
Operation	- Interpretation of results of the monitoring program (settlements, percolations, mass movements, deteriorations, etc.)	

The objective of the geotechnical survey is to study and understand the foundation characteristics in order to assure that the design, construction and operation of the dam can be done with the maximum economy and safety.

According to Oliveira (1979) in the execution of the geotechnical survey for the location of a dam site in rock masses, some basic rules should be followed: - the study should generally be conducted in different steps progressively using more sophisticated methods of investigation; - these progressive studies should permit the engineering geological zoning of the foundation rock mass; - the safety of the dam in relation to the foundation geotechnical conditions depends on the characteristics of each of the engineering geological zones and of the eventual presence of adverse major discontinuities (like faults, weathered veins and shear zones).

Usually the work starts by the study of regional geology producing a map at the largest scale available, frequently between 1/5000 to 1/25000. All the information available through reports, maps, papers and aerial photographs or satellite imagery must be analysed in order to get a good idea of the geology in the area where the project is located.

The seismotectonic characteristics of the area where the dam is to be built will influence the project and eventually the location of the dam. Regional seismic activity is related with the existence of active faults, requiring a detailed study (Sherard et al., 1974; Oliveira, S., 1977). This subject will be referred to later.

The geotechnical study should first use the least expensive and quickest methods available. A significant amount of data is obtained based on discontinuity measurements, geophysical prospection, mechanical survey and laboratory tests.

The geological mapping of the dam site and its surroundings should be executed using a scale, if possible, larger than 1/2000, in addition to representative cross sections of the area.

Geophysical methods are used to get a general idea of the foundation mass structure and to guide later direct survey. Geophysical results must be compared using two or more methods and preferably integrating the geophysical results with other geotechnical survey methods (Rodrigues & Esteves, 1987).

Ultimately more sophisticated, expensive and time consuming techniques would be used. After the interpretation of the survey it should be possible to execute the geotechnical zoning of the foundation mass. The zoning will be based on the analysis of a large number of values having statistical meaning, simplifying the interpretation of the different zone characteristics. Based on the geotechnical zoning it is possible to carry out a small number of characterization tests that can be considered representative of each zone.

In the final report the relevant aspects for the project are presented, analysing all the results obtained and the characteristics of the structure, excavation depth, or rules for excavation, and foundation treatment are defined. Considerations about possible difficulties and problems that could be found in the execution of the structure should also be stated.

Reconnaissance Techniques

The reconnaissance techniques most used in the study, prospection and testing of soil or rock masses for dams can be considered "classic" and are well known. Besides these "classic" techniques some others are assuming a growing importance in the study of dam foundations.

In the mechanical survey we can use the continuous logging of the drilling parameters and the use of destructive drilling associated with diagraphies. These techniques are becoming increasingly used. For the first technique some good results have been obtained in low consolidated materials (e.g.: CFGB, 1982-b; Siegrist & Tobio, 1986). For the second technique good results have been obtained in the study of slope debris, till or fissured rocks, giving sometimes better information than cored drilling which destroys the weaker zones of the samples.

The geophysical methods have experienced greater developments, mainly due to the improvement of electronics and the possibility of using large capacity computers in the processing of large data volumes. In the seismic methods the improvements in seismic reflexion (Rodrigues & Fonseca, 1986), microseismic (Rodrigues & Esteves, 1987) and seismic tomography (Pessoa & Rodrigues, 1989) are worth mentioning. In superficial reconnaissance electromagnetic methods, allowing determination of the resistivity up to 50 or 60 m deep, have presented some encouraging results (Chamon et al, 1986). In the study of underground cavities, gravimetry can be used, but other methods like pole-dipole (electric method) and radar have been used.

The use of indirect survey methods still requires the "classic" reconnaissance techniques, like cored samples, to confirm available information and validate the models on witch the interpretation is based.

INFLUENCE OF GEOLOGY ON THE SELECTION OF THE DAM TYPE

At the beginning of the selection of a new dam site the type of structure to be constructed is usually not defined.

The selection of the dam type can only be adequately done after knowing the local conditions (e.g. morphology of the valley), local geology, geotechnical characteristics of the foundation and the availability of construction materials.

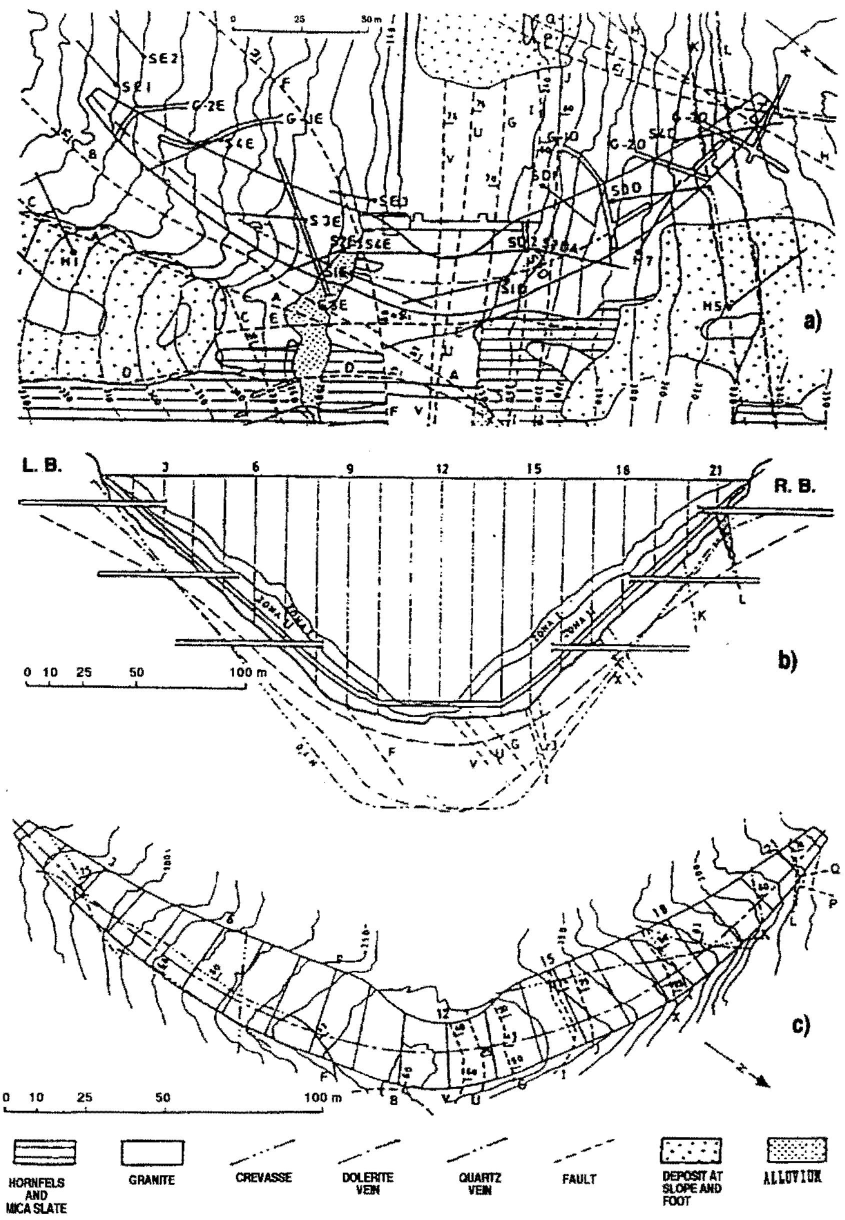


Fig. 3 - Alto Lindoso dam. a) Geological map of the dam site; b) Cross-section; c) Dam's foundations (Cotelo Neiva et al., 1991-a).

The topography of the valley is significantly influenced by such geologic factors as the rock type, conditioning the resistance to erosion and weathering, by the geological structures (Fig. 3) like faults, folds, joints, dykes and by the tectonic history.

Dams are located on valleys and they exist due to local weathering and erosion. Thus weathering, stress relief associated with uplift and erosion or excavation of foundations, compressible foundations and unstable slopes can be expected. Stress relief also increases the frequency of joints and the aperture of fractures.

The construction of arch dams in rock foundations are mainly dependent on the characteristics of strength, deformability and transmissivity of the rock mass. For the construction of embankment dams, considered deformable structures, the characteristics of strength and deformability of the rock mass are not usually important. Transmissivity can have much more importance on the design of this type of dam.

Gravity dams transmit loads to the foundation that are approximately proportional to the height of the dam, and that will probably stay below the strength that a rock foundation can stand without suffering rupture. According to Schalkwyk (1982) for a rockfill dam with an height between 50 and 100 m, the strength required for the foundation is at least 2 MPa, only requiring to remove low strength or compressible soils. As embankment dams are deformable structures they can easily deform to adapt to the deformations of the foundation. Usually embankment structures suffer internal deformations due to their weight, applied loads and creep, that are much higher than the deformations observed on the rock foundations.

Sometimes, despite the adequate morphology of the valley for the construction of a concrete dam the unfavourable foundation characteristics do not recommend its construction (Neiva, 1956; Benoit et al., 1967; Kawashima & Kanazawa, 1982; Novosad, 1990).

In the case of Naussac dam, reported by Coulbois et al. (1982), being 50 m high, the valley shape allowed the construction of an arch dam, but the existence of a lithologic difference between the two banks, granulite on the right bank and very fractured gneiss on the left bank, was unfavourable to this solution and a rockfill was chosen.

On soil foundations, deformability, transmissivity and strength can have a very important effect on the design of the dam. When there are thick alluvial formations having low strength and high deformability, embankment solutions are the most suitable. Earth dams with gentle slopes are frequently chosen instead of rockfills. Several examples can be found in the bibliography pointing to of avoidance a rigid dam due to the deformability of the foundation (Benoit et al., 1967; Folque & Melo, 1977, Serafim & Carvalho, 1970).

(Good foundation rock mass) + (ratio: length/height of the valley less than 5) =
= arch dams are frequently chosen

(Bad foundation rock mass) + (ratio: length/height of the valley greater than 5) =
= embankment dams are suitable

For the embankment solution it is necessary to check if there are available the quantities and types of adequate construction materials in economic conditions for extraction and transport.

The selection of a rockfill or earthfill dam will depend on factors like the relative abundance of rock and soil, the properties of available construction materials and the distance between the dam and the quarry or borrow areas.

On the Manicouagan 3 dam, in Canada, the main geological constraint was the presence of a deep subglacial canyon filled with alluvium (Benoit et al., 1967). The geometry of the bedrock allowed the construction of an arch dam requiring the execution of a deep excavation in the alluvium (Fig. 4). As this kind of work is very difficult to execute it was concluded that an embankment dam would be less expensive.

At Massingir dam on Mozambique (Serafim & Carvalho, 1970) the variation in the characteristics of the soil foundations obliged the adoption of three different cross sections associated to special constructive measures (Fig. 5). The dam is over three different types of soils: - sand and gravel on the first terrace; - alluvial sand on the main valley; - silt and clay on the abandoned river bed to the south. The dam is also over layers of low strength Cretacic sandstone and over marls and limestones on the flanks of the main valley.

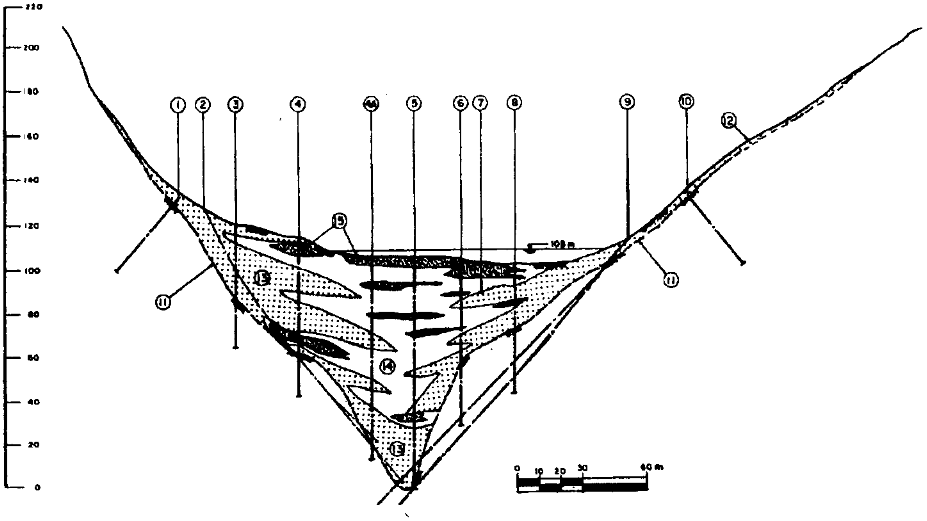


Fig. 4 - Geological section on the glacial valley of Manicouagan 3, in Canada (modified from Dreville et al., 1970).
1 to 10 - boreholes; 11 - bedrock limit; 12 - cover soils; 13 - gravel and blocks; 14 - sand and gravel; 15 - uniform fine sand.

To illustrate the main conditions encountered at Massingir dam, some data is presented. The river has its present bed at a level of 82 m, on a quaternary alluvial formation with about 27 m thickness, lying over Cretacic rocks. The first alluvial terrace is between levels 100 and 120 m and is the oldest quaternary alluvial formation constituted by gravel, with sand and clay. Later the river moved south and excavated a large valley in Cretacic formations. After this, in transgression, the river has deposited in this valley, silt and clay sediments with a maximum depth of 30 m. Again in a regressive movement the river moved north to its present position, deeply excavating the Cretacic rocks and the valley was sedimented with alluvium, constituted by fine to coarse sands, gravels and blocks. This formation corresponds to the main valley of the river, having a U shape, 400 m wide.

As reported by Folque & Melo (1977) the project of Quiminha dam in Angola, was also extremely influenced by the characteristics and behaviour of the alluvial soils of the foundation (Fig. 6). In the foundation there are sediments with thickness up to 40 m, filling a valley excavated in limestone. The interbedding of coarse materials with clay materials of variable geometry, created some difficulties to the geological characterization of the foundation. The difference in thickness of the clay layers, 20 m on the right bank and extremely reduced on the left bank, allowed important differential settlements of the foundation. The maximum absolute expected settlements were about 1.7 m corresponding to 4% of the thickness of the quaternary sediments.

Newbery (1978) reports some cases in tropical zones where intense weathering of the granite foundation was unfavourable to the construction of arch dams and more favourable to embankment or buttress dams.

In valleys with an important alluvial filling beside embankment dams, it is also possible to construct rigid dams if the loads are applied to the bedrock. Two Portuguese examples are the Coimbra Bridge Weir (Açude-Ponte) (Fig. 7) (Maranha das Neves, 1978) and Crestuma dam (Alvares Ribeiro et al., 1982). In these cases the stresses are applied directly to the "in situ" bedrock using piers. Usually this type of structure is constructed on important rivers, with important thickness of alluvial deposits, where all or part of the dam works as spillway or is necessary to lower the upper level of the dam to the bottom of the river during floods.

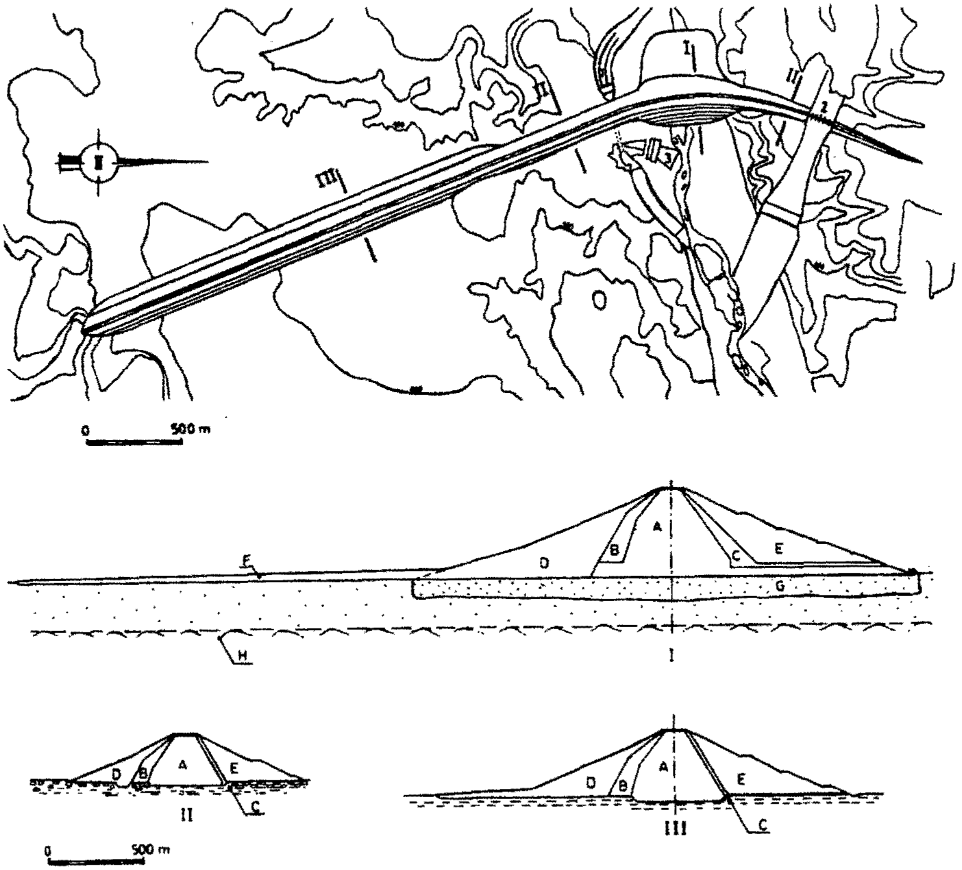


Fig. 5 - Plan and typical cross sections of Massingir dam (Serafim & Carvalho, 1970). I - typical cross section on the main valley; II - typical cross section on gravel and sand; III - typical cross section on the clay material; 1 - water intake and bottom discharge; 2 - spillway; 3 - power plant; A - core; B - upstream transition zone; C - downstream transition zone; D - upstream shoulder; E - downstream shoulder; F - impermeable blanket; G - Alluvium to be compacted; H - bedrock.

Dam sites are essentially the narrowest points in the valleys (Fig. 8 and 9). This is frequently due to the presence of a stronger lithology or a lower rock mass weathering, having downstream a higher gradient. Lagoacho dam site is a characteristic example of this situation, being located in a glacial "verrou" with a larger valley upstream and a downstream increase of gradient. At Lagoacho the valley morphology was significantly influenced by the glacier action.

The geology and morphology of a site will also control the location and type of appurtenant structures like the overflow or the river diversion works.

Natural seismicity has an influence on the design of the dam and its auxiliary structures. Embankment dams are usually chosen in regions with intense seismicity because they can better resist an earthquake than can an arch dam. When there are no records of past earthquake activity, geological evidence can be used as shown by Sherard et al., 1974. (see Fig. 10, 11 and 12).

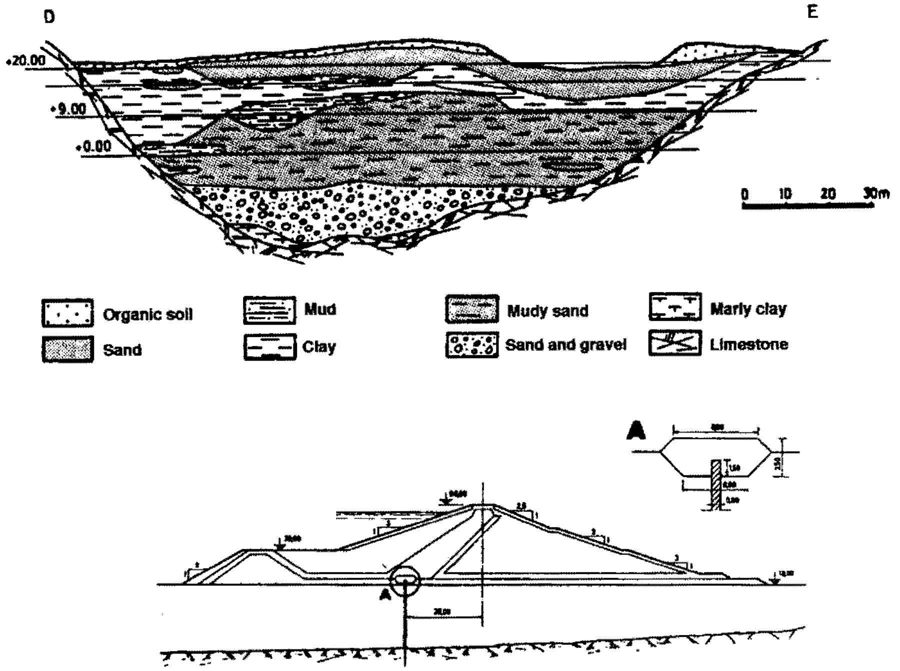
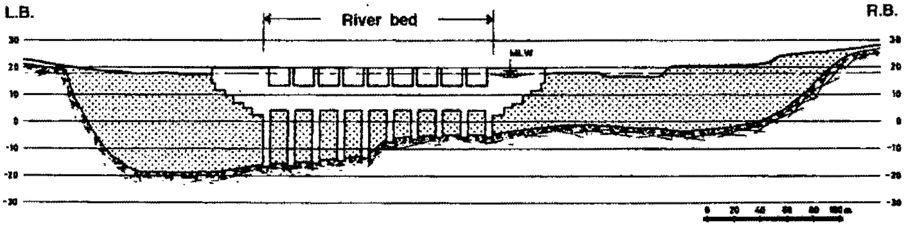
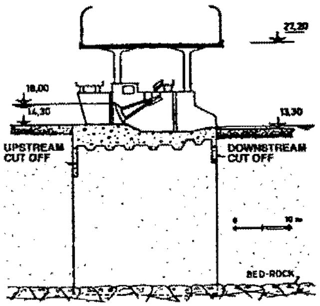


Fig. 6 - Geological section of the valley and cross section of Quiminha dam (modified from Folque & Melo, 1977).



a)



b)

Fig. 7 - Coimbra Bridge Weir (Açude-Ponte) (Maranha das Neves, 1978).
a) Location of the dam in the alluvial valley;
b) Cross section.

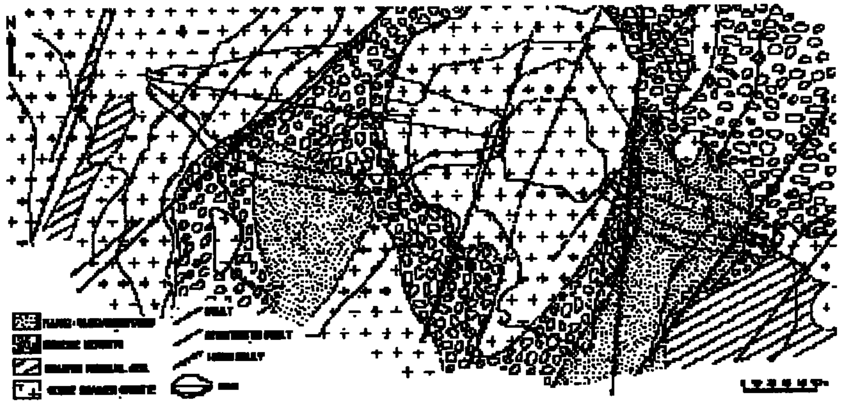


Fig. 8 - Geology of Lagoacho dam site (Quinta Ferreira, 1990).

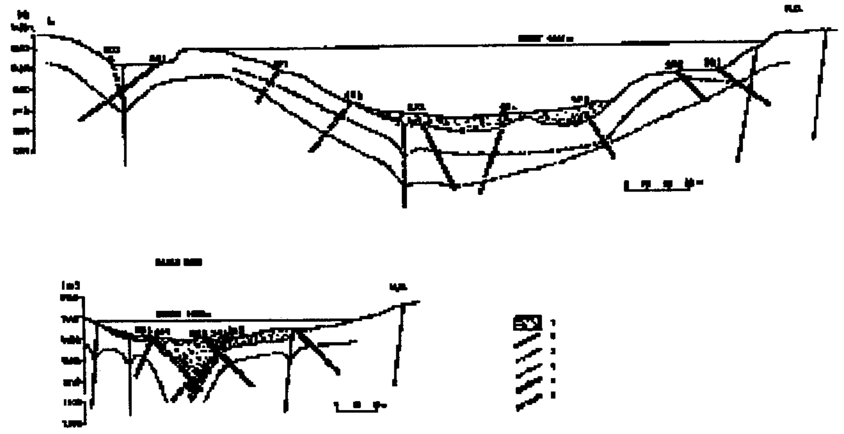


Fig. 9 - Cross-section along the plinth and sedle dam of Lagoacho dam (1 - fluvio-glacial deposits; 2 - fault; 3 - lower limit of 10 Lugeon; 4 - lower limit of 2 Lugeon; 5 - drill-hole in the cross-section; 6 - drill-hole projected in the cross-section) (Quinta Ferreira, 1990).

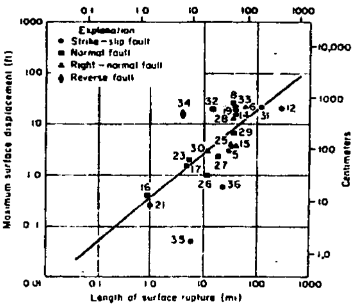


Fig. 10 - Rough correlation between length of break and maximum relative displacement of ground on opposite sides (After Bonilla, 1970, in Sherard et al., 1974).

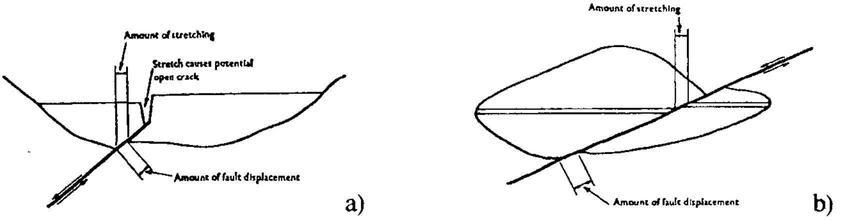
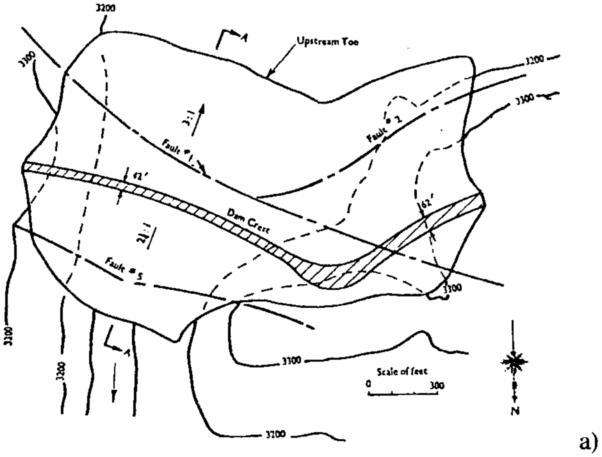


Fig. 11 - Displacement of fault can stretch dam. a) normal fault; b) Strike-slip fault. (Sherard et al., 1974).



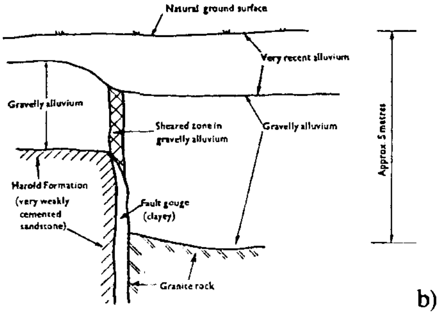


Fig. 12 - Cedar Springs Dam.
a) Plan view and fault locations;
b) Appearance of small active fault exposed in exploratory trench.

FOUNDATION CHARACTERISTICS

A dam must be construced on good foundations. When the ground has poor or deficient characteristics it is necessary to find the best location where either the rocks and soils can be best improved or the dam designed to compensate ground deficiencies.

The need to study the geotechnical properties of a dam foundation increases with the risk of material and human damage that the rupture of the dam would cause downstream.

The most important factors in a dam foundation are adequate strength, low deformability and low transmissivity.

Strength and deformation

Low strength soils like clays must be consolidated or removed. The drainage of the ground water from pores or fractures increases the effective stress. Soils susceptible to liquefaction when subjected to earthquake acceleration must be treated with great care.

The differential deformations must be lower than the dam can stand. This is particularly important for rigid structures like concrete or masonry dams.

The water impounded in the reservoir also applies load to the foundation and to the dam, pushing it downstream. The fluctuations of the reservoir level impose load and unload to the dam, as the water level rises or falls. The resulting deformation must be below the tolerable ground deformation in order to prevent deformation of the dam structure or damaging its cut-off.

Contact between the foundation and the dam

During the construction phase, the stripping of the foundation may disclose important geological details that could not have been detected even during a detailed reconnaissance. This period is critical for the contractor that usually wants to work fast whithout delays. As this is the period during the structure life when the foundation can be best studied, it is important to do a detailed study because the safety of the structure will benefit.

In very weathered rocks the interface between unweathered and weathered materials is usually very irregular. The treatment that is done in the contact between the foundation and the dam can be very diversified depending on the characteristics of the foundation and the type of dam.

For an arch dam all weathered materials are usually removed and the voids, irregular surfaces or openings filled with concrete. Consolidation grouting is usually done on the top layer of the foundation, trying to obtain a better transition zone, and is usually executed with low grouting pressures in order to seal the near surface fissures and voids without generating hydraulic fractures.

On embankment dams the more delicate zone is the contact between the impervious element and the foundation. This zone is critical because the hydraulic behaviour of the structure is dependent on a good connection of structure and foundation. The irregularities of the bedrock increase the possibility of differential settlements that can create fissures on the impervious element. When the rock foundation is intensely fractured, consolidation grouting is usually also necessary.

When there is a thick alluvial cover over the “in situ” rock the need to make the sediments impermeable sometimes a difficult problem. The execution of impervious cut-offs in soils frequently shows unpredicted construction problems. In more difficult situations,.walls constructed with asphalt (Carrère et al., 1982) or other impervious materials are used.

When the alluvial thickness is small and its transmissivity high, one frequently used solution is to remove it and build the foundation of the impervious element directly onto the bedrock. This solution was used in the construction of Beliche dam (Maranha das Neves et al., 1987) and allowed to study the core foundation, turning easier the superficial grouting treatment.

At Lagoacho dam the reduced thickness of the fluvio-glacial soils only raised special concern in the glacial canyons that were found in the middle of the main and secondary valleys (Fig. 9). The plinth was constructed over the soils in the bottom of the valley and later grouted to create a cut-off.

As earlier stated, the construction of rigid structures on soil foundations is sometimes chosen, as in the Coimbra Bridge Weir or Crestuma dam. In these cases the stresses are applied directly to the “in situ” bedrock using piers.

Hydrogeological conditions

The percolation of water through the foundations of the dams differs in importance according to the specific characteristics of the dam, the economic value of the water and its effect on the safety of the dam. The study of the dam foundation transmissivity is one of the fundamental aspects that can influence the project of the dam.

In rock foundations, the test currently used is the pumping-in of water using pressure. The procedure initially proposed by Lugeon (1932), has only undergone small changes with time, and is described by several authors (Louis, 1974; Cassan, 1980; Ewert, 1985). The test is done using several increasing and decreasing pressure stages, measuring the pressure and the water intake, traditionally during ten minutes, for each pressure stage. The interpretation of the results allows the study of the hydraulic behaviour of the discontinuities in which the water is forced to flow. Several methodologies are used (Lancaster-Jones, 1975; Houlsby, 1976; Oliveira, 1972; 1983; 1990; Cassan, 1980; Gómez Laá et al., 1982; Fernandes, 1984; Ewert, 1985; 1990).

Other authors (Foyo Marcos, 1983; Fernández-Bollo & Foyo Marcos, 1987) even think that it is possible to study the geomechanical characteristics of the rock mass using pressures capable of producing hydraulic fracture.

The Lugeon is the unit usually used to report the results, and corresponds to the injection of one litre per minute and metre of borehole using 1 MPa of pressure.

1 Lugeon = 1 litre / minute / metre at a pressure of 1 MPa

Near the surface, and in dams of reduced height the maximum pressure used is frequently under 1 MPa. As this does not allow computation of the Lugeon value, several different procedures are used to compare the water absorption. The computation of absorptions to the 1 MPa pressure is sometimes used and is more accurate when there is proportionality between applied pressures and the water intake in the rock mass.

Other authors (e.g. Fernandes, 1984) prefer to convert the results in Absorption Units (AU). This unit corresponds to the absorption of one litre of water per minute, per metre of borehole and per kgf/cm^2 (1fgf/cm^2 $\approx$ 0.1 MPa) at the maximum pressure of the test, and can be considered that 1 AU is equivalent to 10 Lugeon.

A Lugeon unit is approximately equal to a coefficient of permeability of 10^{-7} m/s.

The opinion of several authors concerning the transformation of Lugeon values into equivalent permeability coefficient is not the same. As examples we refer only two opinions. Oliveira (1990) states that they can be used considering important simplifications, while Ewert (1990) states the opposite based on the fact that used formulas were constructed for soils giving erroneous results for rocks.

Due to the limitations of the Lugeon test some authors (e.g. Nazareth, 1987; 1990; Foyo & Cerda, 1990) have proposed some improvements to the test.

Pumping-out tests on rock masses are seldom used due to the high costs. They are suitable to characterize large volumes. As shown by Tressoldy et al. (1990) the transmissivity changes with the test area of influence.

Evaluating transmissivity conditions on rock foundations

The Lugeon water test is usually executed inside the boreholes used for the reconnaissance of the foundation. The location and orientation of the reconnaissance boreholes is frequently defined after the superficial geological survey, trying the best intersection of the largest number of significative discontinuities. Based on the results of the tests, the transmissivity of the rock mass can be evaluated. The hydraulic zoning of the foundation can be done and the need to create an impermeable foundation or drainage is assessed.

The Lugeon water test is representative of a small volume of the rock mass, allowing to characterize the percolation through the discontinuities intersecting the tested section. Oliveira (1990) considers that the length of each tested section must be related to the distance between discontinuities, in such a way that each test uses at least six discontinuities in order to be considered an average global value for the rock mass. When the rock mass has a small number of fractures the tested section must have a length greater than 5 m.

Concerning the maximum pressure used in the test, the Lugeon criterion is the most frequent, corresponding to a maximum pressure of 1 MPa. The use of this criterion has a great advantage in the enormous experience already obtained and the possibility to empirically relate tests results with the need and type of impermeabilization treatment, according to the dam characteristics (e.g. Fig. 13). Another criterion considers that the maximum pressure should be inferior to the weight of the rock mass above the tested section, in order to avoid hydraulic fracturing and the decompression of the rock mass, deteriorating the natural transmissivity conditions in the foundation. Other authors consider that the maximum pressure should be similar to the hydraulic pressure that the reservoir will impose when full.

On this subject we agree with Ewert (1990) because the maximum pressure should be higher than the hydraulic head that will be created by the reservoir and also should reach a pressure capable to produce hydraulic fracture in order to allow the definition of the maximum injection pressure. The pressure necessary to produce hydraulic fracturing can be proportional to the depth, if the rock mass can heave, or be independent of depth, if the rock links are strong and the fractures are closed or only partially opened. In this case the hydraulic fracturing is controlled by the rock deformation.

In the study of Midões dam foundations, Lugeon tests were carried out on sections of 5 m following the classic process. Used pressures were 0.25, 0.5 and 1 MPa. Obtained lugeon values are plotted on Fig. 14. The results show a coherent set with the Lugeon values decreasing progressively with deph. The abnormal value (36 Lugeon at 12.5 m) corresponds to a fault zone.

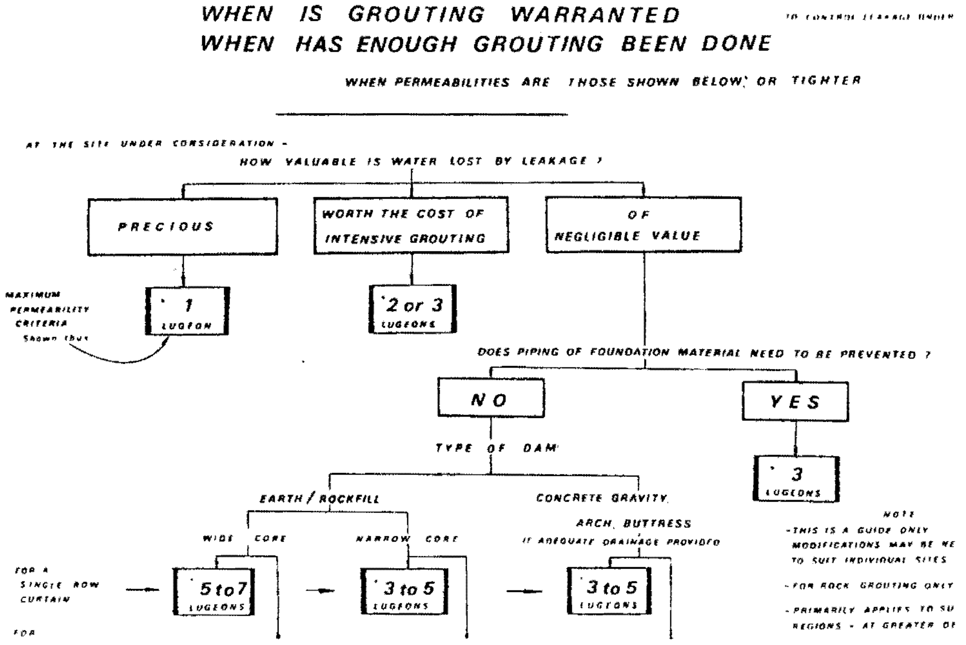


Fig. 13 - Assessment of the need for foundation grouting (Houlsby, 1976).

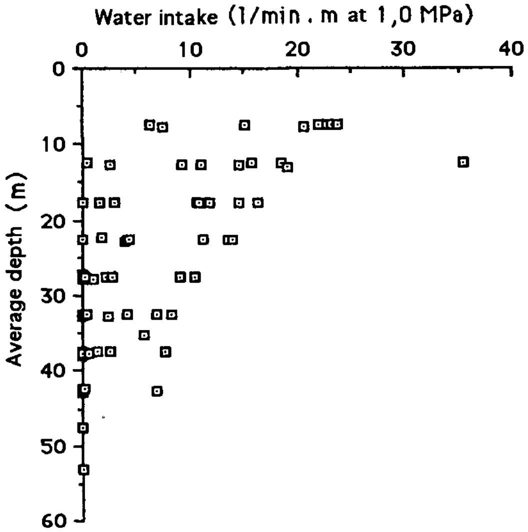


Fig. 14 - Lugeon values versus length of the borehole for the foundation of Midões Dam (Quinta Ferreira, 1990).

Impermeabilization and drainage curtains

The impermeabilization curtain (cut-off) is used to control the leakage through permeable foundation zones and is a very important element for the safety of the dam. It is usually associated with a drainage curtain intended to dissipate ground-water pressure and increase effective stress. Relief wells are also used downstream of embankment dams to dissipate ground-water pressure. With the cut-off we try to reduce, as much as possible, the percolation through the foundation. Frequently it is not possible or necessary to construct a full cut-off reaching low permeability formations and a partial cut-off is used in order to reduce the hydraulic gradient to desired values.

The load applied by a foundation can close fractures and joints, reducing the transmissivity of the ground and thus trapping water which cannot easily drain. If drainage is not possible, undrained conditions develop and the strength of the zone cannot increase with increasing confining pressure. The rupture of Malpasset dam in France is attributed to this cause (Londe, 1967).

In arch dams, to avoid the situation that caused Malpasset dam failure, the drainage curtain must be placed upstream of the stressed zone and downstream of the cut-off.

Authors like Gómez Laá (1982) argue that the high permeabilities obtained in the Lugeon test are frequently the result of hydraulic fracturing during the execution of the test and thus do not represent directly the transmissivity of the rock mass.

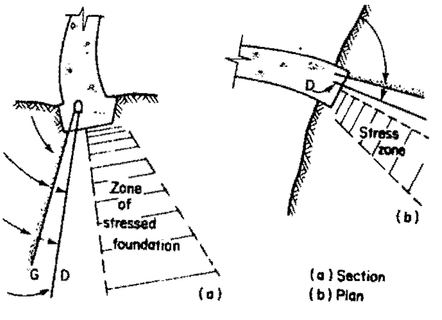


Fig. 15 - Drainage measures for an arch dam. Drainage curtain: downstream (D) of grout (G) cut-off and upstream of stressed zone. The closure of fractures in the stressed zone in-situ reduces permeability and allows development of excessive ground-water pressure (after Londe, 1973 in Blyth & Freitas 1984).

The depth to reach with the cut-off is dependent on the presence of zones of low transmissivity. The criteria for executing the impermeabilization are very diversified but are essentially based on the Lougeon values (e.g.: Houlsby, 1976, p. 309; Paulino Pereira, 1990) or the gradient through the impervious element of the dam.

According to Ewert (1990) the analysis of the grouting programs confirms that the rock masses with less than 5 Lugeon practically are not groutable, but this does not mean that we cannot force grout penetration in the fractures creating hydraulic fracturing and giving the idea that grouting was necessary and was achieved. Rock masses with Lougeon values between 5 and 20 are considered dubious cases, and when possible it is best to fill the reservoir and then decide if it is necessary to grout. Londe (1983) also states that in low transmissivity fractured rocks, lower than 5 Lugeon, grouting is useless while drainage is generally essential. For high transmissivity fractured rocks, higher than 50 Lugeon, grouting is necessary to limit the amount of flow and drainage is not necessary.

We must have in mind that the earlier stated values are general references and that each case must be analysed individually in order to make sound decisions.

Kjærnsly (1982) says that it is usual to inject more grout than necessary to avoid the need to do more grouting after concluding the dam. The execution of the cut-off during operation of the dam can obstruct part of the drainage curtain or even the piezometers.

The impermeabilization using injections is best obtained when all voids can be filled by grout using injection pressures lower than those needed for the hydraulic fracture. Usually injection pressures increase with depth using variable rates (according to the "European school" 100 kPa per meter and in "American school" 23 kPa per metre).

The estimate of the quantities of grout to inject can be made based on absorption values or using the seismic velocities of the rock mass (Knill, 1969). After executing the grouting, the improvements can be monitored by using Lougeon tests or geophysical methods, mainly seismic methods (Knill & Price, 1972; Rodrigues et al., 1983; Rodrigues & Esteves, 1987; Turk & Dearman, 1987). After grouting, the increase in the velocity of longitudinal waves seems to be an adequate indicator to estimate the improvement of the mechanical properties of the rock mass and indirectly to evaluate the transmissivity reduction.

In foundations having important faults it is necessary to execute a deep treatment using injection pressures preferably below the pressure that can create hydraulic fracture. One example of this procedure can be found described by Ichimasu & Futaesaku (1981).

On permeable rock masses the lateral extent of the treatment on the shoulders of the dam is defined based on the water table, and all permeable rock should be grouted when situated below reservoir level. One example is the extensive impermeabilization intended for the lateral rock masses of the 20 m height Atrozela dam at Cascais (Oliveira & Costa Pereira, 1978).

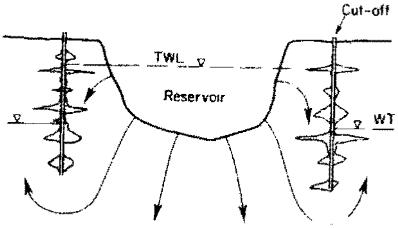


Fig. 16 - Partially penetrating cut-off to reduce (but not stop) reservoir leakage, shown by flow lines (Blyth & Freitas 1984).

Despite the costs required, a detailed study of the hydrogeological conditions before the construction of the dam, should always be done, because it would allow the determination of the water table and its seasonal variations, and to analyse possible changes due to the fill of the reservoir. Ewert (1990) states that is an investment that pays for itself because the elements obtained can allow a better and more economic design of the rock mass treatment.

Soils

To have a precise understanding of a soil foundation a deep study of the lithological, structural and hydrogeological characteristics is necessary. Besides these characteristics, the geotechnical properties of the soils are also dependent on their geological history.

Many dam sites are located in valleys filled by thick alluvium, weak and compressible soils like peat, silt and clay, glacial deposits, or excavated in recent (plio-quaternary) soil formations and thus their foundations interfere with those soil masses. Dams are also constructed on residual soils or soft rocks.

Soil materials can have high permeability and deformabilcty and low strength. The alluvial formations are characterized by great horizontal and vertical variations (see e.g. Massingir dam). Permeable soils are essentially sands with variable content of other coarser materials like gravel and pebbles.

The main deformable soils are loose sands and soft clays. In loose sands liquefaction is the most dangerous phenomenon and with worst consequences and is critical in seismic areas. The packing is dependent on the shape of the grains, their size and way of sedimentation. Pre-consolidation of the soils improves their characteristics, reducing the volume of voids and increasing density and friction angle. On soft clays it can be difficult to foresee their long term behaviour when acted on by the forces applied by the dam. "Quick clays" sedimented in high salinity environments, also can suffer liquefaction.

Depending on the permeability of the foundation soils, on the type of structure and the economical importance of the water, different solutions to control the water percolation and the water pressures in the foundations are used. These solutions can be a total cut-off, an impermeable upstream blanket with associated partial cut-off or downstream relief wells. Whilst the first solution is intended to control the percolation, completely the other devices allow an acceptable percolation. An impermeable upstream blanket associated with a partial cut-off is used when the thickness of the alluvium is high, making the constrution of a total cut-off very expensive and difficult. On the Manicouagan 3 dam, in Canada, injections and a concrete cut-off were used to control the water percolation through the deep subglacial canyon filled with alluvium, (Benoit et al., 1967).

NATURAL CONSTRUCTION MATERIALS

During the studies for the construction of a dam, one important task is to verify the existence of natural materials that can be used in the construction of the dam and auxiliary structures.

At present the best approach to a good environmental and economic policy is to start the analysis of the dam design considering a wide range of possible solutions based on a sound knowledge of the natural resources available. Beside the geometry and morphology of the valley, local geology and available construction materials are of the upmost importance because they will control the cost of the solutions. These materials can range across a wide variety of soils or rocks. Their selection requires knowledge of the characteristics of the materials, the best place for extraction and the way extraction, transport and placement will be done.

For example we can say that clay materials can be used on embankment dams to build impermeable cores or blankets due to their plastic behaviour, adequate strength and low permeability after compaction. Sand can be used on filters, drains and in the preparation of the finer fraction of the concrete mix. Filters are used to prevent the materials being eroded by seeping water and drains are intended to reduce water pressure.

Rock is usually obtained from a quarry or from the excavations necessary for the auxiliary structures (Koch et al., 1987; Mendaña, 1987) or even from the larger fractions separated from soils (Niat et al., 1982; Medina et al., 1988). Quarry selection, planification, extraction and its recovery during and after the end of the works are strongly controlled by the need to reduce environmental impact.

The selection of the best quarry place will depend on the lithology, the thickness of the soil cover, the weathering, the distance to the dam, the presence of fractures and the orientation and spacing of joints. For the selection of the quarry site, superficial geological reconnaissance, geophysical and mechanical surveys are generally used. To compute available volumes all elements obtained in the survey are used. For this objective it is very useful to have cored boreholes that can be related with geophysical data. The rock must have adequate strength and durability to stand extraction, processing, transport and placement and still perform properly during the operation period of the structure.

The method of rock extraction used in the quarry will be dependent on the geology, topography and the equipment used. The quarries having an economical exploration are usually opened using one face cut parallel to one of the vertical joint sets. The cut height is frequently between 10 and 20 m, and when the cut face is higher two or more benches are used.

The aggregates used in the preparation of concrete are mainly separated from sand, gravel, and crushed rock. Aggregates should be sound because weathering would decrease strength and durability of the concrete. The alkali reaction of certain minerals like opal and calcedony with alkali cements can produce deterioration or even the destruction of the concrete (Sims, 1986). The use of pozolanic cement would minimize these deteriorations (Koch et al., 1987). Aggregates should also be clean of clay, shale, organic matter, potentially reactive minerals like pyrite or other weak or adverse constituents like phylitous minerals (e.g. mica). Rock is also used to obtain aggregates or other granular materials, namely for filters or drains after adequate crushing and processing. Beside granulometry, the required exigencies of filter materials is their durability, because they should not suffer deterioration, in order to mantain their drainage characteristics.

For protection rockfill (rip-rap) strength and durability are important properties, because these materials should stand imposed external pressures like wave and wind actions, wetting and drying or freeze and thaw.

RESERVOIRS

In the study of reservoirs some of the problems requiring the intervention of geology are the search of permeable layers or structures that could cause the reservoir to leak; the presence of ancient landslides that could be reactivated after impounding or the possibility of new landslides; the rate of siltation and its influence on the storage reduction of reservoir.

Leakage

As a dam is required to impound water it must be designed and constructed to avoid the leakage of water into the foundations or in the reservoir. According to the ICOLD (1973, 1979) there are many examples of reservoirs showing important leakage.

To avoid leakage, the reservoir must have low transmissivity formations or the natural water level in the valley sides should be above the maximum reservoir level (Fig. 17 and 18).

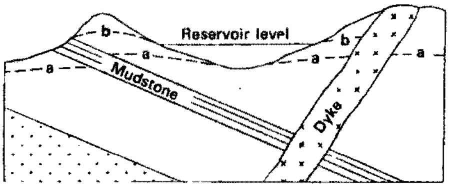


Fig. 17 - Water-tight reservoir assured by sedimentary and igneous aquicludes. a - original water level; b - water level after impounding (Blyth & Freitas, 1984).

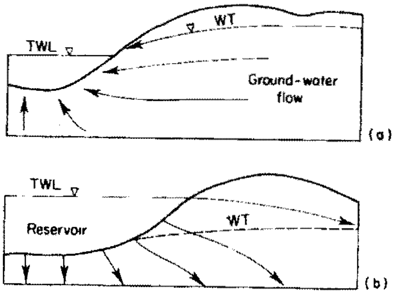


Fig. 18 - Water-tight and leaky reservoirs.
(**a**) The total head of water in the ground exceeds that in the reservoir and there is no leakage of reservoir water.
(**b**) The reverse situation, resulting in leakage. WT - water table; TWL - top water table (Blyth & Freitas, 1984).

As stated earlier it is necessary to investigate carefully the hydrogeological characteristics and fluctuation of water levels in the area of the reservoir to evaluate the possibility of leakage after impounding.

Accurate mapping of geological structure and rock types is necessary to reveal the presence of zones and horizons that may either prohibit or permit excessive leakage from the reservoir.

In the case of soluble or volcanic roks, leakage can be very high and filling of the reservoir may not occur. As described by Oliveira (1988), the hydroelectric scheme of Lagoa do Santo da Serra in Madeira Island, is an example in volcanic rocks. An old natural pond has been considered as a suitable reservoir. The bottom of the pond is at level 700 and with a small earth dyke the reservoir could reach level 724. As the bottom of the natural reservoir used to be hidden by some water during the rainy season, people responsible for the project considered it feasible and started, without any further geologic studies, the construction of a tunnel about 400 m long. When trying to fill the reservoir it was proved that, until the reservoir reached level 717, about 40% of the water was lost due to partial leakage into the ground and that above that level the loss was total. A detailed engineering geologic study proved that the Lagoa (pond) is the cuvette of a volcanic chimney filled with piroclastic, lapili and ashes in the central area until level 717. Above that level very fresh, jointed and porous basalt outcrops in the NE section of the reservoir, allow all the water to come down the hill (Fig. 19).

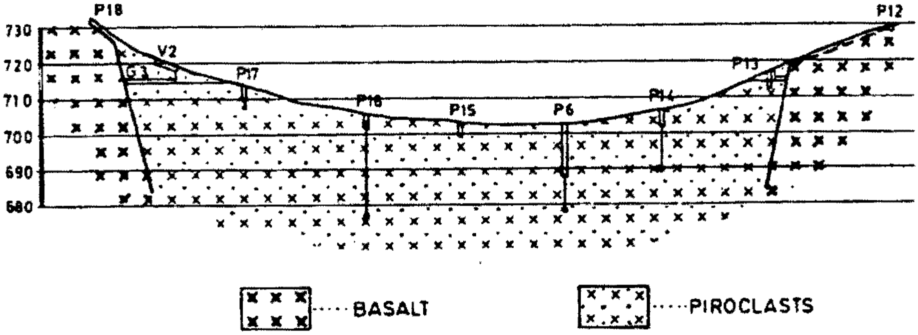


Fig. 19 - Geological section of Lagoa do Santo da Serra in Madeira Island (Oliveira, 1988).

Karsified limestones can present serious watertightness problems in the foundation or reservoir limits. The vertical section of Fig. 20 illustrates the Dol-y-Gaer dam which was built on Carboniferous limestone, whose extent could easily be mapped and through which serious leakage later occurred. Much of the lost water re-appeared downstream, where it was brought to the surface by the presence of relatively impermeable Devonian strata. Remedial measures failed to control the leakage and the Pontsticill dam was constructed downstream, to impound much of the water leaking from the upper reservoir (Blyth & Freitas, 1984).

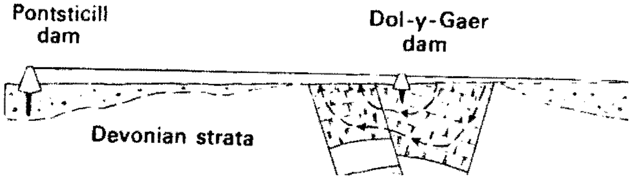


Fig. 20 - Geological section to illustrate leakage at the Taf Fechan reservoirs, S. Wales (Blyth & Freitas, 1984)

Another possible source of leakage can be due to the dissolution of soluble rocks like gypsum or halite, creating easy routing for the reservoir water.

Buried valleys also need to be identified as they are another potential zone for leakage (e.g. Sautet dam in the river Drac in France).

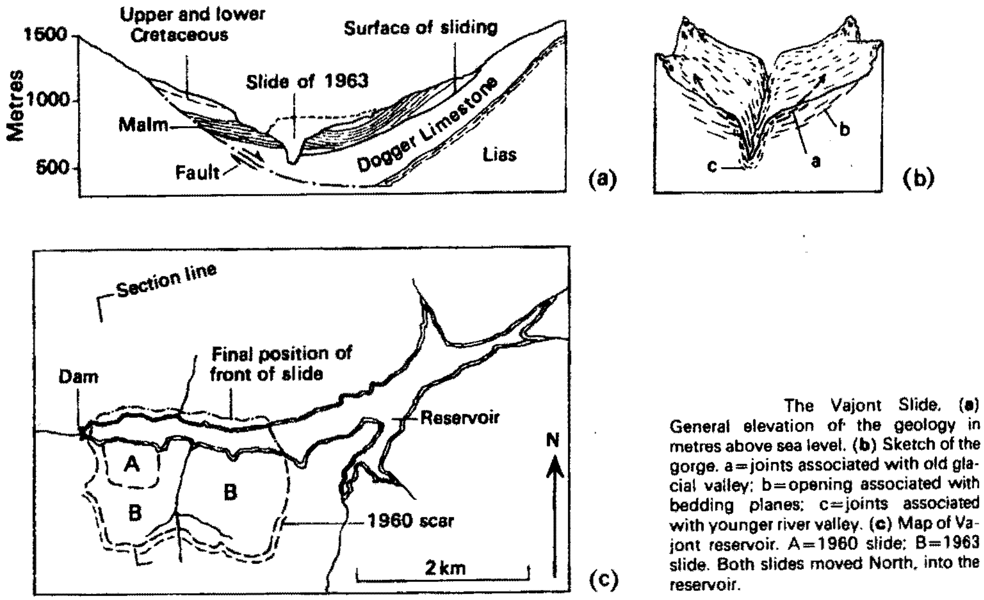
Landslides

Large changes in reservoir levels can cause important slope instability.

The Vajont slide is one of the most important landslides and ocurred in the 9th October 1963 in the north of Italy. A volume of rock of 250 x 10^6 m^3 moved into the reservoir creating an enormous wave that killed more than 1500 people.

Sedimentation

The flow of water carries sediments to the reservoir, and as the dam prevents the alluvium from travelling downstream, they progressively fill the reservoir. If the quantities of carried sediments is important the usable volume of the reservoir can be significantly reduced. As stated by Blyth & Freitas (1984) sediment also accumulates as deltas at the margin of the reservoir, where rivers discharge into the lake. Around the lake a shoreline develops from the action of waves, generated by wind blowing across the lake. These waves erode the topsoil and superficial deposits of weathered rock also contribute sediments to the reservoir.



The Vajont Slide. (a) General elevation of the geology in metres above sea level. (b) Sketch of the gorge. a=joints associated with old glacial valley; b=opening associated with bedding planes; c=joints associated with younger river valley. (c) Map of Vajont reservoir. A=1960 slide; B=1963 slide. Both slides moved North, into the reservoir.

Fig. 21 - The Vajont slide (Blyth & Freitas, 1984).

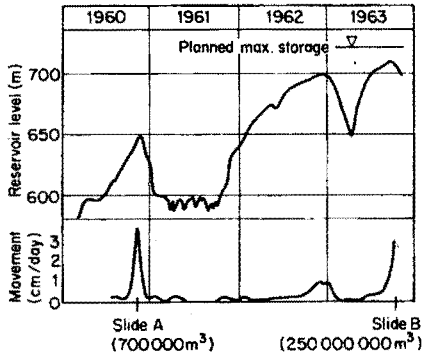


Fig. 22 - Relationship between movement on the Vajont slope and reservoir Level (ICOLD, 1979 in Blyth & Freitas, 1984).

To predict problems arising from sedimentation it is important to know the weathering and erosion process working in the watershed and to map carefully soils and easily erodible formations. The study of recent deposits of alluvium and the measurement of suspended load in the river are also very important.

TUNNELS AND UNDERGROUND POWER-HOUSE

In hydroelectric power plants, tunnels are used to divert water during dam construction in narrow valleys, to duct water from the reservoir to the power-house and back to the river, and to link reservoirs.

In many undertakings the power-house is constructed underground to get advantage of the maximum possible level difference between the reservoir and the outlet.

The engineering geological studies concerning a zone where an underground construction is foreseen has as a final objective the definition of the geotechnical parameters with importance in the design and construction (Oliveira, 1974). They are: deformability; strength; permeability and virgin or initial state of stress (especially with an important thickness of overburden).

From the geological point of view we can say that the most important geological characteristics related to an underground construction are the lithology, the hydrogeological conditions, the tectonic (mainly the presence and properties of discontinuities) and the state of stress.

In a similar way to the study methodology refereed to for the dam site, it is necessary to use progressively more expensive and time consuming survey techniques for the study of an underground construction. Based on the geological information it can be evaluated if the orientation of the tunnel is best aligned to the geological structure of the region. When the underground construction is shallow, the geotechnical exploration can use geophysical techniques like seismic refraction to define the thickness of the soil or weathered rock, and electrical resistance to allow data to be compared with the seismic refraction. The direct survey using cored boreholes will allow study of the lithology and the discontinuities of the rock mass and to carry out index tests on core samples in the laboratory. Inside the boreholes, in situ tests can be done to determine permeability, deformability and in some cases the "in situ" state of stress.

ENVIRONMENT PROTECTION

Environment protection is a growing concern in all large public works, in which hydroelectric power plants and reservoirs are included. Several measures must be taken from the beginning of the planning process in order to achieve a good result with the minimum costs. Planning should go from the selection of the dam type and location, construction materials, use of excavated volumes and complete recovering of the area after construction.

As stated by Costa (1988) there are many possible solutions for recovering quarries but they must be integrated in the regional planning of the area where the quarry is located.

Among several possible examples only two Portuguese examples will be quoted.

For Lagoacho dam, located in the Natural Park of Estrela Mountain “Parque Natural da Serra da Estrela”, it would be possible to construct a gravity dam in concrete or buttress. Due to the need to minimize modifications in natural landscape, whose dominant aspect is the presence of large granitic blocks it was decided that a rockfill dam was the environmentally suitable solution. In feasibility studies, it was decided to locate the quarry in the granite wall located 500 m south of the dam. During the execution of the predesign, to reduce environmental impact and preserve natural landscape it was decided that the initial quarry place should be rejected. Alternatively, another place was chosen, having worst characteristics, located in the middle of the reservoir. This option was justified by the fact that after concluding the works there would be no sign of the quarry, because it would stay below the reservoir level.

Another situation occured at the quarry of Apartadura dam where, as a protective measure for the water wells in the carbonate rock mass, it was considered that the base of the quarry should be above level 570, using a platform inclined 2% in order to allow natural drainage of superficial waters, avoiding their infiltration and possible contamination of the underground water (DGRAH,1983).

In cases of reservoirs created by the construction of dams, important changes in the engineering geological environment upstream and downstream of the works may occur. According to Oliveira (1988) they are as follow.

a) Upstream: - instability of the slopes of the reservoir and the surrounding catchment area; - erosion of the ground in the catchment area; - silting of the reservoir; - hydrogeological conditions of the area; - induced seismicity; - submergence of quarries and other mining activities, or geologic formations hiding fossils or other features of great scientific value as well as fertile land.

b) Downstream: - scouring due to strong discharges from spillways and other outlets; - slope stability of river banks; - hydrogeological conditions of the area; - sedimentation (either reduction of deposition of sediments in existing flood plains and in downstream reservoirs or increase of sedimentation namely proceeding from discharges through gates); - temporary submergence of facilities of all kinds due to discharges from spillways and outlets.

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