Geological and geotechnical studies

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On the topic of geological and geotechnical studies, special attention is given to:
- the various techniques available;
- identification and choice of a dam site;
- geological and geotechnical studies and site investigations to adapt the dam project to the chosen site, in particular including the choice of the most suitable type of dam for the site;
- geological supervision during dam construction.

PRELIMINARIES

This chapter is intended to give some recommendations based on the authors' experience and current practice. Given the specific nature of geological and geotechnical problems, no typical program can be given but the minimum that is usually accepted is stated.

In fact, the fundamental importance of knowledge of the geological and geotechnical context in which the dam will be built, combined with the great variety of foundations that might be encountered, making each dam project unique, preclude any prior definition of the extent and nature of the required site investigations.
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Only an experienced professional has the competence to adapt the studies undertaken to the geological context that they gradually reveal and to identified or assumed problems, following an iterative process that usually results in a site investigation program planned in several stages (with the orientation and contents of each stage defined as the preceding stage is concluded).

Those site investigations should make it possible to avoid, insofar as is possible, encountering any unforeseen problem as the dam is built, leading to improvisation, cost overruns and delays, which are always adverse (especially when the dam is small and financing generally limited with little margin).

Herein we successively look at:
- the various techniques used in geological and geotechnical studies for dam projects;
- methodological recommendations concerning the various stages in the geological and geotechnical investigations, from site identification to construction.

The basic concepts of geotechnics and rock mechanics are assumed to be familiar to the reader who, if necessary, may refer to the many specialised manuals published in those fields.

Techniques

This section looks at all of the techniques that are applicable to dams under a height of about 25 metres. Depending on the nature of the site and the size of the dam, only some of these techniques may need to be employed.

Site inventory

A systematic inventory of dam sites is undertaken when there is a need to find potential storage sites to meet specific needs for water resources within a given area, which may be small (a catchment area measuring a few hundred hectares) or vast (a large catchment area measuring several hundred square kilometres). This approach makes use of several techniques:
- desk study using topographical maps of a scale suited to the size of the envisaged reservoir (1/25 000 for the dams addressed in this document, bearing in mind that very small sites are not identifiable at that scale);
- aerial photography (stereo pairs);
- direct field investigation.

These three techniques are very complementary and it is always preferable to combine them whenever possible, as each provides information that helps to better assess the characteristics of the site:
maps give a "precise" estimation of surface areas and volumes (dam, reservoir, catchment area);
• aerial photography shows the nature of the plant cover as well as land use (the date of the photography is essential and must be as recent as possible);
• field investigations take into account morphological details, among other things, give some preliminary indications on site geology and can reveal smaller sites.

Surveying

Surveying is an essential support for a geologist, who must always be able to locate more or less accurately the formations he observes both in planimetry and in altimetry. The sophistication of the studies done and importance of the problems under study make it possible to distinguish "simplified surveying" from "standard surveying".

Simplified surveying

It is always a good idea to carry out levelling of the first holes drilled without waiting for later detailed surveys in order to plot the analytical geological cross-sections with sufficient accuracy.

Surveying a summary topographical cross-section on the dam axis (with automatic site levelling and land chaining) is also extremely useful in estimating the dam’s volume from the very beginning of the studies, as construction costs are largely proportional to that volume.

Standard surveying

Dam design requires accurate topographical maps based on surveys of the dam site (at scale 1/500 or in greater detail), of ancillary structures if any (scale 1/200 or in greater detail) and the reservoir basin, at least up to the exceptional highest water levels (1/2000 or 1/2500 is generally fairly suitable for basins measuring several dozen hectares; a scale of 1/5000 may be used for larger basins, although accuracy is reduced, and 1/1000 for small reservoirs measuring only a few hectares).

Such surveys are usually done by government designated expert surveyors, usually using computer means (electronic logs, automatic point plotting, contour levels). It is recommended that the surveyor provide a paper copy and a computer file of the survey points that can be used by a design engineer with CAD (Computer Assisted Design) facilities.

It is wise to take advantage of the surveying to indicate on the map all of the specific items whose accurate position must be known (boreholes, investigation pits, springs, various geological structures, etc.). The design engineer may help out by leaving clearly visible numbered markers in the field, or accompany the surveyor in his work.

In some cases (difficult-to-access sites, dense vegetation, very large basin, ongoing land ownership problems, etc.), the map of the basin may be drawn up by aerial stereophotogrammetry (complemented and adjusted by groundcontrols), which is less accurate but which may prove to be sufficient and sometimes more realistic.
PHOTOGEOLOGY

Geological interpretation of aerial photographs (in stereo pairs) can be a useful complement to classic mapping (in particular for structural aspects in a rock context of severe weathering but with no significant plant cover), and even replace it in some cases (when no useable topographic documents are available), but in any case must be accompanied by adjustments in the field.

The usefulness of this technique is most notably the possibility it offers of highlighting structures that are not directly observable in the field by integrating many details that can only be seen with the distance aerial photography permits, and sometimes also large morphological features that are hard to see on the ground or that are masked (by vegetation or other).

The analysis of aerial photographs (preferably recent ones) also gives indications on plant cover and land use in the catchment area. They often prove highly useful in hydrological studies and analysis of sediment transport in the river.

GEOLOGICAL MAPPING

If outcropping permits, a geological map may be drafted at a scale selected according to the desired precision, the stage of study and the size of the site, generally using existing topographical records (existing maps blown up when necessary) or using maps from standard surveying work or more detailed maps if any are available.

The geologist will be attentive to indicate the nature of the formations in the substrate at any outcrops (shown to scale), and overburden in other places, while distinguishing as many different categories as necessary. The map should indicate any useful information on structure (dip, fold, schistosity, faults and cracks, veins, etc.), hydrogeology (springs, losses), and geomorphology (in particular old or recent landslides, indication of karstic formations, etc.).

TRIAL PITS

Trial pits can be dug out with a mechanical shovel for site investigations at the dam site, in borrow areas for an earthfill dam, and possibly for evaluation of reservoir watertightness.

This is essentially done for earthfill dams but may also be used in site investigations for concrete dams when the rock substratum is not very deep in order to assess the extent of the stripping that will be required. However, in the case of a concrete dam, the tests will serve no great purpose as the loose overburden will be removed.

Pits dug with a mechanical shovel (preferably caterpillar type to give access everywhere) are probably the most widely used technique in studies of the geological feasibility of a dam site because of their low cost and the mass of information they provide within a limited time (15 to 20 pits 4 metres deep can be dug per day in most ground formations).
In general, pits are dug "from place to place" in the area to be occupied by the dam and in the reservoir basin (for potential borrow areas). In some cases it may be preferable to dig trenches along a carefully chosen line.

The depth of investigation is limited by the power of the mechanical shovel, the length of its arm and the nature of the ground. Depths from 4 to 5 metres are commonly reached with a shovel of at least 100 HP and a bucket 80 to 100 cm wide with well designed teeth (bucket of the kind used in earthworks).

The geologist can survey fairly precise cross-sections as the pits are dug by measuring the depth of each change in the ground and possibly taking remoulded or undisturbed samples of the various layers crossed (which will later permit comparisons between pits and may help in the correlations to plot analytical geological cross-sections). The level at which any water appears should be noted. Finally, it is important to be sure that no one goes down into a pit that could collapse at any time. No sample should be taken from the bottom of the pit unless it is shored.

It is generally a good idea to leave the pits open for a few hours or even a few days (if safety conditions permit - with the site suitably marked out if necessary), in order to improve possibilities for correlations and observe any phenomena that might take some time to manifest themselves (inflows of water) or to stabilise (ground water level).

Provided some precautions are taken and some information is approached by approximation, the pits can be used for permeability testing when it is deemed useful to roughly estimate the permeability coefficient in the foundation ground. Because they are more or less rudimentary, such tests (LEFRANC, NASBERG, etc.) give results that must be taken with caution because of the great number of parameters that are difficult to control but highly likely to influence them.

Routine practice is to align the pits on the centreline of the future dam. On the river banks, attention must be paid to ensure that the pits give an unbroken cross-section of the substratum. To this end, the work should proceed from the top of the river bank with each pit staggered from the preceding one by a distance such that the drop in elevation of the natural ground between the two points is less than or at most equal to the depth the preceding pit cut down to the substratum (in any case this will only apply if the thickness of overburden varies only slightly between the two points).

**Geophysical studies**

In some cases (rock foundations, consideration of a rigid type dam), techniques of seismic refraction and "petite sismique" (which are relatively quick and easy to perform) can be used to zone seismic wave velocities. They can generally be related to the degree of cracking and weathering in the rock, which sometimes makes it possible to locate accidents (faults or other) thanks to the velocity anomalies they generate.

When the site's morphology offers practically no clear local narrowing, use of this technique in the feasibility or preliminary design stage can help in choosing the dam location by locating one or several zones in which the unweathered bedrock lies nearer the surface.
The position of the unweathered rock in terms of depth is often close to layers with high velocities (> 4000 to 5000 m/s) and is generally decisive in choosing the level at which a concrete dam is set.

In zones of weathered rock or alluvium, electrical prospecting techniques can also be used, whether alone or in combination with seismic techniques. In the former variety, variations of electrical resistivity in the ground are used to deduce variations in lithology, weathering and cracking. Measurements can be made in the form of drillholes, electrical tracing or resistivity panels.

Geophysical measurements should be interpreted by an experienced geophysicist and require calibration on mechanical drillholes (generally with core sampling).

The best way of going about such calibration consists in asking the geophysicist to draft an interim report from which calibration drillholes can be set out as well as possible. The geophysicist will then write a final report after familiarising himself with the results from those drillholes and, if necessary, refining his interpretation.

In very difficult sites where there is a potential or proven risk of running into underground cavities (karst, former mines or quarries, soluble rocks such as gypsum, etc.), the technique of microgravimetry can be used in order to seek out, through systematic exploration, any adverse anomalies in the gravity field. Other site investigations (such as core samples) will then be needed to check the nature of those anomalies but they are then set out in full awareness of objectives and savings can be made versus systematic but blind site investigations (which compensates for the cost of the initial prospecting itself).

**Core sampling**

Core sampling is systematically carried out for dams over 20 metres high but is rarely used for dams under 10 metres high.

Core sampling is intended to give sufficient knowledge of the lithological make-up and structure of the various foundations layers, to be able to draw the analytical geological cross-sections that are necessary for a good understanding of the dam’s foundation conditions.

This technique makes it possible to extend the investigations into every type of terrain, at greater depth than is possible with pits, and to undertake more reliable water testing than can be done in pits (although restricted to fewer points), and also, under certain conditions, to take undisturbed samples of the ground. Today it is possible to record the drilling parameters, which gives continuous information on the nature of the ground being crossed.

The high cost of this technique means that it is rarely used in preliminary stages of study (only for large dams or ones posing problems that justify use of the technique).
When it is used, it is advisable to set out the drillholes according to prior observations made in the field in trial pits, with the goal of answering the precise questions that arose when those pits were investigated (e.g. depth of the competent or watertight substratum of a significant layer).

The depth of the drillholes must be suited to the size of the dam and the geological context. In a valley bottom a drillhole will routinely be as deep as the planned dam is high and should cross the substratum for a thickness of at least 5 metres. On the river banks it should reach the first layers of the substratum found at the valley bottom (taking into account the structure and discontinuities due to dip, faults, etc.), in order to correlate as well as possible the results of all the core samples taken along the entire length of the dam area.

The following principles must be followed to get good quality core samples:

- the core drill must be chosen according to the nature of the ground being sampled. It may be either the ram type (with thin wall, with or without inside sheath, with a stationary piston, with a thick wall), or rotary type (single, double, triple, with or without extension). The French AFNOR standard referenced in the bibliography (p. 66) gives various uses of this equipment;
- the diameter of the core sample should not be less than 60 mm at the final depth of drilling, taking into account any reductions in diameter (caused by poor stand-up of the ground that would impose the use of temporary tubing). The usual diameter for site investigation core samples varies from 86 to 101 mm;
- after extraction, and removal of the "fines" created by the drilling, generally caked around the core sample (the residue of drilling in clay), the core samples must be carefully protected and boxed.

It is recommended to have colour photographs made of the core boxes as soon as the drilling is done, as in most cases these will be the only traces of the samples after a few years (it is rare to be able to keep core samples in good condition because of storage problems, spontaneous crumbling of some materials, theft, etc.). The core samples should be photographed after carefully washing or scraping off the fines, wetted to bring out details, correctly labelled (with the drillhole number and depth), and accompanied by a palette of standard colours and a scale showing a length, preferably in the artificial light of a flash.

As the cores are taken, the geologist should take detailed records of the samples including:

- a description of the ground's lithology according to depth including all pertinent data (nature, appearance, colour, porosity, oxidation, dip of the contacts, etc.) in order to permit correlations with neighbouring drillholes. This is accompanied by a drawing in a log, using a symbolic representation of the samples' nature, if possible a standard one;
- if necessary, the depth of the lower limit of the oxidation zone. This corresponds to the presence of metal oxides at the surfaces of cracks and joints, whether these come from deposits or weathering in situ (this limit generally coincides with the level of flow of surface waters and therefore with the lower limit of the decompressed zone below which cracks can be considered as tight);
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- structural indications, depending on the nature of the ground, e.g. stability of the wall, intense cracking or crushing, percentage recovery or rate of undisturbed sampling (total length of core over footage drilled), cracking factor (median of the length of the samples within a sampling pass), RQD1 if the nature of the ground is suitable (RQD is not very meaningful in a very anisotropic rock, schistosised rock in particular);
- hydrogeological comments such as the water level during and at the end of drilling, fluid losses during drilling, ingress of water, artesian springs, water tests, etc.;
- any information about how the drilling went: start and finish dates, nature and dimension of drilling tools and temporary tubing, any final fittings (piezometer, etc.), position of the limits between core sampling passes, miscellaneous incidents (collapse, falling tools), water levels at the beginning and end of each shift or day.

The number, spacing and depth of the drillholes cannot be set in absolute figures but must be defined during the previous investigations, taking into account the specific features of each site, how heterogeneous the ground foundation is, and the spatial scale of lateral variations in facies, as well as any problems that may crop up.

The drillholes should be set out as far as possible in harmony with other investigation techniques (either by filling in any gaps in the observations or by permitting mutual calibration or by bringing a response to questions posed by those techniques). Drilling that only goes through rock may in general be oriented in any direction with no major difficulty. In loose overburden, the drillholes should be sloped at most 30° from the vertical.

It is common to drill at least three holes along the axis of the dam (one at the valley bottom and one at the top of each abutment), but more if the dam’s crest length is greater than 100 metres. A horizontal spacing of 50 metres and vertical spacing of 10 metres between consecutive drillholes is recommended but those figures may be too high in some cases.

If the base of the dam extends more than about 100 metres on either side of the dam axis, two additional lines of drilling (at the dam’s upstream and downstream limits) may be required, especially when the foundation is very heterogeneous or of mediocre quality.

Core samples may be accompanied by water tests (LUGEON, under pressure, in rock; LEFRANC, by natural flow, in loose overburden), especially on the axis of any watertight elements. Getting meaningful results from water tests requires the use of suitable equipment complying with standardised operating conditions and carrying out tests in a rational manner:
- drilling must be exclusively with clear water (no bentonite or biodegradable slurry) and before each test the drillhole wall must be cleaned (by successive passes of the tool with water injected in until clear water comes out at the drill head), in order to remove any fine deposits (“cake”) that could clog the pores and cracks responsible for permeability and thereby distort measurements;

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1. Rock Quality Designation = total of the lengths of the core samples greater than 10 cm / length of the corresponding drilling.
maximum pressure during LUGEON tests should be adapted to depth. In general pressure\(^1\) is limited to about 0.3 to 0.5 MPa for the range of dams considered here. It should not be forgotten that this kind of test is only valid strictly speaking if the corresponding discharge/pressure curve is practically straight, which must be checked for every test by holding pressure at various stages (held for 10 minutes), following an ascending and then descending cycle (e.g.: 0.05 - 0.1 - 0.2 - 0.3 - 0.2 - 0.1 - 0.05 MPa); in case of "total water loss", continue testing to distinguish between filling of pockets and permanent flow;

- positioning the packer in ground that is strong enough to support the inflating pressure with no creep and homogenous enough to avoid any perforation of the membrane;
- checking head in the annular space between the injection rod and the temporary tube at the beginning and end of the test in order to detect and quantify any flow around the packer;
- preferably carrying out LUGEON tests as the work progresses with the same packer used each time, which halves the risk of water flowing around the packer;
- preferably measuring the pressure in the measurement chamber rather than at the drilling head (which always means inaccuracy in the calculation of head losses), and recording flow and pressure continuously in order to check that they remain constant during the test;
- for LEFRANC tests, the most difficult point is to know or to check the shape of the injection chamber and especially to isolate it correctly from the rest of the drillhole. One technique that is sometimes used is to install a packer for LUGEON tests, and inject water by natural flow by the central tube (constant or variable level). To get a meaningful response, a number of these tests must be done and each change of facies must be tested.

It is possible to take undisturbed soil samples during core drilling. For fine soils, the recommended core drills are: stationary piston or thin wall sheathed ram, triple rotary drill with extension.

Undisturbed soil samples must immediately be oriented and correctly numbered; sealed at both ends with paraffin wax (in order to avoid any loss of water); and handled, stored and shipped with care, or the representativity of the tests done will be questionable.

The lengths of core corresponding to the samples taken can only be examined after the sheath has been opened in the lab. The drilling cross-section should therefore mention that a sample has been taken and the description of the ground will have to be completed later. A wooden block must always be used to replace the part taken out of the core box with an indication of the references of the sample.

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1. Here we speak of effective pressure, i.e. the pressure at the centre of the test pass. If no system is available to measure pressure directly in the testing chamber, account must be taken of head losses and overpressure corresponding to the water column in the system ($\Delta z = \text{drop in altitude between the pressure gauge and natural groundwater level}$): $P_{\text{eff}} = P_{\text{mano}} - P_c + \frac{\Delta z}{100}$ (in MPa).
GEOTECHNICAL LABORATORY TESTS

Knowledge of the physical characteristics and mechanical and hydraulic behaviour of the materials in the dam foundation, and of any materials whose use is envisaged in dam construction, is necessary for the design engineer to design the best, most suitable dam possible for the geotechnical context.

That knowledge is in part acquired through geotechnical tests in a laboratory.

Such tests require the use of standardised procedures and specific equipment. They can only be entrusted to experienced and fully equipped soil and rock mechanics laboratories.

Materials and overburden

For the type of material generally referred to as soil, tests are done on samples taken from the ground (undisturbed or remoulded from drillholes and trial pits). The tests can be divided up into:

- **identification tests**: natural water content, grain size (sieve and sedimentation analysis), Atterberg limits, methyl blue tests, particle unit weight, apparent bulk unit weight, etc.;
- **compaction tests on materials from borrow areas**: Standard Proctor test;
- **mechanical and hydraulic tests**: compressive strength, shear strength (using a triaxial device), oedometer compressibility, permeability using an oedometer or permeameter.

The number of tests of each type must be suited to the probable volume of the embankment, its height, the number of materials of different types that will be used (in the case of zoned dams) and to the natural variability of the materials under study.

As an indication, a minimum testing program recommended for materials from borrow areas for earthfill dams causing no special difficulty is determined according to the volume of material to be investigated:

- **series of identification tests** (natural water content, grain size curves, sieve and sedimentation analysis, Atterberg limits): one for 5 000 to 10 000 m³ of materials to be used with a minimum of five tests;
- **compaction tests** (Standard Proctor and particle unit weight): one for 15 000 to 25 000 m³ with a minimum of five tests;
- **tests of mechanical and hydraulic behaviour** (triaxial shear, oedometer compressibility, permeability): one for 30 000 to 50 000 m³ with a minimum of three tests (but no test of this type is recommended when $H^2V < 5$).

For the foundation, the number of tests to be done can be of the same order of magnitude if loose overburden is thick (compaction tests are then pointless).

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1. The volume to be investigated must be 1.5 to 2 times greater than the geometrical volume of the dam.
The section Geotechnical studies in Chapter IV, p. 68 emphasises the advantages of a simple test (water content) and explains what practical conclusions should be drawn from the results of those various tests.

**Rockfill**

For aggregate and rockfill, the laboratory tests required are:
- **measurement of intrinsic characteristics**: apparent density, mineralogical study (examination of thin slices under a microscope);
- **measurement of state characteristics**: water content, grain size range and block size range, shape coefficients, porosity, degree of cracking, continuity index;
- **measurement of withstand characteristics**: impact (Los Angeles or LA test), abrasion (Micro-Deval test with water), compressive strength Rc (on cylindrical core samples), freeze thaw cycles.

**SITE TESTS AND MEASUREMENTS**

Several types of tests and measurements can be done in situ at various stages of study on a dam site according to a variety of criteria (nature of the foundation, geotechnical problems, dam size, etc.).

They can be used to roughly measure the foundation's mechanical characteristics, incorporating the effect of discontinuities in the rock mass.

The tests done will depend on the nature of the foundation. In loose overburden, we can cite:
- **static or dynamic penetrometer tests**, which in particular distinguish between layers of different consistence without offering the possibility of directly and reliably linking peak resistance to their mechanical characteristics;
- **pressure meter tests** to obtain a stress-strain relation in the ground (e.g. determination of a strain modulus, creep pressure and limit pressure);
- **shear vane apparatus** to measure the undrained cohesion of the ground when it is less than 0.1 MPa. It is not possible to measure the cohesion of layers whose thickness is less than the height of the vane apparatus blades;
- **phicometer** to give an approximate direct measurement in the drillhole of the shear strength of heterogeneous or coarse soils.

These various in situ tests are less rarely used to study a dam than for other constructions except when the foundation is of very mediocre quality, for example mud.

On rocky terrains, the classic tests are as follows, the first two concerning the foundation, and the second two knowledge of materials:
- **dilatometer deformability test in the drillhole**, **plate bearing or flat-jack test** to measure the strain modulus of the rock in various directions (these tests are difficult to do, require highly qualified labour and are very expensive, which generally restricts their use to the largest structures);
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- measurement of seismic velocities in the foundation rock, which gives a global value for the quality of that rock;
- rockfill blasting tests using various blasting systems and charges should be done, with a determination of the characteristics of the resulting rockfill (block size distribution, shapes, amount of tailings, etc.);
- full size rockfill compaction test embankments.

Recommendations for conduct of the studies

The sequencing suggested hereafter is obviously subjective. It corresponds to routine practice for dams of a certain size but obviously it would be possible to envisage a different breakdown of the geological and geotechnical studies, in particular for small dams (with the phases simplified and combined), or according to the specific features of the site whether they are technical or not (for example land ownership problems may cause difficulties in access and can speed up or delay some site investigations).

Similarly, the naming of these phases is not standardised, and practice varies considerably from one project to another. Outside questions of terminology, the important point is that the content of the studies corresponds to the stages that must be gone through in succession when a dam project is set up and carried out.

Site identification and selection

Objective

If possible, the ideal situation is a location near the needs to be met, permitting storage of the required volume of water (in relation with the results of the hydrological study, i.e. filling by natural or mechanical means), with a geometrically optimal structure (ratio of the volume stored to the volume of the dam, which is directly related to its cost). In the case of a reservoir for recreational purposes, the surface area of the lake will be more important.

Methodology

Systematic inventory of potential dam sites is generally carried out over a certain area and according to criteria that are related to the nature of the needs to be met.

Projects can be sorted in a preliminary manner in this stage according to various considerations (suitability to the size of the catchment area and therefore natural inflow to meet storage requirements; land use constraints such as flooding of inhabited areas, roads or other networks, etc.; potential of the site's geometry; proximity to needs; and so on).
Brief preliminary calculations will be done on each site to determine the main geometrical characteristics:
- depth-area curve, depth-volume curve (dam and reservoir);
- for one or several values of storage: height, crest length and volume of the dam (where necessary for each type of dam envisaged at this stage), flooded surface area, ratio of storage to dam volume.

When carrying out these studies, measurements of lengths and surface areas from available topographical documents will be used as well as calculations of volumes through incorporation of depth-area curves. The use of specific computer programs on PCs helps in these calculations and makes it possible to print out comparative charts with graphs.

A preliminary cost estimate for the dam according to one or several dimensioning hypotheses is generally carried out in order to compare sites and/or seek out an economic optimum. This is done by applying ratios or benchmark costs taken from the designer’s previous experience with dams of the same type, using data bases specific to each engineering firm complemented by a calculation of the same ratios for the recorded cost of dams of the same type (after discounting all of those prices).

It is then possible to rank the sites selected after this first sort, according to criteria that will vary in nature and priority according to the nature of the project, and which must be chosen by the designer.

Dam selection according to the principles set out above is in particular applicable for the various alternatives for a single site. It can in fact be necessary to study several possibilities for storage and/or layout unless there is only one clearly localised topographical narrowing at the site.

**Geological surface study**

**Objective**

After the stage of dam site identification, a visual examination by a geologist with experience in dams is vital before the studies are continued. This only takes a day or even half a day.

The site tour is intended to determine the broad lines of the site geology before any heavier site investigation techniques are implemented. It has many purposes:
- to situate the site in the local and regional geological context;
- to detect any prohibitory geological conditions that might be immediately visible;
- to orient the rest of the studies, and in particular define and set out later site investigations;
- possibly to refine the dam layout, taking into account geomorphological or other details.
**Methodology of the geological surface study**

Before the site tour, the geologist refers to existing geological maps (1/50 000, or if none 1/80 000) which essentially enable him to place the site in its local geological lithostratigraphic and structural context. In some cases, this preliminary examination alone can result in a strong presumption that the geology is unfavourable (for example karstic formations).

Prior knowledge of the geological context is vital as it enables examination of the site to be oriented towards a search for certain types of indications using previous experience with similar contexts.

Depending on the region concerned by the site in question, locating major regional tectonic structures can be of great importance in the rest of the studies and can sometimes explain the special behaviour of some foundations.

The methods used in this kind of site investigation will vary according to the size of the dam under study and the geological context. They will consist at least in touring the dam site and all or part of the reservoir basin while noting any possible observation, and can be complemented by geological mapping at a suitable scale, surveying lithostratigraphic cross-sections with sampling, examination of aerial photographs and in some cases examination of satellite images.

The result of this first site investigation is a preliminary assessment (sometimes called prefeasibility) on the wisdom of undertaking more detailed studies. In this stage sites can be classified in the following categories:

- *favourable sites*, when no prohibitory condition has been revealed;
- *unfavourable sites*, where problems appear that would be hard to solve and/or would have an economic impact out of proportion with the advantages to be procured by dam construction;
- *doubtful sites*, that can be divided up between those where no surface observation is possible because of outcropping conditions and those where uncertainties persist as to the interpretation and/or gaps in those observations. Investigations in continuous pits dug out with a mechanical shovel are then necessary to rank the site in one of the two preceding categories.

It is useful to record the observations made during this phase of study and the conclusions drawn from them on a summary sheet like the one given hereafter and proposed by B. COUTURIER1.

In addition to filling in the data required in this sheet, sketching a rapid geological profile on the spot along the proposed dam axis is an opportunity for the geologist to express his vision of the site after these preliminary investigations. The geological cross-section should distinguish between observed facts, interpolation, and pure intuition, and will be more precise when outcropping conditions are good.

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1. See Bibliography, reference 3, p. 66.
It can sometimes be difficult to classify a site in the "unfavourable" category, and the engineer will then tend to qualify it as "doubtful" so that it will not be abandoned without further investigations. But although it is difficult to dictate a general rule, experience shows that it is generally preferable in case of a serious doubt to abandon a site that in fact is favourable rather than undertake in-depth and therefore costly studies on a site which could prove to be unfavourable at a later stage of the project. This approach is all the more essential when there are other alternatives available.
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GEOLOGICAL FEASIBILITY STUDY

The term "feasibility study" calls for a few preliminary remarks:

- this essential step in a dam project is given this name to indicate that it is the point beyond which only a very small possibility of failure should persist (i.e. that the project will be abandoned because of geological problems that were not detected previously) and on which the initiation of more in-depth (and therefore more costly) studies depends;
- however the term does not mean that the project's geological feasibility cannot be further questioned during later design stages, in especially difficult cases which should remain exceptional;
- it would seem preferable that the person in charge of the study have the means to form an objective opinion at this stage and one that is as reliable as possible, even if, in dubious cases, this means carrying out a few more detailed site investigations that were not initially foreseen rather than delaying the decision to the preliminary design stage (which would mean financing a complete preliminary design without being assured of a successful conclusion);
- a certain variety of practice among engineering firms can be noted on this topic, between the explanation given above and the definition of the feasibility diagnosis report in the preliminary design stage, according to the type and size of dam, and maybe also to the dam owners involved. In particular it may occur that development is no longer handled by the same entity in the preliminary design stage. The essential point is still that the engineer should carry out his mission in accordance with his client's expectations and provide him with assistance in decision-making throughout his project.

Objective

After the geologist gives a preliminary opinion in favour of the site, a number of more in-depth studies and investigations must be carried out in order to:

- confirm that there are no prohibitive geological and geotechnical conditions that could contradict the previous opinion;
- specify in greater detail the project's geological context;
- progressively refine the definition of the most suitable type of dam for this context and its exact layout;
- specify in greater detail, in the case of a fill dam, what might be the best location for the spillway;
- orient and define the site investigations that will be necessary in later development phases (preliminary design).

The geological feasibility studies are generally conducted in parallel with other types of feasibility studies:

- land ownership, which is of growing importance and can predominate over other aspects of the project;
- environmental, as ecological aspects of dam projects are studied in environmental impact assessments that should take into account the consequences of the work envisaged on the natural milieu, both at the site and in its vicinity and on the river downstream;
• economic, as the viability of the project must be studied according to its purpose, or possibly purposes (irrigation, increased dry weather river flow and pollution control, flood routing and protection from flooding, tourism and recreation);
• local development, as a dam project is sometimes an opportunity to initiate reflection on the future of rural areas in difficulty (revival of the local economy by attracting vacationers, etc.).

Although it may seem logical to conclude on the geological feasibility of the project before initiating these studies, their growing importance and the time needed to carry them out often mean that they must be initiated simultaneously and sometimes even that geological studies must be suspended until these other feasibility studies have reached a favourable conclusion.

This last point reinforces the importance of the surface geology study mentioned above (see Geological Surface Study, p. 49) and is the reason behind the recommendations made concerning the potential consequences of an overly optimistic diagnosis in case of any doubt.

It is in this stage of study (feasibility) that the essential characteristics of the site should be known and, as far as possible, major problems that could lead to a decision against the project should be detected.

Although there is generally a technical solution to any problem encountered, the cost may in some cases be disproportionate versus the dam's economic advantages and thus render it unfeasible.

Methodology of the geological feasibility study

Geological feasibility studies require the use of various techniques according to the size of the dam, the nature of the geological context and/or the habits of the geologist.

The methodology recommended hereafter for geological feasibility study of dams of the type addressed in the present volume therefore does not pretend to be universal and must often be adapted to the specific features of the case at hand.

A typical feasibility study could be conducted in whole or in part in the following stages:

STAGE 1: Desk study

For any dam, even the smallest, it is of great interest to consult existing geological maps and the accompanying documentation. For dams about twenty metres high or more, it can be of interest to search within regional geological literature (articles in specialised journals, theses, monographs, notes to geological maps) for any previous studies done on the region of the site under study or simply mentions of details that could be useful in understanding the context and the geological history of the area (location and description of outcappings, of fossil-bearing formations, borrow areas for various useable materials, particular structures, cavities, springs or watershed leakage, etc.).
STAGE 2: Detailed site tour and mapping

The geologist undertakes a detailed tour of the dam site and the reservoir basin and maps all of the details. If it is believed that a saddle dam may be necessary because of the reservoir’s altitude, its site must also be given attentive geological study. In fact, although such dams are generally very small, failure can release a significant volume of water. At the same time, saddles are often in zones where the substratum is of mediocre quality. If the context is suitable, a geological map may be drafted in the course of this study (at a scale of 1/25 000 to 1/5000 depending on the surface area concerned).

Conversely, local geology can in certain cases make any surface observation ineffective, because there are no outcroppings (in France the soft Tertiary sandstone of the Aquitaine area is an example), and this stage, although still necessary, can be shortened. Among the investigations to be done, special attention must be paid to detecting any instability, either at the dam site itself or in and around the reservoir basin (landslides, effusions due to solifluxion, rockfalls, boulder falls, or unstable slopes, rock walls or entire river banks).

This kind of investigation must be systematic, especially in areas where there are frequent signs of instability.

The activity and extent of any phenomena observed should be evaluated as well as the risk that they would be reactivated or worsened by the works (excavations, quarrying) and by the dam itself being operated (emptying the reservoir), in order to define any strengthening or river bank drainage systems that might be necessary.

The presence of extensive zones of instability is generally a very unfavorable circumstance for dams, and a project can only be pursued in such a context if the greatest possible precautions are taken to guarantee the dam’s safety, and if due thought is given to take into account the requirements that these problems would inevitably impose on the developer or the dam operator during the scheme’s lifetime.

STAGE 3: Hydrogeological and structural studies

These brief studies are done during the detailed site tour and can in some cases result in either specific mapping or simply data marked on the overall geological map.

- brief hydrogeological study

In this stage, the goal is to define the broad outlines of the hydrological conditions in the foundation of the dam and the corresponding reservoir basin, and their local context.

Generally, this study involves an inventory of trial pits (collecting data such as water levels and variations in them, geological layers, operating discharge, etc.), springs, resurgences or losses.

Depending on how dense the inventoried points are, an attempt can be made to sketch out the natural groundwater level in the dam area and deduce some preliminary ideas of its probable behaviour due to creation of a lake (if the water table on the river banks is higher than the level of the future reservoir,
it will play the role of a hydraulic barrage and prevent any leakage to the sides even if the ground is permeable; if there is a karstic system at a lower level than the future lake, there is a risk of flows past the dam if any outlet exists at a lower level downstream of the site or in an adjacent valley, etc.).

The results of the hydrogeological study can be quite heavily dependent on the season it is done in and rainfall in preceding months or years. The consequences for the project must therefore be deduced with precaution, in particular making sure that the worst cases have been properly identified and taken into consideration.

*brief structural study*

When the terrain is suitable (rock foundation), a brief survey of the main structural features of the site (dip, strike and density of cracking, major faults, folds, etc.) can support the geologist’s opinion as concerns the mechanical strength and watertightness of the foundation. Sometimes this will help in choosing the most suitable type of dam and in general contributes to the definition and layout of later site investigations.

Furthermore, searching in the literature for data on the regional structural context can orient the field study or help in interpreting field data. For example, it would make it possible to distinguish between families of regionally significant strikes, to associate them through that distinction to one or another tectonic phase, to foresee what state they are likely to be in (open or closed joints), or later to explain their behaviour during in situ tests, according to their orientation versus the present regional tectonic stress field.

**STAGE 4: Trial pits excavated by mechanical shovel**

(*site and borrow areas for fill dams*)

This is a vital complement to the detailed site tour discussed above. It is all the more important when outcrop conditions are poor.

In rocky ground, the depth of investigation is in general limited to the weathered surface layer, but at least indications can be obtained on the depth of the first competent layers, and in particular those of the substratum under the alluvial matter that is generally present in a valley bottom.

In particular it is recommended to check whether any fossil river valley exists, by the river’s own meandering or due to human action.

In accordance with the principles set out above (see "Trial pits" above in this chapter, p. 40), it is recommended to dig at least:

- a line of pits along the envisaged dam axis, with one pit every 15 to 20 metres (horizontal distance) on average,
- pits distributed in the area(s) envisaged for extraction of dam construction materials, one per hectare on average. The objective is to obtain preliminary indications on the thickness and nature of the loose material available in the reservoir basin, and/or on the cover that would have to be stripped off to reach useable rock materials if necessary, which would help in orienting the choice of the type(s) of dam that could be built on the site in question.
STAGE 5: Core sampling, if any
Core sampling at this stage of study is generally restricted to dams of a certain size or with particularly tricky geological problems, for which this technique alone is deemed likely to enable the geologist to emit an objective opinion (risk of high permeability in the foundation that would influence feasibility, substratum that cannot be reached with a mechanical shovel in pits, etc.).

STAGE 6: Brief survey
Levelling of the investigation pits and especially the drillholes is vital to achieve a good correlation between cross-sections. A rapid levelling instrument and land chain give satisfactory accuracy. It is wise to leave marks (rods, benchmarks) that can be reused in regular surveys during later design stages (the drilling can then be set out more accurately).

STAGE 7: Interpretation and drafting of the final report
Interpretation of the data collected during site tours and in the various trial pits or drillholes makes it necessary to set up geological profiles in numbers and in locations tailored to each case (in general, there will be a profile for each axis envisaged for the dam, along with cross-sections running perpendicular to or obliquely across this axis to show the geological make up of the foundation; cross-sections in the potential borrow areas on the site can also be drawn). The final opinion is then given in the form of a report that reviews the various problems that may be encountered on a dam site, for example along the following outline:

1 Introduction
   1.1 Purpose of the study
   1.2 Geographical location
   1.3 Summary of previous studies
2 Geology of the dam site
   2.1 Morphology
   2.2 Lithology
   2.3 Structure
   2.4 Foundation quality - abutment stability
   2.5 Foundation watertightness
3 Geology of the reservoir basin
   3.1 Morphology
   3.2 Lithology
   3.3 Structure
   3.4 Stability of reservoir slopes
   3.5 Reservoir watertightness
4 Materials available near the site
5 Conclusions
   5.1 Site investigation program
   5.2 Opinion on feasibility
One important element in the conclusion on the feasibility study is the choice of a type (possibly types) of dam that is/are the most suitable to the geological context revealed by the study with special attention paid to foundation quality and with account taken of the availability of usable materials on site.

A precise definition of the site investigation works that must be undertaken during later stages of study is also of great importance. It enables the investigations to progress continuously by foreseeing the means needed to answer any questions that have been raised or fill in gaps in the data that remain after the feasibility study.

**GEOLOGICAL AND GEOTECHNICAL STUDIES IN THE PRELIMINARY DESIGN STAGE**

*Objective*

Specialised studies prior to establishment of the preliminary design of a dam are only done if the feasibility study concludes in favour of the project and should allow the owner to make a decision as to whether to undertake the process of building the dam.

The purpose of the preliminary design study is to define the general outline of the dam, meeting the needs expressed by the client and fitted to the context, if necessary reviewing the various alternatives that may be considered and costing each of them approximately but realistically.

The importance of this first estimation of capital cost is very great as it will often serve as a basis in seeking financing and evaluating the economic advantages to construction.

For this reason, the owner must be safeguarded from any later nasty surprise by trying to have a generous approach to this cost - without accumulating contingencies - in particular with no attempt to hide any of the technical problems that may have been revealed or that are simply suspected.

In France this stage of study for dams 20 metres high or higher corresponds to the Preliminary Brief that must be submitted to the Permanent Technical Committee on Dams. Conversely, for the smaller dams that are more specifically addressed in this work, it frequently happens that this phase of study is combined with the tender design in the form of specialised design studies.

*Methodology for geological and geotechnical studies at the preliminary design stage*

Specialised geological and geotechnical studies for establishment of the preliminary design of a dam usually include the following stages:
Geological and geotechnical studies

Detailed site investigations

The geologist supervises the site investigations as defined during the feasibility studies and where necessary modifies the programme to adapt it to the information collected (layout, depth, number of drillholes, nature of the in situ tests, sampling, etc.).

Within this effort, he may make additional observations in the field, sometimes after conditions of visibility have been improved (when scrub has been cleared, for relatively large dams), may draw up a detailed geological map if necessary and may survey cracking on outcrops or in the bottom of trial pits (when the foundation is rock).

The investigations carried out are generally the following:

- **detailed survey**: it is generally in this stage of study that the surveys of the dam site and reservoir basin described in the section on topography at the beginning of this chapter are done (p. 39). All the drillholes and trial pits in the dam foundation and reservoir basin must be indicated on detailed maps.

- **trial pits**: this technique is often used at the stage of design investigations to complement other investigations, clarify any areas of doubt, and study one or several dam and, if necessary, spillway layouts.

  Trenches oriented in meaningful directions with respect to the dam or geological structures (generally along the dam axis and according to how the dam intersects the pre-existing topography) are recommended in this stage of study for large dams or where the geology is particularly complex.

- **geophysical studies**: in this stage rock foundations are investigated by seismic refraction or by "petite sismique". A classic system consists in:
  - one seismic profile along the dam axis (which should extend quite extensively outside the dam area into each bank);
  - one or several profiles running perpendicular to that axis (for example one in the valley bottom and one on each bank);
  - one or several profiles on the axes foreseen for the ancillary works.

- **core sampling**: this is generally done in this stage of study, essentially along the dam axis (and/or that of any watertight structure), and more rarely in the reservoir basin or in borrow areas (to study specific problems or thick overburden, investigate borrow areas of considerable thicknesses or rockfill quarries, etc.).

- **detailed investigation of borrow areas (for fill dams), including sampling**: this consists in digging trial pits by mechanical shovel in a tighter pattern than in previous investigations and taking remoulded samples.

In this stage of study, the trial pits should not be spaced less than 50 metres apart (four pits per hectare, depending on local conditions). It is preferable to space the pits as regularly as possible while organising them along parallel topographical profiles and perpendicularly to the contour levels.

A detailed cross-section of each pit is recorded, mentioning any samples taken. The thickness of the unusable material that must be stripped off from the surface (organic top soil); the depth at which flows of water are encountered and if possible of the water table (as well as foreseeable variations in it), the thickness of any intermediary layer that must be stripped off; and any instability in the walls should all be noted.

Samples should be taken according to changes in the ground’s nature, which often means taking a sample every metre of depth on average, limited to the ground that, at first consideration, can be used (above the water table in particular).
The weight of the samples must be sufficient to carry out the planned geotechnical tests (approximately 2 kg for a simple identification, at least 20 kg for compaction tests, or even more in the case of very coarse materials). If possible, the sampling should be done by the laboratory in charge of the testing.

- investigation of concrete aggregate in borrow areas (conventional concrete or RCC): these borrow areas are investigated by mechanical shovel in the same way as the earthfill borrow areas; as for investigation of potential quarries, this involves study of the rock levels involved (petrographic nature, structural study, density of cracking, thickness to be stripped off), if necessary accompanied by core sampling and geophysical tests. In general, there can be no question of opening new quarries, except any that would be flooded by the reservoir.

- in situ tests: the tests mentioned in the section on In situ Tests (p. 47) and Measurements may be done, if the dam or the problems encountered are important enough to warrant them.

Interpretation of data

All of the information provided by the site investigations is interpreted by the geologist who thereby improves his knowledge of the site. Depending on the size of the planned dam, the geological nature of the site and the problems encountered, he will establish any necessary documents: geological cross-sections, permeability and fracturing profiles, structural diagrams.

Geotechnical tests in the laboratory

A more or less considerable part of the necessary testing (see "Geotechnical laboratory tests" above in this chapter, p. 46 ...) is done at this stage of study according to various criteria (dam size, budget or land ownership requirements, consultant’s engineering practice, etc.). However, it is economically advantageous to do all of the sampling at once even if only some samples are studied in the laboratory at the preliminary design stage, especially for small dams. In any case, all of the recommended tests must be done in the tender design stage. It is acceptable to do only a limited number during the preliminary design, for example restricting investigations to definition tests.

Geotechnical summary

The geotechnical summary is based on the reports on laboratory tests, site investigations and in situ measurements, and is focused on distinguishing between families of homogeneous materials, whether in the foundation or in borrow areas, indicating for each the ranges of values for the various measured parameters.

The first stability calculations can be done on the basis of this summary and make it possible to define probable cross-section(s) for earthfill dams and foundation level for other types of dams.

The geotechnical summary should also include a judgement on materials availability at the site according to the type of dam planned and possibly draw attention to the need to investigate new borrow areas before the works begin.
Final report

The final report is drafted after all the preceding stages have been completed and includes:
- a summary of all the geological studies done since the beginning;
- the geotechnical summary mentioned above (preliminary geotechnical study);
- definition of investigations for the tender design stage (core sampling, undisturbed or remoulded samples, geophysical tests, geotechnical tests in a laboratory and in situ, etc.);
- supporting arguments for the type of dam recommended as the most suitable for the site;
- a preliminary sketch of the dam (zoning, slopes, cutoff trench excavations, etc.) and an opinion on foundation treatment and if necessary treatment of the reservoir basin.

GEOLOGICAL AND GEOTECHNICAL STUDIES IN THE TENDER DESIGN STAGE

For most small dams, this phase is combined with the preliminary design phase.

Objective

Except in special cases, geological aspects are familiar at this point, and only extremely localised site investigations will generally be necessary (in particular on foundations of ancillary works such as the spillway, outlet tunnels, diversion tunnels, inspection adits, intake tower, secondary dams if they were not considered in the preliminary design).

However, if there is any significant change in the dam layout (or just the axis of the watertight system) since the preliminary design site investigations, new core sampling and water tests will be necessary on the new layout.

On the other hand, in this stage of study most of the geotechnical studies proper (soil and rock mechanics according to the case) are necessary:
- taking samples in numbers suited to the size of the dam and the conditions encountered (geological complexity and variability of the soils), in the foundation and in the planned borrow areas;
- laboratory tests (with a schedule tailored to give good knowledge of the foundation for the structures and the borrow areas). Their purpose is to give the designer the necessary elements for tender design of the dam and to enable recommendations to be made on geological and geotechnical aspects during the works and later monitoring of the dam throughout its life. In France this stage of study for dams 20 metres high or higher corresponds to the final brief that must be submitted to the Permanent Technical Committee on Dams.
Methodology of the tender design geological and geotechnical studies

Geological and geotechnical studies in tender design phases include all or some of the following elements, but are vary variable depending on the characteristics of each dam (size, complexity, type, etc.).

- Any additional site investigations needed on the foundations of the dam and ancillary works, in particular relatively cohesionless terrain, changes of layout, or insufficient previous investigations (because of land ownership problems for example), including trial pits, core drilling with water tests and/or undisturbed samples, in-situ testing (by penetrometer, etc.).

- Detailed investigations of borrow areas in trial pits with sampling for laboratory tests (in particular prospecting for new borrow areas if the volume of material available is insufficient, sometimes because dam volume is increased or in case of a late change in dam type).

- Geotechnical tests in the laboratory (soil and/or rock mechanics) on undisturbed and remoulded samples, for the foundation and construction materials.

- Chemical and radiometric analyses of materials or foundation soil.

- Geotechnical (and geological where necessary) summary on the foundation and materials from the borrow areas, leading to stability calculations to define a dam cross-section for an earthfill dam or the foundation level for a rigid structure.

- Final choice of axes (main and ancillary structures, watertight system), of the type of structure, of the materials to build it.

- Precise definition of the nature and form of the watertight systems, dam zoning (where appropriate), borrow areas, conditions for material placement, monitoring systems for the foundation and the dam.

- Recommendations for works supervision and monitoring of the dam in operation (precautions to be taken, in particular stability of river banks and excavation slopes during the works and when the reservoir is emptied; control of water content when building fill dams; hold points requiring the geologist’s release before works are continued; detailed measures to be decided depending on what is observed during the work; etc.).

Geology and geotechnics in the construction phase

This phase essentially involves drafting the geological and geotechnical parts of the Particular Technical Specifications in the construction tender documents (which may be for earthworks, preparatory works for civil works construction, grouting, diaphragm wall, monitoring, etc.).

The Particular Technical Specifications are most notably intended to make perfectly

1. Chapter IV (p. 101) gives information on how to draw up such specifications for a fill dam.
clear to the contractors tendering for the works any special points that should be taken into account in making their bids, and especially in carrying out the work. They include various documents to inform the contractors about hydrology, geology, and the results of site investigations.

The special points that should appear in the Detailed Technical Specifications are as follows and include, but are certainly not limited to:

- conditions for sorting, selecting and using fill materials, compaction standards (range of water content and compactness, limit values for the degree of saturation and/or pore pressure, grading curves, techniques and instructions for inspection of materials, etc.);
- criteria for hold points and acceptance of excavations;
- intended slopes after excavation (excavations and borrow areas);
- particular specifications concerning grouting, where appropriate (depth, pressure, holding criteria, e.g. pressure/volume, etc.);
- particular specifications concerning the diaphragm wall, where appropriate (hold criteria, keeping samples, precautions concerning piezometry, etc.);
- particular specifications concerning the drainage curtain, where appropriate (orientation of drillholes versus dip, spacing, depth, treatment of the cut-offs);
- specifications concerning piezometers (nature, sensitive areas requiring special surveillance, etc.).

**GEOLOGICAL SUPERVISION DURING CONSTRUCTION**

**Objective**

The participation of the person who did all of the preliminary geological studies and was involved in setting up the design is vital as the dam is being built.

In fact, changes to details or sometimes even more important aspects may be required at any time during the work as the preliminary site investigations, even if they are very detailed, really only concern a very small part of the terrain involved. This is all the more true when the geological and geotechnical parameters are highly variable.

It is important to note that the construction phase is an integral part of the studies, because it is only at this moment that geology can be seen life-size and continuously and that any problems or important elements that may have been overlooked in the site investigations can be detected. Account must be taken of them through adaptations or modifications to the initially planned construction techniques, for example by deepening the watertight systems in places, stripping off cohesionless ground, adapting the zoning of fill, adding drains, adapting the depth of piezometers, etc.

Such modifications, which must sometimes be decided on very quickly on the construction site because of the often swift pace of construction, must be notified in good time to the contractors concerned, in writing (work order, inspection report, mention in a site log) with drawings and sketches.

They must then be filed with the As Built Documents, as the History of construction that
is highly useful when the origin of problems or abnormal behaviour must be investigated several months or years after the work is finished. This recommendation is just as valid for the smallest dams.

**Methodology for geological work supervision**

To meet this objective, the geologist must be involved in construction through periodic visits, some of them scheduled according to works phases that require his assistance (acceptance of excavations, etc.), and the rest on a regular basis to be determined according to the characteristics of construction (dimension of the structures, geological complexity, contractor’s experience).

It is therefore important that the geologist be kept informed in good time of how the work is progressing in order to be able to schedule his visits and avoid:

- not being able to carry out the planned observations and acceptance;
- delaying the works (works stoppage or filling in excavations, etc.), which is always a difficulty and creates conflicts that usually have an adverse effect on the quality of the work.

A non-exhaustive list of the tasks to be accomplished during construction of a dam is as follows:

- **Supervising excavation of all kinds (abutment contact, cut-off trench, surface stripping, tunnels excavated in the rock, etc.):**
  - comparison with plans, decision to stop or continue the excavation (adapting the level where the excavations are stopped to actual geological conditions);
  - monitoring the stability of excavations, river banks and slopes (excavated or backfilled), if necessary including the decision to reinforce (pinning unstable boulders, gentler slopes, nailing or shoring up loose slopes, etc.).

- **Geological survey of excavations (abutment contact, cut-off trench, surface stripping, ancillary concrete structures such as tunnels, spillway or intake tower):** this is generally done for structures of a certain size when the excavations are contractually taken over as foreseen in the contract and can involve photography, sampling, plotting crack patterns, and precise surveying of particular points visible in the excavations.

- **Geological survey of tunnels excavated in the rock (generally restricted to the largest of the structures dealt with herein):** representation of the nature of the terrains and their structure (cracking, dip, schistosity, porosity) on a detailed drawing of the tunnel’s cross-section, indicating all of the hydrogeological elements (cavities, inflows of water, leaks, etc.).

- **Supervision of sampling of construction materials for earthfill dams:**
  - comparison of the terrains actually encountered with plans and inspection that borrow material is in compliance with the contract specifications;
  - search for new borrow areas if necessary;
- adapting to operating conditions: sorting materials, zoning fill, treating materials by drying, wetting, screening, etc.;
- monitoring the stability of the remaining slopes and adapting operation of the borrow areas in case of problems.

- Supervision of how aggregates, borrow areas and quarries are run (for RCC, riprap, etc.):
  - comparison with plans;
  - inspection of conformity of extracted materials to contract specifications (grain size or block size, nature, shape, mechanical characteristics, etc.).

- Supervision of drainage and draining shaft construction in the foundation. Attention must be concentrated on:
  - checking that the zones to be drained or decompressed are actually and correctly crossed (supervision of drilling, examination of cuttings, recording parameters, logs, etc.), and if necessary adapting the depth and orientation of the drains;
  - the absence of siltation during drilling (no use of drilling slurry, careful cleaning at the end of the drilling until clear water is achieved);
  - development of the pits;
  - conformity of filter devices (size, nature and layout of the strainers) to the specifications and to the conditions actually encountered, and adapting them if necessary;
  - proper isolation of any zones that will not accommodate flows of water;
  - final check on functioning (which may happen only after partial or total filling of the reservoir), including in particular no entrainment of soil particles in the collected water (which might mean the beginning of piping).

- Supervision of grouting in grout curtains (if any):
  - definition, in liaison with the contractor’s specialists, of the size of the test section and grouting instructions (limit pressures and/or volumes, hold criteria);
  - establishment of reconstituted geological cross-sections by recording the parameters in uncored drilling;
  - possibly modifications in the depth of the curtain (deepening at permeable faults, etc.), or its length to each side (extending wing cut-offs);
  - possibly modifications in spacing between drillholes, grout mix and sometimes type, grouting parameters (pressure, volume, flow);
  - definition and supervision of investigation and inspection drilling including water tests;
  - where necessary deciding to re-treat the foundation in case of poor results after tests;
  - summary and interpretation of grout consumption and grouting pressures.

- Supervision of construction of diaphragm walls (if any):
  - establishment of the cross-section of the land crossed by taking samples from the bucket, if the type of tool used and/or the nature of the terrains permit;
  - acceptance of the excavation (taking a sample by bucket at the end of excavations), especially when a particular socketing stratum must be reached;
- special attention to monitoring the continuity of the wall;
- surveillance of the stability of walls, of the width and verticality of the excavation (by observing how cables or rods are centred with respect to the sides of the excavation as the bucket goes up and down);
- inspection of any overbreaks (which are visible on the concreting curves, in the case of plastic concrete diaphragm walls where the excavation slurry is replaced with plastic concrete);
- monitoring of groundwater level on either side of the wall during the work (it must be constantly ensured that the slurry or grout in the excavation is at least 1.5 to 2 metres lower than the surface of the water table in the natural ground in order to guarantee stability of the walls);
- any decisions to modify the structure's geometry (increasing or decreasing depth and sideways extension) according to the geological conditions actually encountered.
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