# PROJECT DESIGN: DAMS AND RESERVOIRS

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## Contents



## Summary

A concise review of the principles of the project design of dams is presented. This involves feasibility studies, preliminary design, selection of type of dam, and final detailed design. The procedure differs according to the choice of dam, such as gravity, fill, or other concrete or composite dam. Examples are given of large dams across the world, and of principles of safe and economical dam design. Temporary works and ancillary structures are also discussed, as well as construction aspects. Sound engineering principles to guide the designer are emphasized. Special attention is given to structural and hydraulic design: resisting forces, and to preventing seepage and erosion damage. Management considerations and organization of the technical activities are key issues addressed.

## 1. Introduction

The design of a project is the next phase after planning has indicated that the project is viable. Design involves the main components of a water supply system, i.e., the dam, the reservoir it impounds, and the water transfer system to the community to be served.

The design phase follows the feasibility studies already executed. These studies identified the availability of a dependable water supply, the optimum site for a dam, and the full supply level needed to impound the storage volume required in the reservoir. The type and route of the water transfer conduit to the user area, be it pipeline, tunnel, canal, aqueduct or combinations of these were also important considerations. In the dam site selection exercise, already dealt with, some notion of the type of dam to be selected might have already been made (see chapter *Water Supply: Dams, Reservoirs and Water Transfers*).

Prefeasibility and feasibility cost estimates also have been drawn up previously. After a decision has been taken to proceed with the project implementation, a preliminary budget, over a number of years forward, is drawn up. Only then the process of detailed design and optimization commenced.

The design phase of a large dam can logically be divided into two stages: preliminary design and detailed design. The preliminary design phase will include investigating a number of parallel options as to types of dam and methods of construction, which will be subjected to cost estimates to determine the most economical tentative design. If adopted, that will then be the starting point of detailed design. This concentrates more on the type of dam selected, the method of construction and the chronological deployment of phased construction. Following the completion of the detailed design phase, bids for construction will be invited, and a contract award made to the successful bidder.

An engineering firm, usually a consortium of established firms, based on prequalification, will be assigned to the task of final design, engineering, and supervision of the construction of the project. On large projects, several contracts could be let in parallel and simultaneously, or in succession, and several engineering groups assigned to cater for each. For example, one firm may be responsible for the dam and ancillary works, another for tunnels, one for mechanical equipment, one for site drilling and investigations, others for establishment, preliminary works, environmental control and rehabilitation measures, and so forth.

## 2. Preliminary Design

The main construction cost item is usually the dam itself, and a great deal of effort goes into optimizing, regarding selection of type of dam and choice of ancillary works.

### 2.1 Type of Dam

Generally speaking, there are two main categories of large dams: fixed dams, and mobile dams or barrages.

- The fixed dam is a rigid substantial impounding structure across a watercourse intended mainly for water storage or level control in the reservoir behind it. It also has ancillary structures: the spillway, the intake, the water supply conduits leading away from it, and the low level outlets for drawdown purposes. It may also incorporate a hydropower station or pumping station, as needed.

- The mobile dam or barrage is characterized by a low-level sill embodying a water-conducting structure, with a large number of gates set between piers across a broad river. These can be operated so as to control mainly the flow, with storage being incidental. It could be combined into a hydroelectric power station, pumping plant and/or navigation canals and shipping locks. It should also present as little resistance as possible to the passage of sediment or debris, ice or river traffic.

In this article, the main attention will be given to dams of the first type, i.e., fixed dams. Mobile dams or barrages, such as tidal-closure and river-regime control dam are dealt with in other articles.

## 2.2 Fixed Dams

Fixed dams are classified into fill dams, gravity dams, buttress dams, arch dams and composite dams (see chapter *Large Dams*).

- Fill dams. These are earth-fill and rock-fill dams. For water-tightness, fill dams need to have either an impervious core, an impervious upstream facing or an upstream blanket (as explained in section 5.1). To prevent under-seepage fill dams should be provided with a cutoff trench extending down to impervious substrata. This trench should join up with the impervious core facing or blanket mentioned above, in order to prevent underseepage and associated pore-pressures which would endanger the stability of the structure (see chapter *Loads on Earth- and Rock-Fill Dams Arising from Water and Wind*).

- The core, in the case of earth-fill dams, could be constructed of a dense clay zone, or as a centrally located asphalt, slurry or grout cutoff wall. The upstream facing, in the case of rock-fill dams, could be a surface layer of asphalt or concrete. A notable example of a large fill dam (earth-fill) is Aswan High Dam in Egypt, rising 111 meters high above riverbed above a 225 meters deep cutoff grout curtain, containing 42 million cubic meters of earth-fill.

- Gravity dams. These are solid, and can be built from masonry, dressed stone-faced rubble masonry, mass-concrete, or roller-compacted concrete. Grande Dixence Dam in Switzerland is the world's highest at 285 meters, containing 5.9 million cubic meters of concrete, and Bhakra Dam in India next highest at 226 meters, containing 4.1 million cubic meters of concrete.

- Buttress dams. Buttress dams are not solid and can be of the slab-and-buttress, or Ambursen dam type, or be multiple-arch and buttress, massive buttress, diamond-head and bulb-head buttress dams. An example is Farahnaz Palavi Dam in Iran, 107 meters high and 360 meters in length (broad-head buttress dam). Daniel Johnson Dam in Canada, 214 meters high, 1310 meters long, is a multiple arch/dome and buttress dam.

- Arch dams. These can be built from masonry, mass concrete, reinforced concrete or roller-compacted concrete. Arch dams are also classified according to single-curvature, double-curvature and dome types. Single or multiple arches (with buttresses) are further choices possible. The highest two arch dams are Inguri in the former USSR (272 meters high, 680 meters long and four million cubic meters in volume) and Mauvoisin in Switzerland (237 meters high). One of the most massive arch dams is Hoover Dam in the

US (221 meters high, 379 meters crest length and 3.3 million cubic meters in volume).

- Composite dams. A single dam may include more than one type of construction/design, e.g., Roselend Dam in France is a domed arch dam combined with buttresses. Itaipu Dam in Brazil is a buttress dam with gravity and embankment sections, a built-in power house and chute spillways. La Grande 1, 2 and 3 in Canada is a vast complex of gravity dams and barrages interconnecting several lakes. Many concrete dams across river sections have fill embankments on either side, so-called composite dams.

### 2.3 The World's Leading Large Dams

Some of the largest and highest dams in the world are concrete dams, for example, Grande Dixence in Switzerland (285 meters high); Hoover, Shasta, Grand Coulee (168 meters high, 8 million cubic meters in volume) and Glen Canyon in the US. Large earth dams have impressive proportions, such as Fort Peck Dam, (76 meters high and 96 million cubic meters in volume) and Oroville Dam (236 meters high and over 59 million cubic meters in volume) in the US, and Mangla Dam (116 meters high and 65 million cubic meters in volume) in Pakistan. Nurek Dam, the world's highest dam at 317 meters plus a 16 meters deep concrete cutoff to riverbed, is an earth dam located in Russia near the Afghanistan border. Tarbela Dam in Pakistan is the dam with the largest volume content in its earth-fill embankment (145 million cubic meters in volume).

The Afsluitdijk (closure dam), built over the Zuyder Zee in the Netherlands, is an unusually long earth dam and is 30 kilometers in length. The highest rock-fill dam is Rogun in Russia (300 meters high). Akosombo Dam in Ghana is an earth/rock-fill dam, 141 meters high. The dam with the largest reservoir capacity is Owen Falls Dam, a 31 meters high gravity dam on the Victoria Nile in Uganda, with 205 000 million cubic meters storage capacity (including Lake Victoria). The highest concrete-faced rock-fill dam (CFRD) is Aguamilpa in Mexico (187 meters high); there are several others over 200 meters high under design. A notably large concrete dam will be the Sandouping Dam, under construction at the beginning of the twenty-first century, and forming part of the Three Gorges Project in China.

### 2.4 Ancillary Structures

As mentioned before, the main impoundment structure is supplemented by ancillary, but essential, functional units. These are the main spillway, the auxiliary spillway(s), the intake works for water supply, the outlet works for drawdown, and the hydropower and/or pump stations. There may also be secondary embankments, navigational channels and locks, and environmental adjuncts such as fish-ladders, access ramps and roads to the reservoir, bank protection works and security enclosures (see chapter *Design of Spillways and Outlet works for Dams*).

These ancillary structures may to some extent be embodied in the main structure of the dam and most often are found integrally built into a concrete dam. Often they may be in the form of separate structures, especially in the case of a fill dam. This depends mainly on the outcome of the optimization studies in the preliminary design process.

## 3. Temporary Works

Apart from the above, the permanent works, there are temporary works of various kinds. These are the following: diversion works (bypass canals, coffer dams, bypass tunnels), quarries and borrow pits, site establishments (crushing, mixing and batching plants) and craneage (blondin cableway tracks and suspension towers). Some of these, especially river diversion works such as cofferdams and diversion tunnels, may be incorporated into the final works as part of the completed project. Major cost considerations are involved in the site layout, and the scheduling, material sources, and environmental re-establishment. Besides these works mentioned above, there are temporary support establishments (workshops, stores, living quarters) as well as access roads, landscaping and recreation facilities.

## 4. Design Options and Safety Criteria; Economics

Before entering into the detailed design aspects, and comparing the different types and options open to the design engineer, it is important to stress the economics of site and materials. The site characteristics and aggregate sources available for construction lend themselves to the optimal choice of dam.

Fill dams are obvious choices for broad and wide valleys with poor foundations at the dam sites. Materials for fill dams are: alluvium (sand and gravel), moraine, colluvium, rock (boulder beds), and clay deposits. Materials for concrete gravity or arch dams, which are dictated by narrow U- or V-shaped canyon-type sites with good foundations, are rock, sand, boulders and gravel deposits.

The following quotations from *Ancient Dams of Iran* give a historic perspective, and some hindsight on a time-proven success record. Basic features of the ancient dams of Iran (some 60 dams built since 3000 years ago) are the following:

Dam site. Many considerations of the modern site selection practice, such as topography, availability of construction materials, diversion works during construction, stream flow regime, and so on, seem to have been taken into account for selecting the most appropriate dam site during those times. Erection of many ancient dams in remote mountainous areas where access is still difficult, indicates how carefully all possible sites were investigated and eventually the most suitable ones selected.

Foundation Conditions. Preliminary investigations to obtain basic information on the foundation conditions of the ancient dams of Iran have shown that wherever a shallow bed rock or an outcrop of sound formation had been available, it had formed the dam foundation. In such cases the structure has remained stable over centuries, though its reservoir is fully silted-up, whereas those built on alluvium or stream deposits have suffered from foundation weakness and had failed due to a foundation failure. This leads to the conclusion that the majority of ancient dam failures could be due to insecure foundations.

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**Biographical Sketch**

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