CONCRETE DAM ENGINEERING

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Keywords: concrete dam, temperature efects, gravity dams, buttress dams, multiple arch dams, dome buttress dams, arch dams, coarse aggregate

Contents

Summary

The article describes the basics and engineering details of concrete dam design and construction. It deals with various types of designs, and different materials of construction, utilizing cement and coarse aggregate. Concrete dams can be classified according to type and according to construction material. All dams must first be designed to resist the forces of water against their upstream faces, their own self-weight, and foundation reactions. Furthermore, they must be so constructed as to be as watertight as possible, and be able to resist internal pressures due to water seepage. Spillways of dams are important auxiliary structures often forming integral parts of the main structure. Consideration must also be given to safe design of spillways and elimination of possible scours and malfunctions of a hydraulic kind.

The types of dams dealt with in this article are gravity dams, buttress dams, multiple arch and dome buttress dams, and arch dams. The types of materials and construction techniques used in these are mass concrete, roller compacted concrete, masonry and rubble masonry concrete. Ordinary Portland Cement, blast furnace cement, fly ash and pozzolans are additives commonly used for economy, as well as temperature control. The effects of hydration temperature and its mitigation are discussed with reference to dams without construction joints. Properties of aggregates, details of form-work, and various construction techniques, are also discussed. Precautions to ensure quality and sound workmanship are emphasized. Diagrams showing behavior, isometric figures and photographs complete the coverage.

1. Introduction

Dam engineering embraces several aspects and disciplines of civil engineering, including hydrology, hydraulics, geology, geomechanics, geohydrology, sedimentation transport, materials engineering and structures. Most of these aspects become obvious when the function performed by a dam is considered, together with the various phenomena caused by its existence. In essence, a dam creates an artificial phreatic surface within the ground and bedrock immediately surrounding its impoundment, the nature and extent of which will depend predominantly on the permeability of the *in-situ* geology and the location of the groundwater table (see Figures 1 and 2).

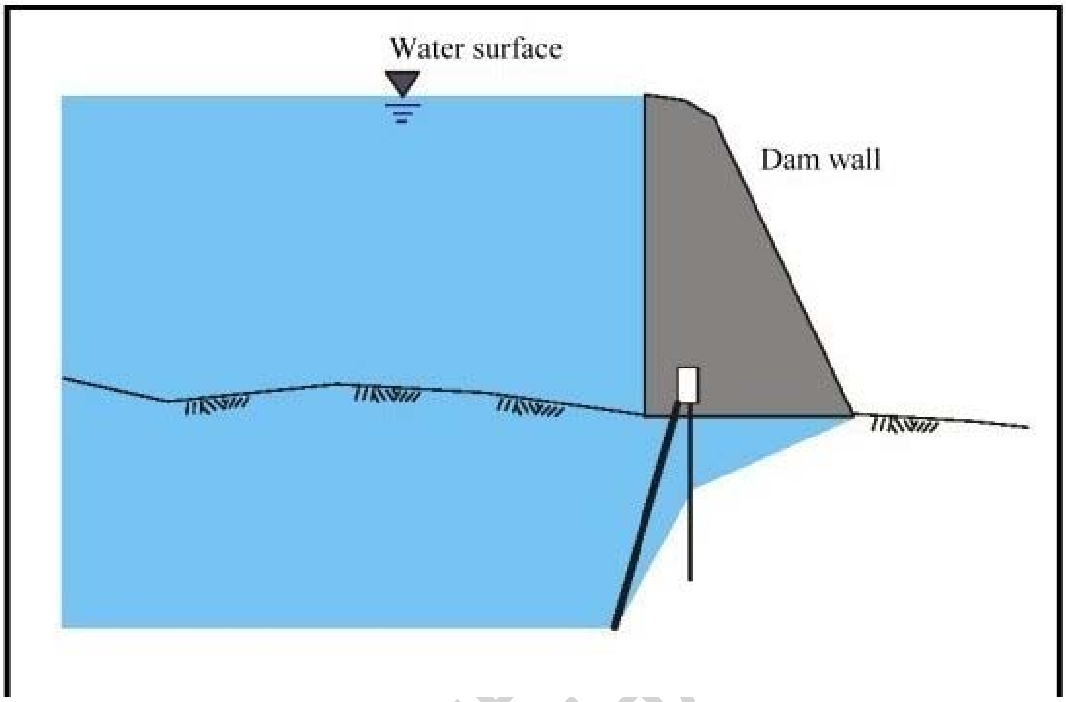

Figure 1. Water pressure action

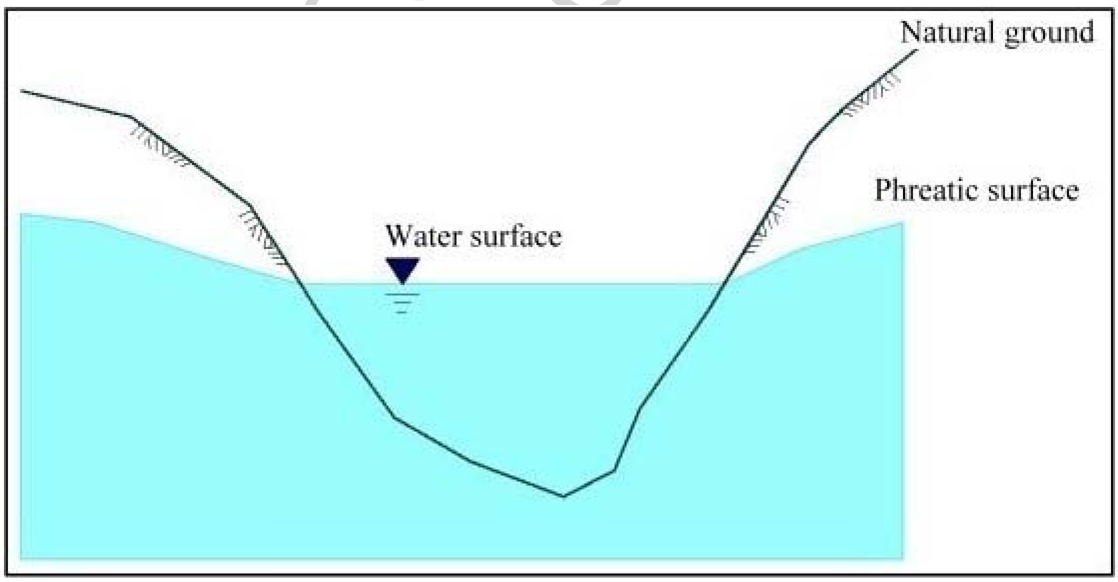

Figure 2. Impoundment and groundwater

The dam wall itself functions to carry the water load directly, where the dam closes off the valley, as well as to reduce the phreatic surface and associated water pressures in the valley flanks and floor immediately upstream of the wall to nil at the toe of the dam wall (see Figure 3). In addition to solving the problem of water pressure gradients, the dam wall is required to transfer the hydrostatic water load, carried on its upstream face, into the flanks and floor of the valley which it dams, and to facilitate the return of river and flood flows down into the valley downstream without damage. By creating a higher, impounded water level upstream than downstream, potential energy is generated, which potential is converted into kinetic energy, in the form of water velocity, as and when the dam spills.

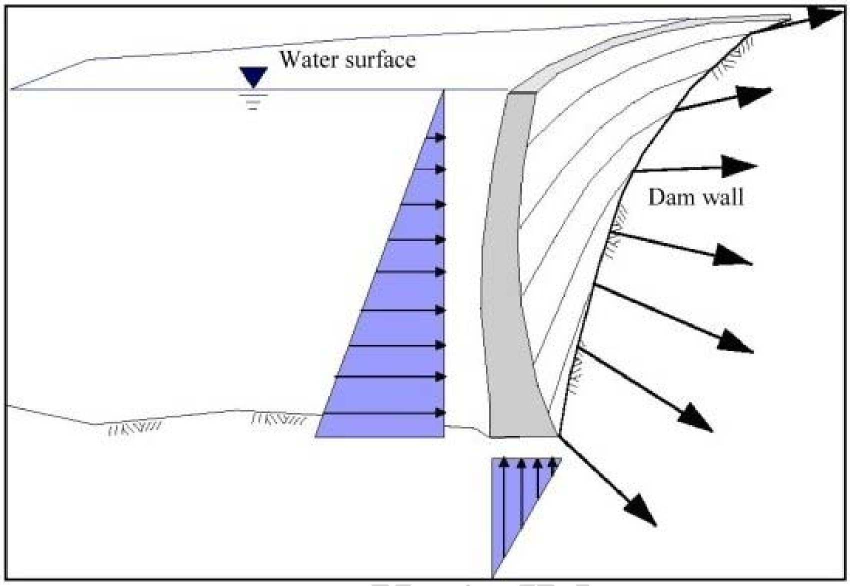

Figure 3. Hydrostatic loads

It is worth bearing in mind that water falling through a height of just 5 m, without energy dissipation, will develop a velocity of almost 10 m s^{-1}, which is in excess of the velocity capacity of virtually all channel lining systems, except concrete and natural, coarsely jointed bedrock (see Figure 4).

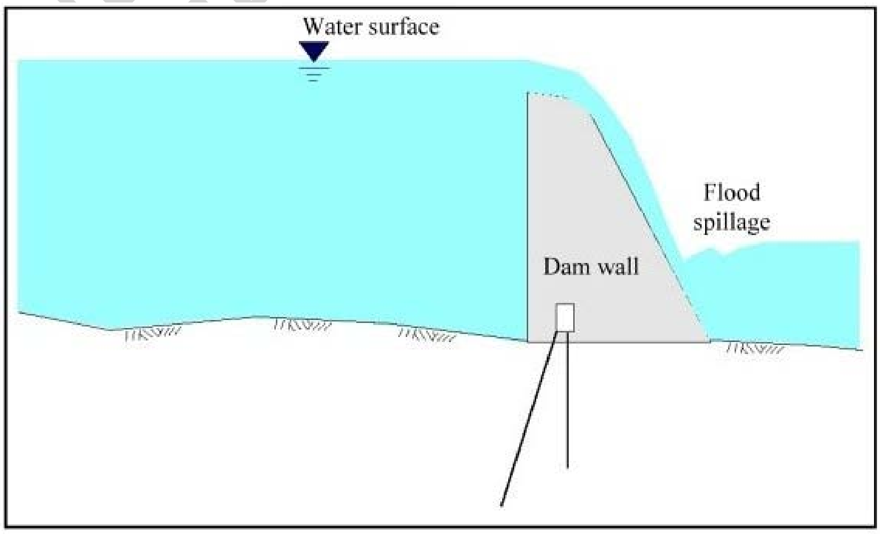

Figure 4. Spillage energy

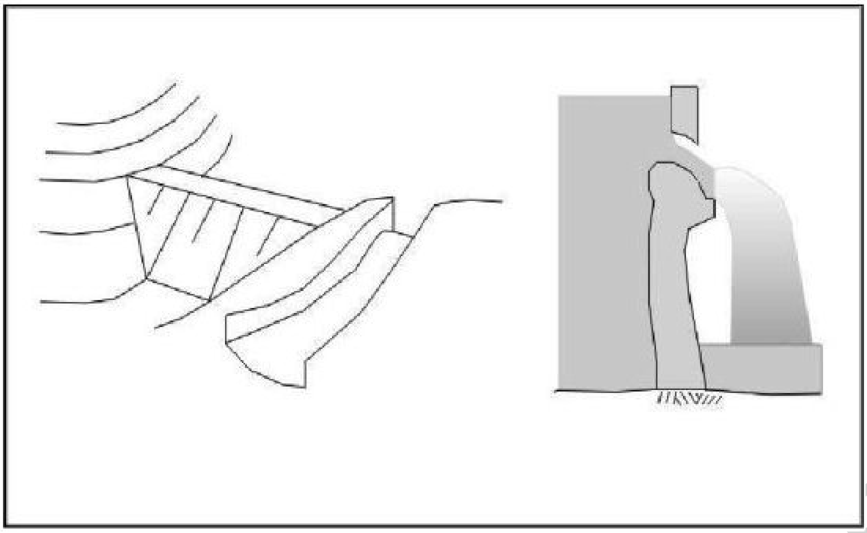

Figure 5. Various spillway configurations

Dam engineering involves the solution of the aforementioned problems and others, using various configurations of dam walls, cut-offs and spillways by the most appropriate and economical means, usually making use of locally available materials (see Figure 5). In addition to the creation of an impoundment, dam engineering obviously extends to include the draw-off and delivery of the impounded water for its intended purpose, be this for hydropower or water supply. Accordingly, off-take works, inlet towers, outlet works, outlet conduits, valves, sluices, gates and pipelines form important components of any dam (see chapter *Design of Spillways and Outlet Works for Dams*).

Each dam site is unique, combining a specific set of properties, including valley topography, flood hydrology, dam height, geology, available materials, siltation characteristics and seismology, which together determine and limit the scope for dam types and designs. In this article, some of the factors of influence on the optimum dam type selection exercise are illustrated.

2. Concrete Dams

2.1 General

A few general rules exist for concrete dams, the first and most important of which is the necessity for competent foundations. This requirement often causes construction cost overruns, as worse than anticipated founding conditions are encountered and additional excavation is necessary. However, it cannot be overstated, that the founding of concrete on competent, massive rock is essential for all significant concrete dam types. On the basis of this central requirement, it can be seen that a comprehensive geological/geotechnical foundation and materials investigation is of pivotal importance.

This investigation, which will usually include the drilling of rock cores with diamond drills, is usually undertaken during the feasibility and early design stages, when it is often difficult to commit significant sums of money to the project and accordingly it is very rare that time and funds permit the extent of an evaluation that might ideally be required. Furthermore, even the most comprehensive foundation investigations cannot be considered absolutely conclusive in terms of interpretative accuracy. Another factor equally applicable to all concrete dam types is the requirement for effective construction supervision and quality control.

2.2 Types of Dams

The broad term "concrete dams" can be considered to include all types of dam in which the basic structural element comprises cemented aggregates. At one end of the spectrum would be a roller compacted, unformed embankment comprising natural colluvial or alluvial aggregates mixed with cement and water using a plough or rotivator, while at the other would be a thin arch dam, constructed in monolithic, shuttered blocks using 30 MPa mass concrete. In terms of material types, "concrete dams" would include dressed masonry, rubble masonry, colcrete, plum concrete, cyclopean concrete, roller compacted concrete (RCC) and ordinary mass concrete of various aggregate sizes and strengths (see chapter *Large Dams*).

Soil cement would be considered a stabilized fill, although a certain overlap between stabilized fill and RCC exists in the form of sand cement and natural aggregate RCC, or hard-fill dams. In terms of structure types, concrete dams may take many forms including gravity, arch-gravity, slab and buttress, massive head buttress, diamond head buttress, massive arch buttress, multiple arch buttress, dome buttress, constant radius single curvature arch, double curvature arch, multiple centered arch, parabolic arch, etc. A single dam can encompass more than one of the above structure types and the configuration can include embankments of various types, although these are not addressed within the scope of this article (see chapter *Construction of Small Earth-Fill Dams*).

The relative economy of each dam type varies with site conditions and height, with each type often being most applicable within specific height ranges. Having listed each of the dam type groups, an examination is now made of how each type functions, and the specific requirements of each in terms of topography and geomechanics of the foundation rock.

2.2.1 Gravity Dams

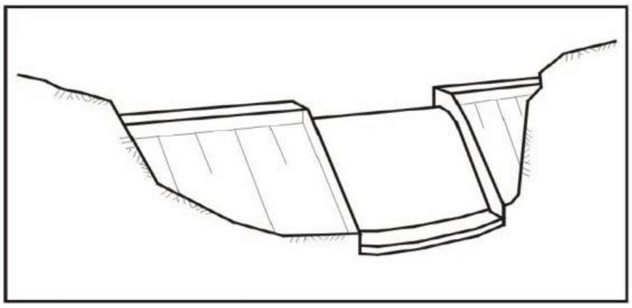

Figure 6. Gravity dam

The dam type that could be described as the most basic and simplest of functions is the gravity dam, a structure which in simplistic terms, transfers horizontal hydrostatic water load directly down into the foundation primarily by means of mass (see Figure 6).

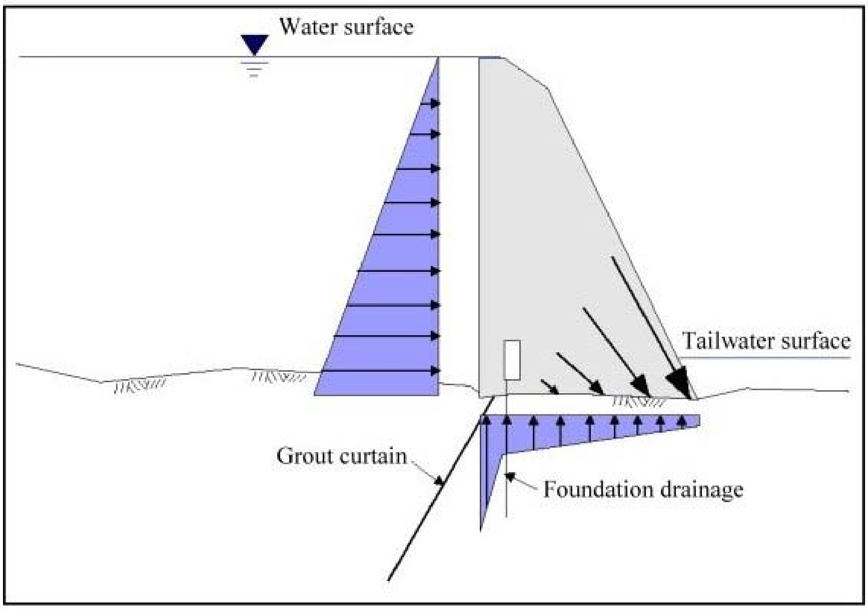

Figure 7. Loads and forces in a gravity dam

On a small scale, such dams will often be constructed without foundation drainage and in some instances, even without foundation grouting, in which case a significant additional lifting and overturning moment will be applied to the structure as a result of uplift pressures in the foundation. If the foundation is drained and grouted, then uplift forces are considerably reduced (see Figure 7). The standard practice for the design of major dams is to accept full hydrostatic uplift at the upstream face of the dam wall, reducing to tailwater + 1/3 [full head-tailwater], which assumes 67% efficiency of the foundation drainage, at the location of the drain, and reducing further to tailwater head at the toe of the dam. These uplift pressures act vertically upward on the foundation surface of the dam wall.

Assuming adequate foundation bearing capacity, the critical failure mechanisms for gravity dams are overturning and sliding, and the dam wall structure is evaluated for factor of safety against overturning and sliding and for associated wall stresses under a variety of normal and extreme loading conditions. Factors influencing loading and associated stability include reservoir hydrostatic, foundation uplift hydrostatic, siltation, gravity (dam mass), temperature and earthquake loads, and foundation mechanical characteristics. The required factors of safety depend on the confidence levels of information, the likely occurrence, or recurrence intervals of loading cases, normal and extreme, and the requirement to limit compressive and tensile stresses.

If vertical tensile stresses at the upstream heel and on the upstream face are high, to the extent that cracking of the concrete on the horizontal construction joints is possible, stability analyses, including the effects of uplift within an anticipated crack, must be completed at the level of potential cracking. Generally speaking, for all but the highest dams, if factors of safety and heel tensile stresses are acceptable, toe compressive stresses will usually be within an acceptable range (see Figures 8 and 9).

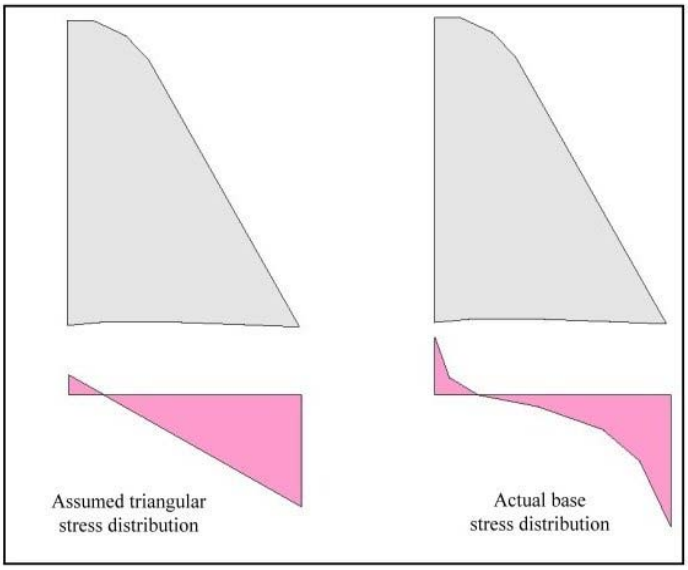

Figure 8. Uplift distribution in a gravity dam

Bearing capacity of the foundation rock mass will rarely be a problem. If the rock mass is sufficiently coarsely jointed and massive to be made impermeable by certain grouting, then the inherent bearing capacity is likely to be adequate for all but high concrete gravity dams. Gravity dams can be constructed in any of the various concrete variants, with the majority of conventional structures built in conventional concrete, RCC and, to a lesser extent, masonry.

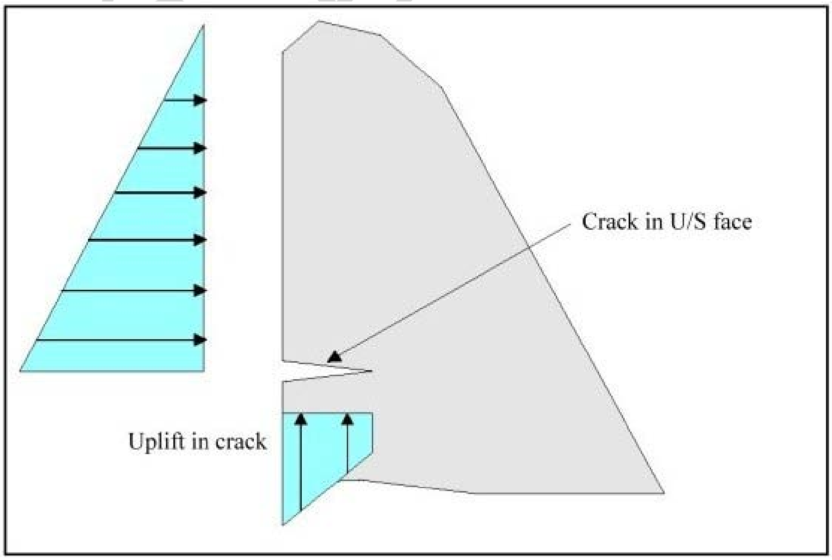

Figure 9. Uplift in cracked section in a gravity dam

2.2.2 Buttress Dams

In a similar manner to gravity dams, buttress dams function structurally essentially in two dimensions, transferring water load down into the valley bedrock. As a consequence of a significantly reduced concrete foundation contact area compared with that of a gravity dam, uplift pressures are substantially reduced, and buttress dams accordingly require a lesser volume of concrete per unit length, although shutter areas are increased. Dam toe and foundation bearing stresses are increased, and often water weight is used to enhance stability by sloping the upstream face exposed to hydrostatic pressure. Generally, the restriction of upstream heel tensions and factors of safety against sliding are more critical than factors of safety against overturning (see Figure 10).

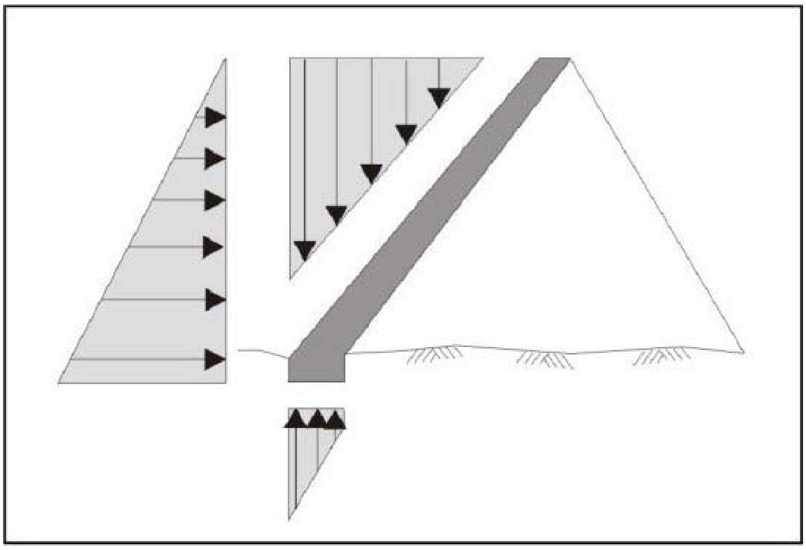

Figure 10. Forces on a buttress dam

A large number of variations of the buttress dam exist, each type making use of a different means to transfer water load laterally into the buttresses. Although buttress dams are rarely the solutions for high dams, the basic types of buttress dams are described in the following five subsections:

2.2.2.1 Slab and Buttress

This dam type is the most common buttress dam, using the flexural capacity of the slab to bridge laterally between the buttresses. This buttress dam type is most applicable on a small scale, with the requirement to arch between buttresses and/or to incline the upstream face to carry additional water load to be competitive on a large scale.

2.2.2.2 Massive and Diamond Head Buttress

Massive and diamond head buttress dams require relatively closely spaced buttresses and function on the basis of the buttress "head" being sufficiently massive, or efficiently

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Biographical Sketch

Quentin Shaw is of British nationality, and he obtained the following academic qualifications at Universities in the UK: B.Sc.-Civil Engineering (Birmingham) and M.Sc.-Dams (Brighton). He is a Professional Engineer (Pr. Eng.) in South Africa and Member of the South African Institution of Civil Engineers (MSAICE); as well as a Certified Engineer (C. Eng.) and Member of the Institution of Civil Engineers (MICE) in the UK.His key experience comprises the following:He is a specialist engineer on dams, particularly focusing on the fields of Roller Compacted Concrete (RCC) and arch dams. He has been involved in dam engineering since 1984 and he has worked on more than sixty dams, varying in height from five to 220 meters. From a base in South Africa, he has been involved on dam- and hydropower projects in ten countries around the world.

An area of particular specialization for him has been the RCC arch dam, and he has worked on the design, construction and safety evaluation of various completed and planned examples of this type of dam. With regard to dams on a smaller scale, he has dedicated his energy successfully to the ongoing development of cost-effective and labor-intensive masonry arch-dam construction technology.

Projects of particular interest, that he has participated in, include the following:

Çine Dam, Turkey, a 135 meters high RCC gravity dam.

Thukela Water Project, South Africa: Jana Dam, a 180 meters high RCC gravity dam; and Mielietuin Dam, a 98 meters high RCC arch dam.

Wolwedans Dam, South Africa, a 70 meters high RCC arch/gravity dam.

Sounda Dam, Congo, a phased 47 to 85 meters high RCC arch dam.

Baynes Dam, Namibia/Angola, a 220 meters high RCC arch/gravity dam.

Quentin has acted in the capacity of both an arch dam- and an RCC dam specialist on major international projects. He is the author of ten technical papers on dam engineering, and has made contributions at a number of international and local forums, such as organized by the International Commission on Large Dams (ICOLD), and the Concrete Society in South Africa.Mr. Shaw is co-founder, and the director in charge of the dams and hydropower activities, of a firm of Specialist Consulting Engineers, based in Pretoria, South Africa.