2.12.1.1 Design and Construction of Dams, Reservoirs, and Balancing Lakes

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Glossary

Gravity dam: a rigid dam, made of masonry or concrete, withstanding water pressure by means of its own weight.

Arch dam: a masonry or concrete dam that transfers reservoir pressure to the valley banks by means of its horizontally arched shape.

Spillway: a special part of the dam that allows floods through or above the dam.

Roller compacted concrete (R.C.C.): a cost- and time-efficient construction method for concrete dams.

Hardfill: natural soil treated with cement at low cost, which allows the soil to take on some of the qualities of concrete.

I.C.O.L.D.: the International Commission on Large Dams. Created in 1928, I.C.O.L.D. consists of 80 associated national committees.

Summary

The general data presented in sections two and three gives an idea of the extreme diversity of the millions of very large or very small dams worldwide. Dam design and construction methods for the most usual types of large dams are presented and justified in section four. The possibility and usefulness of building as many dams in the 21st century as have been built in the 20th is analyzed in section six.

1) Introduction

For thousands of years, dams have been used to store water and to create energy. However, 90 percent of global dam investments have been made after 1950, both in terms of the millions of small or medium sized dams and the thousands of dams higher than 50^m. The characteristics of these dams vary greatly. This article gives basic data concerning dams and reservoirs, explains the reasons for typical dam designs and construction methods, and underlines the importance of the study of reservoirs' environmental impact. It tries to forecast the future of dams, and considers whether dams will contribute to the development of the world's poorest countries in the next century, much as they did for the world's richest countries in the last.

2) General Data in 2000

There are millions of dams: these artificial reservoirs thus create a storage of over 6 000 billion m^3 of water.

- Ninety-seven percent of this total storage is created by the "large dams." As classified by International Commissions on Large Dams (I.C.O.L.D.), large dams include the 40 000 dams higher than 15^m and a few thousand lower dams with storage of over 3 million m^3.
- Two percent of the total storage is created by over 150 000 small dams (5 to 15^m high) with reservoirs between 100 000 and 3 million m^3.
- One percent is created by the millions of other small dams with reservoirs under 100,000 m^3.

Problems of design and construction refer essentially to large dams but may apply also to dams 10^m high.

Among large dams there is extreme diversity of height, storage, river flow, range of cost, purpose, foundation, and dam types. The main differences are summarized below:

2.1 Number of dams over 15^m according to height and dam material.

Height Number of dams

	Earthfill or Rockfill	Concrete or Masonry	Total
60-300 ^{m}	800	1 200	2 000

30-60 ^{m}	5 000	2 500	7 500
15-30 ^{m}	27 000	3 500	30 500
	32 800	7 200	40 000

Over 50 percent of higher dams are in concrete but 90 percent of all dams under 30^{m} high are fill dams.

2.2 Storage

The topography of dams and reservoirs varies considerably from narrow gorges and steep valleys to very flat areas and very long low embankments; reservoir volume may differ from 1 to 100 for two dams of same height.

A rough splitting of total storage according to unit storage of dams is presented below:

Unit Storage (in millions of m^3)	Number of dams	Total Storage (in billions of m^3)	Total area (in thousands of km^2)
Over 1000	700	5 000	250
10-1000	10 000	1 000	80
0.1-10	150 000	150	40
Less than 0.1	Millions	50	30
		6 200	400

This total storage (6 200 billion m^3) is sometimes compared with the yearly level of water utilization, which is in the range of 4 000 billion m^3, and mainly put to use for agriculture. This comparison is questionable, as most dam storage is for hydroelectricity, and is often located in countries as Canada and Russia, where water needs are easily satisfied.

Natural lakes have a global volume 25 times as much as the global volume of dam reservoirs existing in the year 2000 and a global area three times more important. The flow of many rivers is regulated by natural lakes, often with rather small changes in level. In theory, many natural lakes offer the technical potential for enormous artificial storage by building dams at the offtake. However, in unpopulated areas such potential storage is often not needed, while in long-populated areas significant changes in water levels may not be acceptable.

Important storage over large natural lakes may, however, be useful with small changes in level: in Siberia, for example, varying the level of Lake Baïkal (1 600m deep) by only 1m allows the regulation of 40 billion m^3 of water for the Angara river. Large natural lakes also allow flood control of the Yang Tse in China, while in Uganda a 3m variation in Lake Victoria's water level represents a storage of 200 billion m^3 and may control the Upper White Nile.

The total artificial storage created above natural lakes represents about 10 percent of total dam storage. Corresponding dams are rather low, do not raise special problems, and are not studied specifically in this article.

For 10 percent of emerged areas worldwide, rivers are not flowing to seas but to inland lakes or swamps. The area of these lakes vary yearly, according to rainfall, evaporation, and the volume of tributaries' flow, and may be permanently reduced if upstream water utilization increases. In the former U.S.S.R., irrigating 50 000 km^2 from the water of the Syr Daria and the Amou Daria has reduced by 20 000 km^2 the area of the Aral Sea.

2.3 Investments

The total value of dams investments up to the year 2000 is estimated to have been in the range of 1 500 billion US dollars (excluding the cost of powerhouses). Over 90 percent has been realized since 1950 at about the same yearly investment rate, with more dams in the sixties and higher unit value recently. In the sixties, most dam investments were in developed countries, but now most occur in developing countries. Yearly investments from 1990 to 2000 were in the range of 30 billion US dollars. The unit cost of large dams averages 30 million US dollars, but may vary from over one billion to less than one million.

The average investment per m^3 of storage is \$0.25; it is much less for large hydroelectric schemes, but may be well over one US dollar per m^3 for medium storage dams. The average cost per m^2 of lake is four US dollars, but costs may range from under one US dollar for large schemes to over ten US dollars for small ones. Clearly, these values vary in relation to local economic and physical conditions.

Most dam investments are recent, but the hundreds of thousands of small dams (and water mills) built many centuries ago have had enormous impact on the progress of industry and agriculture in many parts of the world. And 4 000 large dams (including 1 000 over 30^{m} high) were built between 1900 and 1950, bringing key experience to the design of later dams.

2.4 River flows

Hundreds of dams have been built on many large rivers with average flows between 1 000 and 20 000 m^3/s, and a few thousand have been built on rivers with an average flow over 10 m^3/s. However, the great majority of large dams and small dams are built on rivers having an average flow in the range of one m^3/s or less.

River flows vary considerably through the year and, in the case of most medium and small rivers and many large ones, are quite nil for months. This justifies the construction of most dams.

In small or medium catchment areas the peak flow during exceptional floods may reach 100 or 1 000 times the average yearly flow. In very large rivers the peak flow may be ten times the average yearly flow. Consequently, the capacity of the spillways, which are the structures allowing flood water through the dams, is rather high:

- 20 are over 50 000 m^3/s
- 3 000 are between 1 000 and 10 000 m^3/s
- 15 000 are between 100 and 1 000 m^3/s

and the total capacity of large dam spillways is 20 million m^3/s when the average river flow worldwide totals one million m^3/s.

3) The purpose of dams

Dams have various purposes: the production of electricity; water storage for irrigation, industry, or human consumption; flood control; and also navigation and recreation.

- The utilization of dams varies considerably according to country.
- Over one-third of dams worldwide are multipurpose.
- A key characteristic of dams is their longevity: some operating dams are over one thousand years old and the great majority of dams built in the nineteenth century are still operating fully today. The best utilization of many existing dams varies according to economic changes, and their operational targets may be usefully reviewed from time to time.

3.1 Hydroelectricity

Less than 15 percent of large dams produce electricity, but this percentage includes most of the world's highest dams and largest reservoirs. Roughly 50 percent of dam investments and 80 percent of relevant total water storage are devoted to hydropower. Most very large reservoirs are in unpopulated areas, such as in Canada or Russia, but large hydroelectric dams have been built in over 100 countries.

The total installed hydropower in the year 2000 was close to 700 000 MW for a yearly production of 2 700 GWH, which is 20 percent of the total electric production worldwide. Hydropower increases by three percent yearly, and achieving an annual total of 6 000 to 8 000 GWH by 2100 appears to be a reasonable target, with most of the increase being in developing countries.

High capacity electric lines favor large hydropower plants, but many thousands of mini or micro hydroplants have also been built around the world for local utilization. Hundreds of thousands of mechanical water mills had already been built some five hundred years ago using very small dams.

Hydroelectricity offers great advantages in electric networks to adjust the power supply to peaks or quick changes in power demand. Further facilities to very important networks may be offered by large power plants operating between two lakes at very different levels: these plants supply power during peaks of demand and pump water up to the higher lake during nights and weekends. They are generally in the range of 1 000 MW.

3.2 Water storage for irrigation, industrial, and human consumption

This storage is the essential purpose of over two-thirds of all large and small dams. The corresponding total storage may hardly be assessed exactly, as it is partly shared with hydropower in many large schemes. The relevant useful storage is in the range of 1 000 billion m^3, and is generally used for yearly storage, mainly for irrigation. The total investment in this storage is about one-third of dam investments.

In 2000, irrigation water taken from dams produced food for about 15 percent of the world's population (almost one billion people). It is estimated that during the first half of the twenty-first century, the population of Asia, Africa, and South America will increase by almost three billion people, and many further large dams may be built to provide food for them. In most of these countries, rivers are fully dry for half of the year. Water storage for industrial and drinkable water is thus a key target, one that is partly reached by existing dams, often through multipurpose schemes.

3.3 Flood control

Most river valleys are occupied by growing populations. Buildings and homes not threatened by the usual floods may be damaged by the highest floods of a century. Although weather forecasting and telecommunications have reduced human losses from floods the amount of flood damage continues to increase worldwide. The purpose of flood control is to reduce by 20 or 50 percent the peak flow value of these high floods.

Filling part or all of a reservoir's capacity during a flood peak may be cost-effective. Twenty percent of large dams are designed, partly or entirely, for this purpose, and many other dams have or may have a useful impact on flood peaks.

As one billion people will live in areas exposed to floods, the utilization of dams for flood control should increase. Past investment in this has been about 10 percent of total dam investments, but the value of avoided damages is much higher, particularly in countries such as China, the United States, and Japan.

However, although many flood control investments may be very cost-effective in the long term, they are often left unrealized. It is politically difficult to raise the money for them and to disturb local populations in order to avoid potentially high losses in 10 or 50 years.

3.4 Navigation

Five hundred large dams have been partly or completely built for navigation. They allow or improve heavy transport on many of the largest rivers around the world, such as the Nile, Yang Tse, Parana, Volga, Rhine, and Danube. These dams are most often special, low gated structures, and are sometimes called "barrages." One particular problem of such dams is to keep existing navigation facilities in operation during the various phases of construction.

Dam reservoirs may also be necessary to supply water for the operation of locks, for instance, on the Panama canal.

3.5 Recreation

Many small dams, and a small percent of large dams, are designed specifically for recreation. However, a great number of both large and small dams are actually used for tourism and recreation, even if they were not initially designed for this purpose.

4) Design and construction

4.1 General comments

The design of dams is a specialized and complex task for the following reasons:

- All dams are different.
- The consequences of dam failure may be disastrous.
- The force of water pressure is enormous.
- The level of acceptable leakage is low; usually it is in the range of liters per second, and often totals less than the losses by reservoir evaporation.
- The foundation is a key part of the structure and needs careful exploration and improvement.

- The control of floods is an essential element in dam design and may also be a difficult problem during construction on large rivers.
- The local seismic risk may modify the design.
- The impact of reservoirs on the environment demands special study.
- Almost all materials used for dams are local: their characteristics have to be identified and improved upon. Each dam's design is based upon the optimized utilization of its materials as well as upon the possible construction methods and the available equipment to transport and improve millions of tons of various materials.

The history and progress of dam design and construction, the state of the art today, and possible future trends are presented below for the main types of dams: earthfill, rockfill, gravity structures, and arches.

4.2 Earthfill dams

For many centuries, earthfill was employed in the construction of hundreds of thousands of small dams used for irrigation or water mills, built with materials close to their sites. Many reservoirs stored millions of m^3, but such dams were usually lower than 10^m, though this height was raised progressively. Dams in Japan reached 20^m in the eighteenth century, while in Great Britain industrial development led to the attainment of this height in the early nineteenth century. In the United States dam height for large reservoirs had progressed to 50^m by 1920. Little theory applied to all these dams but experience was obtained from the great number of structures and from many incidents and accidents.

Between 1920 and 1940 the United States had a key impact upon the development of earthfill dams through the analysis, testing, and treatment of soil, and through the development of heavy equipment for the transport and improvement of natural earth, such as trucks, motorscrapers, bulldozers, and heavy compactors. Other industrialized countries used such equipment for all their fill dams after 1950; between 1950 and 2000, 12 000 earthfill dams were built around the world, using heavy equipment. This figure includes 4 000 dams higher than 30^m and 100 higher than 100^m. Heavy equipment has not only improved cost efficiency but also quality and safety. The rate of failure for these dams has been three per thousand and the lessons of these accidents have improved the safety of the dams most recently constructed.

But since 1950, over 20 000 large earthfill dams (90 percent of which are lower than 30^{m}) have also been built by means of manual labor. These dams are located in developing countries, mainly China and other Asian nations. Much imagination has gone into using materials very close to the dams. This effort has been vital for agricultural development and flood control, but such quick construction has not allowed dam builders time to learn from experience. The rate of failure for such pre-1980 dams has been around three percent, as has the rate for the dams built before 1930 in industrialized countries. A large part of these failures in Asia are caused by exceptionally high monsoon floods. The safety of these dams increased sharply after 1980.

Such difference between construction methods may be explained by the enormous gap in labor cost: 10 or 20 US dollars per hour in industrial countries and 0.1 or 0.2 US dollars in many Asian countries, when the cost of fuel or equipment is not much different. However, the increasing cost of labor is likely to make the hand placement of fill too costly, and it is likely that in the twenty-first century all fill dams will be built using heavy equipment, with the possible exception of small dams early in the century.

A great advantage of earthfill dams is that they may be built upon soft soil foundations and may accept some settlement without serious drawbacks, whereas concrete dams usually require rock foundations.

Earthfill dam designs have to solve four problems of structure and foundation: mechanical stability, imperviousness, internal erosion, and external erosion.

Theoretical understanding of the mechanical behavior of fill dams is now well established, based upon great developments in the investigation, testing, and control of these dams. Stability is reached by reasonable slopes and the optimization of the amount of water content in fine material. This control and improvement of the quality of natural materials is the key to the development of fill dams.

In the great majority of earthfill dams, imperviousness is obtained by fine and most often clayey materials. Most old small dams were homogeneous but many medium-sized dams built in Great Britain in the nineteenth century had a central, thin, well-compacted clay core within a pervious dam body.

If very fine materials favor imperviousness, they may be gradually washed out in the case of local leakage. This internal erosion was the main cause of earthfill dam failure until drains and filters came into extensive use after 1950.

Another potential problem of earthfill dams is external erosion, caused by floods overtopping the crest. Many small clayey dams are able to withstand overtopping caused by small floods (with nappes 0^m3 deep), but larger floods certainly cause earthfill dams to fail, and non-cohesive fine materials cannot support overtopping at all. Floods have thus caused half of all earthfill dam failures.

Overtopping is prevented by using a special gated or ungated structure (built in masonry or concrete) to control floods. This structure, called a spillway, is presented in Chapter 4.8.

Many solutions and cross sections have been used to solve the problems of mechanical stability, imperviousness, and internal erosion. There are two main solutions employed today; their usage is determined according to dam height:

- For relatively low dams, homogenous cross-sections in impervious materials are complemented by a drainage mechanism made of sandy materials, which may collect water in the case of a possible leakage but which avoids erosion of the finest impervious materials (fig. 1). Alternately, the upstream part of the dam is made of impervious material and the downstream part is made of more pervious material.
- For higher dams imperviousness is insured by thin or by a thick internal clay core placed in the center or upstream part. To avoid internal erosion of the clay core, filters of coarser materials such as sand and gravel are placed between the core and the downstream body of the dam (fig. 2). Filters are also placed upstream from the core in order to avoid damage of the core when the reservoir is emptied quickly. Filters are rather costly and are more complicated to construct than the homogenous dam, but this solution proves safe: the failure of such dams by internal erosion has usually been caused only by foundation problems or by the careless treatment of special points such as embedded pipes in the dam body.

The construction of very large earthfill dams is an intricate matter, requiring complex organization. Hundreds of dams each require between ten and one hundred million of m^3 of materials. It is then necessary to choose, transport, spread in thin layers, and compact thousands of tons of natural materials per hour. Special parts such as filters need very important crushing and screening plants. As fill quality may be hampered by heavy rains or freezing, a schedule of works has to be designed and adjusted accordingly. For all these reasons the unit cost of a m^3 of fill dam is much higher than the cost of a simple earth excavation.

If the construction of a very large dams takes years, most medium and small dams are built during a few months of the dry season in order to avoid heavy rains and floods. Correspondingly, the rate of construction with heavy equipment is then in the range of hundreds of tons per hour. Typical designs are adapted to the local conditions; analysis and treatment of materials are simpler than for very large schemes but good quality materials are still necessary, however, and the principles of construction are still the same. When suitable natural materials are not available for imperviousness, filters, or drainage, using industrial geomembranes or geotextiles may be a good solution for dams lower than 30^m.

Earthfill dams will probably remain, in many cases, the preferred type of structure for both small and medium-sized dams, as well as for high dams built on soft foundations.

However, the economic and technical progress of rockfill and concrete dams during the last thirty years will open to them a large part of future medium and high dams, which are by far the most important dam investments.

4.3 Rockfill dams

There are about 2 000 large rockfill dams today. Ninety-five percent of them have been built since 1950. Most are higher than 30^m. Rockfill dams have been used for only two percent of dams lower than 30^m, but they represent 15 percent of higher dams and 25 percent of dams higher than 100^m.

In the mid-twentieth century there was great improvement in both the quality and cost of rockfill. New solutions and equipment for drilling and blasting in quarries considerably reduced costs. Spreading rockfill in the dam body in layers 0.50 or 1m thick and compacting it with heavy equipment improved the mechanical qualities of dams and reduced settlement to very low figures. Another advantage of rockfill is possibility it offers of working in very cold or rainy conditions.

A large part of rockfill dams use designs similar to the high earthfill dams. Imperviousness is also insured by a rather thin clay core but the upstream and downstream parts are of rockfill, not earthfill. Better mechanical qualities allow steeper external slopes and reduced quantities, and save costs overall. After 1970, the improved quality of rockfill has favored the development of a very cost effective type of medium and high dam, the Concrete Faced Rockfill Dam (C.F.R.D.), which also applies to dams well over 100^m (fig. 3). The whole dam body is in rockfill; construction is thus easier than with the traditional Earth Core Rockfill Dam. Imperviousness is insured by an upstream reinforced concrete lining about 0^m50 thick. The lack of rockfill settlement and the careful design and construction of reinforced concrete slabs insure the good quality and imperviousness of such dams. There is a trend towards extending – with caution – this answer to soft foundations, or to use coarse pervious natural materials such as gravel for the dam body instead of using rockfill. It is likely that in the future, this solution will be greatly used for dams over 30^m or 50^m high. However, the main risk for rockfill dams remains the possibility of overtopping caused by exceptionally high floods, as dams can be fully destroyed by a water nappe depth of 1^m over the crest: thus, the capacity of rockfill dam spillways should be the same as for earthfill dams.

Bituminous concrete has also been used as facing or as a diaphragm for about 100 rockfill dams with heights of up to 100^m. Using such diaphrams may be a cost effective solution, especially in very cold or very rainy climates, and may decrease the length of construction schedule.

4.4 Gravity Dams

Today, there are 4 500 large gravity dams – that is, rigid structures withstanding water pressure thanks to their own weight. Only 10 percent of all large dams are gravity dams. But within large dams higher than 30^m, this percentage rises to 25 percent.

Gravity dams comprise two percent of Chinese dams, but 50 percent of the dams in southern Europe. This great discrepancy maybe attributed not only to physical reasons (as gravity dams usually require rocky foundations) but to economic reasons as well.
The progress of gravity dams is clearly linked to improvements in cementitious material: lime or volcanic ash was used for 2 000 years, until cement was introduced after 1900. The history, design,

and state of the art of gravity dams are essentially linked to three different construction methods: masonry, classical concrete, and roller compacted concrete.

4.4.1

1 200 large gravity dams are masonry dams, usually lower than 60^{m}.

500 have been built before 1930 mainly in the most industrialized countries. Before 1900, cross sections were often too thin, as internal uplift pressures were underestimated and the quality of the foundations was sometimes unsuitable. The quality of the masonry was occasionally poor. Consequently, three percent of these dams failed either due to sliding in the foundation or breaches of the masonry.

Seven hundred masonry dams were built after 1950, mostly in Asia. Design was improved by better profiles, including inclined upstream faces and concrete upstream faces, and was better adapted to their foundations. Further, the increasing cost of labor in all countries shall lead to wider use of concrete gravity dams.

4.4.2

3 000 large concrete gravity dams were built between 1900 and 1980, all having about the same profile. Construction methods were progressively made uniform, reaching standardization around 1930.

The cross section of such dams is in principle the minimum volume profile that gives no tensile strength to the dam body under normal conditions (fig. 4). The upstream face is vertical although seismic or sliding risks occasionally makes some inclination preferable; the latter has sometimes been used in Asia. The downstream face is usually inclined at 0.8:1 and a minimum width is kept in the upper part for practical reasons. Construction is done in separate blocks about 15^{m} wide. Concrete is transported from batching plants by means of bins a few m^3 and placed by tower or cable cranes in internally vibrated layers about 2^{m} high. This gives optimum density, imperviousness, and mechanical characteristics; quality control is also much easier. Imperviousness is insured by the concrete dam body.

This type of dam proved to have the safest design with few failures before 1930, and only one such failure occurred among the 2 500 large dams built later. Very large structures were built, each using millions of m^3 of concrete.

Classical concrete dams have a great advantage over fill dams in that they support overtopping by floods. However, they require a fair rock foundation, while fill dams may be constructed upon soft materials.

The development of overly stringent dam specifications progressively increased construction costs for gravity dams. In industrialized countries, the construction costs for fill dams became very financially competitive in the mid-20th century, thanks to the use of heavy equipment. In developing countries, most dams built after 1950 were earthfill dams constructed using very low cost labor. Consequently, by 1970 gravity dams were essentially used only for special structures such as spillways or water intake for power houses.

4.4.3 Roller compacted concrete dams (R.C.C. dams)

From 1980 onwards, a practical change in construction method deeply modified the cost and design of many gravity dams. The use of earthmoving equipment to transport, spread in thin horizontal layers, and compact concrete allowed the retention of concrete's mechanical qualities while reducing cement content, cost, and construction time.

The space needed in order to use larger equipment means that this method of dam construction is not easily used for small dams, but 150 dams higher than 30^m had been built before the year 2000, first in the US and Japan, then all around the world.. These dams combine classical design and the roller compacted concrete construction method. Internal obstacles such as galleries have been avoided. As the risk of leakage is higher than with traditional methods, a watertight upstream facing is often used and may be made by the improvement of concrete characteristics and treatment on a width of 0.5 or 1^m. This method has been used for dams up to 150^m high.

Most often, the cross section of an R.C.C. dam is similar to the traditional cross section of a gravity dam with similar concrete performance. In addition, there is a trend to use a thicker and more symmetrical profile (fig. 5) with an upstream facing: the reduced stress permits reduced mechanical concrete performances, less cement, and cheaper material treatment. This type of dam construction has the advantage of being better adapted to weaker rock foundations (or even to soft foundations for low dams), to heavy earthquakes, and to any extra load due to unforeseen floods. Just as in the 20th century the earthfill dam showed itself to be adaptable to local conditions and available materials, so too will the gravity dam in the 21st century.

4.5 Arch dams

There are 2 000 large arch dams in existence today. Water pressure upon their structure is transferred to the banks by a horizontal arching effect. This type of dam requires a rather narrow valley and a good rock foundation, thus the number of favorable sites is limited.

Half of these dams were built in China after 1950, and are masonry arches 15 to 50^{m} high with vertical faces but variable radii and thicknesses. They usually possess an upstream imperviousness made of concrete or specially treated masonry.

There are 1 000 large concrete arch dams. Ninety percent have been built in developed countries, half of them in southern Europe. Concrete arch dams around the world represent two percent of dams lower than 50^{m} but 20 percent of higher dams and 50 percent of the 100 highest dams worldwide. As the strength applied to a horizontal arch ring is water depth multiplied by arch radius, arches over 50^{m} high are designed with a radius increasing from the bottom to the top of the dam: this imposes a double curvature shape, considerably reduces the concrete volume, and allows for an elegantly shaped dam.

This type of dam requires a specialized design and a very sound knowledge of foundation: their safety performance is close to that of concrete gravity dams.

4.6 Other dams

Some kinds of dam designs have been used and shall probably be abandoned in the future, while other kinds are, of course, likely to be developed.

4.6.1 Buttress dams and multiarches

Five hundred concrete buttress dams or multiple arch dams of all sizes were built in industrialized countries between 1910 and 1970. These dams had a lower concrete volume than gravity dams, and were constructed in valleys too wide for arch dams but possessing solid rock foundations. They had varied – and often elegant – designs, but they had the disadvantage of being vulnerable to local weaknesses in foundation or structure, and two percent of these dams failed. This, and the cost efficiency of R.C.C. dams, is likely to put such dams out of economic competition.

4.6.2 Hydraulic earthfill dams

A very economic way to transport large quantities of fine non-cohesive materials is to pump a mixture of soil and water. However, very strict precautions are necessary to obtain a safe structure and to avoid the risks of internal sliding, internal erosion, or liquefaction caused by earthquakes. This transport method was used in the U.S.A. during the early 20th century, but abandoned in favor of heavy equipment. It is traditionally used for many small and medium sized dams in the Yellow River Basin in China, where the silt content of the river flow is the highest in the world.

This method is also used all around the world in tailing dams, which are not studied in this report. These dams do not create reservoirs, but the water used to create mine tailing deposits creates small lakes, which exert force upon low or high tailing dams, leading to serious failure risks.

4.6.3 Composite dams

When different materials may be used with the same methods and equipment, it may be attractive to use them in the same cross sections.

When the cost of labor was very low, masonry and handmade earthfill dam construction methods were often used together; similarly, rockfill and earthfill dam methods that used the same heavy equipment were jointly employed in the construction of many high dams. It is then logical to associate roller compacted (R.C.C.) dams with mechanized earthfill or rockfill dams as they use the same equipment and access. The following solutions have already been tried and are likely to extend to many dams in the future:

- the downstream slope of low earthfill dams may be lined with R.C.C. to allow overtopping by floods
- R.C.C. spillways may be included in concrete faced rockfill dams (C.F.R.D.) profile
- possibly the most attractive solution may be to join a roller compacted concrete core with upstream and downstream earthfill or rockfill (fig. 6). This solution has many advantages and may also be extended to low dams. As earthfill is only used as deadweight it is particularly attractive if the quality or imperviousness of available earth materials are not suited for classic earthfill dam construction. It is easily connected with an R.C.C. spillway, and requires a rocky foundation. It is less expensive than an R.C.C. profile. It may be an especially attractive solution in countries with a low cost of labor.

4.7 Foundations

The foundation is a key part of dam design and construction:

- Two-thirds of masonry or concrete dam failures and 20 percent of fill dam failures have been caused by problems with their foundations.
- The cost of foundation treatments varies greatly and, on average, is in the range of 20 percent of a dam's total investment.
- The study of foundations is ever more complex than the study of dam bodies, as the foundation is a natural and often very heterogeneous material specific to each dam site. It has to withstand great stress, to be watertight at the right places, and internal erosion should be strictly avoided.

Most low dams are founded on soft soil and most high dams on rock, but this is not a general rule and many dams are founded partly on rock and partly on soil either in the deepest place or in the banks. Further, rock quality may vary considerably along each dam.

The principles of dam foundation studies were accurately defined by Terzaghi in 1929 : "To avoid the shortcomings … requires first of all expert translation of the findings of the geologist into physical and mechanical terms. Next it requires the evaluation of the most unfavorable mechanical possibilities which would be expected under the existing geological conditions; and finally to assume for the design of the structure the most unfavourable possibilities." These principles remain valid for the 21st century.

The study of foundations includes three parts:

- The investigation of the foundation, through geological analysis, seismic measurements, boreholes, permeability measures, and through laboratory analysis of soft soil or rock elements.
- The design of the dam, including the final choice of the dam type according to the foundation (or the decision to choose another dam site).
- The design of the foundation treatment, including the depth and the shape of excavation, rock improvement through grouting or anchorage, watertightness through grout curtains or concrete diaphragm walls, and drainage by tunnels or boreholes. (Drainage is as important as watertightness in order to avoid uplift and internal erosion.)

Great progress has been made since 1950 in the equipment used for the exploration and treatment of foundations, bringing essential tools for safety improvement and allowing dam construction on difficult foundations. The exploration and treatment of foundations down to 100 meters deep is now not uncommon.

It is also useful to underline, as for the dam body, the importance of instruments that measure, register, and monitor small movements, water pressure, and leakage. Great progress has also been made in this field: the total cost of such instrumentation is in the range of one percent of the investment.

4.8 Floods through dams: spillways

Most dam reservoirs are not designed to store the water generated by exceptional floods. The corresponding high flows are allowed through spillways:

- When the maximum flood peak is over 1 000m 3/s, most spillways are equipped with gates which are partly or completely open during exceptional floods. During normal operating conditions, these gates are closed and keep the reservoir level as high as possible. In the year 2000, the most typical spillway gates were sector gates placed in the upper part of the reservoir. The safety of gated dams requires careful maintenance and well-trained operators in order to avoid the jamming of gates or unadapted operation.

- Hundreds of very large spillways, and most spillways with flood peaks under 1 000m 3/s (i.e. the majority of large dams and almost all small dams), consist of ungated, horizontal, long concrete sills, allowing the free flow of floods with a nappe depth of a few meters. There are no problems with maintenance or operation, but the normal operating level is a few meters under the maximum level reached during exceptional floods. Useful storage is then reduced, often by 20, or even 50 percent, as compared with a gated spillway.

Instead of using a simple straight shape for free flow spillways, it is possible to use concrete walls with a layout in a labyrinth shape, which multiplies by 2 to 4 the flow for the same nappe depth. This solution may be very cost effective and specialy in countries where the cost of skilled labor is low.

The cost of spillways began increasing at the end of the 20th century, for the following reasons:

- Designs must now take into account floods more extraordinary than in the past.
- Extraordinary floods were routinely underestimated up until the seventies and eighties.
- In the future, most dams will be built in countries with intense rains.

Moreover, in the 21st century climate changes may impact the values of extreme floods.

There is consequently a trend towards using the solutions outlined above for floods with a yearly probability of 1/100 or 1/500, and to use cheap fuse elements that may bend, tilt, or be eroded by more extraordinary floods. Such elements may be replaced some time after the end of the flood. Many fuse solutions have been used, such as fusedykes, flashboards, and fusegates, especially in the US, China, and France. Fuse elements may also be used to increase the capacity of existing spillways.

Most small and medium dams may be built during a dry season when relevant construction works will not be disturbed by floods. But floods may disturb the works of more important dams on large rivers. The risks of damages due to exceptional floods over a partly built fill dam cannot be avoided completely: but human risks may be avoided. For very large rivers, the design of permanent structures is adapted to take into account the necessity of river control during construction. During the construction of a dam on a medium or small river, the flow is often diverted to temporary tunnels in the banks.

5) The Environmental and Social Impact of Dams

5.1 The Environmental Impact of Dams

Before 1970, studies of the environmental impact of dams were often too limited, as the environment was of little concern worldwide. Many old reservoirs would now be built differently and some would not even be built at all.

Environmental studies may identify and quantify the impact of a dam, as well as proposing ways to mitigate this impact and to improve the project. However, determining the impact of a dam is often a subjective matter: creating a lake, for instance, might be considered both as a welcome development or as a disaster; preventing flash floods might be regarded both as progress or as an unacceptable modification of an ecosystem. Indeed, some ecologists and environmentalists are systematically opposed to the construction of any dam whatsoever.

The main direct environmental impacts of dam reservoirs are the inundation of areas and the modification of river flows. In the year 2000, the total area of dam reservoirs was about 400 000 km^2, or one-third of the world's natural lakes area. Worldwide, this represents only one percent of the areas modified for agriculture. However, the relative impact of the total area of dam reservoirs is more important that this figure might suggest, as river valleys are attractive habitats for many plant and animal species.

Worldwide, there are 2 000 reservoirs over 10 km^2 each. They cover 300 000 km^2 collectively, and some individual dams are well over 1 000 km^2. However, 40 000 reservoirs of large dams, and all the reservoirs of small dams, have a unit area in the range of 1 km^2 or less. The scale and nature of impact are thus very different and it is unjustifiable to generalize about the impressive impact of very large reservoirs.

Dam reservoirs modify the volume and schedule of flow. This impact may be negative, if it reduces flow in the dry season; it may be positive, if it prevents flash floods and increases the natural flow during the dry season. Large reservoirs may also affect the existing water quality.

For large rivers and reservoirs, long term changes in ecosystems are thus unavoidable. Successful adaptation or mitigation requires careful study based upon worldwide experience.

The sedimentation of reservoirs generally has a negative impact, which is serious for 10 or 20 percent of dam reservoirs and may reduce their useful life to under 100 (or sometimes 50) years. One of the key subjects of future dam studies will be the reduction of the negative impact of sedimentation.

A very positive effect of hydroelectric dams is the saving of fossil fuel, which would be necessary in thermal plants. In the 21st century, hydroelectric dams built before 2000 and up to 2050 will save over 100 billion tons of fossil fuel (oil, coal, and gas).

5.2 Social Impact

Dam reservoirs naturally have a huge and direct social impact: through the year, they provide food and power, guarantee water supply, and control floods. They also have an indirect positive impact: they favor regional agricultural and industrial development and help prevent the migration of hundreds of millions of rural inhabitants to city slums, particularly in Asia.

However, many very large dams have had a very significant negative social impact: the resettlement of people from reservoir areas. In the second half of the 20th century over 20 million people have been thus affected, most of them in Southeast Asia. The costs and complex organization that resettlement demands was often overlooked during the sixties, but at the end of the 20th century and today, proper organization and fair amounts of money are usually devoted to this problem. In certain cases, resettlement receives 20 to 50 percent of a reservoir's total investment. The resettlement of hundreds of thousands of people requires long and special study, similar to the studies needed for the development of large cities. Resettlement may offer the opportunity to improve living conditions in developing countries, but it also brings conflict – particularly the reluctance of old people to leave their family homes. In the cases of some very large reservoirs, resettlement has raised special problems in regards to tribal peoples whose culture is bound to local conditions.

For some large river projects changes in flow may have a negative impact downstream, affecting fisheries or floodplain activities.

Although the impact of dams upon human health worldwide is largely positive (especially in regards to the water supply) some large reservoirs have provided environments favoring the development of tropical diseases such as malaria.

It should, however, be emphasized that over 90 percent of large dams have no negative social impact at all. Further, in the case of most of largest dams, resettlement – if well-studied and financed accordingly – may be conducted in a fair manner.

6) The Future of Dams

6.1 New Dams

The worldwide hydropower potential is 3 times the capacity of existing schemes.

Taking in account population increase and climatic changes, the need of water storage for irrigation or floods control will more than double along the 20th century as well as the need of dams.

The year rate of dam investment during the 1990s was consistent with rates through out the last half of the 20th century, but most construction has shifted from developed countries to developing countries. For dams, as for all other major infrastructure, safety has dramatically improved during the 20th century.

Most rich countries have already used a large part of the best available dam sites. Their populations are not growing and – well-supplied with water and energy – have little acute need for further dam construction, except in special cases such as drought in southern European countries or devastating floods in Japan. In addition, dam opponents actively attempt to prevent further construction. It is thus likely that the rate of dam development in these countries will be much lower in the 21st century than in the 20th, although the construction of many extra dams will still be justified.

The situation is the opposite in most developing countries. The global population is increasing by over 50 million people yearly. The need for energy, food, and water is enormous. In the developing world, 80 percent of cost effective hydropower resources have not yet been developed, storage possibilities are huge, and floods devastating. Governments wish to be self-sufficient in terms of food and energy, and consider anti-dam propaganda an act of economic war. Thus the countries that can build dams using their own technical and financial resources will probably do so intensively during for most of the 21st century, as China, India, Brazil, Turkey, Iran, Morocco, and other countries were doing at the end of the 20th. However, dam construction might also be slower for the poorest countries, as they will need external financial support. This funding is not favored by the anti-dam ecological movement or by alternative suppliers of food and energy.

It is thus likely that the annual dam investment rates of the late 20th century will extend into most of the 21st century, and will focus on fast growing countries where dams will help development. A forecast of the evolution of technical dams should thus take into account key points:

- Most future dams will be built in countries where labor costs are low (but likely to increase rapidly) and where rainfall and thus floods are relatively high.
- Earth dams will remain the preferred solution for small dams and many medium dams, but handmade earthfill construction – once common in the 20th century – will continue to disappear. It is likely that the use of geomembranes and geotextiles will increase for small dams.
- Concrete faced rockfill dams have a great future for dams over 50^{m} high.
- Masonry is likely to disappear except for some low dams. Progress is likely to be in relation to the development of roller compacted concrete under various shapes and natural characteristics: classical gravity profiles, thicker profiles more adapted to various foundations, and composite profiles. Designs should be optimized according to local conditions and available materials.
- Arch dams will have key advantages in a number of sites, especially for very high dams.
- Evolution may also be anticipated in design criteria and solutions used for flood control and spillways, for instance in the development of labyrinth walls for free flow spillways.

- Designs will take the environment into account more, even in terms of dam architecture. It should be easy, for instance, to give most low earthfill dams better placement in the natural environment by using a curved layout, smooth connections to banks, and grassing the slopes.

6.2 Existing Dams

The benefits of dams are high, but they are often far from maximized. Dams have a very long life span, and the economic conditions prevailing at their construction are very different after 20 or 50 years. Their optimal functions may vary, for instance, from maximum hydropower production to better flood control or irrigation storage. Safety improvements, modified management criteria, and sometimes storage increases, may be justified. Governments that spend huge amounts of money to build new dams should consider how to optimize existing dams. The yearly income of dams in 2000 was in the range of 200 billion US dollars. Studying, then optimizing, their capacities, targets, and operation may well be an extremely cost effective investment, complementary to the construction of new dams.

E O L S S

Art 2-12-01-01

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As contractor, F. Lempérière has been responsible for the construction of 20 dams on large rivers, including the Nile, Rhône, Rhine, and Zambezi, and has been involved in the design of several dams. A member of I.C.O.L.D., he has served as Vice-Chairman of the Committee on Technology and as Chairman of the Committee on Costs. He is Honorary Chairman of the French Committee on Large Dams, and also chairs HydroCoop, a non-profit association for the international exchange of technology concerning floods, dams, and spillways.

2.12.1.1 Figures :

TYPICAL DAM PROFILES

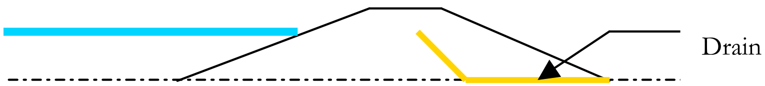

Fig. 1
LOW EARTHFILL DAM

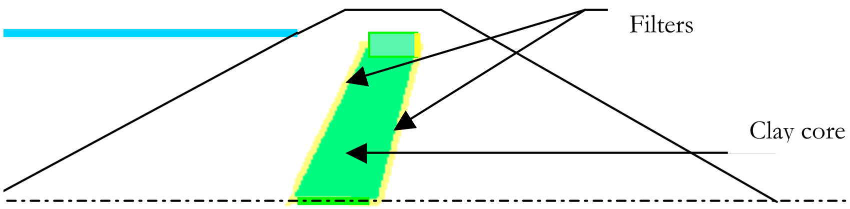

Fig. 2
EARTHFILL DAM

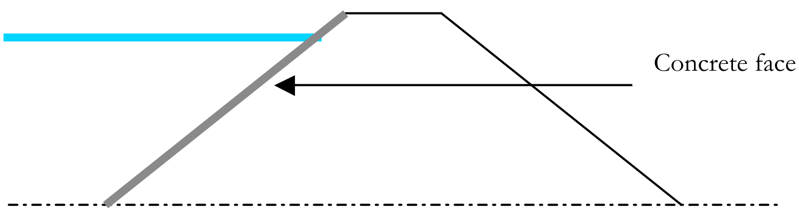

Fig. 3
CONCRETE FACED ROCKFILL DAM

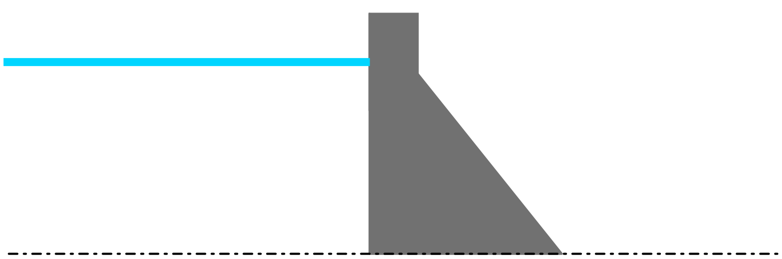

Fig. 4
TRADITIONAL GRAVITY DAM

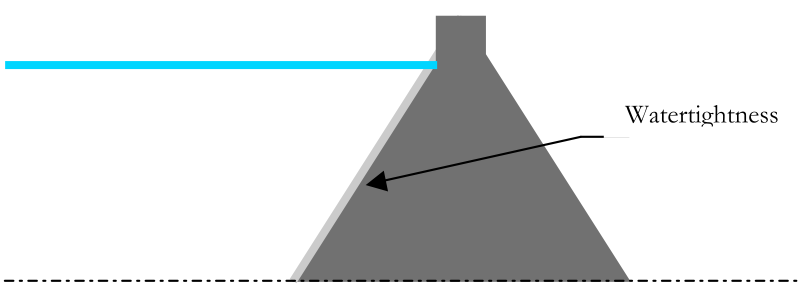

Fig. 5
ALT. GRAVITY DAM (HARDFILL)

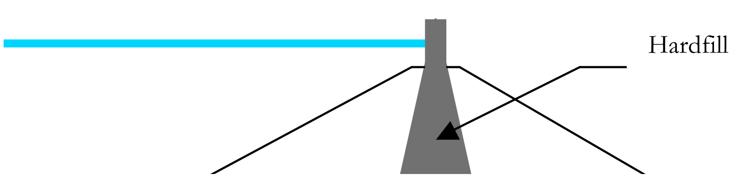

Fig. 6
COMPOSITE DAM
(EARTHFILL –