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Construction techniques and auxiliary facilities used in the construction of masonry and early concrete dams

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The evolution in the design and construction of dams —since the first dam building we know of— has been largely conditioned by three basic factors: Knowledge and use of materials, technological development and the scientific knowledge of each period. These three aspects are closely related, and it is very difficult to establish the precise role played by each of them through the course of history. However, it is possible to identify those periods in which the most significant progress was made in each of these fields.

As far as knowledge and use of materials is concerned, it was the Roman engineers and architects who improved and generalised the use of lime mortars, and began the addition of puzzolanic matters. The second relevant period in the use of materials was not to come until the end of the XVIII century, when J. Smeaton begins the first investigations which were to lead to L. Vicat manufacturing an artificial cement in the first quarter of the XIX century. The early decades of the XX century constitute what is known as the initial concrete phase, in which concrete for large blocks reached its maturity and gradually replaced masonry (Díez-Cascón and Bueno 2001). The second phase, which continued up until the 70s, saw the maximum state of development of conventional concretes. The final phase in the evolution of the concrete used for dam construction begins in the progressive development of rolled compacted concrete.

The technology of manufacture and building developed by the Romans builders, understood as the optimisation of resources, rational organisation of work and the «normalization» of procedures, was not improved until the end of the XIX century when the use of steam power spread to the machinery used in dam construction.

Scientific knowledge of the behaviour of dams includes the study of the laws which define both the behaviour of structures and their foundations, as well as the hydraulic performance of the outlets; disciplines which, because of their interrelation and dependence in the case of dams, must necessarily be studied together.

The first qualitative leap forward in the study of structural behaviour occurs in the second half of the XIX century, when Sazilly, Delocre and Rankine propose the first rigorous calculation methods based on the principles of rational mechanics.[1] The first decades of the XIX century were to see great advances in this field, with the appearance of the first modern methods for the structural analysis of different types of dams.

The hydraulic knowledge employed in the construction of the first dams is intuitive in nature and only partial. Research into this area begins in Italy during the XVI and XVII centuries,[2] and makes important progress in France during the XVIII century.[3] The XVIII century sees the emergence of great French and English engineers,[4] who direct their efforts at the theoretical study of fluid kinematics. The last great leap forward in the field of hydraulics

occurs at the beginning of the XX century when, through dimensional analysis and systematic experimentation, it focuses its attention on the study of local effects.

Studies relative to foundations are more recent. On the one hand Soil Mechanics begins in 1773 with the contributions of Coulomb, developing through the XIX century up until the boost given by Terzhagi in the first quarter of the XX century; while Rock Mechanics, emerging in Switzerland at the end of the XIX century, does not reach maturity until the mid XX century.

Hence, the first time in history when the advances in the fields of materials, technology and scientific knowledge in relation to dam construction really coincide is that which covers the period from the mid XIX century to the first decades of the XX century. This period of great advances implies for masonry dams the transition from masonry to concrete, along with a profound transformation of the auxiliary facilities and construction techniques. This paper centres on the relationship existing between the change in the material used and the evolution of facilities and construction techniques employed during this period.

The evolution of facilities and construction methods in masonry dams

Focusing solely on the advance in knowledge of materials and technology available, we can establish the following periods in the evolution of masonry dam design:

- Pre-technological period, up until 1850.
- Maximum development of stone masonry dams.
- The first concrete dams.
- The development of conventional concrete dams.
- The development of rolled compacted concrete, since the last quarter of the XX century.

Excepting the first and last stages, both the extension and the beginning, as well as the end of each of these periods varied between countries. In this paper we make a comparative analysis of the development of dams in the United States —which we use as the country for reference during the period studied —and in Europe.

Pre-technological period

This period, which covers from the construction of the first dams —the first references go back to the third millennium BC— to the mid XIX century, is characterised by the slow evolution in their design and construction (Schnitter 1994). The references available about auxiliary facilities and construction methods are scarce, and these can only really be studied by looking at the remains of dams still visible today and from the references available about other engineering work such as bridges, roads, etc.

It seems clear that in each period the construction techniques used were similar in all these types of construction, adapted to the volume and importance of each. Thus, animals were used for transport, while on the work site itself the positioning of materials was done manually, with the aid of pulleys, burtons and other similar devices for lifting when the weight was too great (Díez-Cascón and Bueno 2001). Figure No 1 shows a representation by a modern artist of a type of crane[5] —following a description written by Vitubrio— used by Roman engineers in their constructions to lift large blocks of stone. The facilities used to shift materials cannot explain the qualitative leap represented by Roman constructions, which could only be performed thanks to the rational organisation of building work and the development or improvement of other auxiliary facilities such as topographic and dewatering instruments.

The posterior improvement of Roman construction techniques and auxiliary facilities was very slow and it would probably be more precise to refer to the next centuries as a period of progressive perfection rather

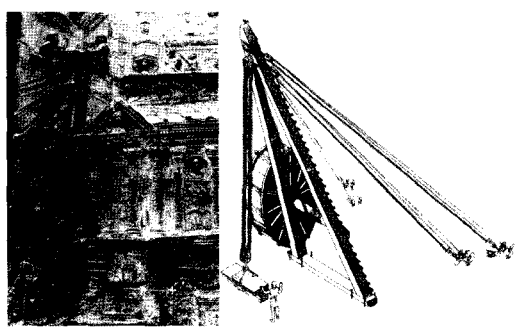

Figure 1
Roman Crane

than of evolution. As an illustrative example, figure No 2 shows the designs made by J. Betesolo and J. de Laguna for the cranes used in the construction of El Escorial, which differ from the Roman cranes only in the steel truss on which they stand, thus becoming a forerunner of present day cranes (García 1997).

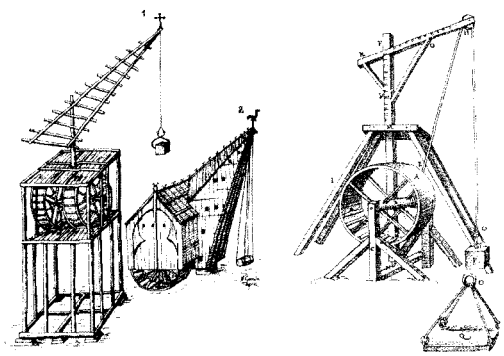

Figure 2
Crane designed for the construction of El Escorial. (Spain)

Analysis of the most representative dams of this period[6] allows us to affirm that they were not constructed thanks to any significant innovation or improvement in auxiliary facilities, which were still to be a long time coming.

Maximum development of stone dams

The auxiliary facilities and mechanical devices using animal power, workers or hydraulic power reached their peak development during the first half of the XIX century. The fact that the majority of dams were built far from population centres, combined with the scarce economic resources available for their construction were just some of the causes for the delay in application of steam power for construction with respect to other types of building work and industrial activities.

In the mid XIX century in Europe and the United States steam power begins to be used in dam construction for the operation of cranes, workshop and quarrying machinery, transport of materials and generation of electrical energy. Although this application is initially rudimentary and its use is very patchy —even within a single country— depending on the characteristics of each work, this fact and the start of the use of artificial cement mark the beginning of the fastest and most important advance up until then in dam construction. Thanks to the continuous technological improvement of auxiliary facilities and the quality of cements, the last quarter of this century and the first three decades of the of the XX century constitute the «golden age» of stone masonry dam construction, both with regard to the number of dams and the dimensions of the projects.

One of the direct indicators of the degree of technological development of the auxiliary facilities used in dam construction is the relationship between volume of the dam built and the manpower employed. The progressive increase in the cost of this manpower accelerated the development of better auxiliary facilities. The construction of the Pontón de la Oliva Dam[7] is a representative example of the massive use of manpower during the mid XIX century.

Despite being the most important hydraulic work in Spain at the time, the auxiliary facilities used were very limited. Up to four hundred animals, one thousand five hundred prisoners and two hundred workers were employed for excavation of the foundations; five hundred of them to manually pump out the foundation ditches, aided by four steam pumps (Bello 1929). The increase in manpower costs and the development of specific machinery for excavation and transport would make it possible, barely half a century later, to excavate the foundations of the great American irrigation dams, such as for example Eléphant Butte Dam,[8] using totally mechanised means.

Obtaining materials and transport to the site

In the mid XIX century, the location of the first masonry dams was almost totally conditioned by the existence of nearby stone quarries from which to obtain the necessary stone, both in the volume and the size required for stones and ashlars. The low density of land transport networks made it necessary to use beasts of burden –along roads and paths especially opened up for the purpose —in order to transport materials and the limited auxiliary facilities. Equally, the absence in the proximity of the dam of limestone

quarries to manufacture hydraulic lime made it necessary to transport it from the scarce factories existing. This meant a considerable increase in the cost of the work despite the poor dosage of the mortars and the reduced percentage per cubic metre of masonry.

The continuous improvement in quality of the artificial portland cements meant that the hydraulic limes and natural cements[9] fell into decline. The increase seen in the last decades of the XIX century in the dimensions of dams, and the richer dosage of mortars in stonework, means that the volume of cement rises considerably. These improvements in the materials used were not accompanied by significant improvements of transport facilities available, which on many occasions meant that it was necessary to set up artificial cement mills at the dam site. For the construction of the Rooselvelt Dam,[10] the lowest bid received from cement manufacturers for cement delivered at the dam site was $4.89 per barrel. The Reclamation Service found cement materials at the dam site and there built and operated a cement mill with a capacity of about 400 barrels per twenty-four hours. The mill operated for a period of about five years and three months with a total output of 338,452 barrels, the average cost being of $3.14 per barrel.

The reduction in manufacturing and transport costs, thanks to the technological development of the railways and other auxiliary means of transport, gradually generalised the external supply of cement for the manufacture of mortars and concretes. An illustrative example of the difficulties caused by the location of dams in largely inaccessible places, and the growing complexity of the auxiliary facilities used for the transport of the cement and of the equipment used for its construction, is the case of the Gem Lake Dam:[11]

> . . . where the cement had to be transported 500 km by wide gauge railway, 135 by narrow gauge, 110 along desert terrain, with caterpillar tractors, thus being brought to the machine house. It was then loaded onto a tram, covering 1500 m with a 375 m difference in altitude; it was then transported on barges across Gem Lake and was loaded onto another tram, upon which it climbed another 165 metres (Gómez-Navarro, 2: 989).

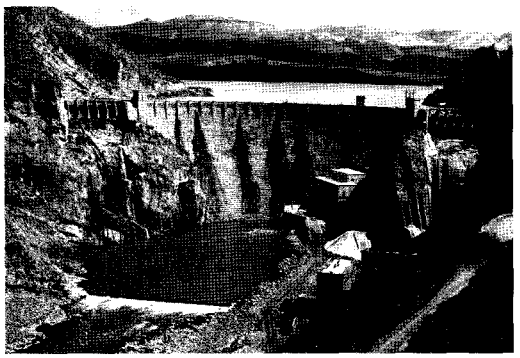

Figure 3
View of Roosevelt Dam. (USA)

The facilities and construction machinery available at the beginning of the XX century made it possible to easily construct long tracks —even in high mountains— for access to the dam site. In some cases in which the terrain was not too abrupt and the volume of material to be transported was important, sections of railway line were made especially; this system was limited —until well into the XX century— to the most industrialised countries such as Great Britain.

Possibly the «The Elan Valley Dams» constitute the group of dams which best define the state of technology at the turn of the century. These dams, constructed in the high moorlands of mid-Wales, would permit the water supply to the city of Birmingham by a huge pipeline over 70 miles long. The scheme, developed during the last decade of the XIX century and the first decade of the XX century, consists of six masonry gravity dams with well finished ashlar facing.[12] Although these dams do not stand out individually for their height, dam volume or water capacity, the most advanced auxiliary facilities of the time were used in their construction. Their joint planning, together with the organisation and optimisation of the auxiliary facilities, was to mark the pattern for masonry dams during the next four decades.

Before work could start on the construction of these dams, however, it was first necessary to build an extensive private railway network. This was required to transport the massive amounts of building materials and essential supplies needed at many sites, widely spread within the two river valleys. At the peak of the dam-building operation the network is thought to have extended to some 33 miles in length,

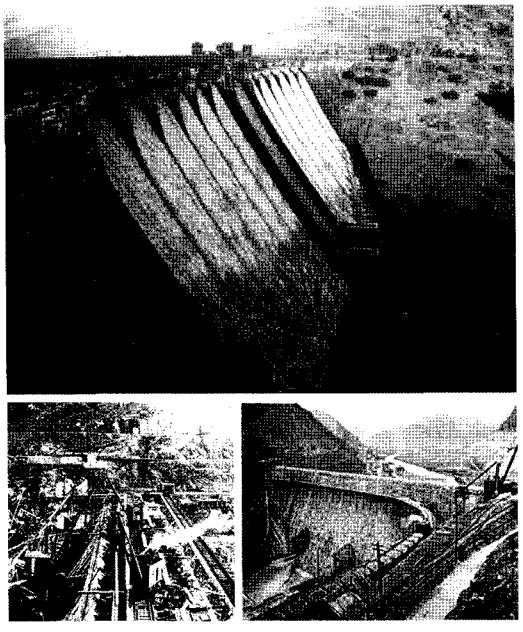

Figure 4
Construction of Elan Valley dams. (UK)

and eight saddletank locomotives were used to move about one thousand tons of building materials every day. Many of the branches of the Elan Valley Railway network ran along the bottom of the valleys, which were flooded after the completion of the dams. These linked quarries, cement sheds, workshops, and stone-dressing yards with the construction sites at the base of the dams. Temporary branch lines were also used at various levels, cut into the sides of the valleys for delivering stone and other materials as close as possible to where they were needed. So the layout was always changing as the work went on. A common practice for all the dams was to use a section of railway track cantilevered out from the face of the towering dam wall. These were supported by timbers resting on masonry pegs jutting out at regular intervals along the almost vertical dam wall. In spite of the danger, this arrangement was very successful.

Despite this progress, the transport of materials and of the auxiliary installations to abrupt terrain, devoid of any access routes, meant that more specific systems had to be developed. The construction of the Camarasa Dam[13] made it necessary to build a funicular railway 415 metres long and up a 22% slope to transport materials up to the cement plant located at the top of the slope. For the construction of the dam at Chambon in France a decade later, the scheme would be repeated using the most modern means and materials of the moment. The monocable funicular was 10450 m long, supported on 62 metallic towers up to 40 m in height. The maximum span between towers was 868 m and the height difference 535 m. The 193 dump cars, with a capacity of 250 Kg, were spaced at 120 m and moved at a speed of 2 m/s, which assured the transport of 15 Tn/hour (Gómez 1932).

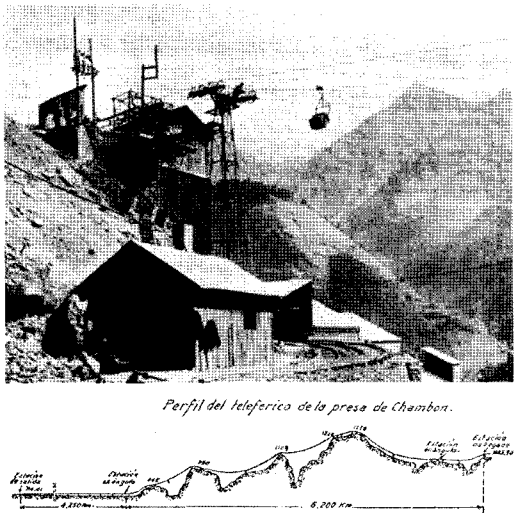

Figure 5
Monocable funicular. Chambon Dam. (France)

Transport of materials to the body of the dam

The correct organisation of the transport of the materials manufactured from the quarries, workshops and mixers to the dam site and their transport to the final worksite is more complex and more decisive from the point of view of the rhythm of construction than the transport of materials and facilities from the supply areas to the construction zone. It is probably in this phase where one can best appreciate the differences in technological development between countries.

The description of the facilities and methods used in the construction of the El Villar Dam —a spanish masonry dam 56 m. high and built between 1870 to 1879— is a significant example of the scarce introduction of mechanical power in the construction of spanish dams during the second half of the XIX century, despite the fact that the number of dams built and their dimensions was of great importance. The transport of materials to the site of the aforementioned dam was done by horses which descended the steep paths opened for the purpose, while the dewatering of the foundations was done using two Letestu double body pumps. The transport of stones and ashlars from the quarry, situated above the top of the dam, to the site was done using a system employed, with continuous improvements, in numerous Spanish dams and in the rest of the world. The ashlars were transported in wagons to the edge of the slope and they descended the slope on an inclined surface with two parallel tracks along which the ascending and the descending wagons circulated, the two being joined by a strong chain which went through a pulley situated at the top (Boix 1875). This same scheme, substituting manpower with electrical power or with power from internal combustion engine, would be repeated for various purposes in the construction of the Infante Jaime Dam and Príncipe Alfonso Dam, work on which was terminated in 1923 and 1930 respectively. Once the wagons which transported the heaviest stones reached the head of the dam, their distribution was done by a complex network of auxiliary rails to the cranes. This arrangement, which on occasions greatly complicated the work, was gradually simplified when the cranes used increased in capacity and other auxiliary facilities such as cableways appeared.

The construction methods used in other more technologically advanced European countries, followed similar schemes, but the results were far superior due to the use of much more specialised machinery and the massive use of steam power. In the construction of the Virny Dam,[14] barely ten years after the Spanish El Villar Dam, seven steam cranes were employed, each with an engineer, and eighteen men laid an average of 40 cubic yards per day. Another representative example are the dams of the Ellan River Valley, mentioned earlier, in which the transport to the dam itself was done using auxiliary rails, branching off from the main lines of communication between the different dams, and along which big wagons were pushed by locomotives.

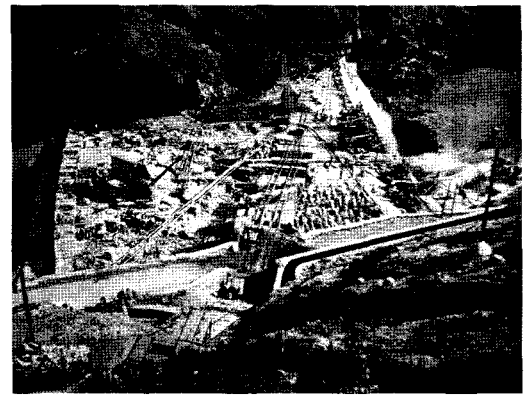

Figure 6
Construction of Camporredondo Dam. Inclined surface for the transport of materials to the damsite. (Spain)

In the construction of masonry and concrete dams during this period, the type of crane used in most cases is that known as a «derrick». This name, of American origin, has been applied by analogy to different cranes with similar mechanical systems and powered by different types of energy. The initial American scheme of the derrick crane was a long oblique arm, articulated at its base, and tightened at the top end to a tripod anchored to the ground, which permitted the base to turn and the load to be moved vertically. Both the tripod part of the crane, which was held in place by great blocks of stone, and the sloping mast were originally made of wood for ease of dismantling and of transport to other sites.

The evolution in the design of derricks —as to load capacity, mast scope and energy source— was very rapid as from the last two decades of the XIX century. However, this process was not equal in all countries; there was a clear difference between those countries which habitually used the most advanced cranes — the USA and Britain— and the rest, in which their use was limited to the most important dams. The factors which influenced this use were numerous and included the dimensions of the dam, the availability of other facilities to move the derrick from one site to another, the use in the construction of steam or electrical power, the maximum weight to be shifted and the characteristics of the site. This is the reason of

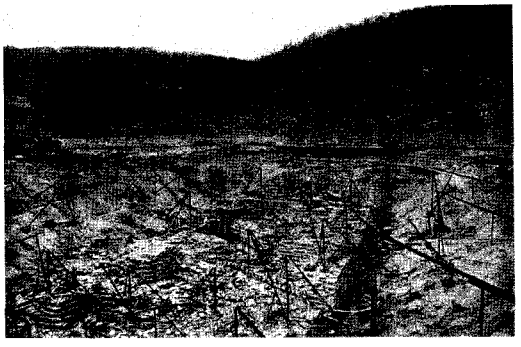

Figure 7
Construction of New Croton Dam. Arrangement of derricks. (USA)

the co-existence in a single country —and even at times on a single worksite— of technologically very different cranes.

Thus, the use of derricks operated by steam power was already common in England in 1885, and by the beginning of the XX century a degree of development in the use of cranes and other auxiliary facilities had been reached which was not surpassed in the first three decades of the century. The following quotation, in reference to the construction of the Ellan valley dams at the beginning of the XX century, reflects the degree of development of auxiliary facilities and their correct organisation on the worksite:

> It may be observed here, in illustration of the skilful organisation of these large works, where over 1,000 men are employed, that in the whole of the operations only seven horses are in use, though one or two more will be required later on as the work increases (Barclay 1898).

At the beginning of the XX century, the progressive increase in the number of derricks used in dam construction made it essential to study, prior to commencement of the work, the most suitable location for each of the cranes during the various phases of construction. Depending on the dimensions of the dam and the means used to move the derricks, these would be positioned outside the faces of the dams, aligned longitudinally beneath the cableways, mounted on rails or steel trusses which were imbedded in the interior of the body of the dam (Smith 1915).

No only did this increasingly intense use of auxiliary facilities increase the rate of construction, but it also modified the mentality of dam construction».In a few years the consideration of the facilities and installations as individual elements changed and they began to be seen as a planned group in which each fulfilled a function, did not hinder the rest and collaborated in the final result, appearing what could be called «The planning of Dam Construction». (Díez-Cascón and Bueno 2001)

La Peña Dam[15] is the first Spanish dam in which the perfect location of all the auxiliary facilities, the clarity in the realisation of the work and its general cleanliness stand out. The construction in Spain of the first great hydroelectric systems will accelerate this process since, unlike irrigation and flood defence work done by the State, private companies needed to make greater investment in auxiliary facilities and in the organisation of the work itself in order to reap benefits on capital in as short a time as possible.

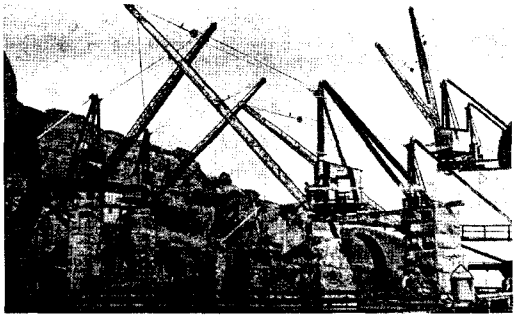

Figure 8
Construction of La Peña Dam. (Spain)

Power sources

Although the use of steam in the machinery used for dam construction is late compared with other industries activities, its use continues until the second decade of the XX century. British constructors were the first to systematically and intensively use steam, employing it to move small locomotives, cranes, and various workshop and quarry machines.

Early on, equipment powered by compressed air was found to be very valuable in the course of the

construction work. The air compressors were then known as «wind-jammers», and they made use of very long tubes to power tools at some distance from the steam-driven power source. This type of plant was used for drilling rock to make holes for dynamite, for drilling in quarries, and for use in metal working shops. An account written in 1898, referring to the construction of the Elan Valley dams, noted that: «so widely distributed is the plant that there are something like two miles of tube employed from the one station».

Technical and technological progress boosted by the First World War meant that from 1920 it was possible to introduce the internal combustion engine and caterpillars in moving machinery, while all engines were soon replaced by electric ones. From the third decade of the century diesel engines replaced electric ones in certain types of work.

Electrical power for operating machinery was initially obtained from small steam generators[16] and the construction of small hydroelectric jumps close to the worksite.[17] Later, the development of the large electricity networks meant it was easy to link up to them by means of auxiliary lines, which in some cases were extremely long.[18]

THE FIRST CONCRETE DAMS

The introduction of artificial cement in dam construction begins in the mid XIX century. Initially it was used individually or mixed with hydraulic lime, the first mortars being characterised by a very poor dosage of conglomerate. The need to increase the solidity of dams —increasingly large in size— and the fall in the price of cement due to increased production explains why at the end of the century masonry dams are constructed with cement mortars, and the dosages are more and more generous. At the turn of the century the first concrete dams appear,[19] thus beginning a process of transition which is to extend to the fourth decade of the century. From this moment, the construction of masonry dams will be limited to sites with special local conditions.[20] This process of evolution is led by the American constructors mainly because of the greater development of the American cement industry —which was able to adapt rapidly to new needs— and in part because of the lack of labour in rural areas.

This change in the material used is possible thanks to better knowledge of materials, but is also largely conditioned by the development of specific auxiliary facilities for getting the concrete to the worksite, without which the change would not have come about or would have taken much longer. This fact also explains the leadership of the Americans, since the greater European tradition for construction of masonry dams acts as a hindrance, by trying to apply the traditional methods used for positioning masonry on site to concrete.

The installations for the manufacture of materials were reduced in the case of masonry dams to the equipment needed for working the quarry, a storage area for the conglomerate and a manual or animal-powered mixer. The introduction of steam power permitted the later use of crushers to obtain artificial sand, sand washing equipment and automatic mixers with greater capacity.

This scheme is greatly complicated with the introduction of concrete, which makes it necessary to develope new and more powerful auxiliary facilities, which in turn require greater precision and reliability as they become the key to productivity in construction. Amongst this equipment the following are noteworthy:

- Crusher plant and facilities for washing and classification of dry materials.
- Silos for cement and dry materials.
- Sand, stone and cement mixers.
- Laboratory for control of materials.

The auxiliary facilities for the placing of the material on the dam used up until this moment are not suitable for this new material, and their adaptation for the simultaneous transport of concrete and a certain amount of large stones does not achieve the desired rate. This situation makes it necessary to develop new construction methods, to use new auxiliary facilities and to improve the existing ones.

The use of cableways to transfer the materials to the dam developed quickly in the first years of the 20th century; either for American masonry dams, as Pathfinder Dam and Roosevelt Dam, or cyclopean concrete ones. This system was first applied in Spain during the construction of La Peña dam. Cableways were the most economical machines possible in a large number or variety of cases. Besides handling the material with celerity and a minimum consumption of power they were available for many

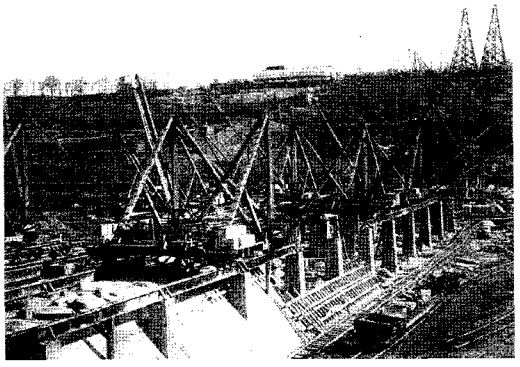

Figure 9. Construction of Kensico Dam. Arrangement of derricks and cableway towers. (USA)

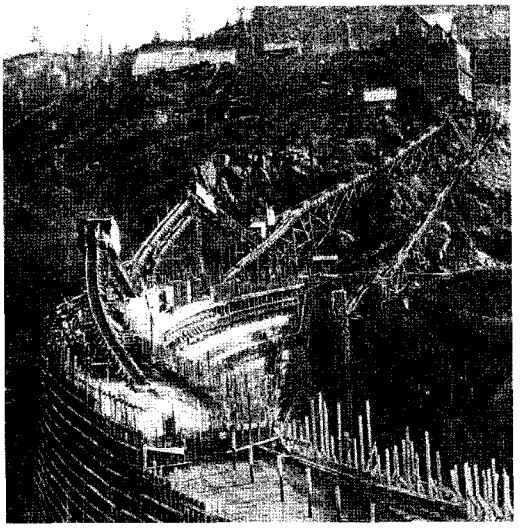

Figure 10
Construction of Spaulding Dam. Belt conveyor for concrete. (USA)

incidental operations such as erecting, moving, loading or unloading heavy items of equipment or material.

The first configurations of the cableway systems were very variable. They consisted of two or more parallel cables with fixed anchorages to towers placed in both ends of the dam. When the topography at the end of the dam permitted, they might be arranged so as to traverse up and downstream, for which purpose the towers and anchorages were mounted on trucks running on several tracks. This configuration was useful to reduce the number of cables needed. The load was transferred to the dam with the help of a hook —able to move vertically— connected to a carriage that travelled along the cables.

Another way of placing the material on the dam was the use of trucks running on tracks to the derricks that transferred the trucks to the place of use. This

Cableways used in the construction of some Spanish and American dams

Presa	Fecha	Height	Country	Length	No cables	Load
Sodom	1888–93	29 m	United States	203 m	2	6 ton
Pathfinder	1905–09	65 m	United States	107 m	2	15 + 10 ton
Cross River Dam	1905–07	52 m	United States	381 m	2	
Olive Bridge	1908–13	76 m	United States	468 m	4	
Owyhee	1928–32	127 m	United States	398 m	1	25.4 ton
Boulder	1930–36	221 m	United States	784 m	6	5 × 25.4 + 150 ton
Norris	1936	80 m	United States	586 m	2	18.3 ton
Talarn	1912–16	86 m	Spain	320 m	2	11 ton
Ricobayo	1929–34	95 m	Spain	310 m	4	11.5 ton
Cuerda del Pozo	1931–41	40 m	Spain	505 m	2	4 ton

method, similar to that used for masonry was only suited to very long, but not very high dams.

The way of delivering the concrete by chutes and belt conveyors was developed in the USA in the second decade. The concrete was elevated at some centrally-located tower, dumped into a hopper and then distributed by means of chutes, which were suspended from guys or from an arm or boom revolving in a horizontal plane about the tower as a centre. This method was used for the construction of the Lake Sapulding Dam, 1912, reaching a rate of 200 cubic yards per hour.

A system similar to the previous one consisted of the use of towers and chutes into which the concrete was poured with a quantity of water. This system was first used during the construction of Talarn, Camarasa and Montejaque Dams in Spain, Barbarine and Spitallamen Dams in Switzerland and Baker and O'Shaugneysen Dams in the USA.

Finally, in very long dams, a bridge or an auxiliary structure was built parallel to the dam and along which the materials travelled and from which they were poured onto or were transported to the body of the dam. During the construction of the Big Creek main dam, a construction trestle the full height and length of the dam was built in twenty six days just outside the upstream face, and coinciding with the line of the face so that the trestle timbers also served to support the forms. From cars running along the top of the trestle concrete materials were delivered to the twelve mixers installed within the trestle below; from the mixers wooden chutes conveyed the concrete to the dam.

With the use of concrete in the massive body of the dam, the importance of heat dissipation during setting increased considerably, becoming a major factor to be taken into account during construction. From this moment on it becomes necessary to use contraction joints, such that dams are no longer built as a solid block shuttered between two parameters of masonry, but rather as multiple blocks shuttered using wooden or metallic sheets. The need to alter shutters between the blocks and the fact of breaking the continuity between the different worksites makes it necessary to increase the number of auxiliary facilities and their aerial transport to the different parts of the dam.

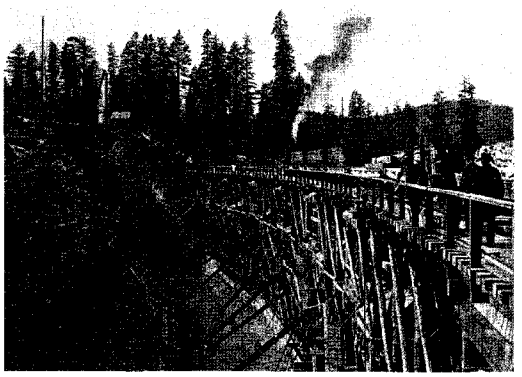

Figure 11
Construction of Big Creek Dam. Delivery of materials to mixers and delivery of concrete from mixers. (USA)

Conclusion

The analysis carried out of masonry and concrete dam constructions during the period from the mid XIX century to the first decades of the XX century shows the profound changes which took place both in the materials used and in the facilities and methods employed.

The relation between the change in material and the technological progress reached by the auxiliary facilities is two-directional. On the one hand the improvement and development of new auxiliary facilities would have been much less marked, since once the organisation and performance achieved in masonry dams reached its peak it would have made no sense to use more complex technologies. But at the same time, if the technological advances of the XIX and XX centuries had not taken place, then the use of artificial cement would have been reduced for many years to the manufacture of better quality mortars for masonry, and so the use of concrete in dam construction would have been delayed considerably.

Notes

1. The first applications of Rational Mechanic to the analysis and construction of dams were made in France in the period that covers from the mid XVIII to the mid

Performance of masonry and concrete:

Average rate of construction in some Spanish and American dams

Presa	Fecha	Height	Country	Type	Rate
Guadalcacín	1906–10	44 m	Spain	Rubble masonry	31 m^3/day
La Peña	1910–13	59 m	Spain	Rubble masonry	100 m^3/day
Buseo	1914	51 m	Spain	Rubble masonry	60 m^3/day
Talarn	1912–16	86 m	Spain	Cyclopean concrete	300 m^3/day
Infante Jaime	1916–23	37 m	Spain	Rubble masonry	50 m^3/day
Príncipe Alfonso	1922–30	76 m	Spain	Cyclopean concrete	150 m^3/day
Camarasa	1919–20	92 m	Spain	Concrete	650 m^3/day
Gallipuen	1927	38 m	Spain	Concrete	35 m^3/day
Jándula	1928–32	90 m	Spain	Concrete	600 m^3/day
Fuensanta	1933	83 m	Spain	Concrete	300 m^3/day
Ricobayo	1929–34	95 m	Spain	Concrete	800 m^3/day
Sodom	1888–93	29 m	United States	Rubble masonry	2295 m^3/month
Titicus	1890–95	33 m	United States	Rubble masonry	2480 m^3/month
New Croton	1892–1906	72 m	United States	Rubble masonry	13150 m^3/month (max)
Boonton	1900–06	31 m	United States	Cyclopean masonry	16065 m^3/month (max)
Pathfinder	1905–09	65 m	United States	Cyclopean masonry	3856 m^3/month (max)
Cross River Dam	1905–07	52 m	United States	Cyclopean masonry	14100 m^3/month (max)
Croton Falls	1906–11	53 m	United States	Cyclopean masonry	18525 m^3/month (max)
Arrowrock	1911–15	107 m	United States	Concrete	43 m^3/man/month
Owyhee	1928–32	127 m	United States	Concrete	140 m^3/man/month

XIX century, using profiles which can be qualified as «exiguous» and «mistaken» (Díez-Cascón and Bueno 2001).

2. Leonardo da Vici, Galileo, Catelli and Torricelli.
3. Bernouilli, Euler, Lagrange, Poleni and Bossut.
4. The French: Chezy, Navier, Cauchy, Saint-Venant, Darcy, Bazin and Boussinesq; and the English: Froude, Airy, Stokes, Reynolds, Rayleigh and Manning.
5. Reconstruction of the most powerful lifting machine, with an impulse wheel operated by five men, which appears in the funeral bas-relief of the Haterii family dating from the year 100 AD, discovered in a tomb near to the Porta Maggiore, in Rome (Adam 1989).
6. Some of the most important Spanish dams of this period are: Almansa, Tibi, Elche and Relleu dams (XVI and XVII centuries); the dams constructed by Villarreal de Bérriz (XVIII century) and the buttress dams of Extremadura (XVIII century).
7. Masonry gravity dam, 32 metres high over foundations, constructed in the period 1851–57 for water supply to Madrid.
8. Cyclopean concrete gravity dam, 81 metres high over foundations, constructed in New Mexico (USA) in the period 1911–16.
9. This transition process was far more rapid in the United States due to the greater dynamism of its cement industry.
10. Rubble masonry gravity dam, 86 meters high over

foundations, built on the Salt River (USA) between 1905 and 1911 (Chester 1915).

11. Multiple-Arch concrete dam, 23 m in height, built by the California Eddison Company about in California.
12. Four dams constructed in the valley of the Elan River — Caban Coch Dam, Careg-ddu Dam, Pen-y-Gareg Dam and Craig Goch Dam— and two more in the Claerwen River —Claerwen Dam and the unfinished Dol-y-Mynach Dam— just before the junction with the Elan.
13. Cyclopean concrete gravity dam, 102 meters high and a world record of the time, was built on the Segre River (Spain) between 1917 and 1920.
14. Cyclopean rubble masonry dam, Max. height 136 ft, built between 1882 and 1889 in Wales.
15. Cyclopean rubble masonry dam, 59 m high, built between 1910 and 13 on the Gallego River.
16. Known as «locomóviles» in Spain.
17. For the construction of the Spanish dam of Camporredondo, 76 m. high and finished in 1930, an auxiliary hydroelectric jump of 150 hp was built.
18. For the construction of the Spanish Jándula Dam, 88 m high and built between 1928 and 1932, an auxiliary cable run of 25 km was needed.
19. Amongst others the Spanish Regato Dam, built in 1897 ;and the American Shoshone Dam, built from 1903–10.
20. Such as India, China and the Spanish Canary Islands.

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