



Spanish Masonry Dams - Barrages en Maçonnerie en Espagne

Diego Saldaña Arce
Paris, 31th January 2012

Introduction

- ▶ Dam construction in Spain starts at the beginning of our era, when the whole Iberian Peninsula was already a Province of the Roman Empire
- ▶ Since then, dam construction has continued until today without significant pauses, with different rates and objectives depending on the period.
- ▶ The first concrete gravity dam -El Regato dam- was completed in 1898 but, however, the great majority of all dams constructed before the beginning of the Spanish Civil War (1936) were masonry gravity dams
- ▶ After the Civil War the use of masonry decreased quickly, except in the Canary Islands where it was used until the 1970s
- ▶ Earth dams have always been quite unusual and of little importance in Spain until the second half of the 20th century, except during the Roman Period. I am going to include them in this presentation so you can get a whole picture of Spanish dams



Cornalbo dam - 21 m (1st A.D.)

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El Regato dam - 20 m (1897)

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Camporredondo dam - 76 m (1930)

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Introduction

- ▶ In the research group on masonry dams from Cantabria and Burgos Universities, we have been studying the evolution of Spanish dams for the last ten years.
- ▶ First of all, we should clarify what the scope of our research is, or better said, *What type of dams do we mean when we refer to **masonry dams**?*
 - Until the 19th century, we mean traditional masonry dams, that is to say, those dams constructed with masonry work, ashlar work and ancient concrete
 - Since the beginning of the 20th century, we include both traditional masonry dams as well as those in which stone blocks are used for different objectives and with a very variable percentage
- ▶ As a result of this research, we have established four different periods in the evolution of Spanish masonry dams:
 - Roman Period (66 dams)
 - Middle Ages (27 dams)
 - From the 16th century to the middle of the 19th century (48 dams)
 - Since the middle of the 19th century (242 dams)
- ▶ For each of these periods, we have studied the following topics: **Dam Design**, Materials, Outlet Works and Construction Techniques

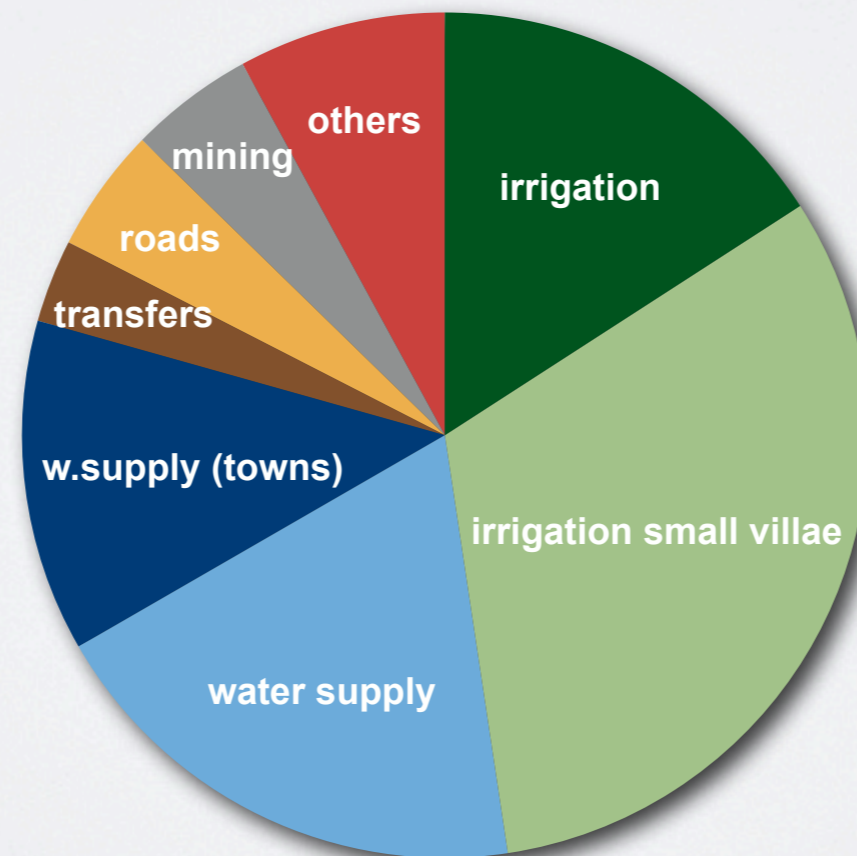


Roman Dams

Roman dams. General Aspects

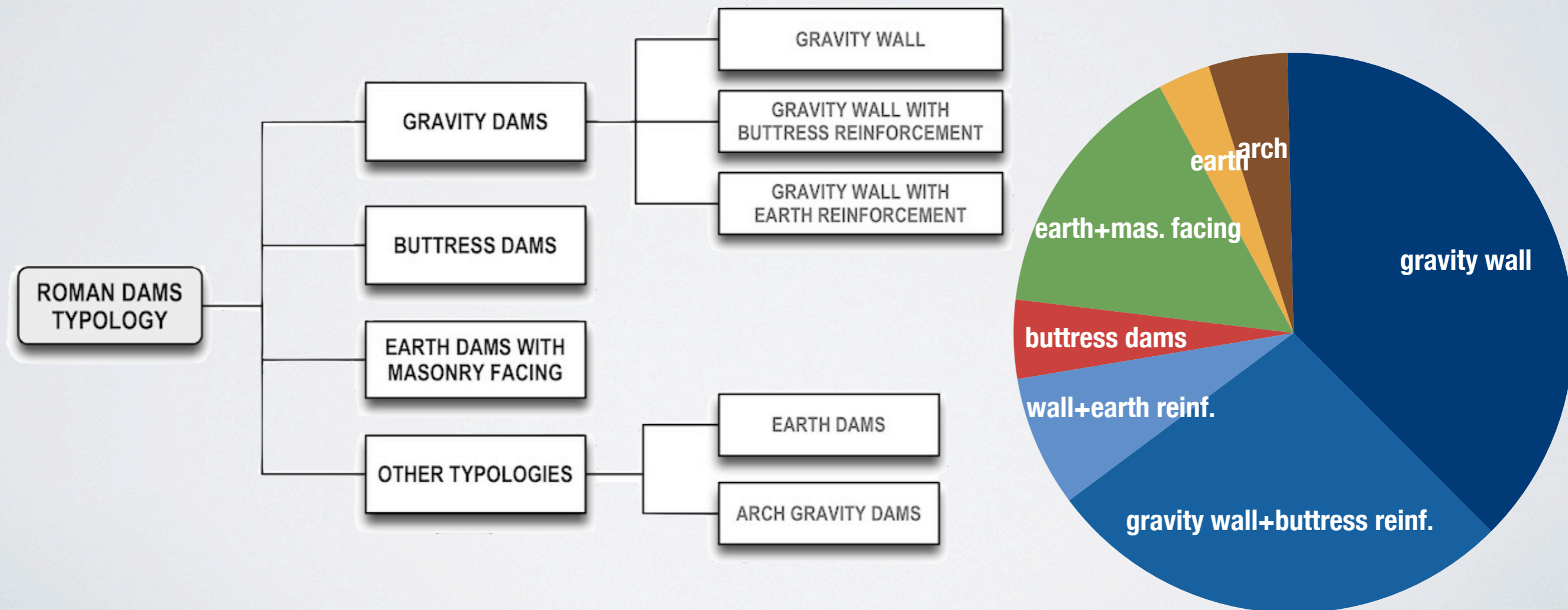
- ▶ Dam construction in Hispania begins sooner than in other Provinces, extending from the first century to the fall of the Roman Empire
- ▶ We know 66 dams -two of them still in use- which include all the kinds of typologies ever used by the Romans
- ▶ Some of these dams can be considered trials of new typologies, which would be used later in other provinces
- ▶ With time, the cumulated experience translated into choosing the best typology for each specific case

PURPOSE OF ROMAN DAMS



Roman dams design. Typological classification

- The typological classification that we propose for Roman dams:
 - Avoids mentioning the possible intentions of the builder, which we obviously do not know
 - Is based on the main resistant scheme of the constructed dam
- So, the typologies considered are the following:

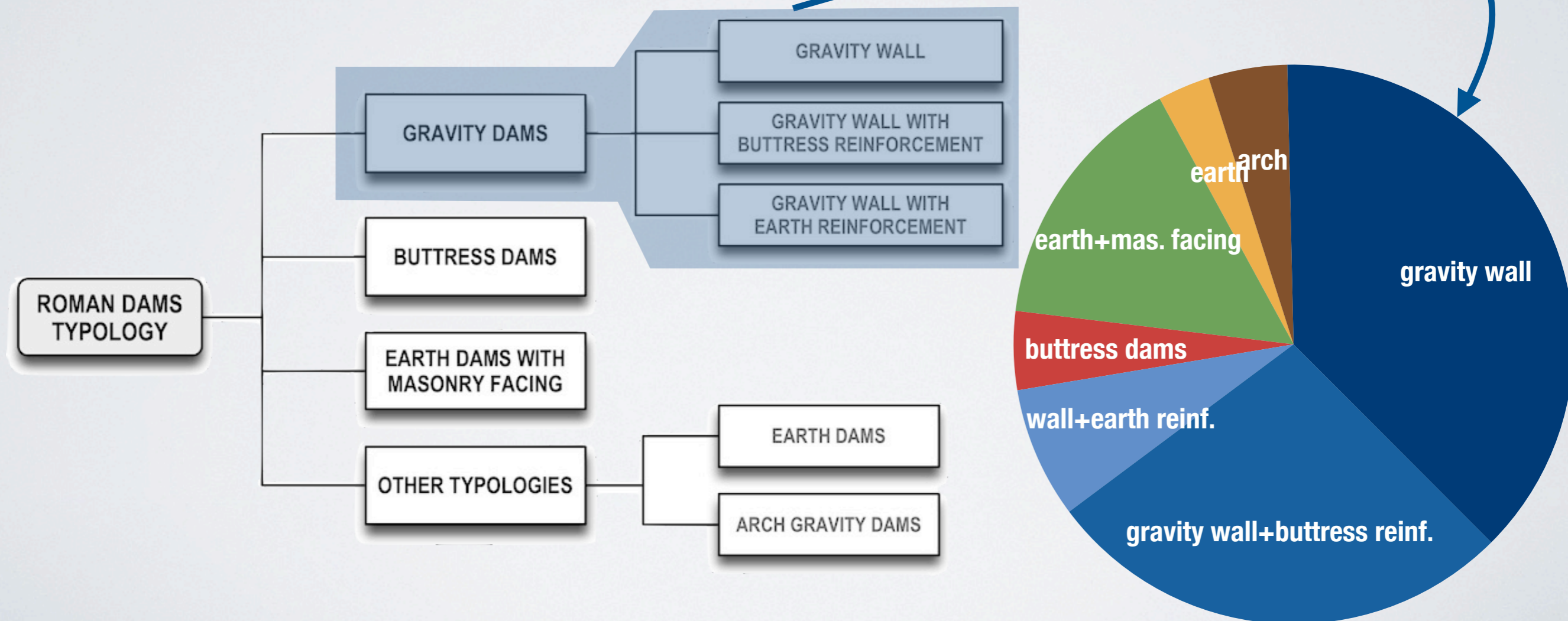


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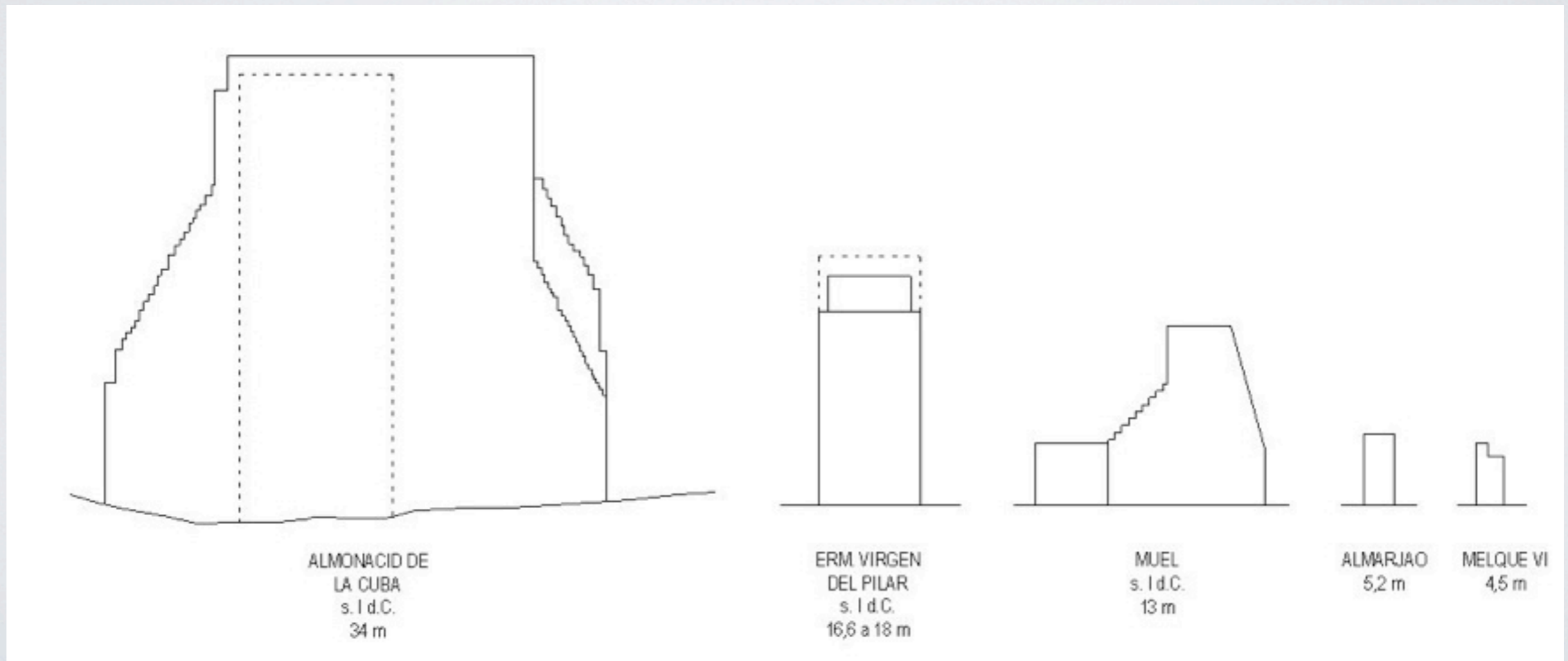
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Roman Dam Design. Gravity wall

- ▶ The simple gravity wall was the gravity typology most often used, 25 dams of this type being known
- ▶ The stability of these dams is based on the weight of a wall with a **rectangular** cross section
- ▶ These dams show a very variable width and height relation (between 0.4, and 2.0)
- ▶ The gravity wall was used for both large and small dams (from 0.8 m to 34 m)



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Moracantá dam - 2 m (2nd Century A.D.)

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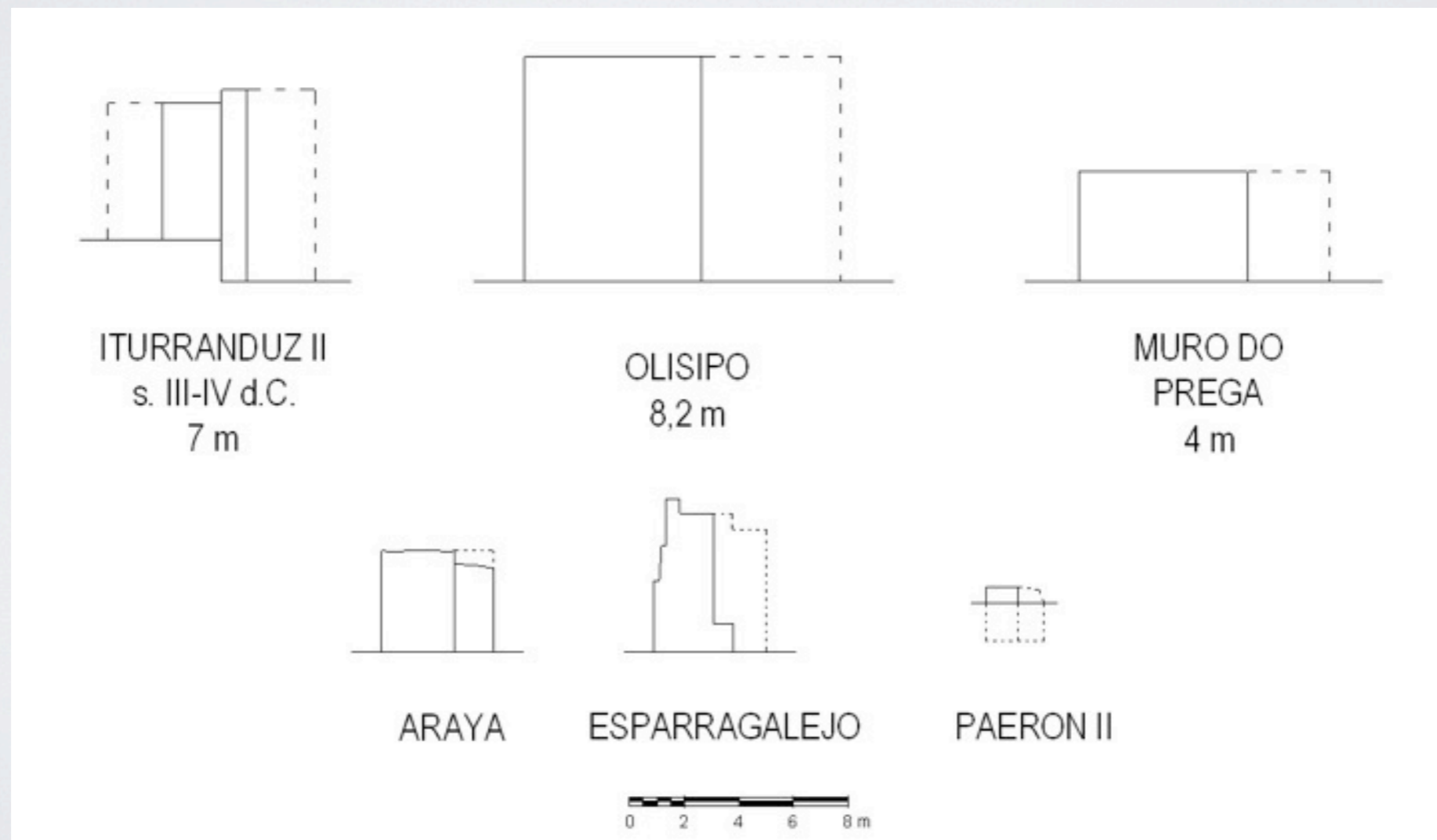
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Almonacid de la Cuba dam - 34 m (1st Century A.D.)

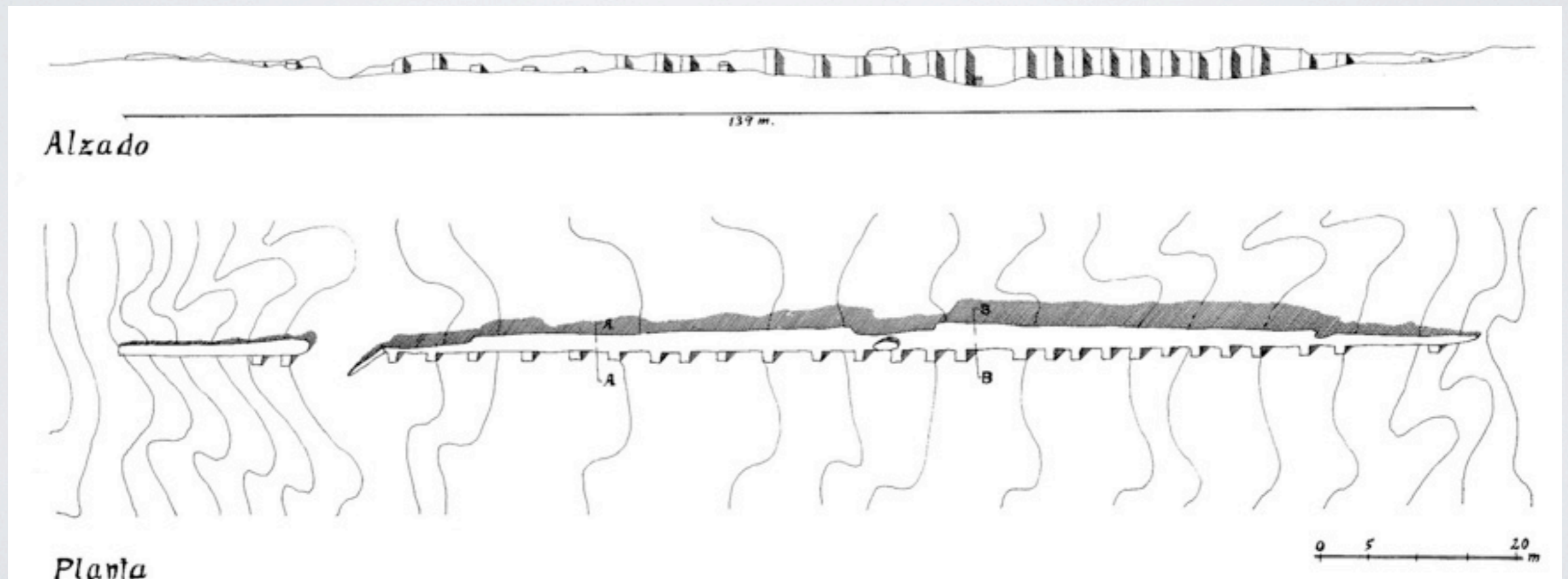
Roman Dam Design. Gravity wall with buttress reinforcement downstream

- ▶ We know 18 dams which were reinforced by Roman engineers, with the addition of buttresses downstream
- ▶ These buttresses were usually placed in the central zone, depending on their contribution to spacing and wall slenderness
- ▶ This typology was generally used in small or medium sized dams



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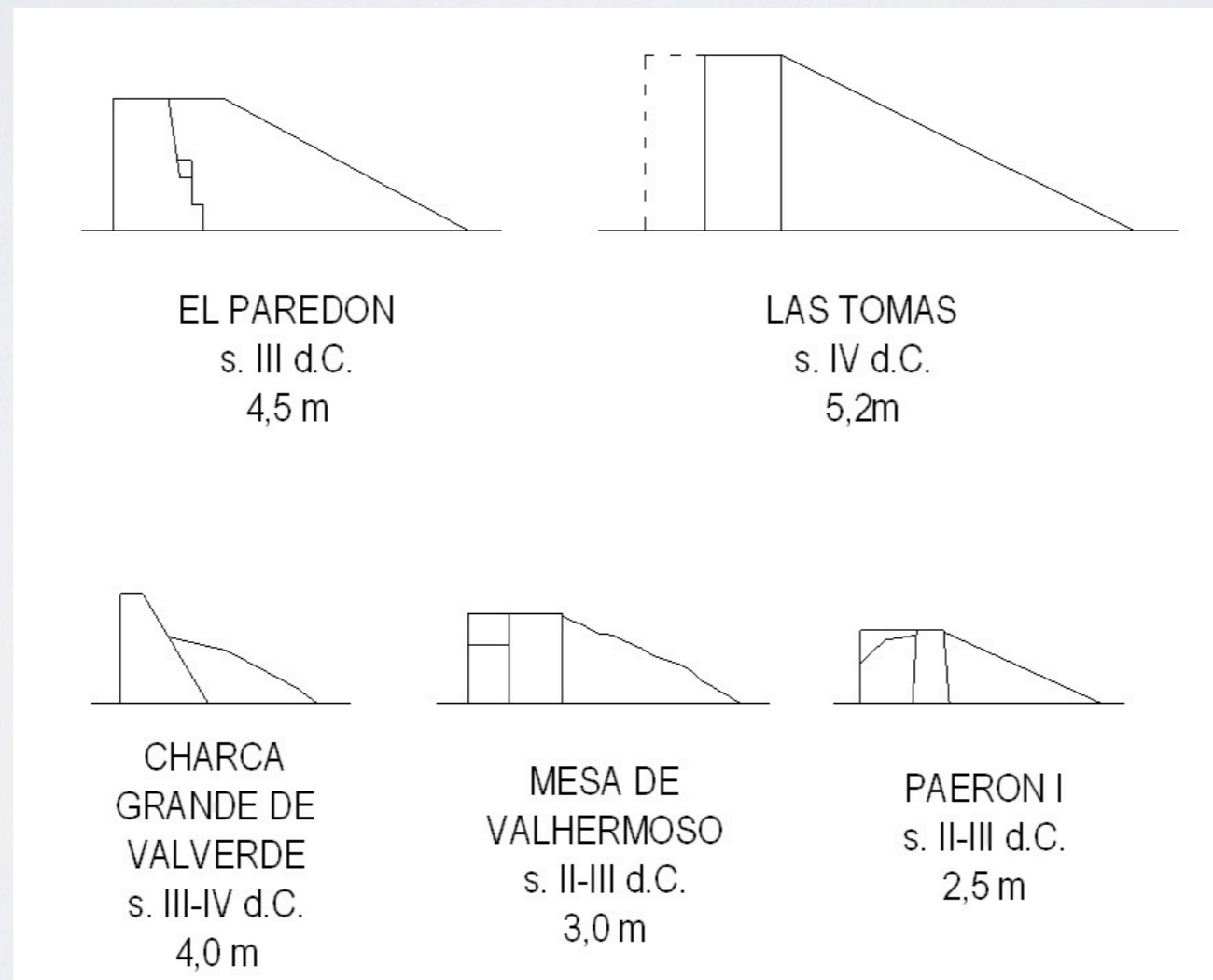
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Araya dam - 4 m (2nd Century A.D.)

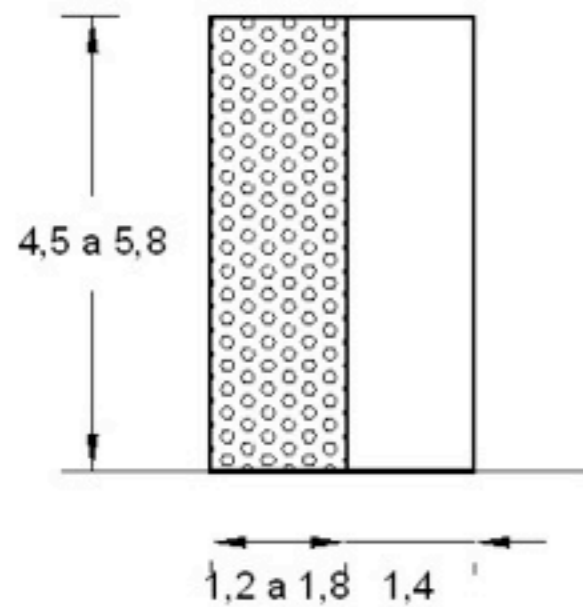
Roman Dam Design. Gravity wall with earth reinforcement downstream

- ▶ Another way to reinforce the rectangular gravity wall consisted in the addition of an earth embankment downstream
- ▶ We have identified 5 dams of this type whose height, as in the previous type, is rather small
- ▶ The width and height relation is smaller and less variable than in the case of a simple wall

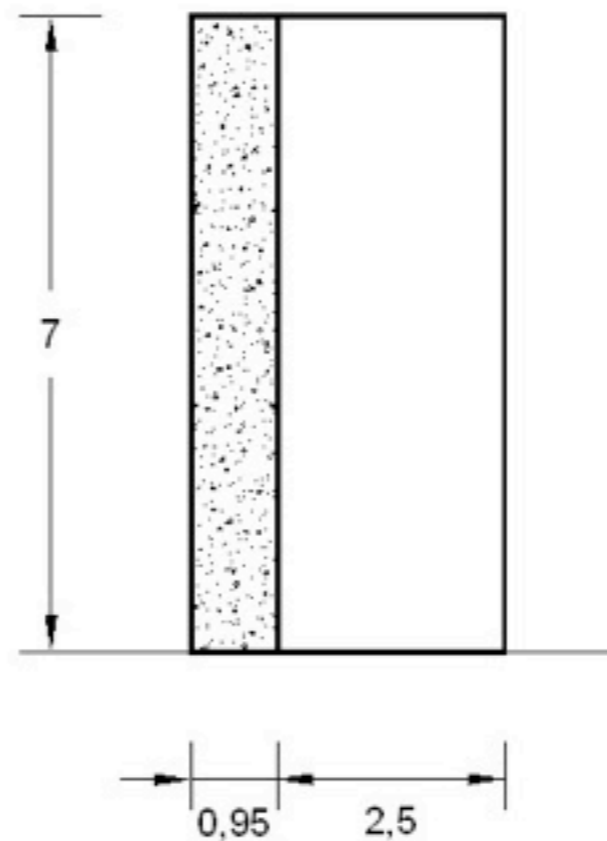


Roman Dam Design. Buttress Dams

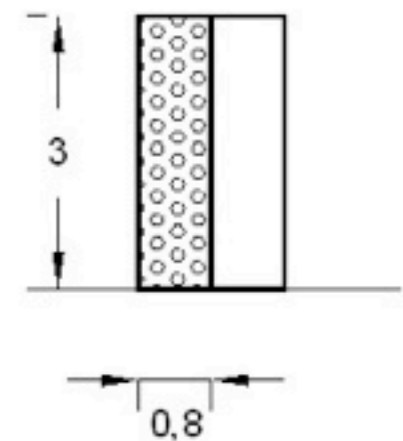
- ▶ The second typology considered is the buttress typology, of which only 3 dams are known
- ▶ Width and height relation is much more reduced in this case (from 0.15 to 0.27)
- ▶ So the buttresses contribution is indispensable to guarantee the stability of the slender wall
- ▶ This scheme was used in medium sized dams, wich probably collapsed shortly after being built



CONSUEGRA



ITURRANDUZ



OLIVA

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Iturranduz dam - 7 m (2nd Century A.D.)

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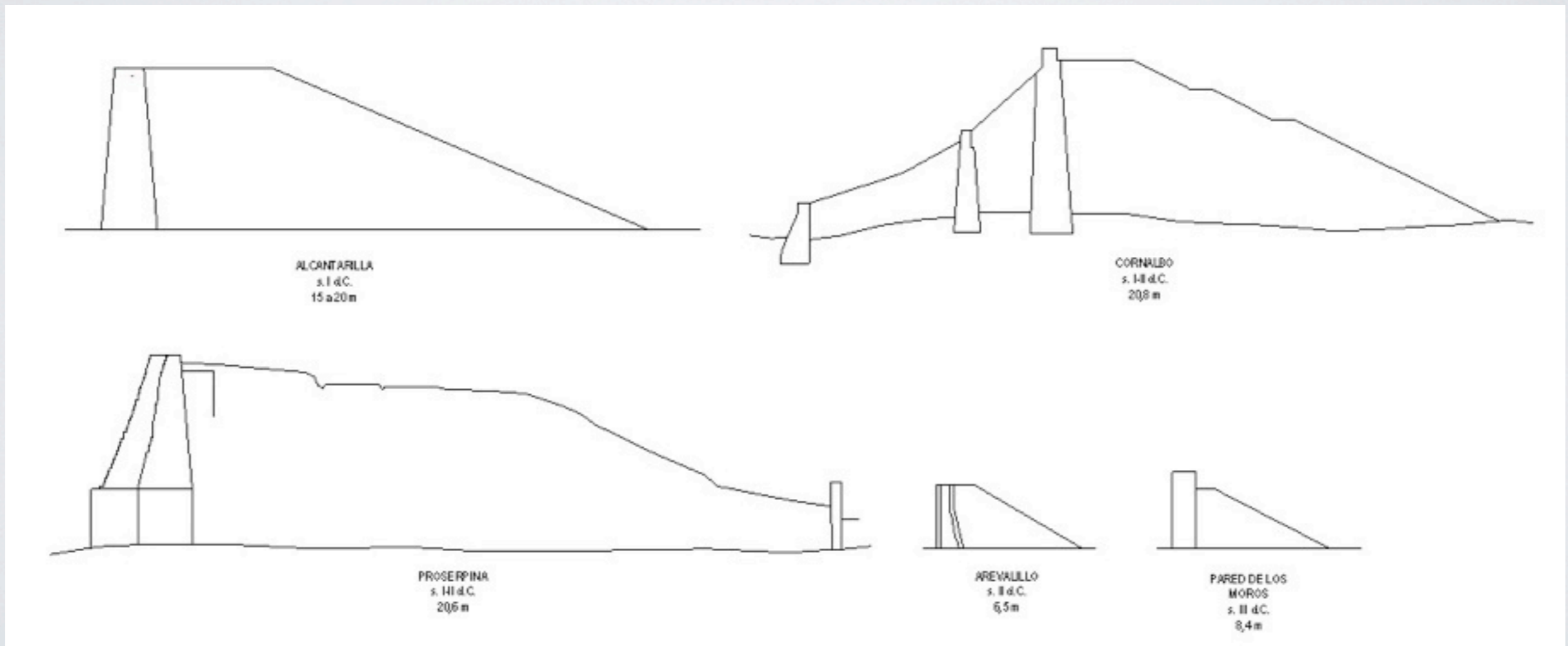
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Consuegra dam - 6 m (3th-4th Century A.D.)

Roman Dam Design. Earth dam with upstream masonry facing

- ▶ The third typology considered could be named “earth dam with upstream masonry facing”, 10 dams of this type being known
- ▶ In this case there is a clear difference between the objectives of the masonry facing (imperviousness) and the earth embankment (structural)
- ▶ In earlier times this typology was used in large dams, including up to 20.8 m high dams



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Alcantarilla dam - 18 m (1st Century A.D.)

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Proserpina dam - 21 m (1st-2nd Century A.D.)

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Cornalbo dam - 21 m (1st-2nd Century A.D.)

Roman Dam Design. Other typologies

- ▶ We only know two **earth dams**, which in any case would have been very scarce and difficult to identify nowadays
- ▶ **Arch dams** were also unusual, only three dams being known, the origin and dimensions of which have not been clearly established



Iruña dam - 7 m



El Hocino dam - 18 m

Roman Dams. Materials

- ▶ Roman builders mastered the use of construction materials, especially conglomerates and concrete.
- ▶ Six different types of masonry were used in dam construction
- ▶ A deeper knowledge of the potential of each type of masonry translated into the use of **homogeneous** walls for small and medium sized dams, and **multilayer walls** in the case of large dams

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OPUS CAEMENTICIUM

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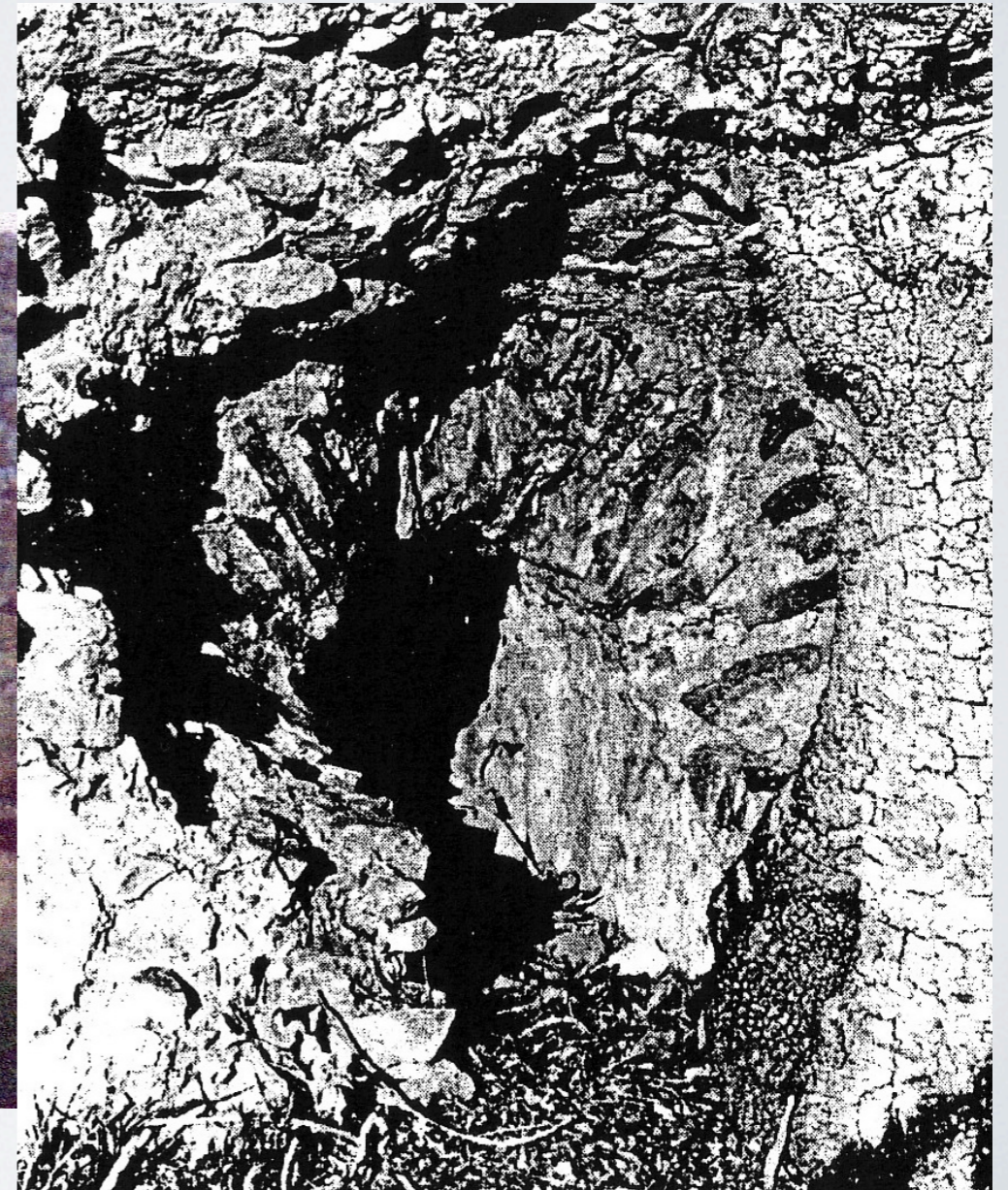


OPUS SIGNINUM

Roman Dams. Materials

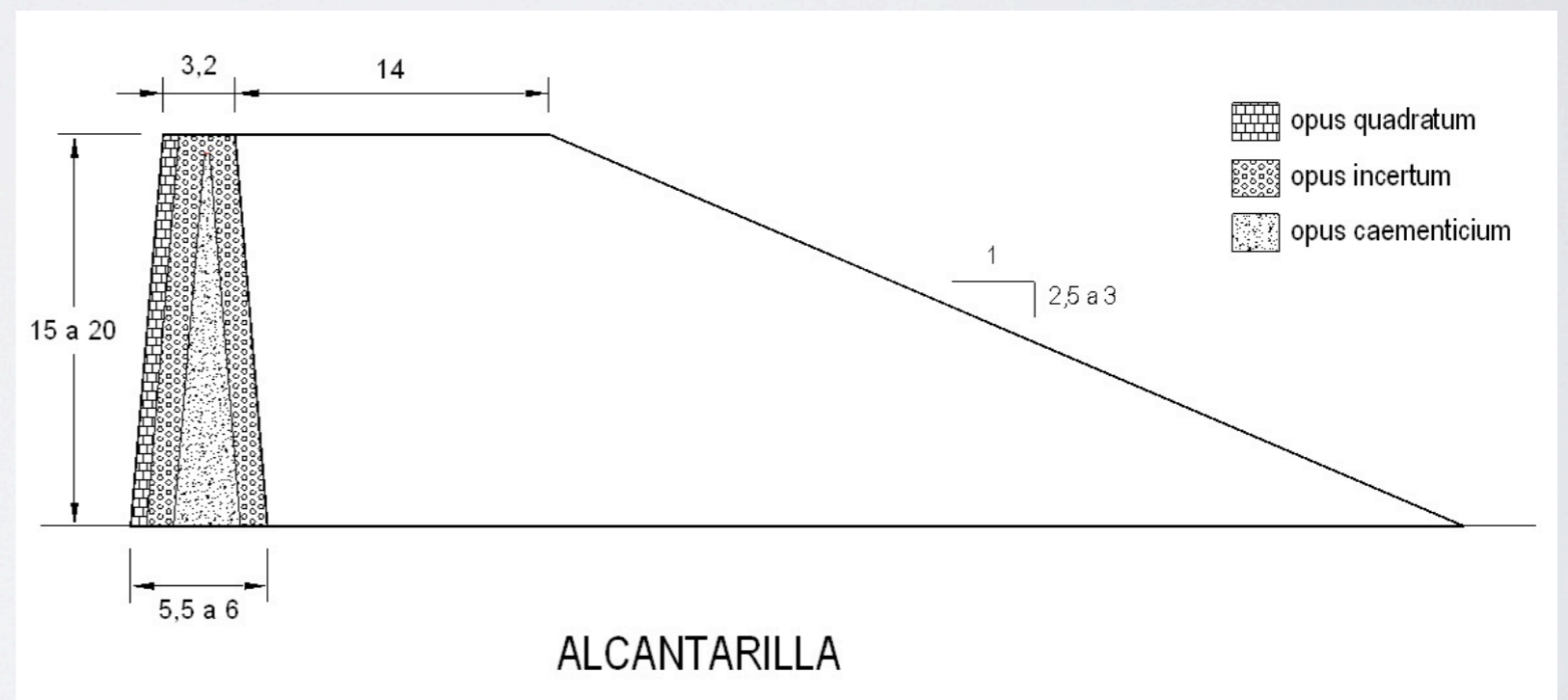
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OPUS TESTACEUM



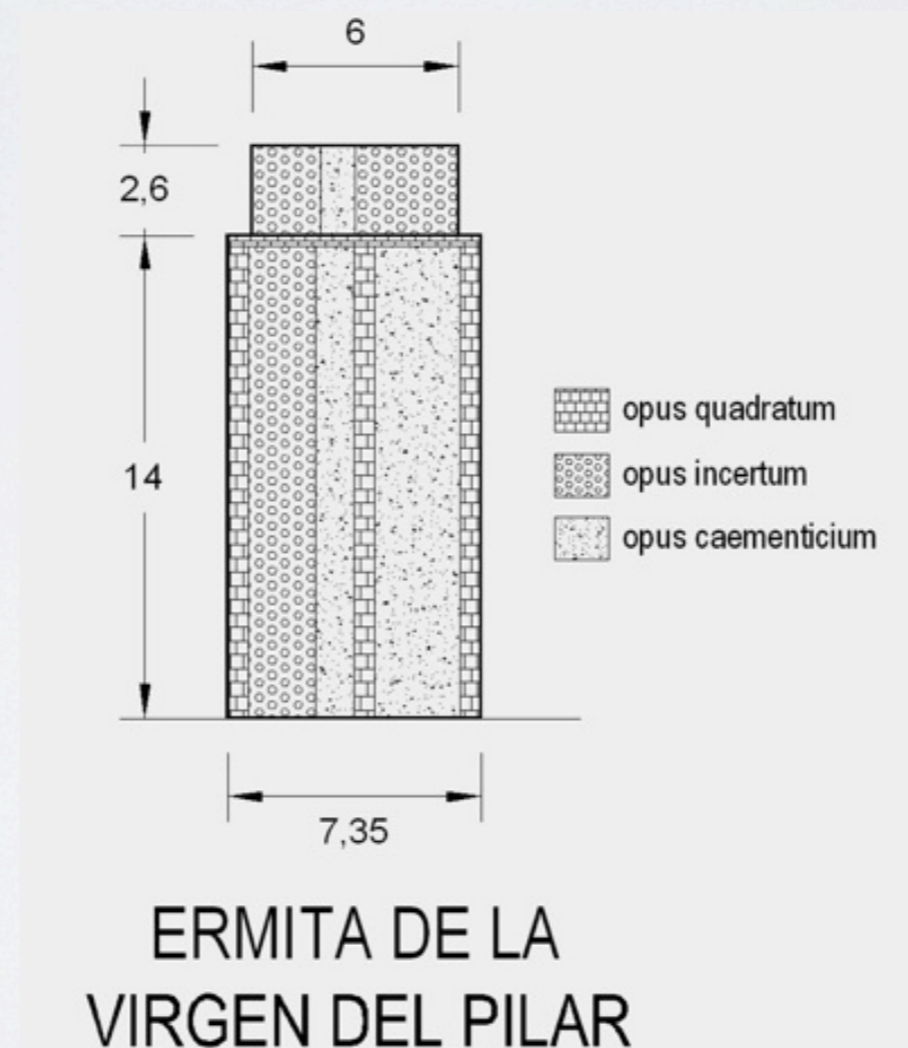
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Roman Dams. Spillways and Intake works

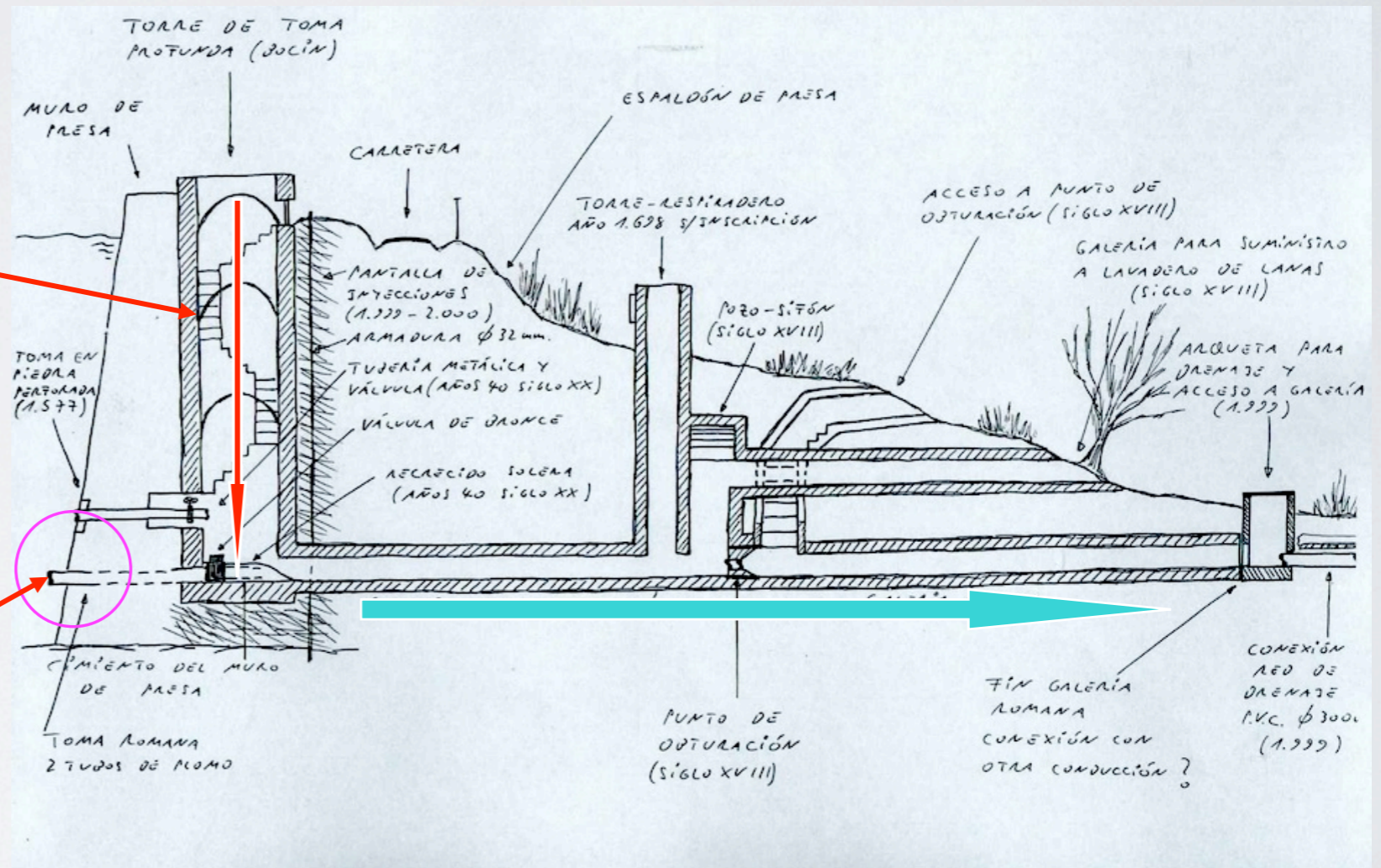
- ▶ **Spillways** in Roman dams were designed with a pragmatic approach
- ▶ In rivers carrying much water, engineers used thick cross sections plus larger **spillways**
- ▶ In all dams over 5 m high (except for one) an **intake tower** was placed, which could be located either downstream or upstream, or inside the reservoir



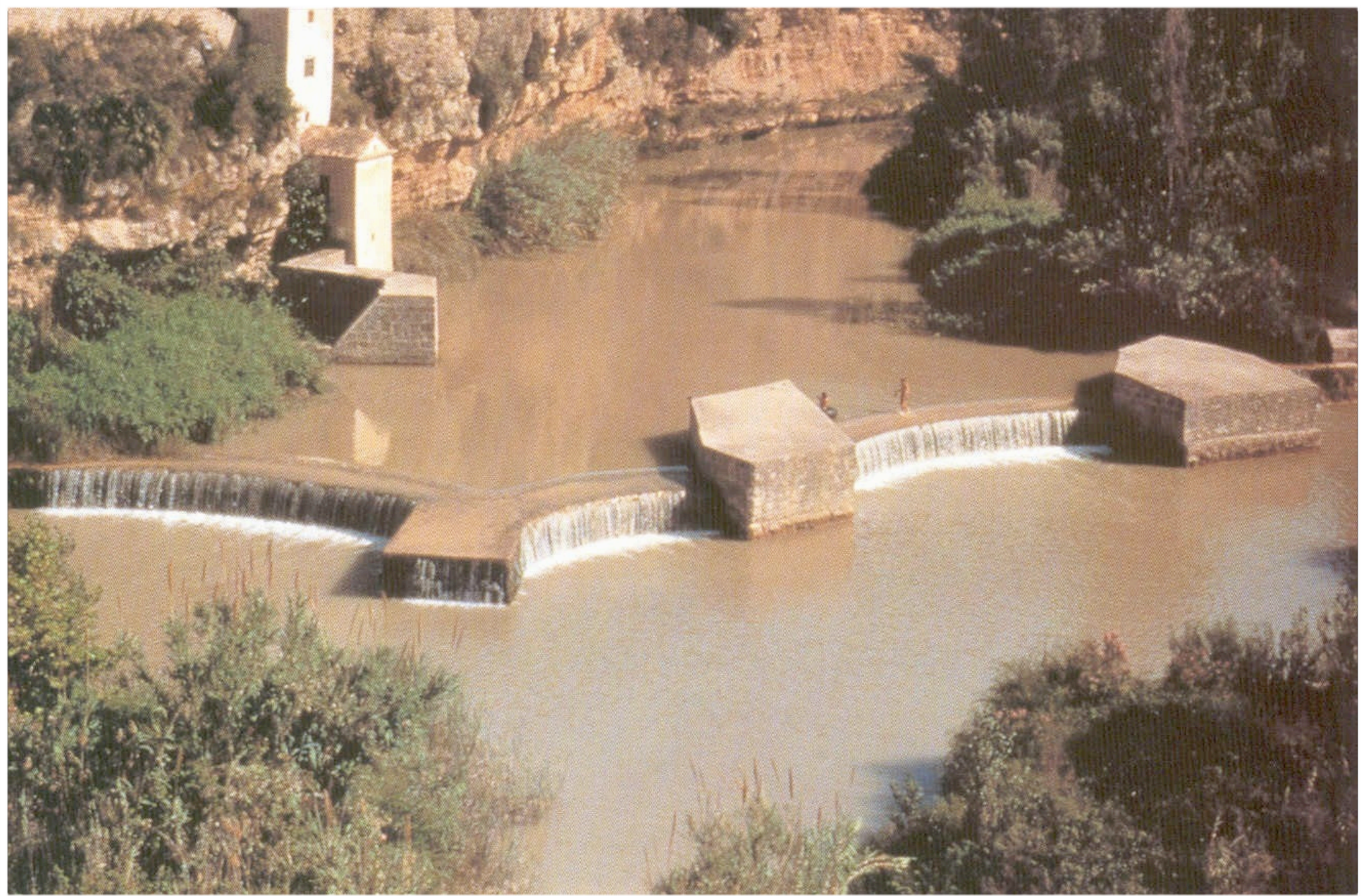
Almonacid de la Cuba dam - 34 m (1st-2nd Century A.D.)

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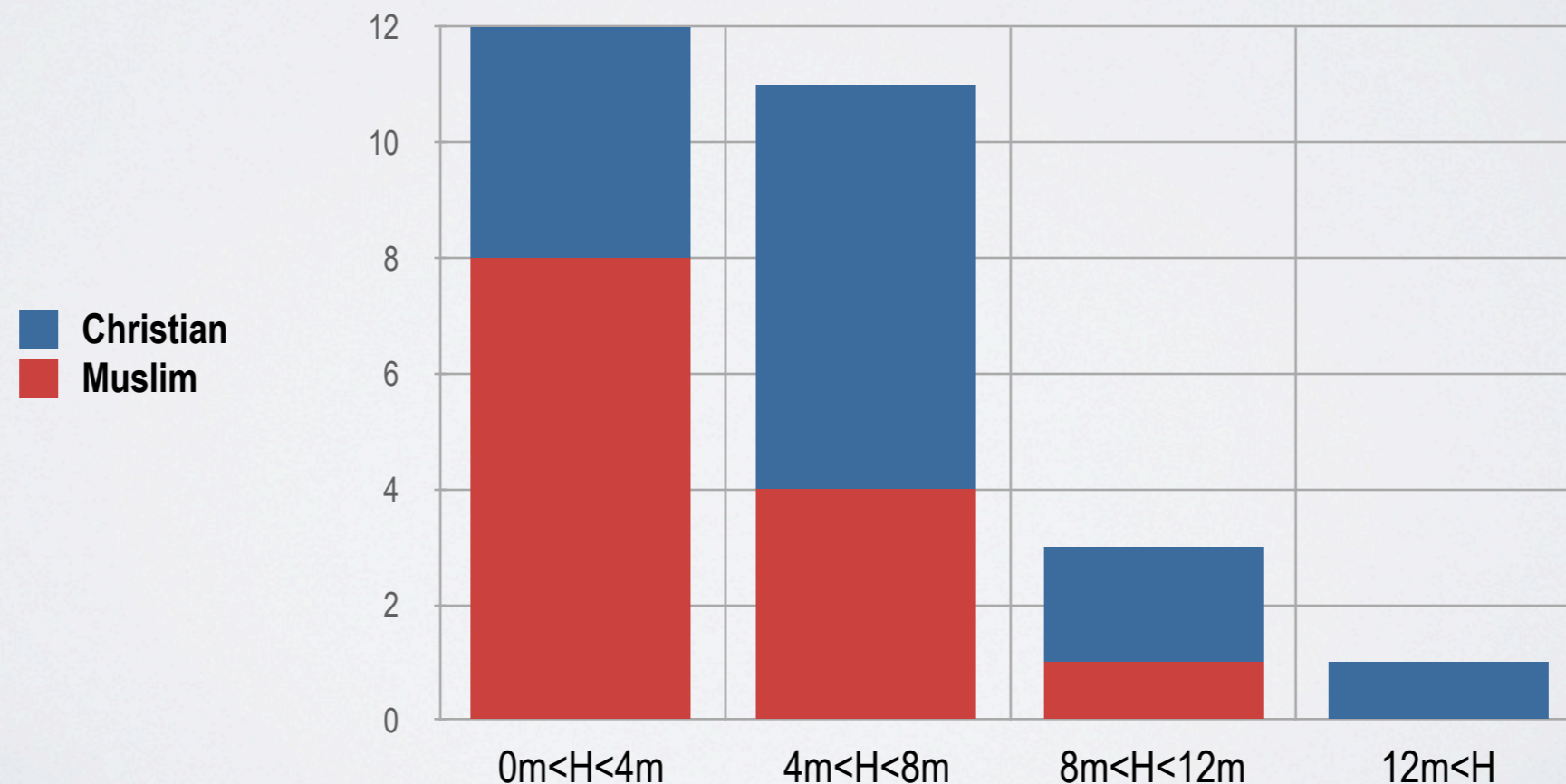
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Middle Ages Dams

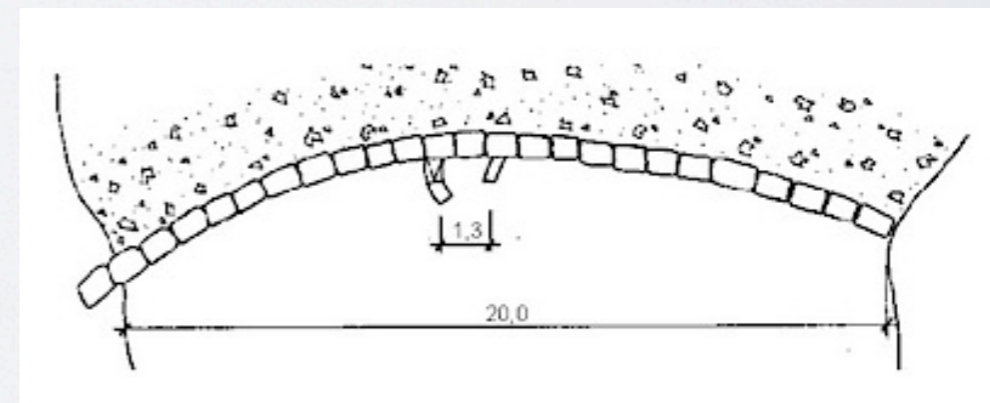
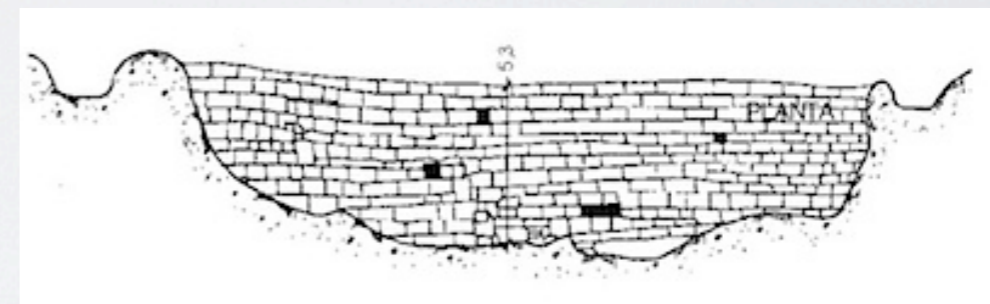
Middle Age Dams. General Aspects

- ▶ During the Middle Ages, the importance of projects developed in Spain decreased due to the changes in the political, social, administrative and economic structures
- ▶ During these centuries, irrigation was the predominant use, the industrial use of the energy appearing at the end of this period.
- ▶ We have studied the 27 most important dams of this period, which were usually diversion dams
- ▶ The size of these dams is clearly smaller than the Roman and Renaissance dams



Middle Age Dams. Dam design

- ▶ All Middle Ages dams known are masonry gravity dams
- ▶ Earth dams, if they have ever existed, were of little importance and were soon destroyed or abandoned
- ▶ The traditional Roman rectangular cross section coexists in this period with other geometries, the sections of which we have classified in four types:
 - Rectangular cross section
 - Steep sloped trapezoidal cross section
 - Soft sloped trapezoidal cross section
 - Triangular cross section



Moneva dam - 5,3 m (15th Century A.D.)

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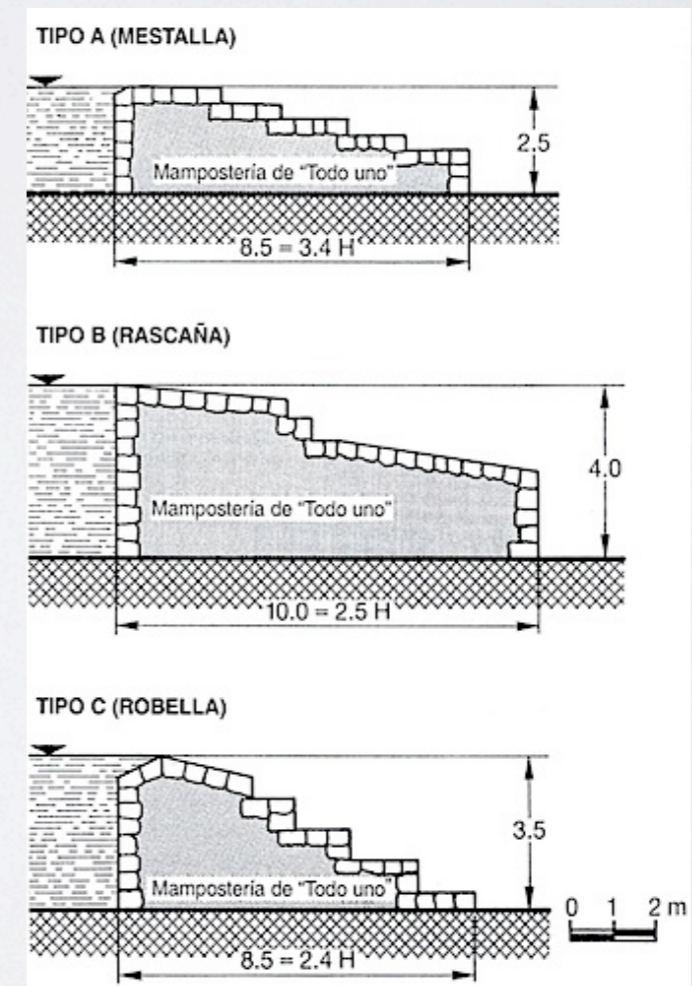
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San Marcos dam - 11 m (14th Century A.D.)

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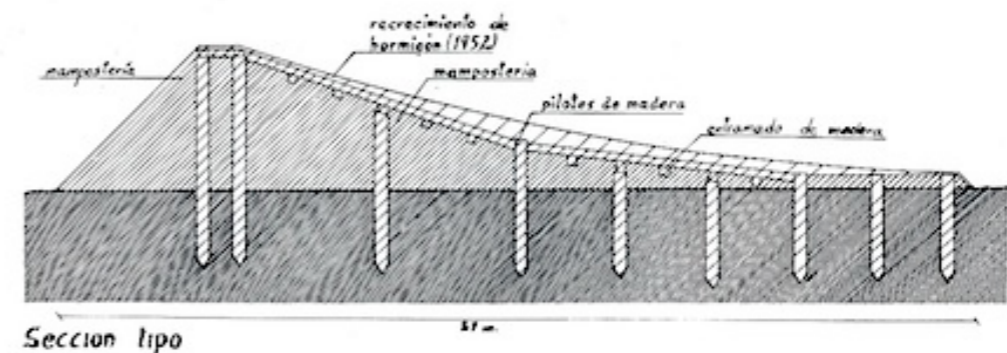


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Balsareny dam - 3 m (14th Century A.D.)



Design of the dams. Innovations

- ▶ Despite the small dimensions of these dams, two important innovations should be noted:
 - The adaptation of the hydraulic profile to avoid the damage to dams located in larger rivers
 - Improvement of dam foundations using wooden pile and primitive slab foundations



Ferrer y Mora dam - 3 m (10th Century A.D.)



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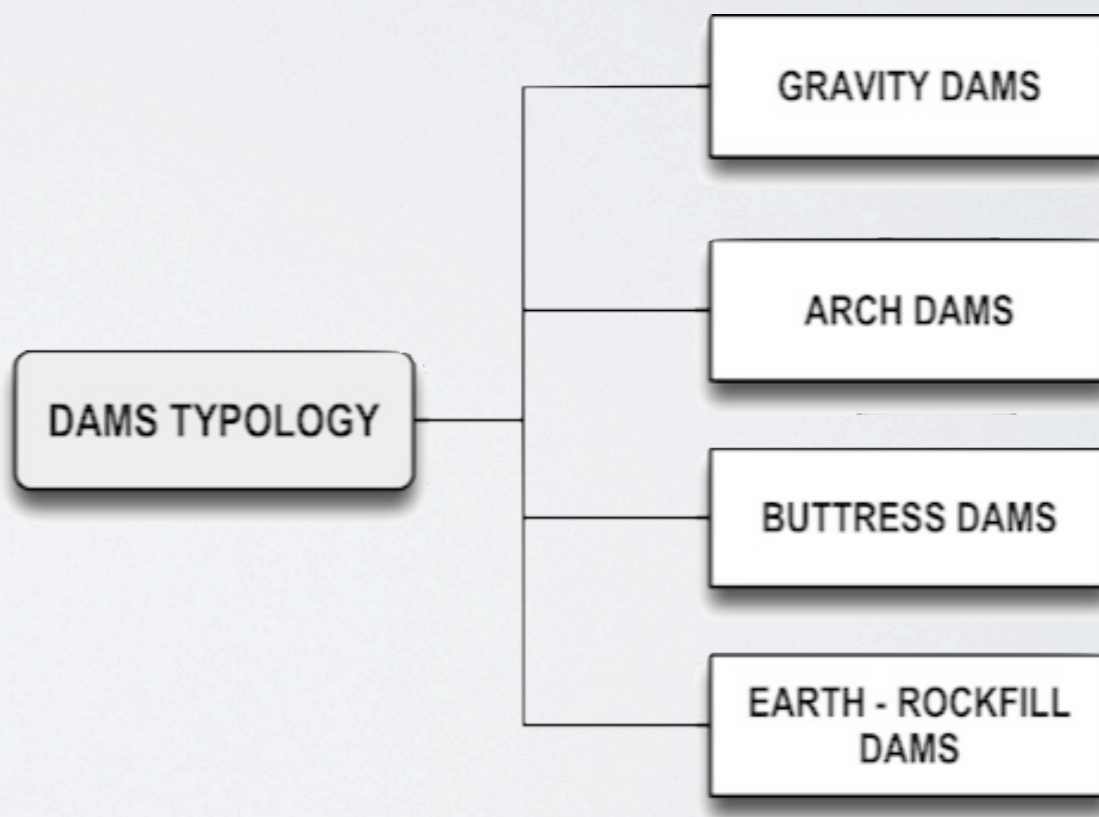
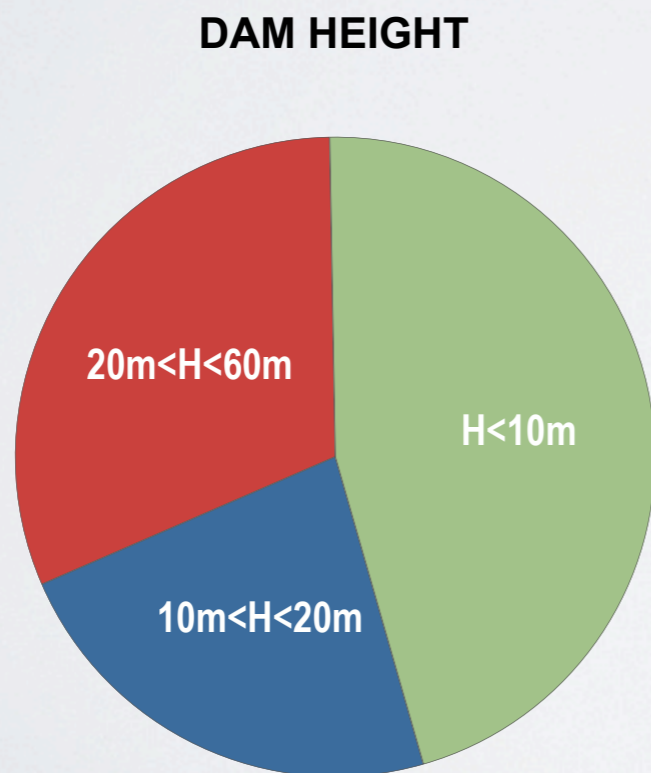
El Vado dam - 4 m (15th Century A.D.)



16th century to the middle of the 19th century

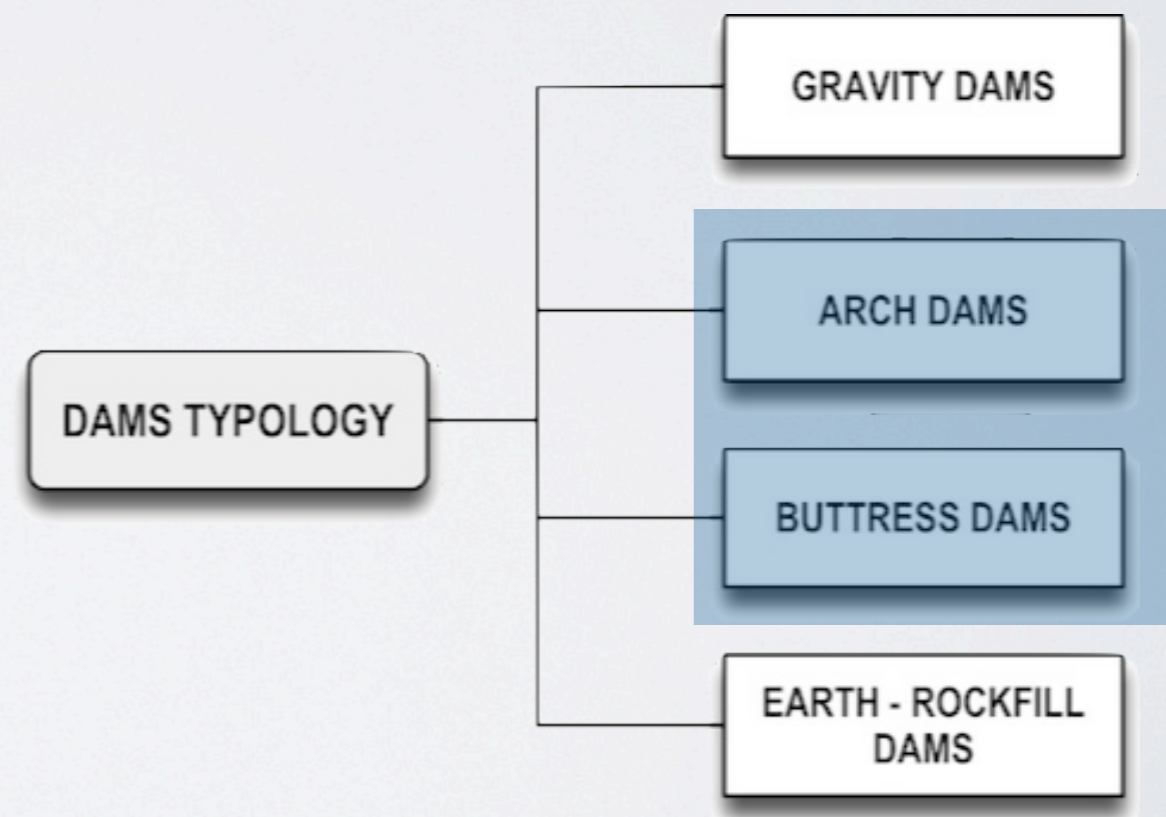
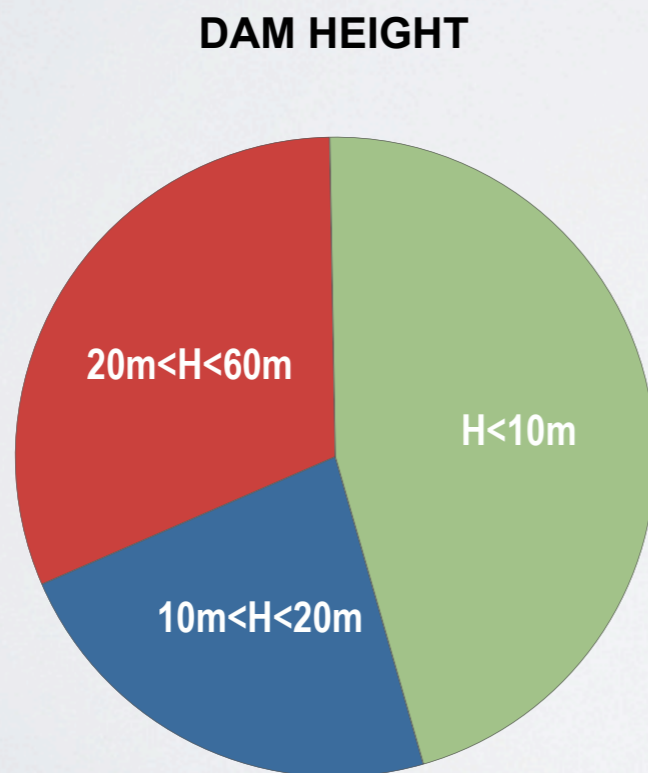
General Aspects

- ▶ During these centuries the rythm and size of dam construction have increased as a consequence of the development of irrigation and industrial uses in some areas.
- ▶ 48 regulation dams are known, seven of which being above 30 m high
- ▶ During this Period there was a great improvement in the knowledge and application of the resistant schemes previously used, especially in the case of the arch and buttress dams



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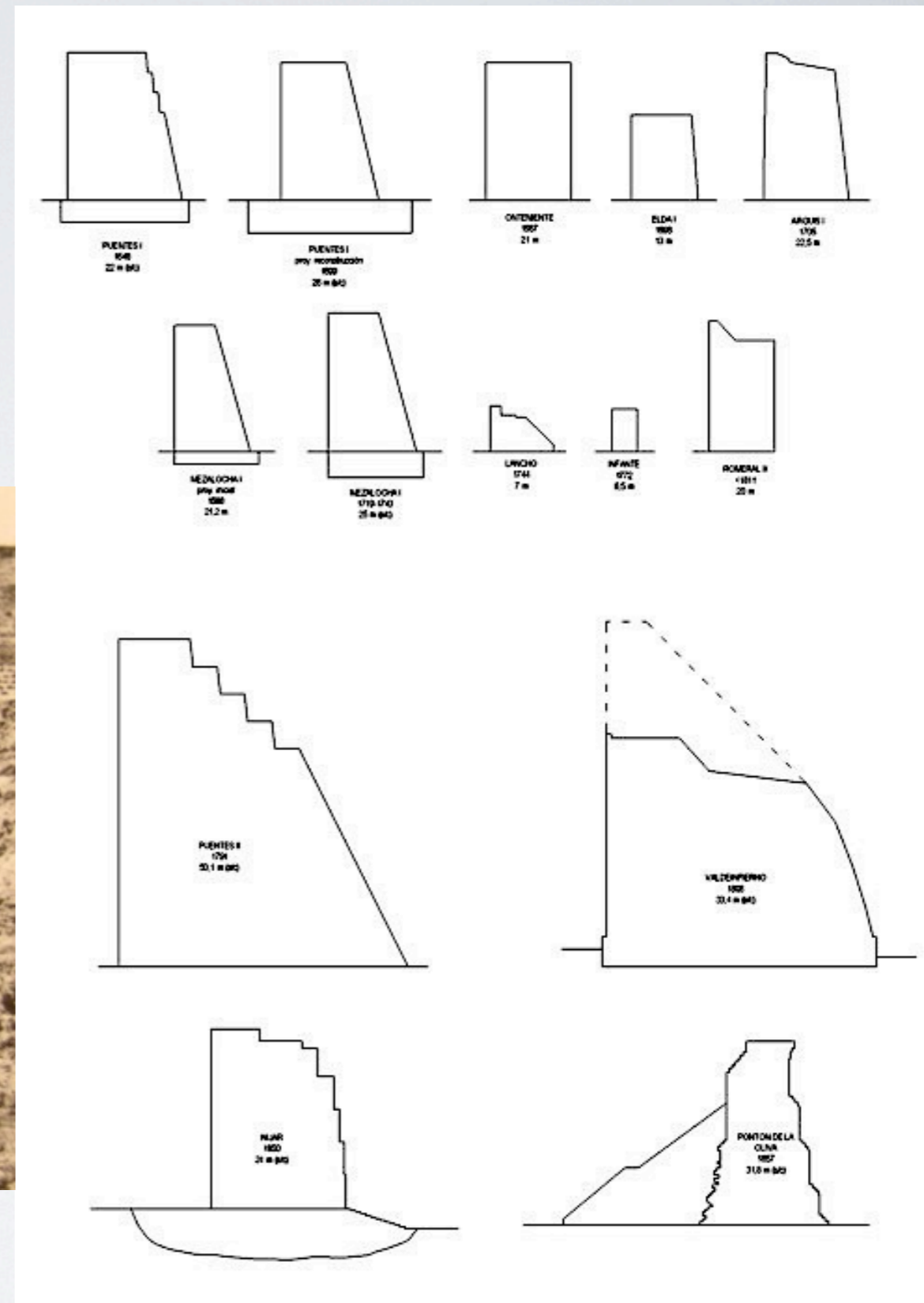


Dam design. Gravity dams

- ▶ The evolution from the Roman rectangular cross section to trapezoidal cross section was consolidated during this time
- ▶ The great majority of these dams are above 20 m high, two of them being close to 50 m high

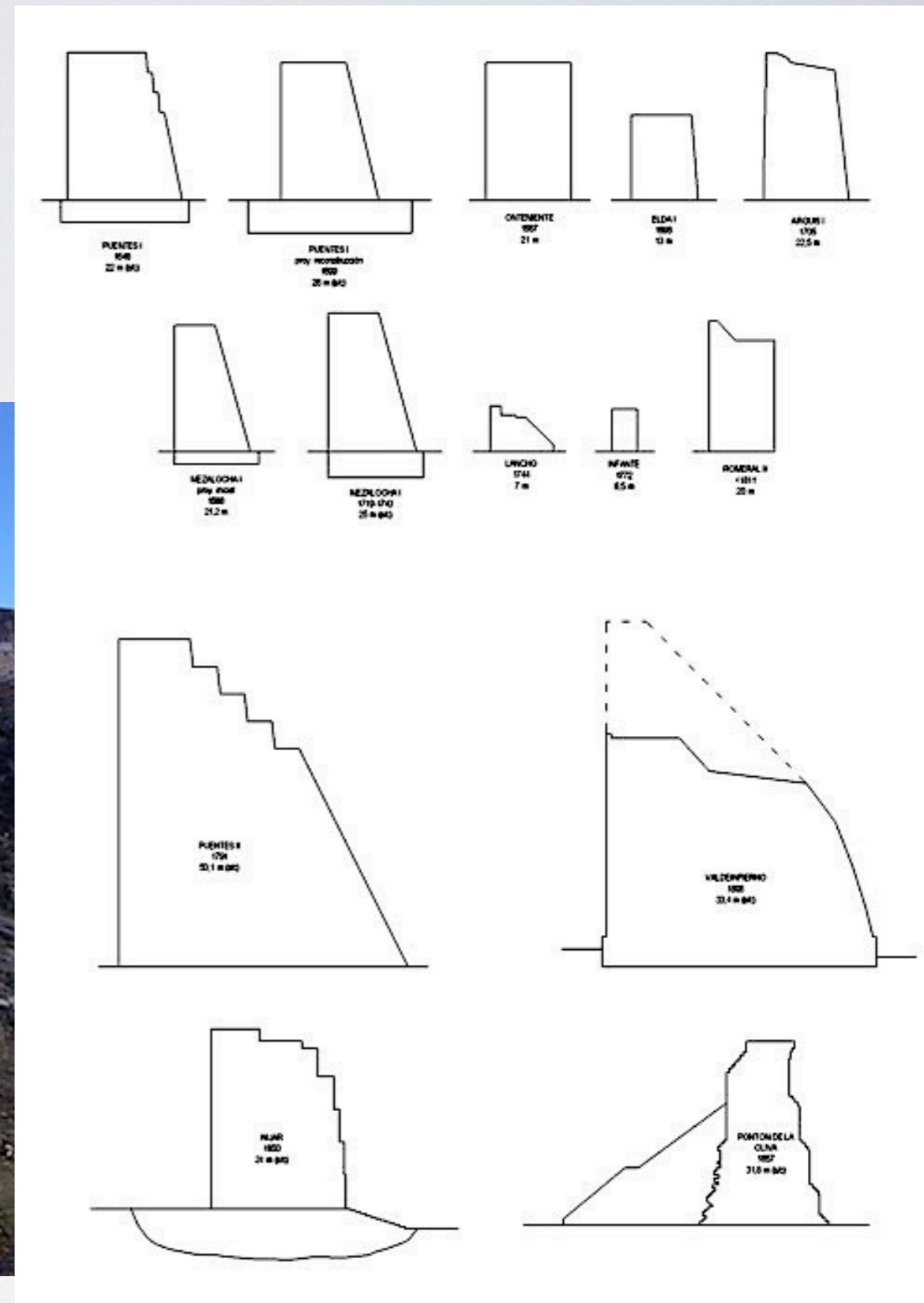


Puentes II dam - 50 m (1791)



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Dam design. Buttress dams

- ▶ Almost 20 buttress dams are known, all of which with an industrial purpose and located in the Extremadura Region
- ▶ Surprisingly, the most slender and accurate designs correspond to the highest dams

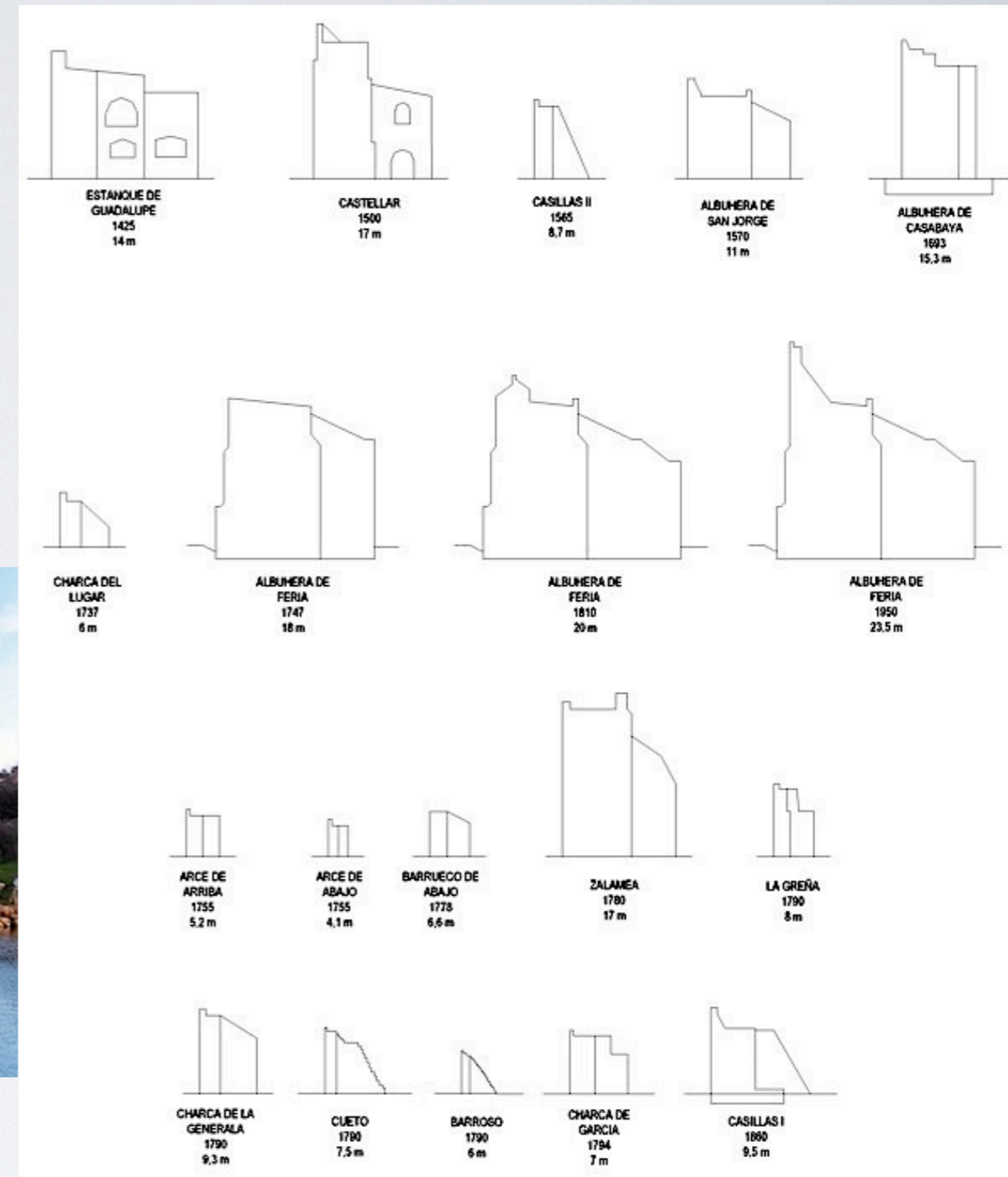


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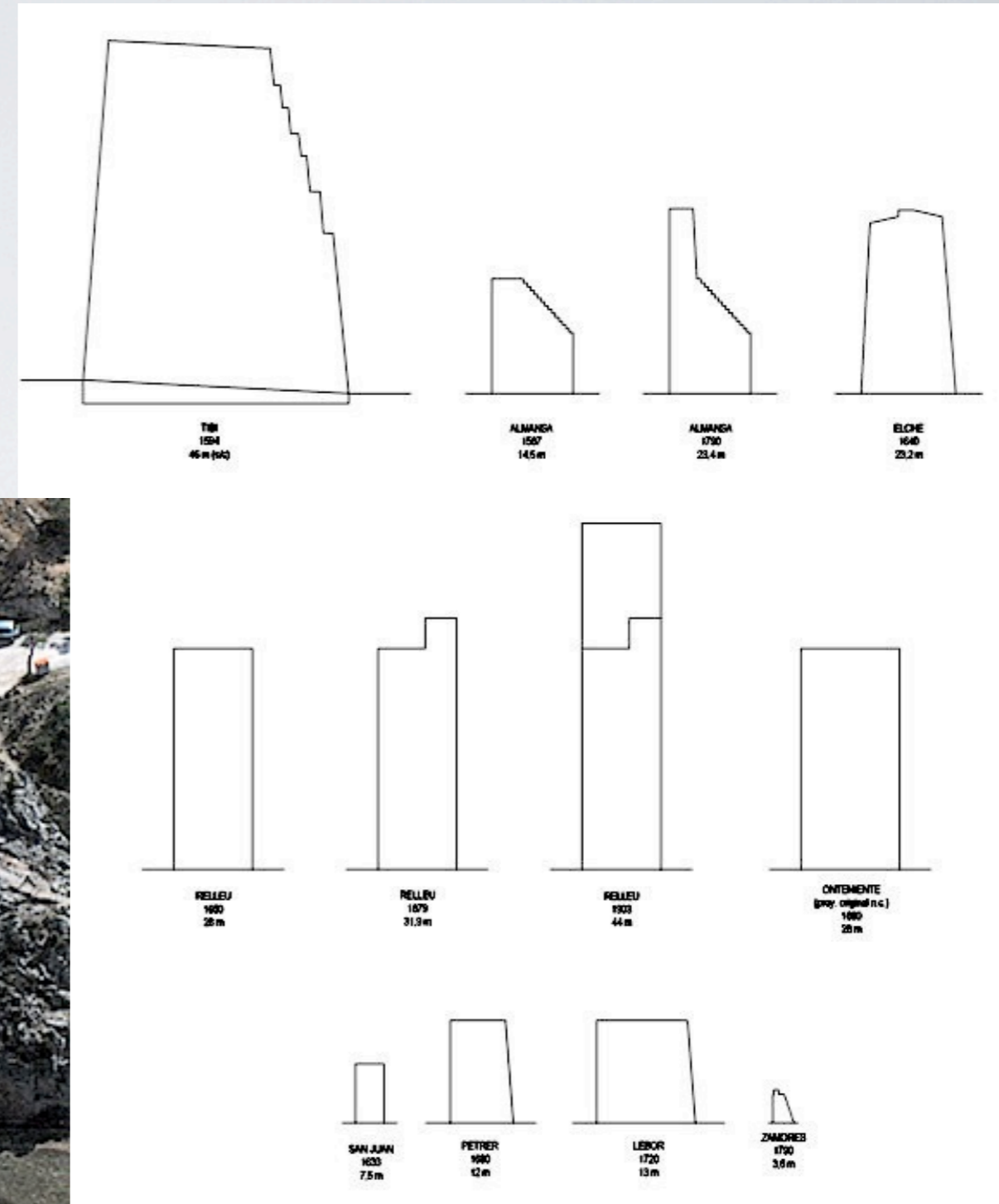


Greña dam - 8 m (1790)



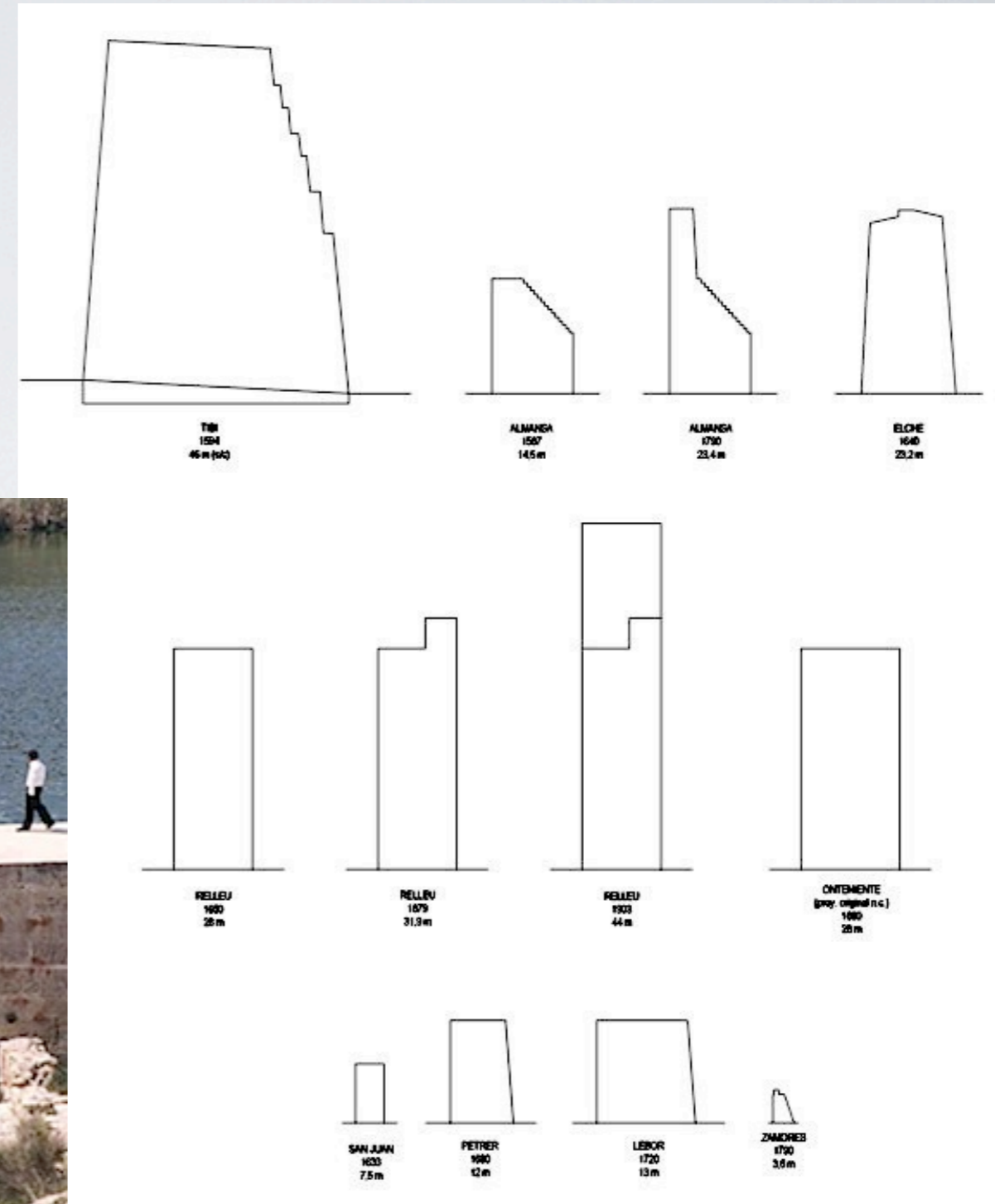
Dam design. Arch dams

- ▶ Since the beginning of this period, there are written documents demonstrating the reduction of the width of the dam taking advantage of the shape of the arch
- ▶ As in buttress dams the slenderness increases with the height of the dam



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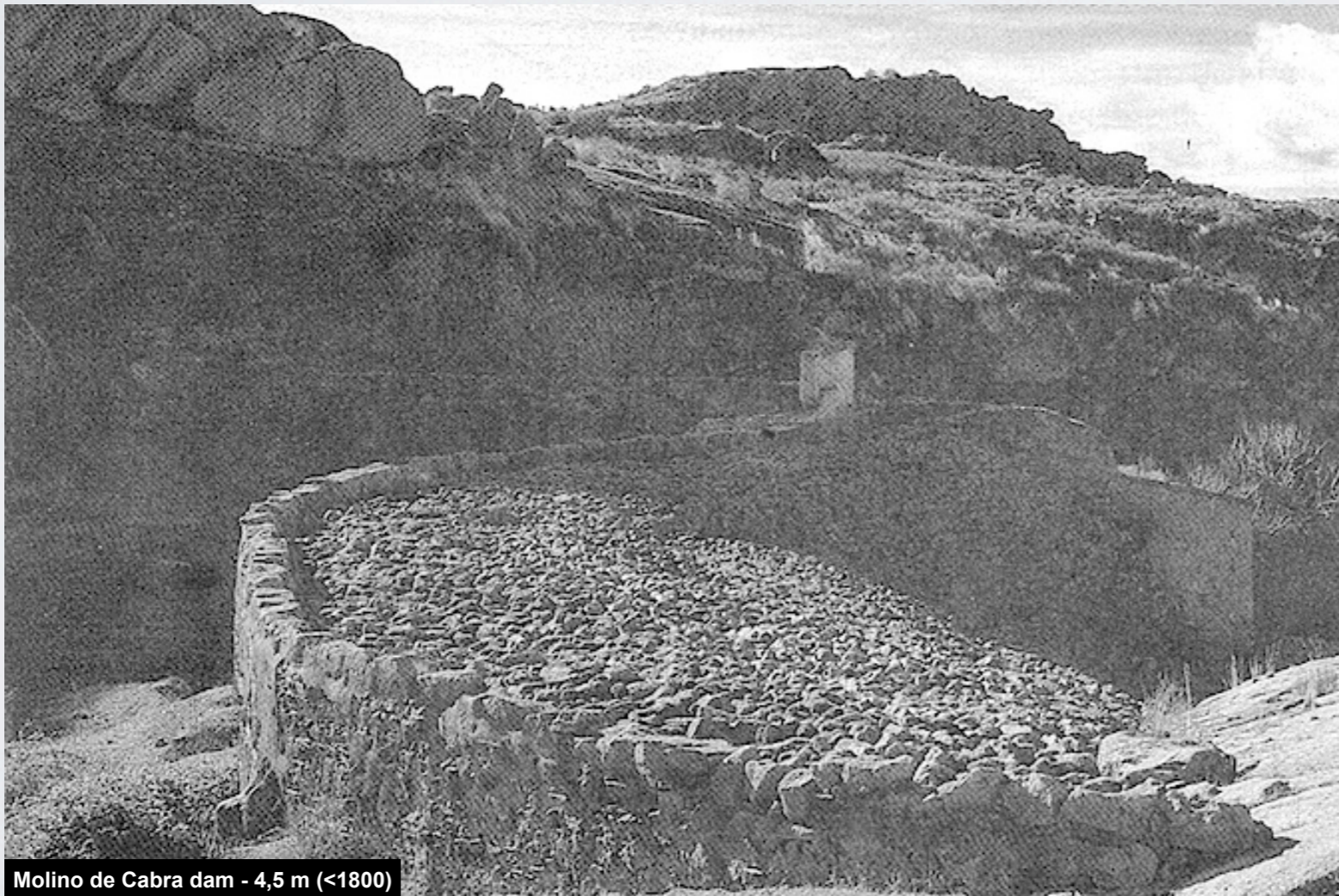
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Elche dam - 23,2 m (1655)

Dam Design. Earth - Rockfill Dams

- ▶ We have identified four types of earth or rockfill dams, which are:
 - Rockfill dams with upstream masonry facing
 - Earth dams with upstream masonry facing
 - Rockfill dams with masonry diaphragm
 - Double masonry wall with earthfill



Molino de Cabra dam - 4,5 m (<1800)



MOLINO DE CABRA
<1800
4,5 m

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Granjilla I dam - 13,5 m (1650)

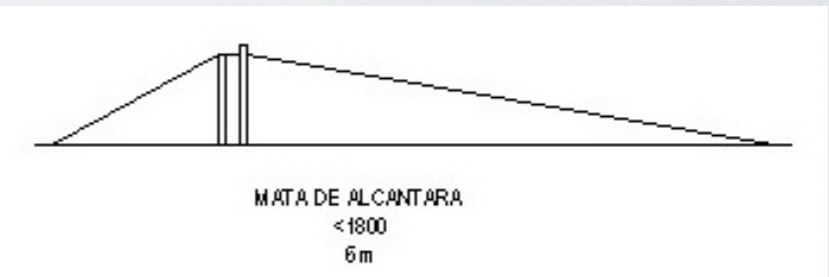


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Mata de Alcántara dam - 6 m (<1800)

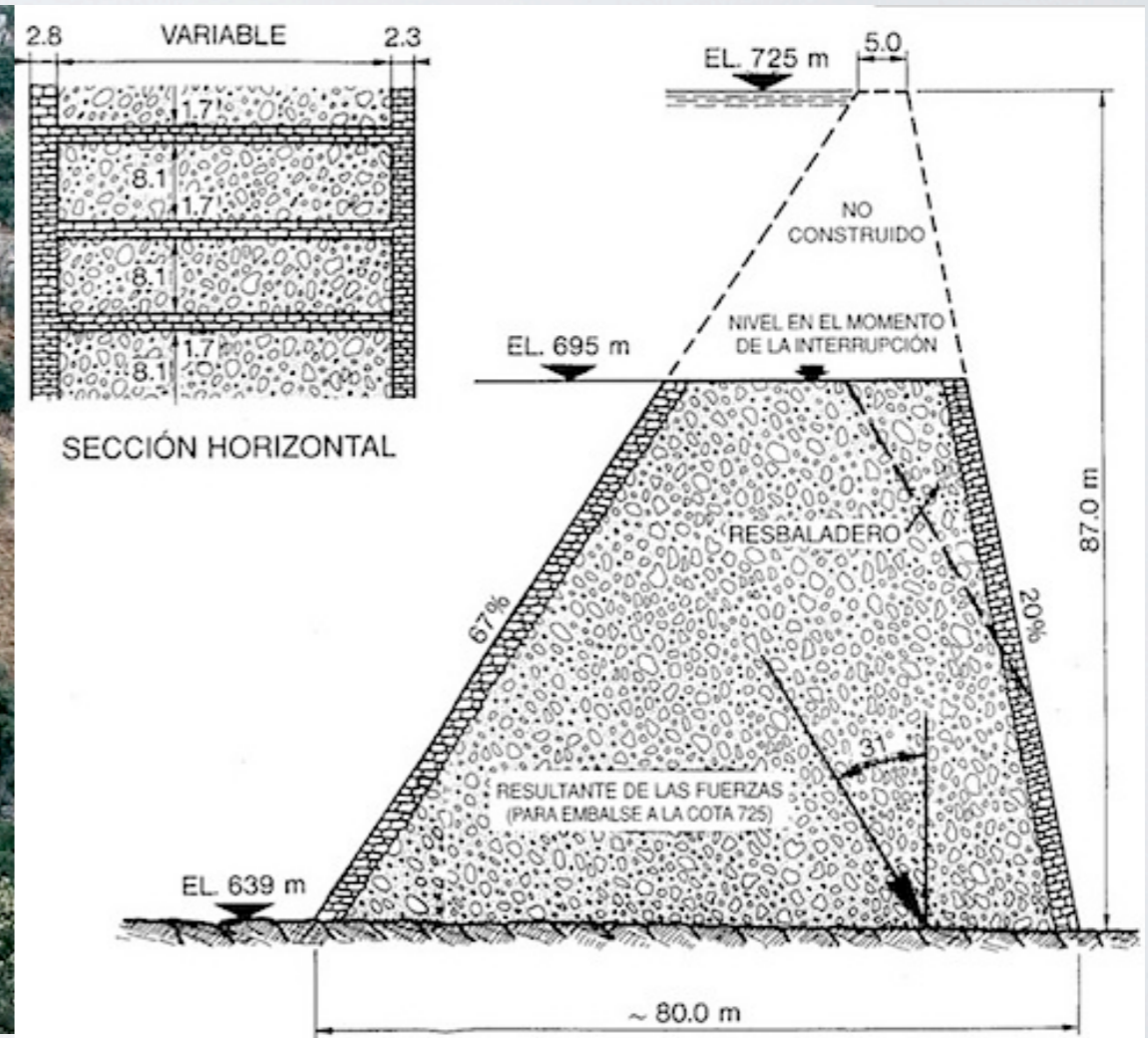


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Gascó dam - 57 m (1788)



Spillways

- ▶ During these centuries, spillway design criteria did not improve substantially compared to previous periods
- ▶ In small dams, simple lateral spillways could evacuate floods which would not be very important in any case
- ▶ In large dams, small lateral spillways were placed, but engineers considered the overtopping as inevitable, thus reinforcing the top of the dam and the downstream facing



Barrueco de Arriba dam - 9 m (1778)

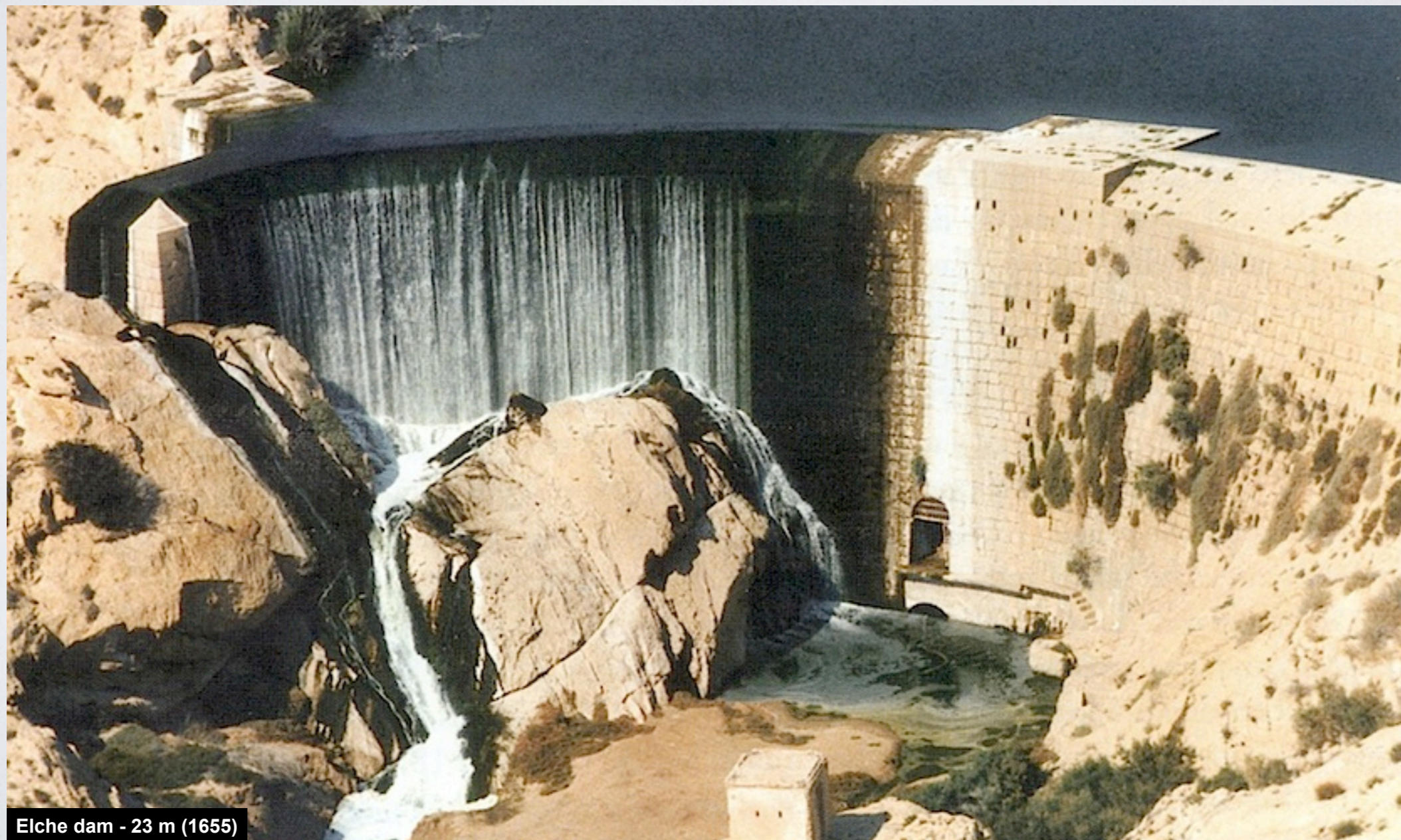
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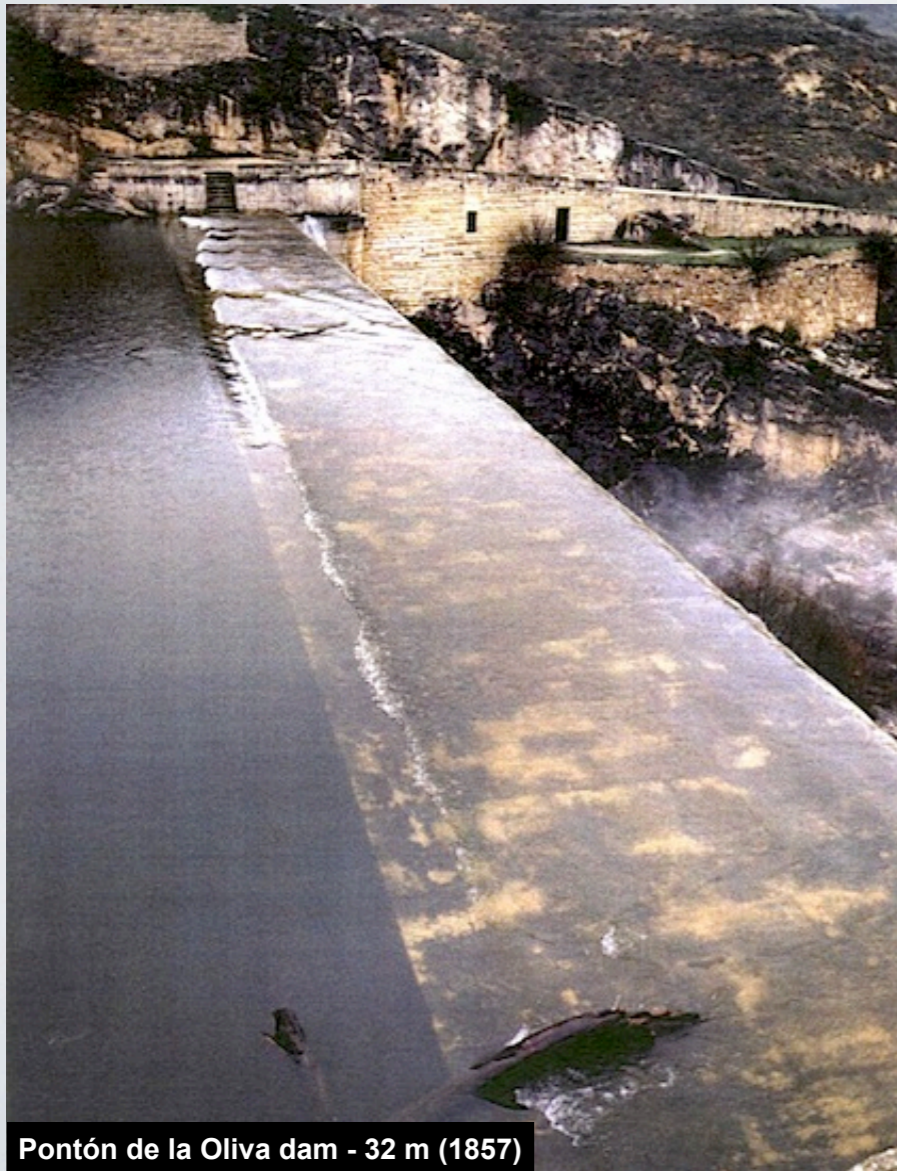
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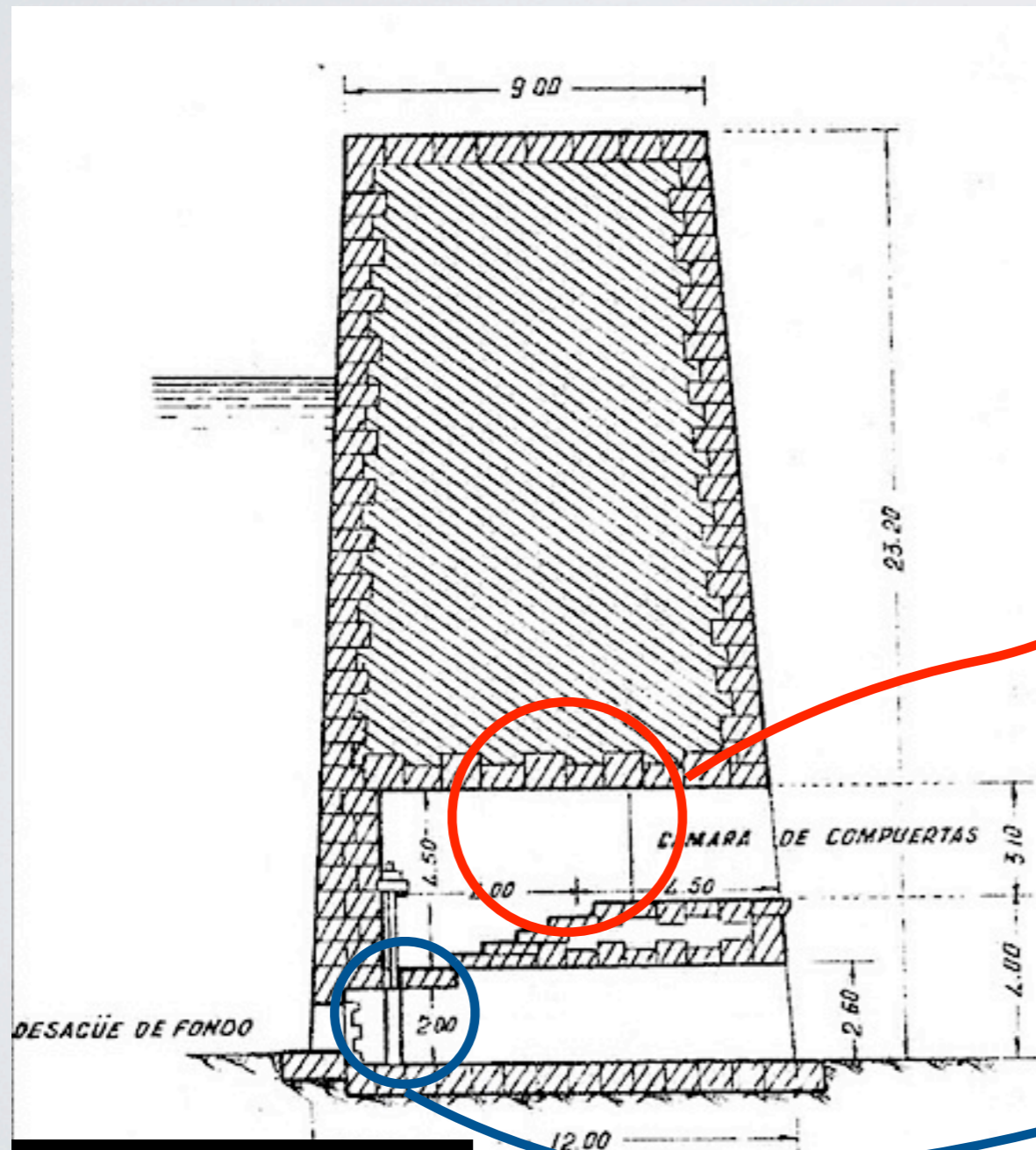


Pontón de la Oliva dam - 32 m (1857)



Outlet works. Bottom outlets and intakes

- ▶ The location of large dams in rivers with a high quantity of sediments required the installation of the first large bottom outlets in the East of Spain
- ▶ The increase in the height of the dam led to a substantial improvement in the design and organization of the water intakes.

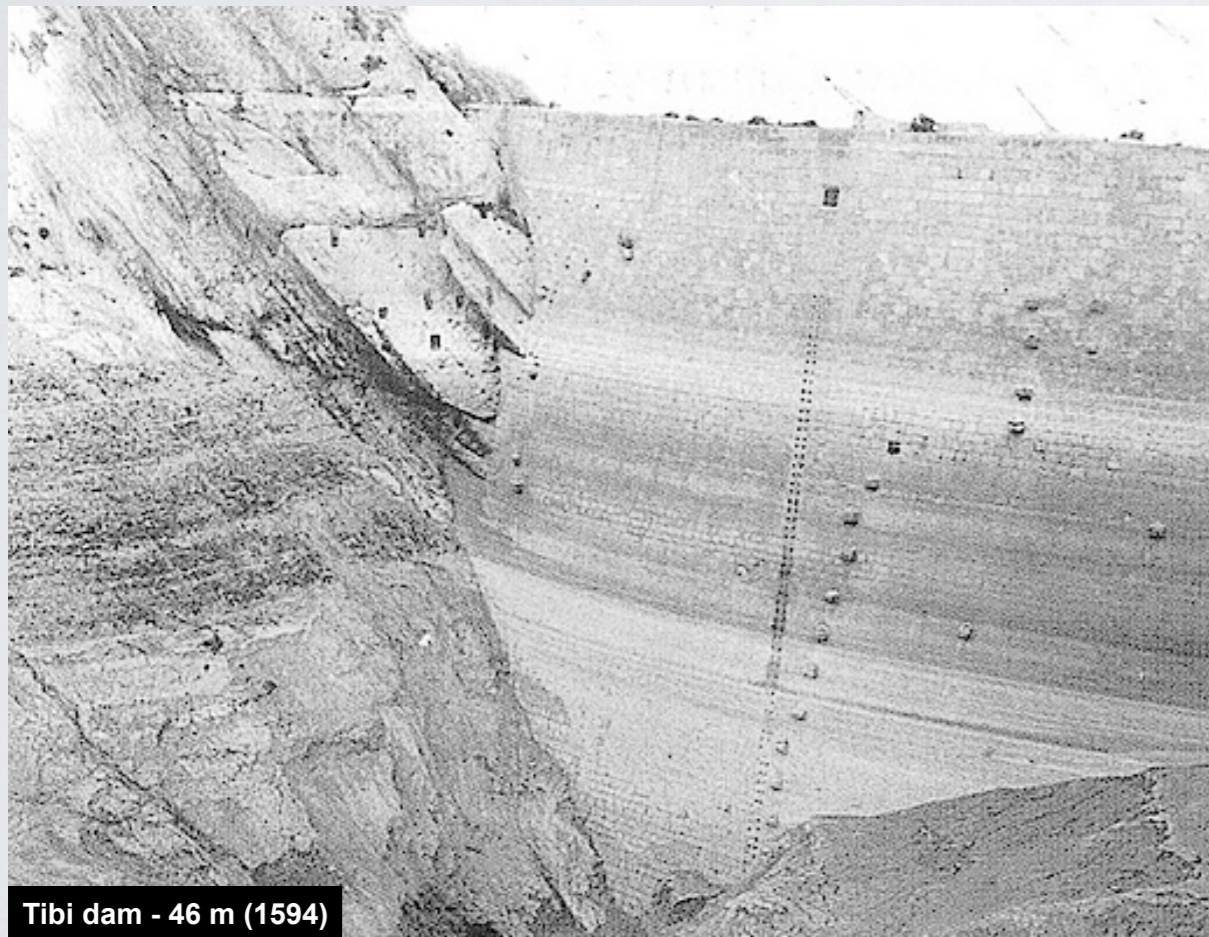


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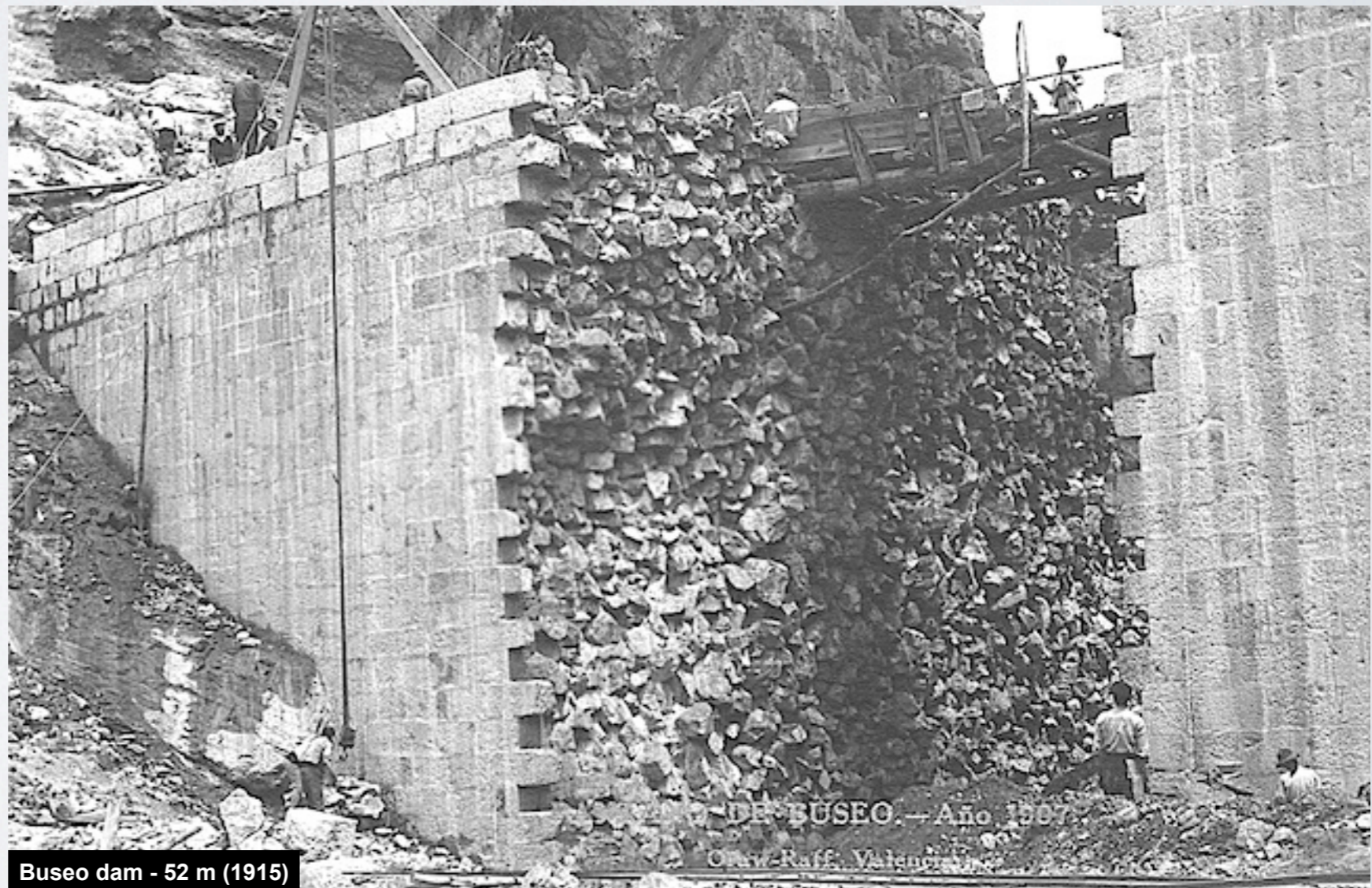




Since the middle of the 19th century

Dams since the middle of the 19th century. General aspects

- ▶ The beginning of this period corresponds to the introduction of Rational Mechanics to dam design
- ▶ The end of this period is more difficult to determine, but we can date the beginning of the Spanish Civil War (1936) as the end of Masonry Dam Construction, although the construction of some dams extended until the 1940s, or even later in the Canary Islands
- ▶ During that time, substantial improvements were made, relating to dam design, materials, and construction techniques as well as auxiliary facilities used in dam construction
- ▶ We know 242 masonry dams in which one or more of the following materials were used:
 - Traditional masonry
 - Cyclopean masonry
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La Peña dam - 59 m (1913)

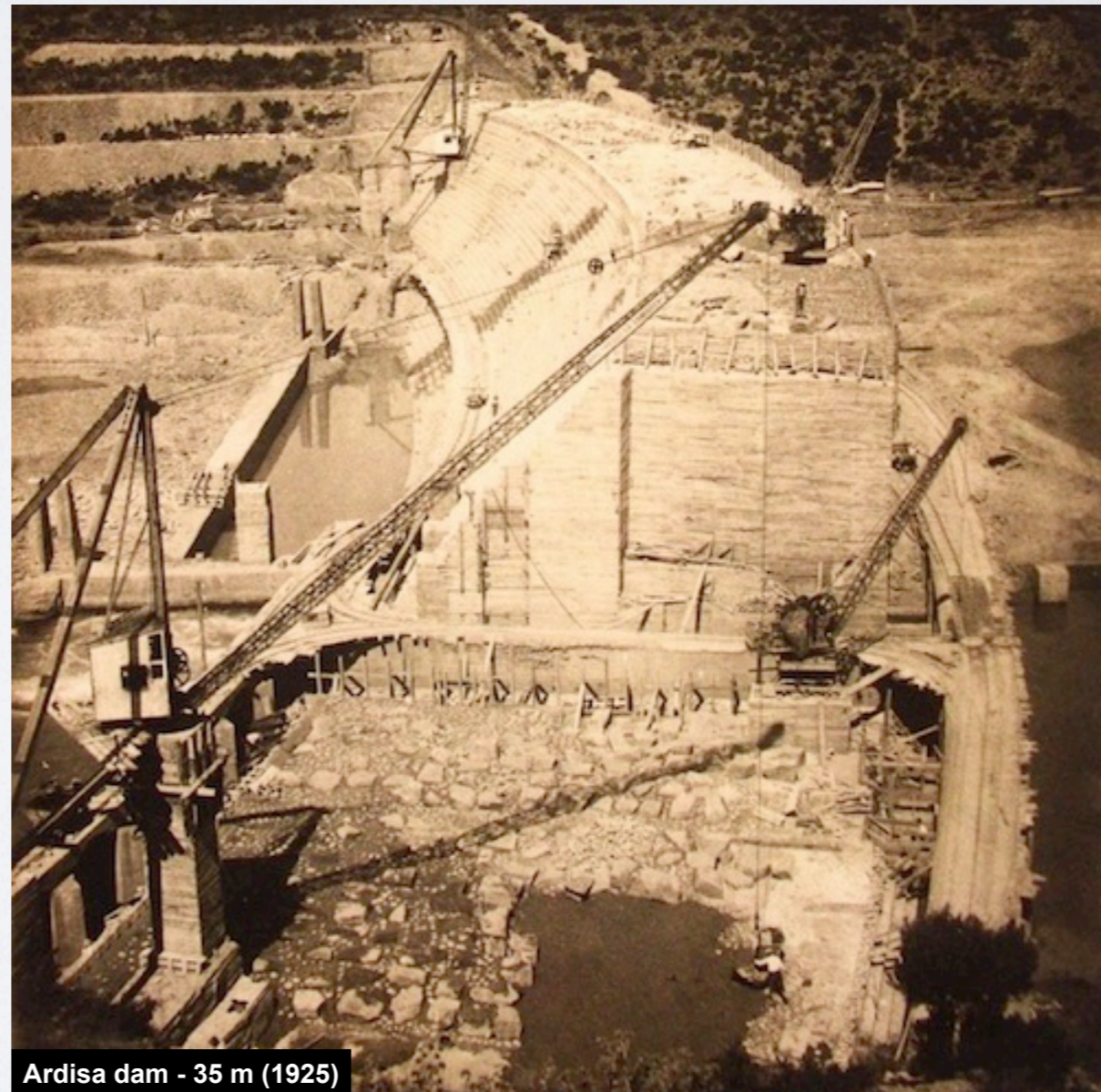
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Ardisa dam - 35 m (1925)

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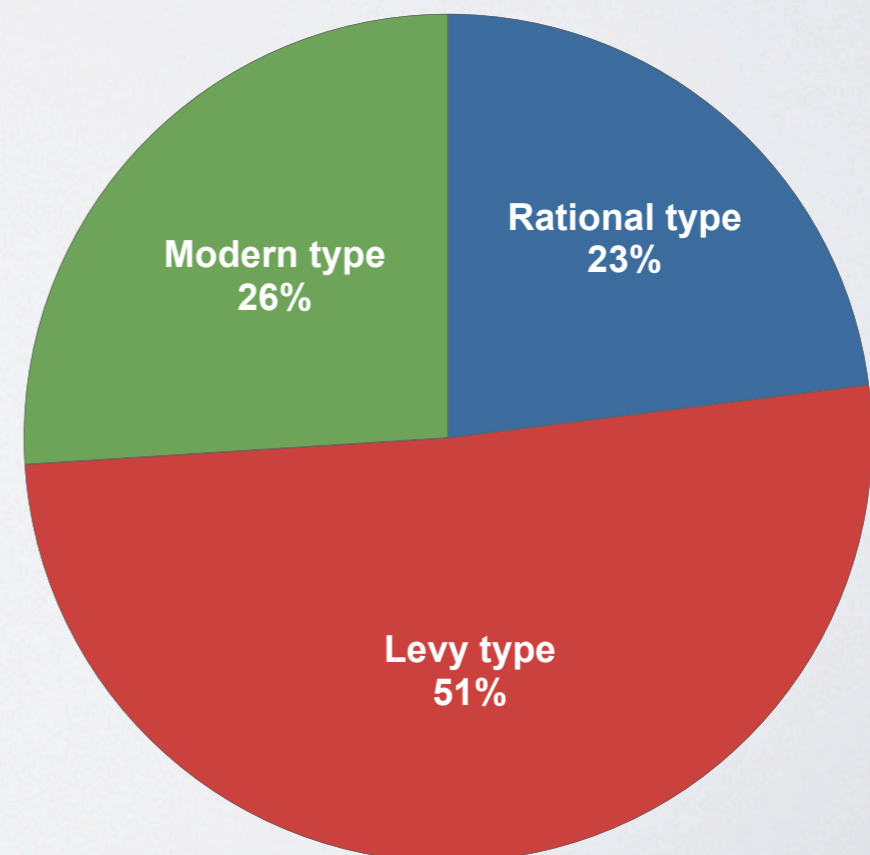
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Puentes III dam - 69 m (1884)

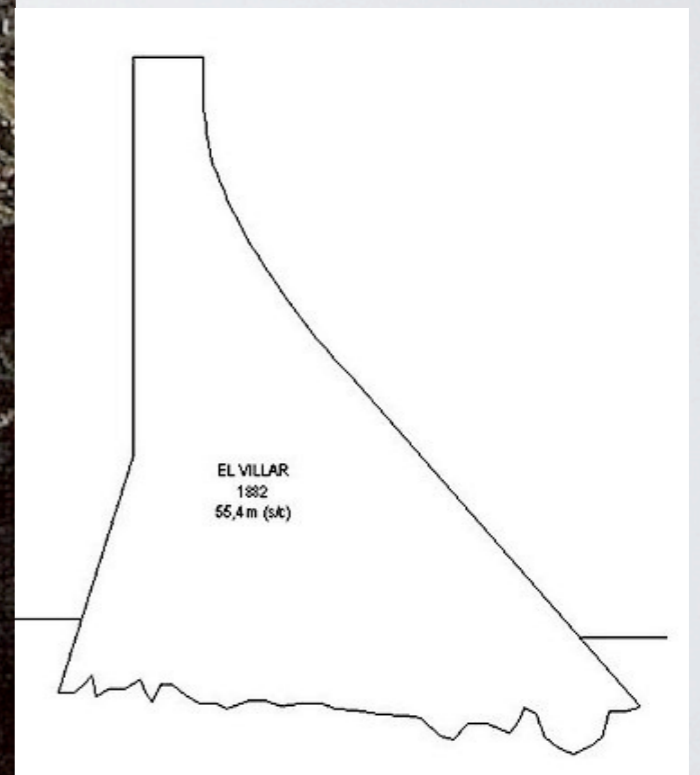
Dams since the middle of the 19th century. Dam design

- ▶ The comprehensive study of such a large number and variety of dams could make the analysis of the evolution of dam engineering more difficult. So, first of all, we have identified two different groups of dams:
 - **Main group of dams** (91 dams or 38% of the total)
 - **Homogeneous groups** of dams: Dams related to mining, power dams in the Pyrenees, and dams in the Canary Islands
- ▶ The difficulties related to the application of Rational Mechanics to other structural typologies explain why almost all dams of this period are gravity dams (we only know 5 buttress dams)
- ▶ The study of the cross section and its stability has led to the classification of each dam into one of the three following types:
 - Dams with a “**Rational type**” cross section
 - Dams with a “**Levy type**” cross section (French influence)
 - Dams with a “**Modern type**” cross section



Dams since the middle of the 19th century. Rational type dams

- ▶ The design of Rational type dams rely on “maximum admissible load” and “same resistance profile” criteria
- ▶ El Villar dam was the first dam with this design, making it the most important Spanish dam of the time, and one of the most important in the world
- ▶ The Spanish design criteria of the last third of the 19th century permitted to avoid the problems suffered by other European dams of the same period

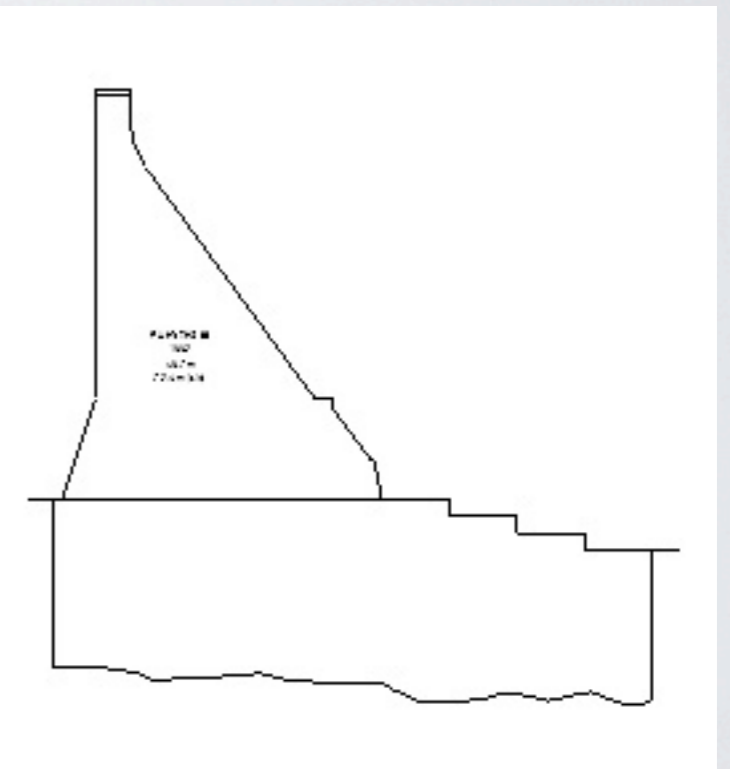


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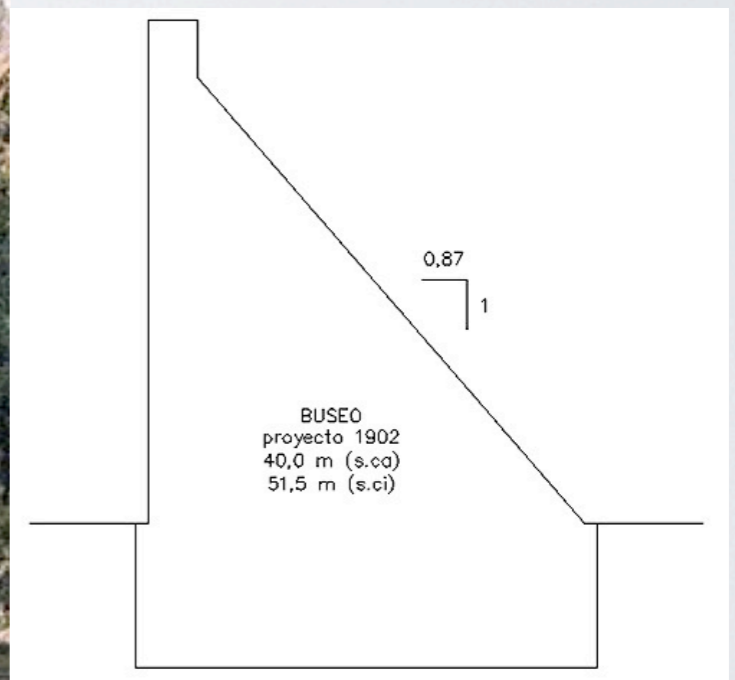


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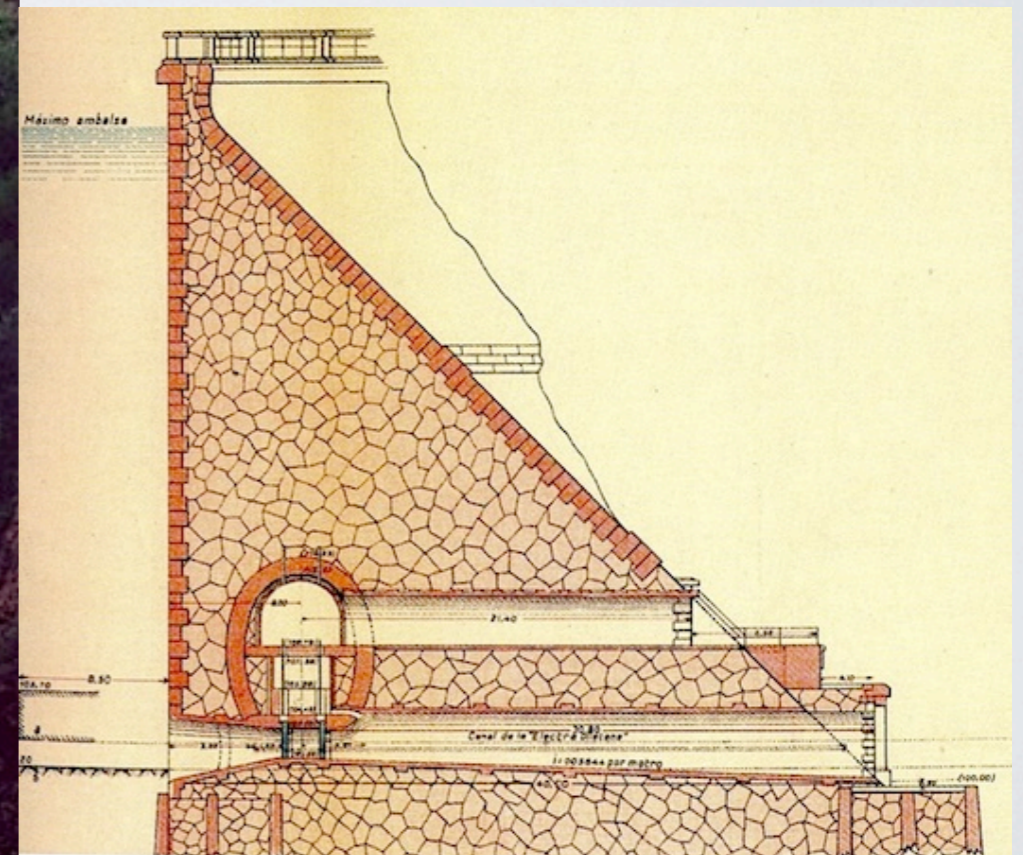
Dams since the middle of the 19th century. Levy type dams

- ▶ The design guidelines established by Le Rond and Levy en 1895, as a reaction to the Bouzey collapse and other incidents, had an influence on the design of the following dams
- ▶ These guidelines were quickly integrated by Spanish dam engineers, despite the satisfactory performance of Spanish dams
- ▶ So we can say without hesitation that almost all Spanish dams built in the first decades of the 20th century correspond to French inspired guidelines



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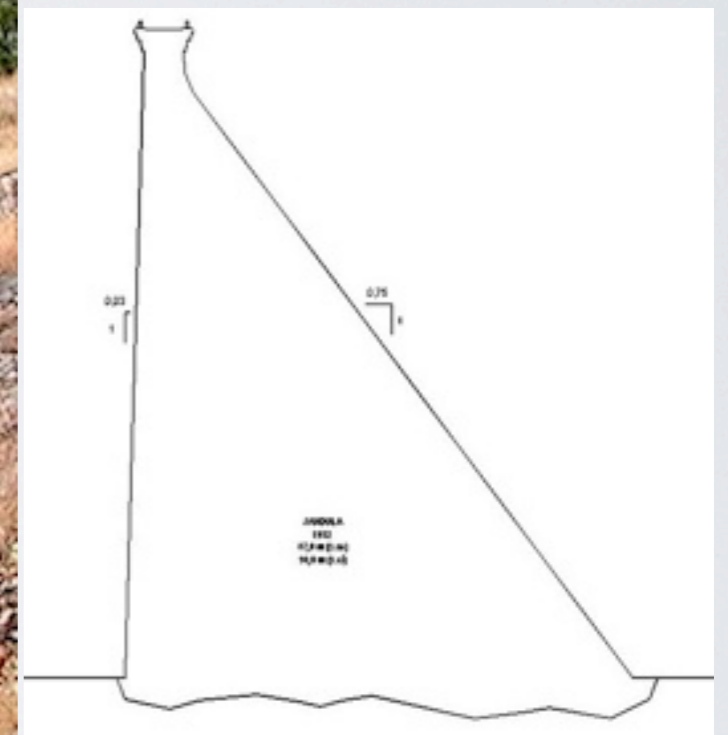
Cueva Foradada dam - 65 m (1929)

Dams since the middle of the 19th century. Modern type dams

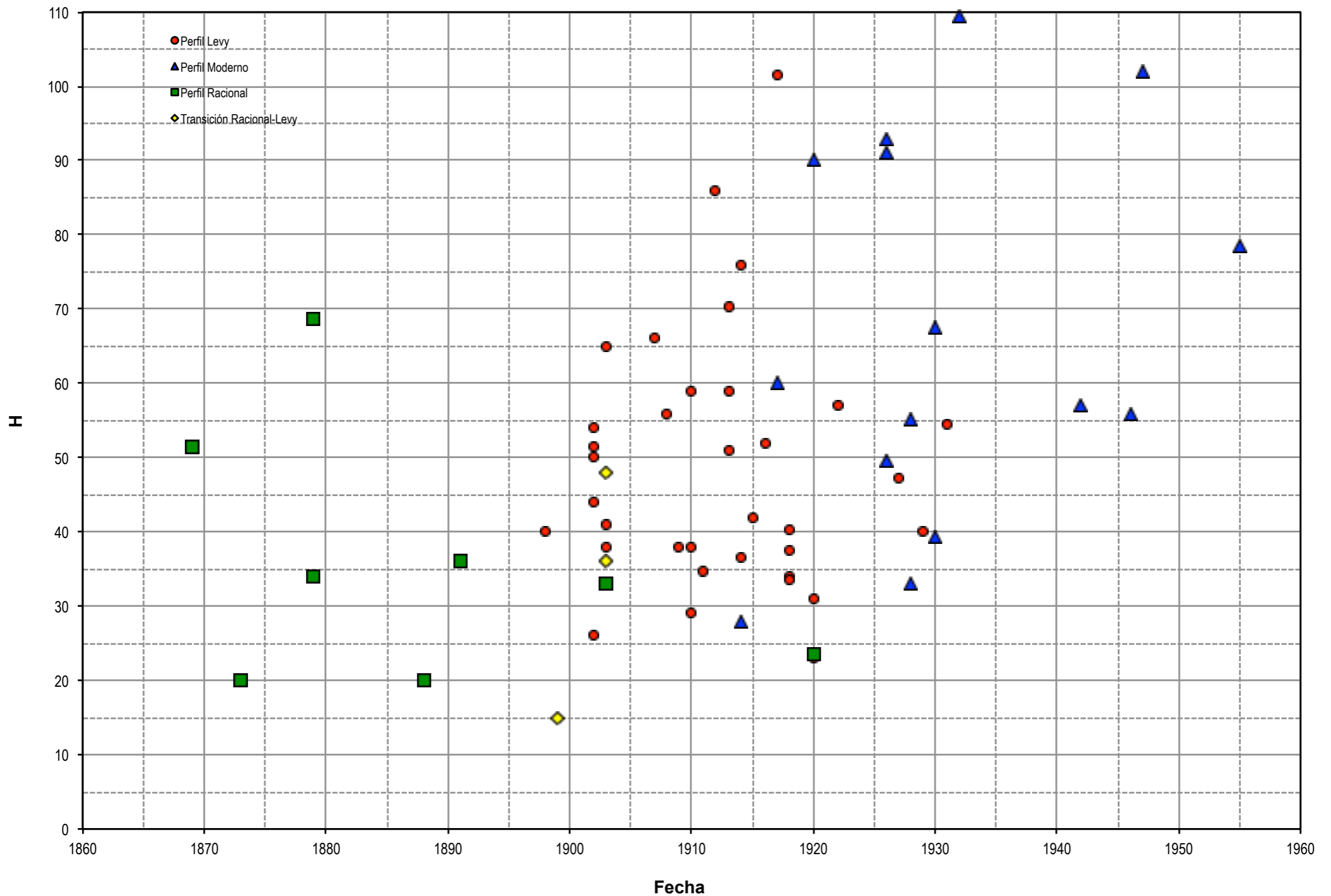
- ▶ Modern cross sections are the result of improvements in the knowledge of internal pressure and the performance of materials, which resulted in the reduction of the total slope
- ▶ The majority of these dams were finished after the end of the Spanish Civil War



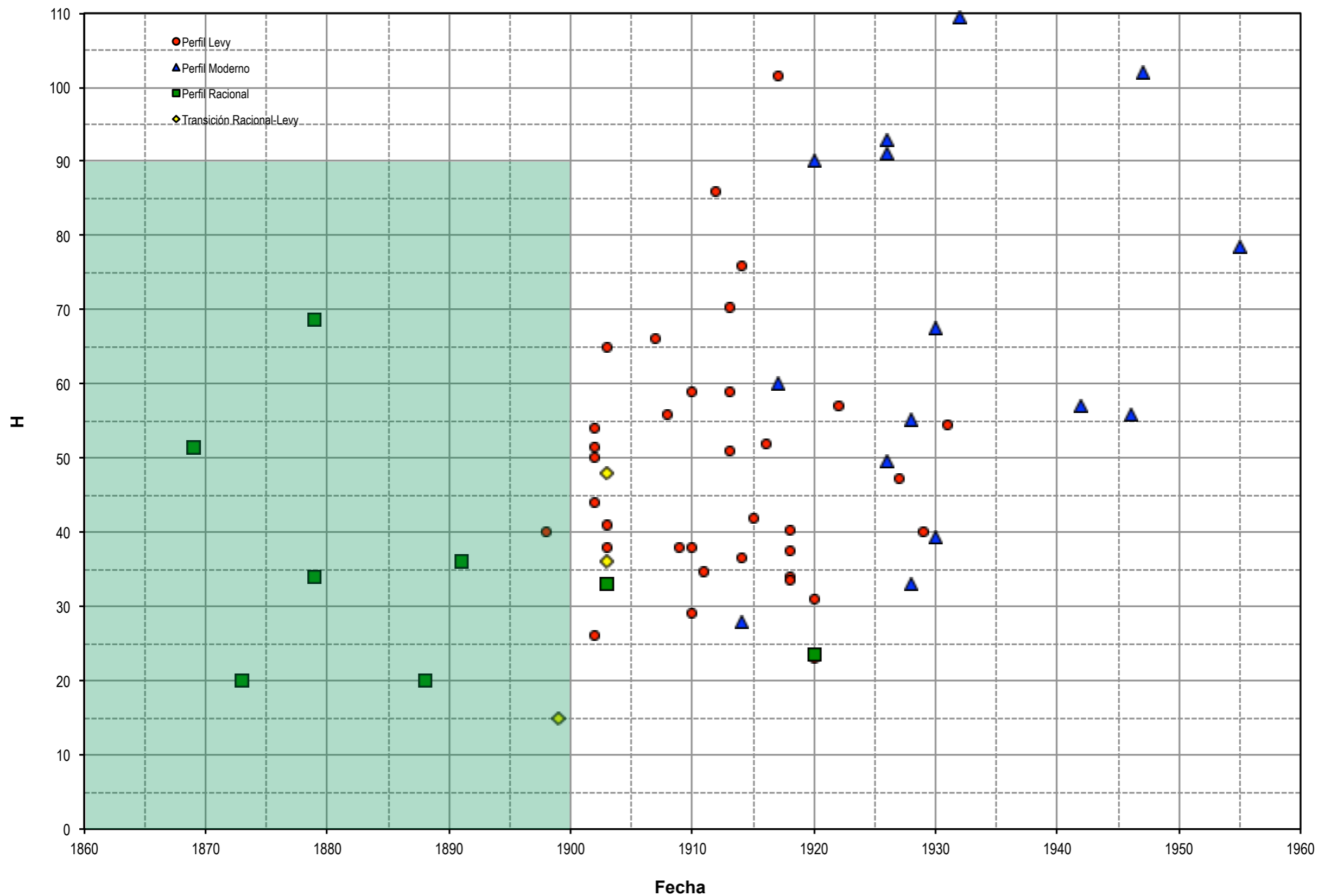
Jándula dam - 90 m (1931)



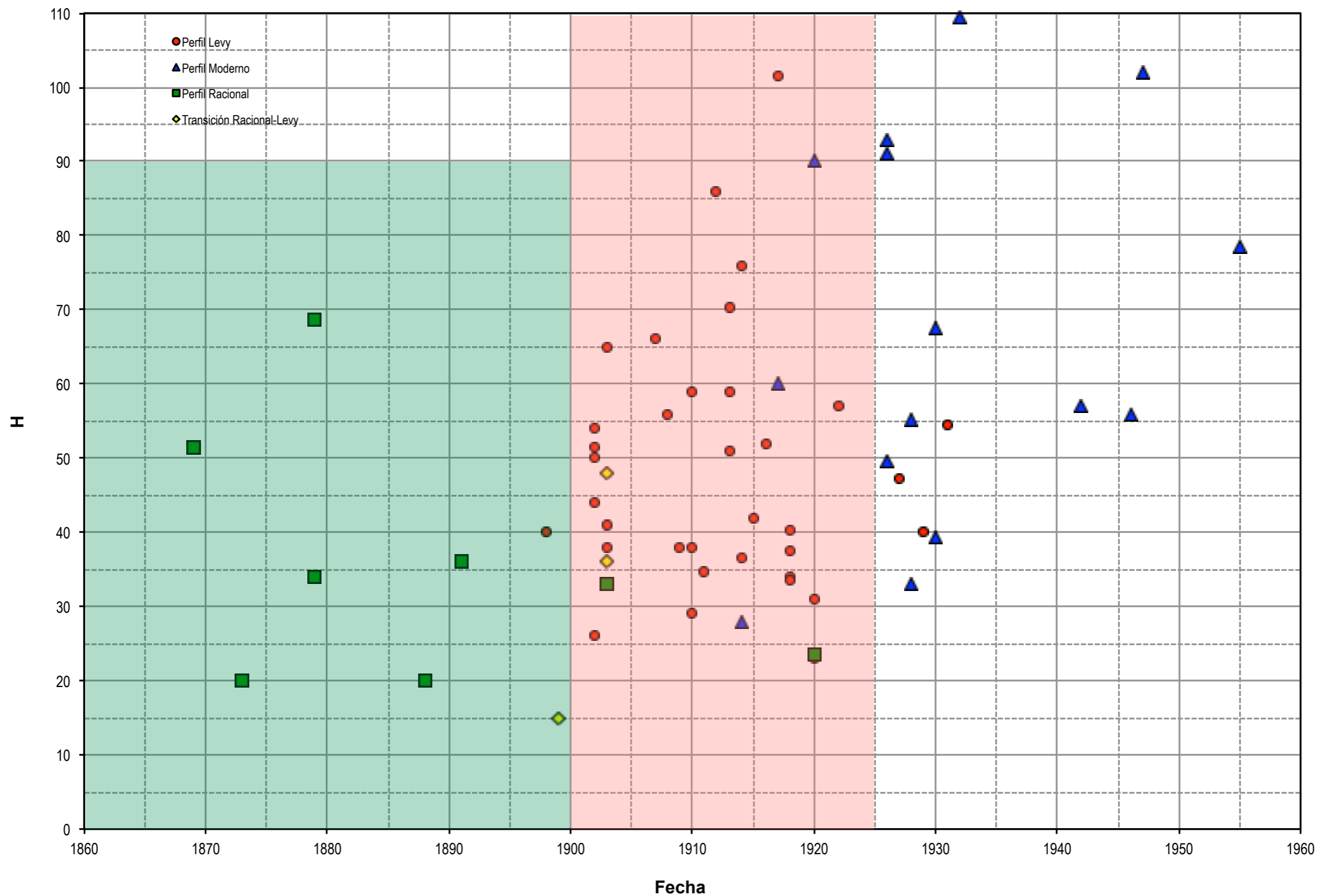
Dams since the middle of the 19th century. Evolution in design



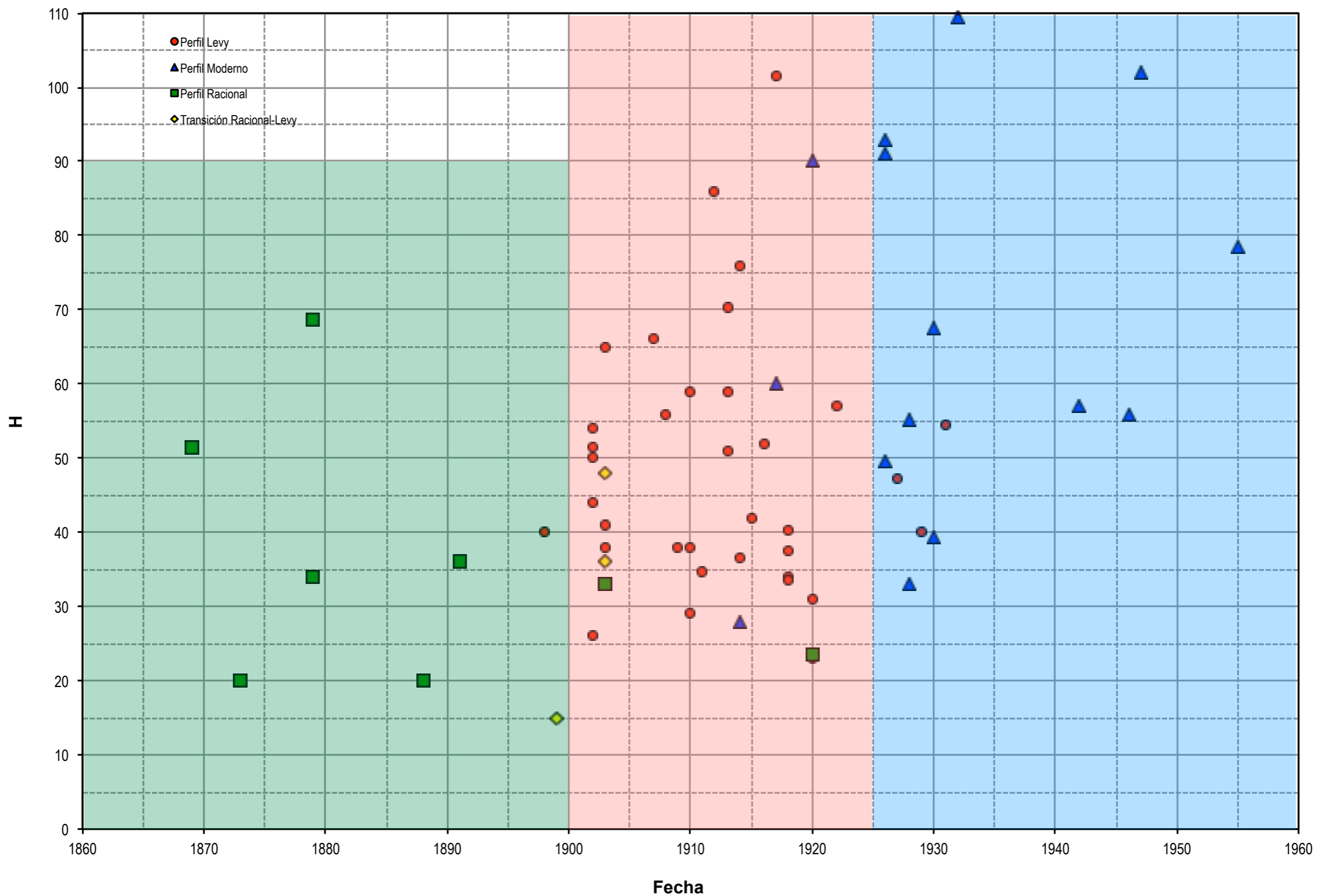
Dams since the middle of the 19th century. Evolution in design



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Dams since the middle of the 19th century. Evolution in design



Dams since the middle of the 19th century. Buttress dams

- ▶ The joint use of buttress typology and masonry was reduced, but it was so in dams of great height and importance within their hydraulic systems.
- ▶ The collapse of the Vega de Tera dam led to the disuse of masonry in the building of buttress dams



Puente Porto dam - 27 m (1953)

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Vega de Tera dam - 34 m (1956)

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Vega de Tera dam - 34 m (1956)

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Merci beaucoup pour votre attention

- ▶ Initially one might have thought that the transition between these three types of sections would have been gradual as quick changes are somewhat unusual in dam engineering.
- ▶ If we consider the finalization date of the dams, we find that there is a time overlap between the three types of sections.
- ▶ However, if we consider the date at which the original project of each dam was written, we found that the overlapping between the three types of profiles is very small.
 - ▶ rational profiles were used exclusively until the year 1900, when they were quickly replaced by the Levy profile
 - ▶ The Levy profile was quickly abandoned in 1925, when modern design criteria were introduced