Aral Sea, Table 1 Relative contents of the principal ions in the Aral Sea water in 1952 and 2008

Ion	Cl^-	SO_4^{2-}	HCO_3^-	Na^+	Mg^{2+}	K^+	Ca^{2+}
Content (%) 1952	34.5	31.1	1.5	21.9	5.2	1.2	4.6
Content (%) 2008	43.3	22.6	0.6	24.8	6.7	1.5	0.5

was extinct in 2003. Nonetheless, despite the enormous mineralization, the Large Sea is still alive – some biological communities demonstrated high resistibility to the salinity growth. According to (Sapozhnikov et al., 2008), over 40 species of microalgae currently populate the Large Sea. The dominant specie in zooplankton is *Artemia parthenogenetica*, whose total stock in the Large Sea is as high as 50,000 t (Arashkevich et al., 2009).

The ongoing Aral Sea crisis also involves a variety of serious problems ranging from air pollution and deterioration of water resources to human health issues and significant challenges to the regional economy.

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Cross-references

Caspian Sea
Classification of Lakes from Hydrological Function
Water Balance of Lakes

ARCH DAMS, DEVELOPMENT FROM CUT-STONE ARCHES TO MODERN DESIGN

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Introduction

Dam designs may be divided into three main types: gravity structures relying on their weight for stability, arched structures using the abutment reaction forces, and buttress dams. Historically, the first dams were earthfill and rockfill embankments, for example, Sadd-El-Kaffara (Egypt BC 2800–2600), Marib (Yemen BC 750), Panda Wewa (Sri Lanka BC 400–300), Cornalvo (Spain AD 150–200). Masonry gravity dams were built at sites where good quality stones were available, for example, Khosr river (Irak BC 694), Al-Harbaqa (Syria AD 132), Kasserine (Tunisia AD 100–200). Note that concrete and stone masonry dams are commonly called “gravity dams.” Sometimes, the dam wall was reinforced by masonry buttresses, for example, Alcantarilla (Spain BC 200–100), Proserpina (Spain AD 130). Later designs included arch dams, relying on the abutment reaction forces to resist the resulting water pressure force. A related design is the multiple-arch buttress dam, consisting of a series of arches supported by buttresses. Smith (1971) and Schnitter (1994) presented comprehensive treatises on the history of dams. However, the arch dam design was rare up to the late nineteenth century, and the historical development of such dams received less attention, with one notable exception (Schnitter, 1976).

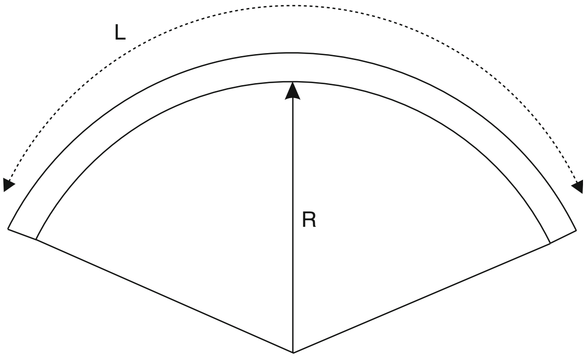
The present contribution shows that the historical development of arch dams progressed during five periods: the Roman arch dams (First centuries BC and AD), the Mongol dams (fourteenth and fifteenth centuries), some advanced masonry dams in the early nineteenth century (1804–1856), the Australian concrete arch dams (1880–1896), and the modern arch shapes at the beginning of the twentieth century (1903–1928).

Terminology

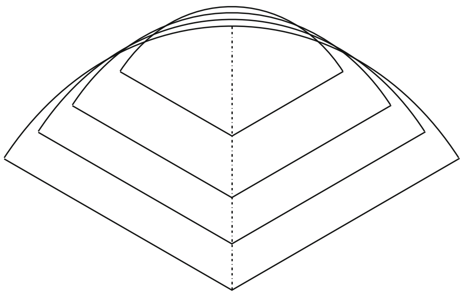
It is inadequate to define a dam as curved or arched because it does not identify the relative importance of the gravity and the abutment forces in providing stability. Such a dam should correctly be called a curved-gravity, thick-arch or thin-arch structure. A *curved-gravity dam* is primarily a gravity structure relying on its weight for its stability, and the wall curvature adds little to its stability. By contrast, an *arch dam* would be unstable without the contribution of the abutment reaction forces.

A *thick-arch dam* relies both on its weight and on the abutment reaction for its stability. A *thin-arch dam* is a leaner structure relying predominantly on the abutment reaction forces for its stability; typically the ratio of the base thickness to the dam height (E/H) is less than one third. Practically, the arch dam design is well adapted to narrow gorges, and it produces substantial savings in costs compared to a gravity dam.

The basic arch dam shapes are the constant-radius arch, the constant-angle arch and the double-curvature arch with increasing complexity. The *constant-radius arch* design, also called the single-radius arch, is a cylindrical shape (Figure 1). The upstream face is usually vertical while the downstream face is battered. The *constant-angle arch* design is a variable-radius arch. The design is based on a constant central opening angle, with the arch radius increasing from base to crest (Figure 1). The concept was first introduced by Albert G. Pelletreau (1843–1900) in 1879 (Pelletreau, 1879). It results in considerable saving in construction material, compared to the constant-radius arch design. Lars R. Jorgensen (1876–1938) who applied the concept demonstrated that the dam contained minimum material for an optimum opening angle of 133.6° (Jorgensen, 1915): he added however that "the use of a smaller central angle [. . .] might be more economical, and 120° or even less [. . .] might give very satisfactory results." The *double-curvature arch* design, also called spherical dome or cupola, has a more complex shape, and vertical curvature is introduced. The shell design results in saving in concrete but requires more technical skills that for a constant-angle arch dam.



Cylindrical arch



Constant-angle (variable-radius) arch

Arch Dams, Development from Cut-Stone Arches to Modern Design, Figure 1 Comparative sketch of single-radius and constant-angle arch dams.

Roman arch dams

The first arch dam is probably the Roman dam at Glanum, built during the first century BC to supply water to the Roman town (Table 1). The Roman dam was rediscovered in 1763 by Esprit Calvet (Benoit, 1935; Goblot, 1967). A recent study by Agusta-Boularot and Paillet (1997) indicated that the dam was made of cut stones held together with crampons and finished with waterproof cordon joints. The site was well selected, and the wall abutments were cut in the rock. A newer dam was built in 1891 at the same place, above the Roman dam foundation, and it still stands today. Another unusual Roman dam was the Esparragalejo dam, near Merida (Table 1). Built around the 1st century AD for irrigation purposes, the structure was a multiple-arch buttress dam, 5.6-m high and 2-m thick at base with circular arches.

Discussion

The Romans built gravity embankment dams (e.g., Alcantarilla, Spain BC 200–100; Proserpina, Spain AD 130), straight masonry gravity dams (e.g., Al-Harbaqua, Syria AD 132), and curved-gravity dams (e.g., Kasserine dam, Tunisia, AD 100? (Saladin, 1886), Çavdarhisar dam, Turkey (Schnitter, 1994)). But the dam at Glanum was unique. It was a slender thin-arch dam (E/H = 0.265). The authors hypothesize that the arch dam design was introduced because the site was favorable to a masonry dam but nearby construction materials were scarce.

The arch technique was applied by the Romans to sewers, aqueducts and bridges, although there is no evidence of scientific design rules. Professor C. O'Connor suggested that, for Roman bridges, the ratio of arch rib thickness to span was about 1/10 for spans less than 15 m and could be reduced down to 1/20 for greater spans (O'Connor, 1993, pp. 168–169). Interestingly, the ratio of dam wall thickness to arch curvature radius was between 1/10 and 1/7 at Glanum, i.e., close to Roman bridge dimensions.

For completeness, some researchers (Schnitter, 1979; Agusta-Boularot and Paillet, 1997) suggested the existence of further Roman arch dams, e.g., Kasserine (Tunisia), Dara (Turkey), Çavdarhisar (Kütahya, Turkey), Örükaya (Çorum, Turkey). The Çavdarhisar and Örükaya dams were flood retention structures; their scour outlet system had cross-section areas of 11 and 3 m^2, respectively (Stark, 1957–1958). A reanalysis of these structures demonstrated that Kasserine, Çavdarhisar, and Örükaya were curved-gravity dams. In the particular case of Dara, the Byzantine historian Procopius (sixth century AD) indicated a curved dam, possibly as at Kasserine, and no remain is visible.

Arch Dams, Development from Cut-Stone Arches to Modern Design, Table 1 Characteristics of historical arch dams

Dam	Date	Design	Constr. material	H (m)	L (m)	e (m)	E (m)	R (m)	θ (deg.)	Remarks
Roman dams										
Les Peirou, Glanum (St-Rémy-de-Provence), France	First century BC	VA-b	Stone masonry	14.7	23.8	3.0	3.9	28.6	48	Town water supply. New arch dam built in 1891. (Authors' inspection (see also Chanson and James, 1998b); Agusta-Boularot and Paillet, 1997)
Esparragalejo, Merida, Spain	First century AB	MV-CB	Stone masonry	5.6	320		2			Irrigation. Rebuilt in 1959. 12 buttresses (8.6-m span) (Schnitter, 1994)
Mongol dam										
Kebar, Qoum, Iran	AD 1300/1600	VA-a	Stone masonry	26 (1)		5 (1)	9(1)	35 (1)	40 (1)	Gravity abutments. Fully silted dam still visible in the 1970s (Goblot, 1965, 1973)
Kalat-e-Naderi, Mashhad, Iran	AD 1350 (?)	VA	Stone masonry	26	74					Goblot, 1965, 1973
Kurit, Tabas, Iran	AD 1350/1850	VA-b	Stone masonry	60/64	27 (1)	1.2 (1)	15 (1)			Still visible in the 1980s (Schnitter, 1994; Goblot, 1965, 1973)
Chabb Abbasi, Tabas, Iran	AD 1400 (?)	VA	Stone masonry	20						Foundation washout without upper wall collapse (Schnitter, 1994; Goblot, 1965, 1973)
Early nineteenth Century dams										
Meer Allum, Hyderabad India	1804 (?)	MV-CB	Stone masonry	12	500			10.6–22.4	180	Designed by Henry Russle. Water supply. Still in use (Schnitter 1994; Smith, 1971; Engineering Record, 1903; Schuyler, 1909)
Jones Falls, Ottawa, Canada	1828–31	VA-a	Stone masonry	18.7	106.7	6.55	8.4	53.3		Designed by John by. Navigation and hydropower. Still in use (Legget, 1957–1959, 1972)

Zola, Aix-en-Provence, France	1847–54	VA-a	Stone masonry	24.5	66	5	13	48.2	77	Designed by Maurice Zola. Town water supply. Still in use for flood retention (authors' inspection (see also Chanson and James, 1998b); Schnitter, 1994; Smith, 1971; Coyne, 1930; Goblot, 1967)
Parramatta, Sydney, Australia	1851–56/1898	VA-a	Stone masonry/ concrete	12.5/15.8	80	2.3/1.46	4.6	48.8		Designed by P. simpson, E.O. Moriarty & W. Randle. Town water supply. Still in use for recreation (Wade, 1909; Ash and Heinrichs, 1996)
Concrete dams										
75-M, Warwick QLD, Australia	1879–80/ 1900-01	VA-a/Buttress	Concrete	5.04/9 (?)	24.5/30	1.07/0.89	2.78	58.5	24	Designed by Henry Stanley. Railway water supply. Still in use (authors' inspection (see also Chanson and James, 1998b))
Lithgow No. 1, Lithgow NSW, Australia	1896/1914	VA-b	Concrete	10.7/11.5	54.3/55	1.07/1.1	3.32	30.48	102	Designed by Cecil Darley. Town water supply. Disused since 1986. (authors' inspection (see also Chanson and James, 1998b); Wade, 1909)
Junction Reefs, Lyndhurst NSW, Australia	1895–97	MV-CB	Concrete & bricks	18.3	131.4	0.5	1.22	8.53	180	Designed by O. Schulze. Hydropower for mining. five arches. Fully silted. (authors' inspection (see also Chanson and James, 1998b); Schulze, 1897)
de Burgh, Barren Jack NSW, Australia	1907–08	VA-b	Reinforced concrete	4.88	30.2 (?)	0.4		20.17		Designed by Ernst de Burgh. Railway water supply. Disused since 1929. Fully silted (authors' inspection (see also Chanson and James, 1998b))

Arch Dams, Development from Cut-Stone Arches to Modern Design, Table 1 (Continued)

Dam	Date	Design	Constr. material	H (m)	L (m)	e (m)	E (m)	R (m)	θ (deg.)	Remarks
Modern designs										
Ithaca, New York, USA	1903	VA-b cupola	Concrete & brick facing	9.1		0.3	2.4	17.6		Cupola designed by G.S. Williams to be 27-m high. Town water supply (Schuyler, 1909)
Hume Lake, California, USA	1908	MV-CB	Reinforced concrete	18.6	206.3	0.46	0.9	7.6	118	Designed by J. Eastwood. Fluming and logging pond. 13 buttresses (Wegmann, 1922)
Salmon Creek, Juneau ALSK, USA	1913–14	VA-b constant-angle	Reinforced concrete	51.2	199	1.83	14.5	45–100.9	113	Constant opening angle designed by L.R. Jorgensen. Hydropower. Still in use (Jorgensen, 1915)
Coolidge, Arizona, USA	1924–28	MV-CB cupola	Reinforced concrete	76	280	1.2	6.1			Cupola arches. Irrigation and hydropower. Modified in 1992–94. Still in use (Schnitter, 1994)

Notes:
Date: construction period (*underlined completion date*); 300/600: construction in 300, heightening in 600.
Design: VA = arch; VA-a = thick arch, VA-b = thin arch, MV-CB = multiple-arch buttress.
Notation: E : dam base thickness; e : dam crest thickness; H : dam height above foundation; L : arch dam crest length; R : radius of curvature of arch wall; θ : arch opening angle; (^{1}) after first dam heightening; (?) : uncertain data.

Mongol arch dams

During the thirteenth century, the Mongols invaded and settled in Iran where they built several large dams, for example, the Saveh dam was a gravity dam built in AD 1285 (H = 25 m, L = 65 m). Around the fourteenth century, they built also some arch dams (Table 1). The Mongol arch dams in Iran had thick-arch walls, and they were significantly higher than the Roman dams. The first arch dam (Kebar, AD 1300) was heightened to 26 m around AD 1600, while the Kurit dam was 60-m high before heightening (Goblot, 1965, 1973). The Kurit dam was extraordinary, having the very-low crest length to dam height ratio L/H of 0.42 after heightening (probably less prior). It is interesting to note that these structures were used for several centuries. Several dams were still standing in the 1970s, although some were subjected to foundation failures, e.g., Chabb Abbasi. The complete upper portion of the dam wall was still standing in the 1970s despite the missing foundation (Goblot, 1973). In the authors' opinion, this highlights the soundness of the arch wall design and the quality of the masonry work. The Mongol dams were further equipped with sophisticated outlet systems (e.g., Kebar, Kurit).

Discussion

Some transfer of expertise on arch dam design might have taken place from the Romans to the Iranians. After the defeat of Valerian's army in AD 260, 70,000 Roman soldiers were captured and transported to Persia where they were forced to work. The Roman army was often involved in large-scale civil engineering works, in particular aqueduct constructions (Fevrier, 1979; Leveau, 1991), and it is likely that it was also involved in dam construction. The Roman prisoners built bridge-weirs and dams in Iran. Examples of bridge-weir include Dezful and Shustar, and an example of dam is Ahwaz (e.g., Smith, 1971; O'Connor, 1993; Schnitter, 1994). Shustar dam is also called Band-i-Kaisar or "Dam-Bridge of Valerian" (O'Connor, 1993). Ahwaz dam, also called Ahvaz weir, was a 900-m long masonry weir on Karun river. Some structures, for example, the Shustar bridge-weir, were still in use when the Mongols invaded in Iran. There is however no proof that the Mongols were aware of the Roman arch dams.

Both the Roman and Mongol dams in Iran were milestones in arch dam development. From the fourteenth century up to the beginning of the nineteenth century, the arch dam development was scattered and disparate. An arch dam was built in Italy at Pontalto in 1612, and the structure was heightened more than six times over the next 270 years from 5-m to 37.8-m. In Spain, Don Pedro Bernardo Villareal De Berriz (1670–1740), a Basque nobleman, designed and built one single-arch and four multiple-arch dams with vertical circular arches in the 1730s. They were low-head structures used for water power purposes, and four of them are still in good condition (Smith, 1971).

Masonry arch dams in the early nineteenth century

During the first part of the nineteenth century, the arch dam design was dominated by four large structures. These were the Meer Allum (India), Jones Falls (Canada), Zola (France), and Parramatta (Australia) dams (Table 1).

In India, Henry Russle, Royal Engineers, built the extraordinary Meer Allum (Mir Alam) dam with a 10-Mm^3 water storage capacity around 1804; see, for example, Engineering Record (1903), Schuyler (1909), Smith (1971), Schnitter (1994). The multiple-arch dam was built to supply water to Hyderabad, and it is still in use. It consists of 21 semicircular vertical arches with span ranging from 21.3 to 44.8 m.

In Canada, Lieutenant-Colonel John BY (1779–1836) built several curved masonry dams between 1827 and 1832 as part of the Rideau waterway system. One structure, the Jones Falls dam, was a true arch dam (Legget, 1957–1959; Smith, 1971; Schnitter, 1994). Completed in 1831, the 18.7-m high dam was a constant-radius arch wall, 8.4-m thick at base (Table 1). The dam is still used today for hydropower and navigation purposes.

François Zola (1795–1847) designed two arch dams in 1832 for the water supply of the city of Aix-en-Provence, France (Coyne, 1930, 1956). One, the Zola dam, was built between 1847 and 1854. It was the first arch dam design based on a rational stress analysis (Schnitter, 1994). The reservoir was used as a town water supply until 1877, and the dam is still in use for flood retention (Figure 2).

One of the first significant hydraulic structures in Australia was the Parramatta dam near Sydney (Figure 3, Table 1). Built between 1851 and 1856, the 12.5-m high arch dam was designed by P. Simpson (1789–1877), E.O. Moriarty (1824–1896), and W. Randle (Ash et Heinrichs 1996). It was a constant-radius arch with a cylinder shape, and it was heightened by 3.35-m in 1898 under the supervision of Cecil West Darley (1842–1928) (Wade, 1909).

Arch Dams, Development from Cut-Stone Arches to Modern Design, Figure 2 Zola dam, Aix-en-Provence, France, in June 1998.

Arch Dams, Development from Cut-Stone Arches to Modern Design, Figure 3 Parramatta dam, Sydney, Australia on September 27, 1999.

Discussion

All four structures were constant-radius arches built in cut-stone masonry. It is generally believed that the thickness of cylindrical arch was calculated using the thin cylinder formula because the concept was familiar at the time to engineers involved in shell and ship hull calculations.

It is worth noting that three dams were built in the British empire. Two structures were designed by Royal Engineers : the Meer Allum multiple-arch dam (1804?) and Jones Falls thick-arch dam (1831). It is possible that these designs influenced the Australian engineers with a transfer of expertise taking place through Royal Engineers. The Royal Engineers in India had a strong involvement in water supply systems, and they were sometimes called upon in Australia. The authors believe that the Royal Engineers in India were aware of the successes of Meer Allum and Jones Falls dams and they might have advised Australian engineers.

The four masonry arch dams are still in use for water supply (Meer Allum), hydropower (Jones Falls), flood retention (Zola), and recreation (Parramatta). Their long-lasting operation demonstrates the soundness of design and the quality of the masonry construction.

Concrete arch dams in Australia

Built near Warwick (QLD), the 75-miles dam was a water supply for steam locomotives (Chanson, 1999). The first dam was designed by Henry Charles Stanley (1840–1921). It was a concrete arch, 5.04-m high, 1.07-m thick at crest, and 2.784-m at the base. The dam was equipped with an overflow spillway, a scour outlet and a water outlet feeding a water tank located below beside the railway line. In 1900–1901, the dam was heightened to 8–10-m under the supervision of STANLEY. The enlargement included the addition of three concrete buttresses (Figure 4). The 75-miles dam in 1880 was the oldest concrete arch dam built in Australia, and possibly the world's oldest concrete arch dam. It was the second arch dam completed in Australia as well as the second dam built entirely of concrete in Australia with a vertical upstream face and battered downstream face (1H:3.6V). The first concrete dam was the Lower Stony Creek dam near Geelong VIC completed in 1873 (Lewis, 1988; Harper, 1998).

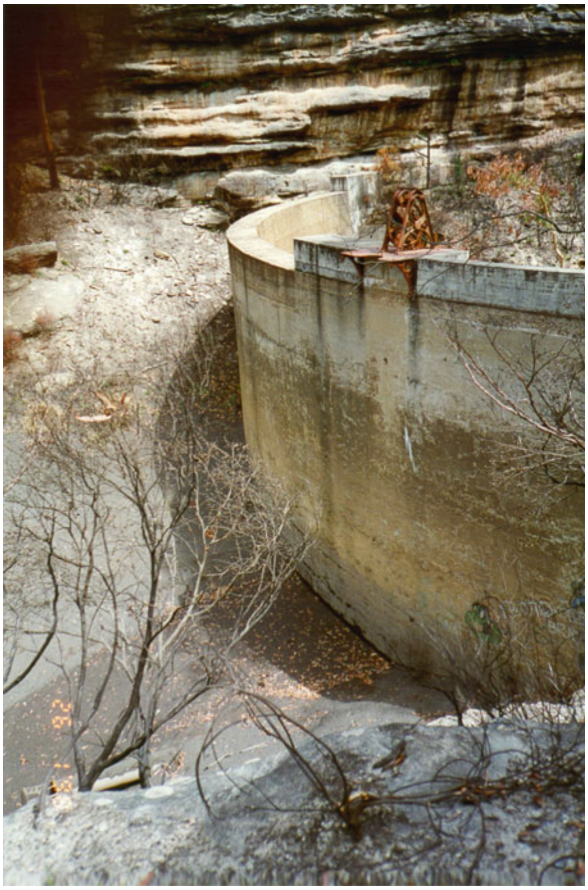
Completed in 1896, Lithgow No. 1 dam was built as a town water supply and designed by C.W. Darley (Figure 5). The 10.7-m high dam was a concrete single-radius thin-arch structure with a vertical upstream face and battered downstream face (1H:3.6V). It was equipped with an overflow section and an outlet system. In 1914 or 1915, the dam was heightened by closing the spillway overflow section and adding new wing walls. A new overfall spillway was built. The dam was disused around 1983–84 because the reservoir did not have enough available head to feed the new wastewater treatment plant. It has been kept empty since 1986, and it is now used as a flood retention reservoir (Figure 5). Lithgow No. 1 dam was the first Australian thin-arch dam, and it is the world's oldest concrete thin-arch structure. The design by Darley became a standard, commonly called "Darley-Wade dam" design in Australia (Chanson and James, 1998b, 2002).

Between 1907 and 1909, Ernest Macartney de BURGH (1863–1929) built two thin-arch dams, de Burgh dam (1907–1908) and Barren Jack City dam (1908–1909), also called Barren Jack Creek dam, as part of the construction of the Burrinjuck reservoir (Barren Jack NSW, 1927), also called Burrenjick or Barren Jack dam (concrete gravity structure, H = 61 m, L = 233 m) (Chanson and James, 1998b). First completed, de Burgh dam was built to supply water to the railway line supplying the construction site, also called Burrenjick or Barren Jack dam (concrete gravity structure, H = 61 m, L = 233 m). It was a reinforced-concrete single-radius thin-arch dam (Figure 6). The concrete wall was reinforced with 20-lb. rails, 1.52-m apart horizontally and 3.048-m apart vertically. The De Burgh dam was a true reinforced-concrete arch with rail reinforcement placed from toe to crest. The wall reinforcement was not a standard design feature of the Darley-Wade dams like the Lithgow No. 1 dam. With Hume Lake dam (see below), the de Burgh dam is the world's oldest reinforced-concrete thin-arch dam.

The oldest multiple-arch dam in Australia

Completed in 1897, the Junction Reefs dam is a multiple-arch dam, 18.3-m high (Figure 7). It was also called Junction Point Reefs dam or Belubula dam (Schulze, 1897; Schnitter, 1994). There are five elliptical arches, each with a 8.5-m span and a 60° lean. The dam foundation and outside walls were made of concrete while the arches and buttresses were built in brick. Brick construction was selected as the cheapest and quickest material to build for the arches, concrete being cheaper only for the foundation (Schulze, 1897). Curiously, the original design included six arches but the final design had only five arches because of delays in the brick-making. The arches were designed in the same way as bridge arches: "the arches were calculated in the same way as bridge [. . .] and the buttresses as

Arch Dams, Development from Cut-Stone Arches to Modern Design, Figure 4 75-Miles dam (Warwick QLD, Australia). (**a**) View from downstream of the dam with the three concrete buttresses (Photograph taken on 23 January 1998). (**b**) Details of the dam crest and buttresses (Photograph taken on January 23, 1998).



Arch Dams, Development from Cut-Stone Arches to Modern Design, Figure 5 Lithgow No. 1 dam (Lithgow NSW, Australia) (Photograph taken on January 26, 1998) View from upstream and right bank.

Arch Dams, Development from Cut-Stone Arches to Modern Design, Figure 6 De Burgh dam (Barren Jack NSW, 1908) (Photograph taken in July 1998) View from right bank during a flood.

bridge piers" (Schulze, 1897, p. 171). Professor C. O'Connor commented that the arch shape and brick laying was unusual, the arch bricks being laid inclined parallel to the upstream arch face while the buttress elliptical shape was not easily understandable. Built to provide hydropower for the nearby gold mine, the dam suffered heavy siltation and the reservoir is fully silted today. The design of Junction Reefs has been well known overseas (Wegmann, 1922; Smith, 1971; Schnitter, 1994).

Modern arch dam designs

The introduction of concrete as a construction material for arch dams marked a significant advance. Designers were able to consider complex curved shapes to minimize the construction material and the overall cost. The developments took place first in North America (Table 1).

Arch Dams, Development from Cut-Stone Arches to Modern Design, Figure 7 Junction Reefs dam (Lyndhurst NSW, Australia) (Photograph taken on December 28, 1997) View from the left bank.

Professor G.S. Williams (1866–1931) designed the world's oldest cupola dam (Figure 8). The Ithaca dam (New York, USA, 1903) was designed to be a 27-m high structure, but construction was stopped when the dam height reached 9-m because of local opposition (Schuyler, 1909; Wegmann, 1922). An interesting construction detail was the brick facing used as concrete formworks.

The oldest concrete multiple-arch dam was designed by John S. Eastwood (1857–1924). The Hume Lake dam (California, USA 1908) was built in the Sierra Nevada Mountains in 114 days (Wegmann, 1922)! The 206-m long 18.6-m high structure consisted of 12 circular arches (15.24-m span) inclined at 58° with the horizontal and vertical in the upper 4.88-m section. The concrete reinforcement included old logging cables (over 12 km) and railroad scrap iron.

Lars R. Jorgensen designed the first constant-angle arch dam: the Salmon Creek dam (Table 1). (This is not strictly correct: Jorgensen (1915) mentioned a smaller constant-angle dam designed by an American H.F. Cameron in the Philippines around 1913–14. The 30-m high dam was used for Manila's water supply.) Completed in 1914, the Salmon Creek dam was 51.2-m high and the opening angle was 113°. The arch radius ranged from 44.96-m at base to 100.9-m at crest.

Another advanced design was the Coolidge dam (Globe Ariz., USA 1928). It was the first cupola-shaped multiple-arch structure. Consisting of three arches, it was designed and constructed by the US Bureau of Indian Affairs, and it is still in use for irrigation and hydropower.

Discussion

Although dams were built as early as BC 3,000, and concrete was used by the Romans, the world's first concrete dams were completed in 1872 : Boyds Corner (New York, USA) built between 1866 and 1872 and Pérolles dam (Switzerland) built from 1869 to 1872. The Boyds Corner dam underwent a major refurbishment in 1990, with the construction of a new spillway (6.1-m wide flip bucket in the central dam section) and the use of post-tensioned anchors to increase the dam stability. Also called La Maigrauge dam, the Pérolles dam was heightening in 1909.

These two dams were followed by others, e.g., Lower Stony Creek (Australia, 1873), San Mateo (San Mateo CAL, USA, 1888), also called Lower Crystal Springs dam. All these were gravity dams. In the United Kingdom, the first mass concrete dam exceeding 15-m in height was the Abbeystead dam completed in 1881 (Binnie, 1987). In Hong Kong, the Tytam dam, completed in 1887, was a concrete gravity structure with masonry stone facing. The Sand River gravity dam, completed in 1906, was the first concrete dam in South Africa (Schuyler, 1909; Wegmann, 1922). Note that the first South African arch dam was completed near Johannesburg in 1898–1899 for mining purposes. In India, the first large concrete structure was the Periar (or Periyar) dam built between 1888 and 1897 near Madras (Schuyler, 1909). In 1870, Rankine's opinion was sought as to the dam profile. In his reply, Rankine extended the method of de Sazilly and Delocre for the design of gravity dam, first applied to the Gouffre d'Enfer dam (Delocre, 1866; Rankine, 1872). This design method is considered as the basic analysis of the stability of gravity dams. Altogether, the construction of concrete dams began in the 1870s and intensified at the turn of the century.

Historically, after the Roman and Mongol era, the arch design fell out of favor until the nineteenth century. The development of arch dams was later facilitated by the introduction of concrete as a construction material.

Arch Dams, Development from Cut-Stone Arches to Modern Design, Figure 8 Ithaca dam (New York, USA), photograph taken in 1998 (Courtesy of Mr G. Toombes).

The world's oldest concrete thick-arch and thin-arch dams were single-radius arches built in non-reinforced concrete. The designs were based on the thin cylinder formula (Wade, 1909; de Burgh, 1917). The Australian concrete arch dam design was acknowledged in Europe and in the USA (Schuyler, 1909; Wade, 1909; Wegmann, 1922; see also Smith, 1971; Schnitter, 1994). Wegmann (in the discussion of Wade, 1909) stated that, in his opinion, "the curved dams built [...] in New South Wales had been designed more logically" than any other arch dams or curved-gravity dams.

Masonry construction: cut-stone or concrete

The zenith of stone masonry dam construction was the 1850–1900 period, and the construction techniques were well documented (Wegmann, 1893; Creager, 1917). Why did the Australian engineers select concrete as dam construction material? In Australia, concrete was used for waterworks, weirs, and dams as early as the 1870s. By world standards, large and innovative concrete works were produced such as the great dome of the Melbourne Public Library (1908–1913) which was the world's largest reinforced-concrete dome at the time (Lewis, 1988). Concrete construction for arch dams was selected because of the lower cost, the facility of construction by unskilled labor and the ease to build irregular shapes compared to stone masonry construction.

Concrete was the cheapest construction material at the end of the century. Darley (1900) estimated the total cost of Australian arch dam at \$8 per m^3 of masonry (Cost in US\$ of the time, with an exchange rate of about £ 1 = US\$ 4.9 (Schuyler, 1909)) (Table 2). Table 2 shows that the cost of concrete dam construction dropped from the 1870s to the 1900s and became lower than that of stone masonry. Darley's choice was consistent, although in advance, with world-known dam engineers. In 1909, Schuyler indicated that cyclopean concrete and mass concrete were both cheaper than rubble masonry and obviously cut-stone masonry for dam construction (Schuyler, 1909, p. 204). In 1922, Wegmann discussed the masonry type for gravity dams : "As far as strength is concerned cut stone would be the best class of masonry for building a dam, but, on account of it great cost, it is only used at the faces and for [..] ornamental work at the top." (Wegmann, 1922, p. 49). (This marked a change of opinion. In 1893, he stated that "rubble masonry is undoubtedly the best material that can be used for building a dam" compared to cut-stone masonry, concrete or rubble (Wegmann, 1893).) Interestingly, a brick construction was selected at Junction Reefs dam as being cheaper than concrete at this particular site.

Another advantage of concrete over cut-stone is the ease of construction by laborers and horse carts. At Lower Stony Creek, "owing chiefly to the scarcity of masons, [...] the dam was built of concrete instead of masonry" (Gordon, 1875, p. 402). Australian concrete dams were built of blocks of stone set in concrete, a technique called plum concrete or cyclopean concrete. "Plum stones to the maximum size that can be handled by two men" were used (Darley, 1900, p. 56). "All the concrete [was] mixed by hand [and] wheeled into place in barrows and trucks" (Wade, 1909, pp. 10–12). The concrete was laid in 3-ft courses "held between mould-boards [formwork] 10 ft long by 3 ft 6 in. high" (Darley, 1900, p. 55). By comparison, stone masonry necessitated a skilled workforce (i.e., stonemason artisans) and a plant to carry stones. For example, a machinery capable to carry 2–6 t was used to handle and place the masonry blocks at Parramatta dam (Figure 3, Ash and Heinrichs, 1996, p. 13). The ease of construction contributed to the lower cost but also suited well a new continent without skilled manpower.

A third advantage of concrete construction was the flexibility of shape: "With concrete [...] labour is saved and concrete has the farther advantage that it can be rammed into any irregular cavity" (Dobson, 1879, p. 111). Dobson referred to the construction of the Lower Stony Creek dam. Concrete offered a flexibility of shapes and curved designs (e.g., cupola shape). The introduction of concrete as a construction material paved the way for

Arch Dams, Development from Cut-Stone Arches to Modern Design, Table 2 Masonry dam construction costs

Dam	Year of completion	Dam type, masonry type	Masonry volume (m^3)	Masonry cost (US$/$m^3$)	Remarks
Gouffre d'Enfer, Fra	1866	Gravity, Stone	39,986	8.0	
Lower Stony Creek, Aus.	1874	Gravity, Concrete	4,000	20.7	
Bear Valley, USA	1884	Arch, Stone	2,599	28.9	Located 1,890 m altitude
Betaloo, Aus.	1890	Gravity, Concrete	45,873	12.4	
La Grange, USA	1894	Gravity, Stone	30,200	18.2	
Williams, USA	1894	Gravity, Stone	3,996	13.2	
Junction Reefs, Aus.	1897	Multiple arch, Brick & concrete	5,352	10.0	Brick arches.
Seligman, USA	1898	Gravity, Stone	13,885	10.8	
Australian arch dams	1900	Arch, Concrete	–	8.0	Darley-Wade arch dams.
Barossa, Aus.	1902	Arch, Concrete	13,743	9.2	
Cataract, Aus.	1907	Gravity, Stone	111,810	14.3	
Cross River, USA	1910	Gravity, Stone	118,506	10.5	

Schulze (1897); Darley (1900); Schuyler (1909); Wegmann (1922); Harper (1998)

the newer modern designs : constant-angle and cupola arch dams, e.g., Ithaca (1903) (Figure 8).

The development of concrete dam construction under the leadership of Dobson and Darley marked the end of large stone masonry dam in Australia. From 1890, the highest large dam in Australia had been a concrete structure until the 1960s (Nimmo, 1966). An interesting parallel is the construction of masonry arch bridges. O'Connor (1974) showed that the construction of (notable) stone arch bridges came to a end basically in 1909. The historical development of bridges was characterized "by a complete cessation in the construction of major stone arches (c. 1909)" (O'Connor, 1974, p. 10). This date coincided with the construction of the Grafton bridge in Auckland (New Zealand) (completion 1910, 98-m clear span).

Multiple-arch dam design

The development of multiple-arch dams attracted some interest in Spain and Italy. Roman engineers built the oldest multiple-arch dam at Esparrageljo in Spain (Schnitter, 1994). In 1530, the architect Baldassare Peruzzi (1481–1536) proposed a multiple-arch dam for the reconstruction of a fishing pond reservoir in Siena, Italy (Schnitter, 1994, pp. 118–119). Turriano (1511–1585) recommended also the selection of multiple-arch dam "for use on large rivers" in his Codex (Garcia-Diego 1976). Villareal de Berriz built five multiple-arch buttress dams in Northern Spain around 1730.

In the nineteenth century, two significant structures were Meer Allum and Junction Reefs. Although Junction Reefs dam was smaller than Meer Allum, it incorporated new advanced features: elliptical arches and a sloping upstream face which enhances the dam stability. Further advances in designs were made with the Hume Lake and Coolidge dams.

Conclusion

The historical development of arch dams may be summarized in five stages (Table 1). The world's oldest arch dams were built by the Romans in France and Spain. They were followed by the Mongols who built dams in Iran during the thirteenth and fourteenth centuries. However, it is not until the nineteenth century that significant progress in arch dam design was made. Four remarkable structures were the Meer Allum dam (India 1804), the Jones Falls dam (Canada 1831), the Zola dam (France 1854), and Parramatta dam (Australia 1856). All four of them are still in use today, and they demonstrated the soundness of arch dam design. Australian engineers pioneered the use of concrete as a construction material for arch dams. The world's oldest concrete arch dam was completed in 1880 : the thick-arch dam at 75-Miles. The world's oldest concrete thin-arch dam was the Lithgow No. 1 dam (1896). Both the 75-Miles and Lithgow No. 1 dams were made of non-reinforced concrete.

Modern arch dam designs were further developed in North America. The world's oldest cupola dam was completed in 1903 at Ithaca. The first constant-angle arch da was completed in 1914. Modern multiple-arch design were completed in 1908 (Hume Lake) and 1928 (Coolidge). Since no major breakthrough has taken place. It is the writers' opinion that the introduction of concrete as construction material marked a major innovation in arch dam shape.

Notation

E dam base thickness (m)
e dam crest thickness (m)
H dam height above foundation (m)
L arch dam crest length (m)
R radius of curvature (m) of arch wall
θ arch opening angle

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ARCTIC LAKES

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Definition

Lakes located in an arctic area. Geographically it is the area north of the Arctic Circle, 66°30′N; climatically it is the area north of the 10°C isotherm for the warmest month, provided the mean temperature of the coldest month is below 0°C.

Arctic lakes may be classified according to the formation of the depression where the lake is formed and the material in the bottom of the lake. Many arctic lakes owe their existence to carving of the landscape by previous or recent glacial erosion. This erosion may result in numerous lakes of all forms and depths; however, often an orientation determined by the direction of the ice movement is seen. Elongated deeper lakes may be formed by the melt water (tunnel valleys). Other deep lakes may be formed by the melting of buried dead ice. In recent tundra areas, lakes may be formed by periglacial processes such as thermokarst and development of pingos. The material of the bed is most often till of variable thickness or solid bed rock. In recent glaciated areas, lakes may be formed at the margin between a glacier or an ice cap and the surrounding landscape. If the ice at the margin is melted or lifted because of buoyancy of the lake water; such lakes can be tapped very fast causing large floods, so called jökulhlaups. On larger glaciers and ice caps, lakes may be formed in depressions into the surface, so that the boundary consists solely of ice. Such lakes may interact with the drainage system of the glacier or the ice cap and may also cause severe floods if the melting in the bottom removes the sealing to the internal drainage system. The thermal conditions of arctic lakes are characterized by mixing and layering caused by the density maximum of water at 4°C. Another characteristic pattern in arctic lakes is the formation of an ice cover that can last from a few days to perennial. The ice cover influences the light conditions and the heat budget of the lake and thereby the biological conditions. Depending on the bathymetry of the lake and the initial chemical composition of the lake water, the formation of ice can cause significant annual variations in the chemical composition. In the case of shallow lakes, the ice formation can cause formation of brine that again may precipitate and develop layered sediment on the bottom of the lake.

Shortly after the disappearance of ice cover, the lake water attains a temperature of 4°C. Warming by solar radiation and advection of warm air heats the water, with surface temperatures up to 10–15°C, while the deeper parts remain at 4°C. A stable layer called the thermocline is formed between the two water masses. In the autumn, cooling causes a new isothermic situation. Then further cooling leads to ice formation when the surface water temperature is close to 0°C. When the lake is ice covered the water temperature rises slowly because of solar radiation penetrating the ice and by thermal heating from the bottom. Deposition of snow diminishes the penetration of solar radiation and insulates the lakewater reducing the heat exchange.

Ice thickness in Greenland and Arctic Canada is 1.5–2 m, increasing from south to north; a maximum of 2.5 m is recorded on Ellesmere Island. Freeze up begins early to mid-September while breakup begins June to August. Lakes in high arctic can be covered by ice for several years, e.g., Romulus Lake on Axel Heiberg Island, but normally at least a moat of open water near the shore is formed. Examples of climatic arctic lakes in Canada are Baker Lake in Nunavut and Lac Klotz on the Ungava Peninsula, both south of the Arctic Circle. Examples of High Arctic lakes are found on the Canadian Arctic Islands. In Greenland, arctic lakes are situated on both sides of the Arctic Circle. Examples of saline arctic lakes are found near Kangerlussuaq, West Greenland, e.g., Braya Lake and Limnea Lake.

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