A Forgotten Chapter in Dam History: Masonry Dams in British India in the Nineteenth Century

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ABSTRACT: British dam practice in the nineteenth century was dominated by the use of earth embankments with puddle clay cores (Binnie, 1981; Skempton, 1990). However, British engineers in India often benefited from more advanced academic training at the East India Company's Seminary, Addiscombe, and later the Cooper's Hill College, and made more widespread use of masonry structures. A pioneering buttress dam at the start of the nineteenth century was followed by Khadakwasla Dam, the first large gravity masonry dam, designed by General J G Fife, who also translated the work of Graeff and Delocre into English (Fife, 1869). Indian-trained engineers later moved to Australia, pioneering the use of masonry arch dams there, to designs generally far in advance of their UK counterparts. In that context the first modern masonry dam was not built in Britain until Abbeystead in 1881.

"The man who ventured to go far beyond established custom among the profession deserved the highest credit and praise…" Colonel John Pennycuick (in Wade, 1909, 32).

DAMS IN INDIA

India is a leading dam building nation, with over 4500 structures over 30m in the ICOLD register. This is the culmination of an achievement dating back millennia, a history in which British engineers played a role for around 150 years as chief European power in south Asia. Jackson (1885) identifies over 90,000 tanks and reservoirs across the Indian Empire, mostly earth embankments of indeterminate age. While a few were impounding dams of some height across river valleys, most were intended to capture monsoon rainfall, or flood waters, and were generally shallow, although several kilometres in length. By 1850 many had fallen into disrepair, and in areas like Rajasthan British officials, in that case Dixon (Cross-Rudkin and Chrimes), did much to revive existing systems. Inevitably, as British power consolidated in the region, its engineers and administrators considered a number of civil engineering projects that involved new dams and reservoirs. Distance and local conditions meant that practice could vary a great deal from that of the home country.

MEER ALUM (MIR ALAM) DAM C.1804-1808

True arch dams, as compared to gravity dams curved in plan, were rare before the twentieth century (Chanson and James, 1999; Schnitter, 1976) In that context the Meer Alum Dam is remarkable. A multi-arch masonry buttress dam beside Hyderabad, over 1km in length (1,120 yards), it is an outstanding example of dam construction from the era before modern analytical design methods. 12 m high it comprises 21 buttressed semicircular arches varying up to c 30m in span.
Responsibility for the design is uncertain. It is named after Mir Alam (d.1808) the anglophile chief adviser to the Nizam of Hyderabad (c.1804–1808), who laid the foundation stone on 20 July 1804, and often attributed to 'Russell', most obviously (Sir) Henry Russell (1783–1852) (Skempton, 2002). Russell went to Hyderabad in1800 as Secretary to the Resident, whom he replaced in the summer of 1804. He then spent most of his career there. But there is nothing to suggest that Russell had any engineering expertise, available from the Madras Corps of Engineers, who had officers stationed in the State. One, Samuel Russell, designed the Residency. Russell went to Madras as an Engineer in 1801, and was definitely in Hyderabad c.1806–1809, resigning from the Service on

13 January 1810. However, there is no evidence he originated the design. It is credible he, or Henry, could have managed the project. The Corps had established a public works section in 1786, and officers like James Caldwell (1770–1863) or Thomas De Haviland (1775–1860) (Skempton, 2002) would have been capable designers. No records have been found in the India Office archives to substantiate this. Some Indian sources date the completion to 8 June 1806.

There is another tradition (Imperial Gazetteer of India (1908), vol.XIII, 311) which attributes the design to French engineers, and identifies the construction cost at 8 lakhs (£80,000). The French military adventurer Michel Joachim Marie Raymond (1755–1798) was active in Hyderabad from 1786 and assembled a military force with some French personnel. His involvement with Tipu eventually led the British to eradicate French influence. It is possible work began under the French and was completed by Russell, but no confirmatory evidence has been found.

One must bear in mind the prowess of the Indians themselves as designers and builders of hydraulic structures. Under the Sultan Ibrahim Kutb Shah (c.1575 AD) another major reservoir was built at Hyderabad – Hussain Sagar. This dam designed by Hazrat Hussain Shah Wah is twice Mir Alum's length and carried the road to Secunderabad. Mir Alam is analysed by Bligh (1910, pp.93-96).

MASONRY DAMS IN OTHER BRITISH COLONIES

The mystery of the genesis of the Mir Alum design is not unique in the annals of British military engineers of the era. On the Rideau Canal in modern Ontario Lieutenant John By designed the Jones Falls Dam – a masonry arched dam with a concave downstream face. (Leggett). While Spanish arch dams were much older (Smith, 1970), there is no evidence By had used them as a precedent. Knowledge of the advantages of a curved profile for a retaining structure is far more likely (Pasley, 1822). There is some evidence other masonry dams on the canal failed (Jackson, 1885).

Just as apparently unprecedented was the arch dam built for Parramatta (New South Wales) water supply in 1851-56. Early dams in Australia were largely earth embankment dams, although some masonry weirs and rock fill structures were built (Kinstler, 1999). The dam is more slender in its profile than the near contemporary Zola Dam, generally acknowledged as the first modern arch dam. Because of its early date and largely unprecedented nature, there has been some debate about the designer, probably E. O. Moriarty (Cross-Rudkin and Chrimes), and what calculations if any were used (Ash, 1986; Ash and Heinrichs, 1999). Parramatta was not the first masonry dam with a curved plan to be proposed in Australia. Colonel George Barney RE, the New South Wales Colonial Engineer, earlier proposed a curved weir across the Yarra.

EARLY MASONRY HYDRAULIC WORKS IN BRITISH INDIA

Disregarding Mir Alum, British engineers executed some major masonry structures in the first half of the nineteenth century, generally indicative of a skilled workforce and increasing understanding of conditions on the sub-continent. These included weirs, barrages and aqueducts of large size and capacity (India, 1922). Early work such as that in the Madras Presidency on the Grand Anicut (originally built 200AD) on the Cauvery (Kaveri) River, and on the Jumna in the Punjab, was of a remedial nature. Soon, however, more radical work was undertaken. Shortcomings of the Grand Anicut led (Sir) Arthur Cotton (Cross Rudkin and Chrimes) to design the Upper Anicut on the Kollidam (Coleroon). Completed in 1836 it was a masonry structure 780m (2562ft) long. Shortcomings led to the construction of the 'Cauvery Dam' 1843-45. Other major weirs and barrages followed into the twentieth century as more ambitious irrigation schemes were erected. Some encountered hydraulic and/or foundation problems. Most significant was perhaps the Khanki weir, whose failure and its solution led to important advances in soil mechanics (Beresford; Clibborn; Skempton, 1979; 1985) reflected in successive editions of *Irrigation works*, by Bligh (1907, 1910).

DAM DESIGN METHODS BEFORE 1870

There is no clear evidence whether British engineers used eighteenth century works by Belidor (Smith, 1971) and Villareal (1736) for dam design. However a number of British sources describe design methods in use before 1870. Telford's memorandum book (Rickman, 1838, Weale, 1859) describes how to calculate the total pressure on reservoir banks or tanks. Gregory (1825) deals with the design of retaining walls for earth (pp.222-224), dykes (p.283) and basins (p.283-) suggesting a curved profile for masonry dams to resist water pressure. Moseley presented design methods for reservoirs. He discusses this in his *Treatise on hydrostatics* (Moseley, 1830), and his *Treatise on mechanics* (1834), returning to it in his *Mechanical principles* (1843, 1855). There he discusses the cases of walls of uniform and variable thickness sustaining the pressure of a liquid, identifying the conditions to prevent courses slipping one upon the other. Rankine's approach, expounded in *Applied mechanics* (Rankine, 1858), and *Civil engineering* (Rankine, 1862) was similar. Early editions of Molesworth's *Pocket book* (Molesworth, 1868) related the thickness of masonry reservoir walls to their height (Molesworth, 1868, p.17). He used a cylinder thickness formula in the context of steam cylinders (Molesworth, 1868, p.117). No immediate notice was taken in Britain of Sazilly (1853) suggesting a more 'rational' approach.

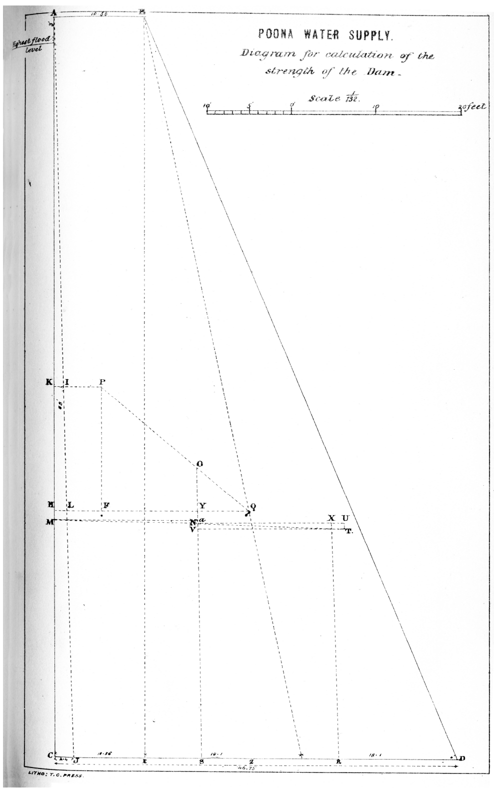
FIFE AND THE CONTRIBUTION OF 'RATIONAL' METHODS OF DAM DESIGN

Engineers like Captain W Jones in Rohilkund (Jones, 1855) and Captain G Wingate (1853) in Badama (Belgaum) were recommending the use of locally sourced masonry for 'bunds' in the 1840s and 1850s. Fife was keen to develop irrigation in the Bombay Presidency as was already happening in Madras and the Punjab and identified Ekrookh near Solapur (Sholapur) as a site for a reservoir. F D Campbell drew up a proposal in 1863. It was apparent to Fife that there was little difference in cost between the earth bund originally proposed, and a dam of uncoursed masonry, with sloped earthwork on each face. The overall length was 7,200ft (2195m) and 72ft (21.9m) high (Bombay, 1866). By this time Fife had established, at least in Bombay, that rubble masonry was safer for large masonry hydraulic structures, reducing the likelihood of leakage, or weakness of mortar leading to failure, along joints. In the end a puddle dam was built (Bombay, 1867).

By then Pune (Poona) was experiencing water problems. The main supply from a weir across the Mutha River downstream from the city, created in 1848, was contaminated by sewage from the city. Fife in 1865 recommended a masonry dam across the Mutha at Khadakwasla, 10 (16km) miles upstream (Fig. 1). This could supply water to Pune, and irrigate land on both sides of the river. The dam rose 94ft (28.7m) above the river bed and 107ft (32.6m) above foundation level (now 41m). The water retaining structure was 3431ft long (1045m) (1540m overall), with a waste weir 1394ft (420m) in length. The weir was 11ft (3.35m) below the crest, and the dam was designed to be 'safe' with a water level of 6ft (1.8m) below.

The dam's chief interest lies in the fact it was the first masonry dam of any size to be built in British India, aside from Mir Alum, and some time before such dams were designed in Britain. Fife (1867(1)) described the design, using Rankine's (1858. 1862) methods for retaining walls (Figure 1). He believed he had erred on the side of caution. Almost immediately he became aware of articles in the 1866 *Annales des ponts et Chaussées* on French dam design (Graeff, Delocre) and began their translation (Fife, 1867(2)). As he noted (Fife, 1869, p 4): 'in studying M. Delocre's memoire, "it is impossible not to be struck with both the economy of his designs and the careful and sound reasoning by which he establishes their sufficiency". Fife was frustrated that many of his proposals were rejected as uneconomic, and saw the new analytical tools as a way of combating such problems. It was this translation Fife (1869), rather than the Khadakwasla reservoir that had the greatest impact on future masonry dam design. It is possible that he was the source for the more idiomatic translation that appeared in *The Engineer* in 1868 which is prefaced by a plea for the development of irrigation in India (Anon, 1868).

TULLOCH, AND RANKINE: MUMBAI WATER SUPPLY



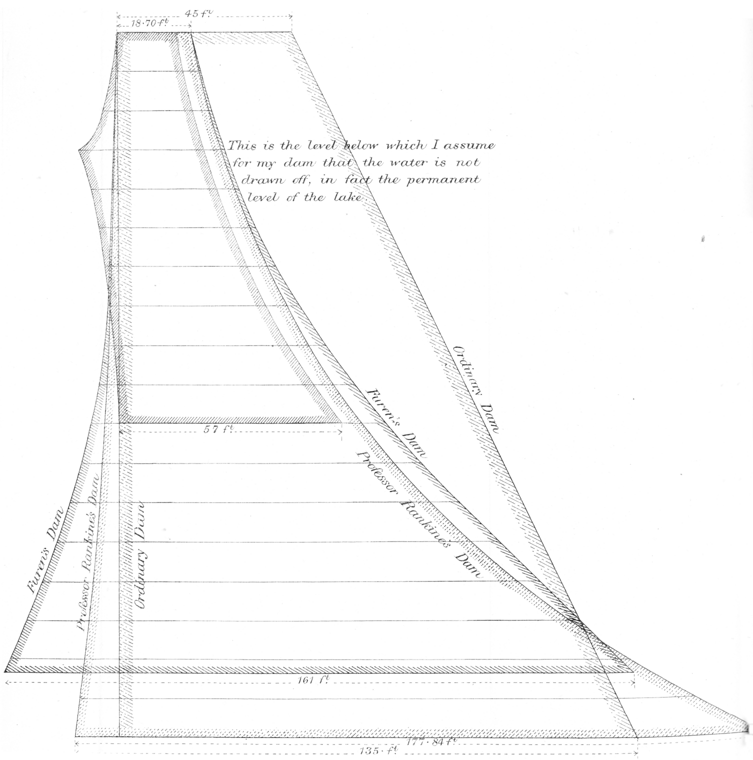


Figure 1(left): Fife's design for Khadakwasla dam; Figure 2 (right): Tulloch and Rankine's designs for Tansa

Fife's careful translation made it potentially available to all colleagues in the Bombay Presidency and the Indian PWD. How easy knowledge transfer was at the time is difficult to assess. Copies were also available at ICE from 1870, and the Royal Engineers Library. In the city of Bombay (Mumbai) there was a lively debate about the city's water supply (Conybeare) No sooner had the Vehar (Vihar) reservoir been built than engineers began to debate its adequacy. Captain Hector Tulloch (Cross-Rudkin and Chrimes) reported. He considered an earth embankment dam, regarding masonry dams as wasteful of material, and probably costly and difficult to build without skilled masons. In part one suspects this was due to knowledge of such dams in Spain, reported on by Scott-Moncrieff (1868). Evidently awareness of the longevity of these dams was moderated by the cost of their heavy profiles. As Tulloch considered his alternatives he 'accidentally' (Tulloch, 1872) came across Fife's translation and realised that economical profiles in masonry had been achieved in France. With the agreement of the Bombay authorities he wrote to Rankine at Glasgow University on 10 October 1870 with a copy of Fife's (1869) report and his own calculations of the best profile for a masonry dam.

Rankine replied on 9 February 1871, commenting on Delocre and Graeff's work, and Tulloch's proposal. He enunciated the underlying mathematical principles of masonry dam design as well as the (later) well known Rankine criteria for safe dam design: that nowhere on any horizontal section of the dam should tension be allowed to develop-whether on the air or water face, and whether the dam was empty or full. While Sazilly's profile achieved this it was not explicit in the theory. Both Sazilly (1853) and Delocre (1866) in fact ignored the issue of tensile strength. Rankine also stressed the need for any resultant pressure to pass through the 'middle third'. He believed that pressure was exerted at a tangent to the face, and that its magnitude would exceed the vertical stress in ratio to the batter of the face ie the maximum principal stresses occur in directions parallel to zero shear. He constructively criticised Tulloch's ideas and provided his own solution. The correspondence was published in 1872 with all of Tulloch's recommendations on Bombay water supply (Tulloch, 1872), and more importantly in *The Engineer*'s first issue of 1872 (Rankine, 1872). This, and the republication in Rankine's collective works (Rankine, 1881) are the most widely cited sources for Rankine's principles. His profile (Figure 2), and the French were both included in the Roorkee Treatise on civil engineering (Roorkee, 1873), available for students at the Thomson civil engineering college.

In Mumbai, although Tulloch's preferred scheme did not go ahead, water shortages led to the adoption of the Tulsi scheme, and the construction of a rubble masonry gravity dam on Rankine's principles. Nominally designed by Rienzi Walton MInstCE, the acting Bombay city engineer, it was a Committee on which Fife sat that endorsed the design. Completed in 1879 it is 26m high, 186 m long, and has a capacity of 87,600,000m^3 (Walton,1872-1874)

Despite recognition of the validity of Rankine's work today it was not generally accepted (Smith, 1994). G L Molesworth, then chief engineer for Indian State Railways, regarded both Rankine's and Delocre and Graeff's approach as too mathematical, and developed an approximate formula (Molesworth, 1874) which was widely referred to, and used in India.

OTHER APPROACHES

Fife was, unsurprisingly, not the only engineer in India looking at masonry dam design. The Ajmere based engineer E L Asher (1870) described a design method using a triangular profile. This was criticised by T Higham (1870), then on the Bari Doab Canal, later Inspector General of Irrigation in India. In Madras George Gordon, Deputy Chief Engineer for the Madras Irrigation and Canal Company, designed a large gravity masonry dam, not long after (probably c.1865) Fife developed his design for Poona. Luckawully reservoir was intended to provide water for the Madras Irrigation and Canal Company by damming the river Budra in a narrow valley. The dam, of stone and brick masonry and concrete, was 174 ft (53m) high, 124 ft (37.8m) wide at the base and 5ft (1.5m) at the top. It was designed for a depth of 170ft (51.8m) of water, although the waste weir was at 160 ft (48.8m), and was initially calculated to resist twice that force of water pressure. To give an additional factor of safety the first 48ft (14.6m) of height were carried up vertically to allow retaining walls to be built to permit the rear (downstream) side, which had a much shallower incline, to be loaded with earth and stones to raise the factor of resistance to 2.6 or more. At much the same time (c. 1869) Gordon was also planning the reconstruction of the Masoor embankment which also involved extensive masonry work. (Mullins).However his concrete arch dam for Geelong water supply (see below) was designed using a modified version of Graeff and Delocre's approach (Gordon, 1875). Fife himself contemplated another large dam at Roxana on the Girna in Khandeish, but the sandy foundations stalled the scheme (Playfair).

CONTEMPORARY VIEWS ON KHADAKWASLA RESERVOIR

Despite Fife's achievement in making the case for rubble masonry in water retaining structures, generally accepted in the Bombay Presidency (*Bombay gazette*) in particular, and the general success of his dam in impounding a large reservoir of 87,600, 000 m^3 capacity, there were critics. His successor in the Deccan, Lieutenant Colonel Playfair(1869) considered it too bold, and in need of more masonry, or gravity. Russell Aitken, involved in the controversy about Bombay's water supply while in India, criticised Fife's design in January 1872 when lecturing at the Royal Engineers Institution in Chatham (Aitken, 1872). Using the recently published Rankine method he found the masonry at the upstream toe to be in tension, although he recognised the masonry had a higher specific gravity then Rankine assumed, giving an element of safety.

J D Schuyler (1901, 1902) relying on H M Wilson (1891) for his information, described the design as ‘amateurish’, an anachronistic conclusion informed by 30 years of ‘rational’ methods. He criticised the tangential plan – for which Fife had designed buttresses at the angles, and the placement of earth on the downstream side. There had been criticism (discussion on Clerke, 1894) that the dam had shown signs of movement when filled, but this was reported as due to thermal movements (Clarke, 1894). A number of other commentators (e.g. Ziegler) observe the placement of earth, as if this was part of post-construction strengthening, but such a system, to preclude leaks, was suggested by Fife for Ekrookh (Bombay, 1866), and was also found at Jones Falls.

LATER MASONRY DAMS IN INDIA

Following Fife’s work and the publication of Rankine and Molesworth’s advice Indian engineers built a number of masonry dams at a time when concrete began to supplant ashlar and rubble masonry for such structures, as it was elsewhere in the world (Sutherland)
Perhaps the most striking in profile is the Betwa or Paricha Dam or weir, designed by H.A. Brownlow, with calculations by J. S. Beresford (McWillam) and William Willcocks (McWilliam) as Resident engineer, completed in 1885 (India, 1887). The water face is curved, and the air face near vertical, with a protective block at the toe, and a small weir downstream to retain water and create a water cushion and protect the toe from erosion under flood conditions (Fig 3c)(Willcocks). The Betwa irrigation scheme originated with Captain Richard Strachey in 1855. Its story is illustrative of the evolution of masonry dams in India. In 1868 Lieutenant F. Home (Cross-Rudkin and Chrimes), Executive Engineer, Bundelkhund Irrigation Survey submitted a project for irrigation from

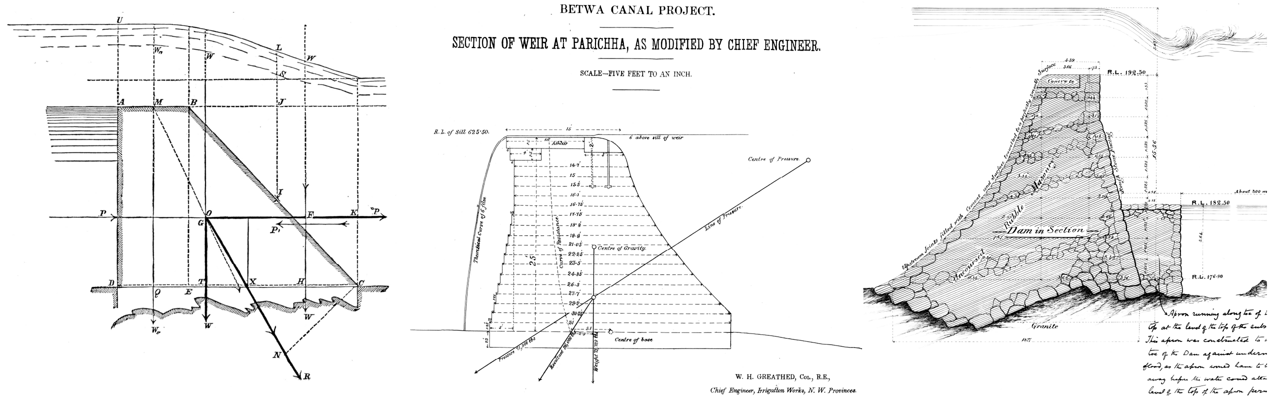


Figure 3 Betwa weir: a: Bagge’s design; b: as modified by Brownlow; c: as built

the Betwa river, with a masonry weir. Lieut Col W.W.H. Greathed, Chief Engineer, Irrigation Works, North Western Provinces, endorsed this , while Strachey, now Inspector General, Irrigation Works, India gave it qualified support, partly based on the success of a masonry dam by Fife c 7m (22ft , possibly at Kurrar) high. On 27 November 1869 Lieutenant Arthur H. Bagge submitted a more detailed report. He identified 4 rocky barriers as possible locations for a dam or weir, favouring Ghuswogan. His design criteria were: the smallest convenient base, to possess a greater stability as the flood increases, and to pass of water as easily as possible. He used a trapezium form, establishing the stability using triangles to calculate where the resultant passes through the base Fig 3a), presumably based on Rankine (1858, 1862). Clinton Anderson, the Superintending Engineer, was aware of the Furens dam and criticised Bagge’s section as too heavy. He had read the papers that appeared in The Engineer in 1868 by Delocre and Graeff and redesigned accordingly with great savings in the profiles, probably the first time such methods were used by a British engineer. He supported Home’s site at Paricha. Although also supported by Greathed and Brownlow (Cross-Rudkin and Chrimes), Chief Engineer Irrigation NWP, the Indian Government were cautious and required more information. James Hair, now Superintendent Bundelkhund Irrigation works, made a further report in late 1874 with a weir, curved in plan, of rubble masonry and kankar lime, with some ashlar in Portland cement. Greathed supported the curved plan, but Hair’s traditional trapezoidal cross-section was criticised by Brownlow. He believed the downstream slope would be vulnerable to erosion from overtopping, and recommended a near plumb downstream face, but with an extended upstream face to increase stability (Fig 3b). Calculations of pressure and resistance were as laid down by Rankine. The weir was of rubble masonry faced with dressed stone. However Colonel J Crofton (Inspector General, Irrigation, India, recommended the use of uncoursed rubble masonry as employed in Bombay, and reducing the height and crest width of the weir in some areas, although Greathed disagreed. The dispute between the Irrigation engineers, NWP, and central government continued until 1881, when work began at Paricha under Major Western. The location was altered to nearby Khoord, using Hair’s plan and Brownlow’s section. The scheme opened on 29 September 1885. The dam is 17m high, 1159m long, with a capacity of 78,760,000 m3.
At Jabalpur (Jubbulpore) J G H Glass MInstCE built a water supply dam at Khandari Nullah of uncoursed rubble masonry 1881-1884. 524m long and up to 23m (74ft) high using local basalt and hydraulic mortar, a maximum pressure of 16,000lb/ft^2 (766kN/m^3) was used in the calculations. Colonel C M Browne RE modified the de-

sign to include the use of cement grout in the wing walls as well as in the foundations, and puddle clay cut offs. J C Addison carried out the calculations following Rankine's recommendations. (India, 1889, 110-115)
Soon after came another dam on Rankine's principles -Bhim Tal- designed September-October 1882 and completed in August 1883 (Ashurst). Irrigation in Bhabur was originally supplied from rivers such as the Gola, but supplies were irregular in the dry season. In the mid-1850s Captain (Sir) Henry Ramsay, Commissioner in the district of Kumaon built a small dam across the outlet of a natural lake, Bhimtal. In the 1870s this was replaced by a larger earth dam with a thin masonry core wall. For a decade this survived despite concerns about its stability until it failed in August 1882 in severe storms. Ramsay determined on a masonry dam to seal the breach. Original proposals for a concrete dam were replaced by one with rubble masonry outer walls and concrete core, because of concerns about the buildability of formwork. Because of problems with springs in the foundations (Indian) Portland cement mortar and Portland cement concrete were used. Although designed following Rankine's recommendations, the configuration of the wing walls meant the structure was much thicker at its base than would otherwise have been necessary. The design of the left wing wall was strengthened by a concrete wall on the advice of Colonel Mayne, RE, Chief Engineer, NWP. The contracts were drawn up by Mayne and work supervised by J Doherty, but the design is assumed to have been the work of Francis Henry Ashurst AMInstCE. The dam was 1270m long and 15m.
Design details have not been found for the Muchkundi gravity dams near Bagalkot in Karnataka, and at Bhatofi near Ahmednagar. The former was completed in 1884 and is 19m high and 158m long, the latter 15m high, and 537m long. (INCOLD)

BHATGARH DAM, NIRA CANAL, C.1881-1892

Later dams took account of other developments in dam theory. Bhargarh was part of the Nira Canal irrigation scheme in Bombay Presidency (Bombay, 1892; Wilson, 1892). 3,020ft (920m) long it rose 127ft (38.7m) above

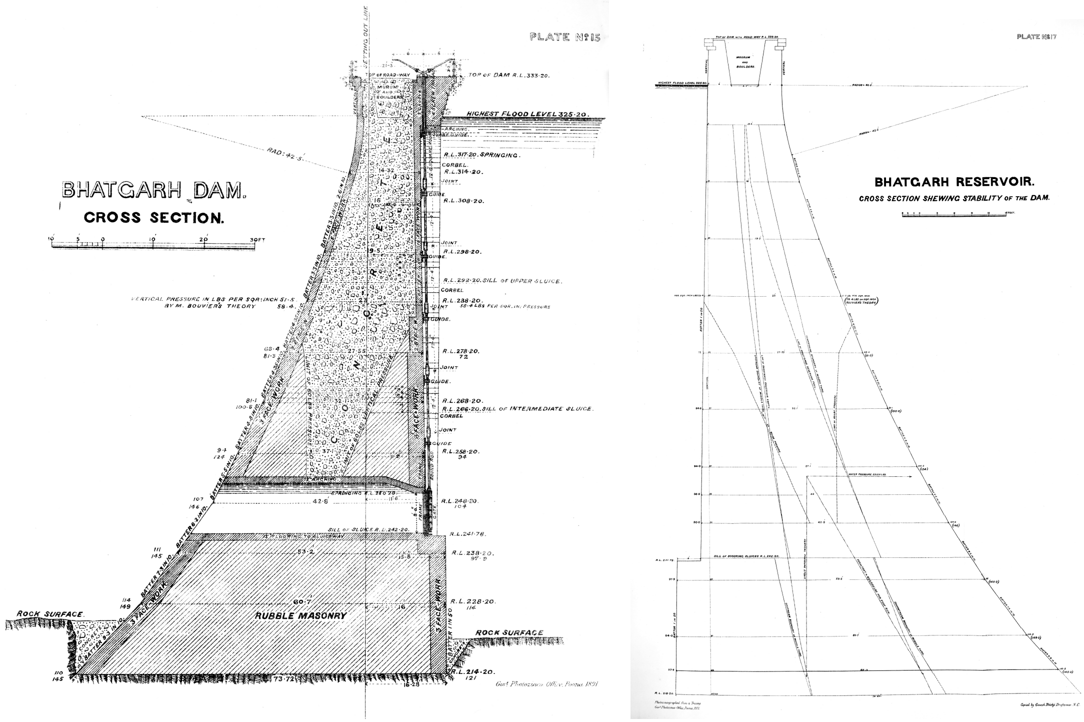


Figure 4 a: Bhatgarh Dam cross-section as built; Figure 4 b: Bhatgarh dam: stability diagram

deepest foundation level. It was originally intended to build the dam of rubble masonry, but tests on concrete gave a satisfactory compressive strength and it was decided to use this where pressure was less than 6olb/in^2 (4.2Kg/cm^2) Large stone blocks, some of a very high density, were incorporated in the concrete to increase the weight of the structure. Rubble masonry was used in the lower part of the dam where the calculated pressure was greatest Fig, 4a). The sluice ways were of ashlar. The calculations were by Arthur Hill (1858-1927) (McWilliam), Resident Engineer on the dam's construction 1881-1892 under J E Whiting (Cross-Rudkin and Chrimes) after whom the reservoir was named.
Hill determined the intensity of vertical pressure should not exceed 120lbs/in2 (8.4Kg/m^2) , the resultant should fall in the middle third, and used an average weight of dam material of 160lbsft2 (11.25Kg/^{2}) in his calculations. He followed Molesworth's (1883) advice, used a graphical method to develop the profile and the calculated pressure was less than using Bouvier's method (Fig 4b).
The dam incorporated 15 under sluices, the first such British design, to deal with siltation, and waste weirs at both ends of the crest with automatic gates. Given the proximity to Khadakwasla (40km) it is instructive to compare the profiles and how dam design had progressed in 20 years.

MUMBAI WATER SUPPLY: TANSA DAM

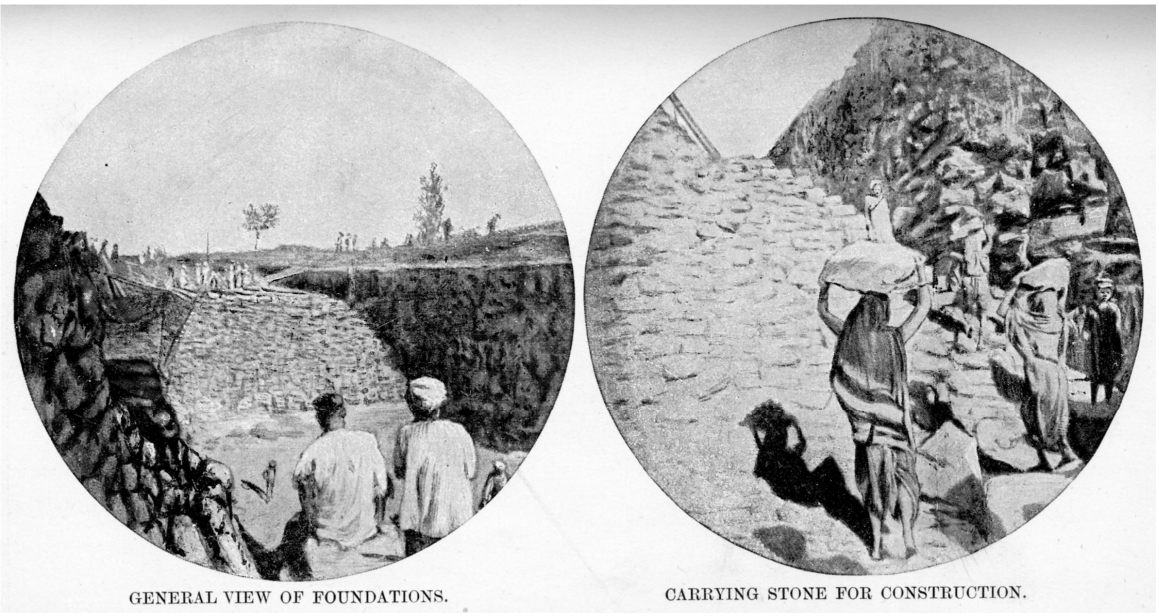
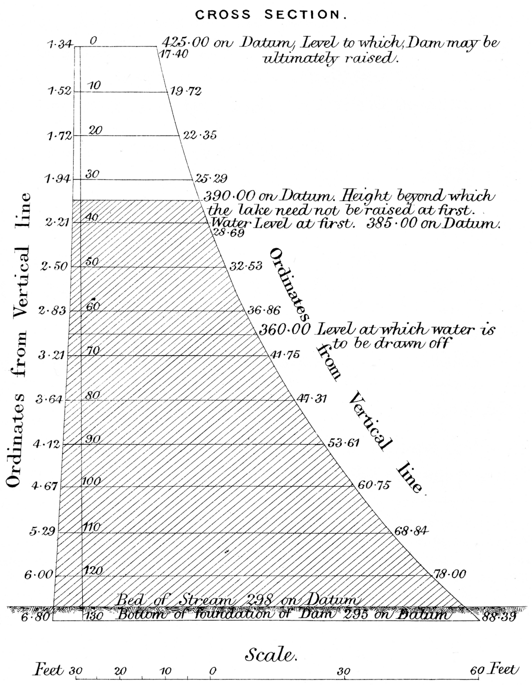


Figure 5: Tansa dam under construction: a foundations; b: female labour

By 1884 the Vehar (Vihar) and Tulsi schemes were inadequate for Mumbai's needs. In February 1885 W J B Clerke (1848-1896), a Bombay engineer with a great deal of experience of tank design (McWilliam) was appointed to review Tulloch's Tansa reservoir scheme, reporting in August. Work began in January 1886 and the scheme was opened on 31 March 1892.

A rubble masonry dam was built in remote countryside across the Tansa Valley c.90km from Mumbai, 2804m (8,800ft) long and 36m (118ft) high (Fig. 5), it had a waste weir 1,650ft (503m) long, and was designed to be raised to 135ft (41m). The masonry was sourced from local trap and basalt, used rocks less than ½ cubic feet in volume, carefully set in 'Kumkur' lime. The mortar was tested in 3in cubes on site, with some samples taken to Kirkaldy in London. Lime was used in preference to Portland cement for cost reasons, its strength being regarded as satisfactory – although tests showed great variance. Over 8,000 people were employed, including women labourers. According to Clerke (1894) the dam was designed using Bouvier's methods as expounded by Molesworth (1883). Design calculations were again carried out by Hill. He believed it a more economic section (Fig. 6) than Rankine (1872) or the section of the Vyrnwy dam, the first such major structure built in Britain, although he had not had access to the Vyrnwy section as built. In the calculations the weight of the dam was taken as 150lbs/ft² (7.2kN/m2), although even when dry this was known to be conservative.



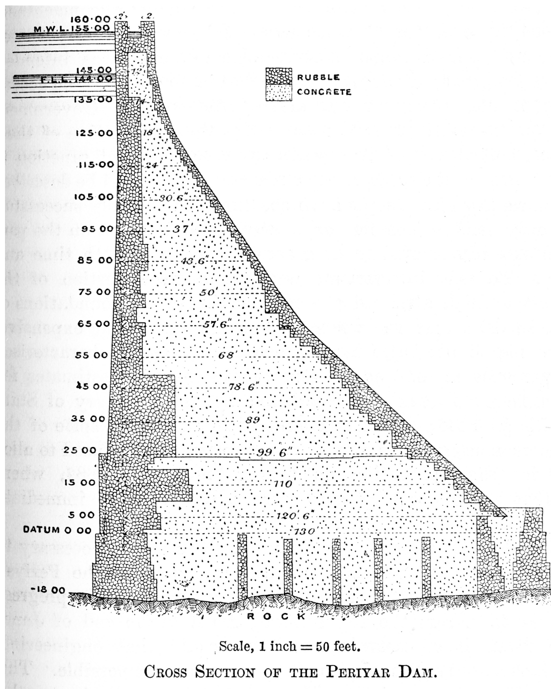


Figure 6 (left): Tansa dam cross-section; Figure 7 (right): Periyar dam cross-section

PERIYAR DAM

The construction of the Periyar Dam is one of the inspirational feats of late nineteenth century engineering. (Mackenzie, 1899; Madras, 1886; Pennycuick 1897). Although not completed until after Tansa, its design process predated that dam. Caldwell had considered diverting the River Periyar, flowing into the Arabian Sea from the western Ghats, into the drought-prone of Vaigai basin in Madura to the east of the Ghats in 1808, but abandoned it because of cost. It was an attractive scheme as the river followed within a few kilometres of the watershed ridge. In 1850 Captain Faber began work on a small dam, again abandoned. Subsequent studies rejected a low impoundment as not providing the control of water necessary for perennial irrigation. In 1862 Joseph Gore Ryves revived the idea, and his 1867 report recommended an earth dam. In 1870 R. Smith recommended hydraulic placement of material, but lack of experience with the technique for such a large structure (53m/175ft high) led General Walker, Chief Engineer of Madras to reject it and call for an investigation of a masonry dam. This was undertaken by Smith and John Pennycuick. Smith had previously rejected this on grounds of cost, but was now in favour, probably influenced by Fife's work.

Pennycuick prepared a profile based on Molesworth (1874). The proposed dam was of masonry facing, longitudinal and cross walls, and concrete fill. There were concerns over differential settlement with this arrangement, which were later addressed. The 1876-77 famine resulted in the project being shelved and it was not until 8 May 1882 that Pennycuick was directed to prepare revised plans and estimates, finalised later that year. He recommended a concrete dam 155ft high, with a lime sand 'plaster' face. Much of Pennycuick's report was concerned with execution of the project, including the 2000+ m (6600 ft) tunnel intended to transport the water from watershed to watershed, and the distributory network in Madura.

Having originally used Molesworth's (1874) formula, Pennycuick considered French dam designs and Rankine's (1872) design for Tansa. He adopted a maximum pressure of 18,000lb/ft^2, for the masonry on each face, Rankine using 22,053lb/ft^2. The middle third rule was slightly breached when the reservoir was empty. In his 1882 report (Madras, 1886, 24-28) Pennycuick explained his method of calculation. He felt Bouvier's (1877) method of selecting an (idealised) maximum pressure point was unrealistic, and the pressure would be higher in the upper layers and centre of the dam. Like Molesworth he carried out a series of calculations to devise a general formula that suited most of his findings. He believed Molesworth to be wasteful. Colonel J O Halsted, the Acting Chief Engineer for Madras recommended referral to Molesworth (Madras, 1886, 77-80) who reported in 1883, and stood by his version of Bouvier which he felt erred on the side of safety. In this view he was supported by Brownlow (Madras, 1886, 80-81). Both evidently believed Bouvier had it right. Molesworth's (1883) recommendations were widely circulated.

The original intention to execute all the works in concrete was modified when it was apparent there were sufficient masons available. About one third of the volume was in rubble masonry, including both faces (fig. 7) The capacity of the dam is 443,000,000m^3. About half of the retained capacity is available for irrigation. The main dam was 200ft (c 60m) wide in the river bottom, 439m (1,300ft), long at the crest, and 54m high. It dwarfed any previous masonry dam. Work began in September 1887. One consideration was percolation through concrete, and tests were conducted by G T Walch in the Godavari delta in 1887, and at Periyar. The conclusion was that it was impossible practically to make the dam completely watertight.

Construction was effectively restricted by jungle fever and flood waters to January until March. These problems were compounded by communications. The site was 11km from the nearest cart road, in uninhabited jungle 32km from cultivated land, and 128km from the nearest railway station. Water carriage and wire ropes were used to reduce cart haulage. The presence of an unexpected chasm 40-60ft (12-18m) wide and 12-18ft (3.6-5.5m) deep, and jets springing up through the base as the hydrostatic pressure increased made it difficult to keep out water from the site. The dam cost c. £175,000, with £47,000 on head works. As Sir John Wolfe Barry remarked: "They must all recognise ... the great care in the calculations, the tenacity of purpose, the resourcefulness of those employed, and the devotion which the staff must have showed in carrying out the undertaking with such difficulties."

THE IMPACT OF FAILURE ON MASONRY DAM DESIGN

The adoption of Rankine's principles into mainstream engineering is reflected in Bligh's *Design of irrigation works* (1907, 1920). However, the debate was not over in 1872, as Smith (1994) has described, and as suggested by the Indian experience. Even in Rankine's *Manual of civil engineering*, where later editions include his advice of 1871/1872 (e.g. Rankine, 1904, p.248), it was not immediately included (Rankine, 1877). The case was finally made as a result of failures.

As Pennycuick and others realised, the 'rational' method was not perfect. Sazilly (1853) had ignored the vertical component of water pressure, and treated a masonry dam as a series of slices, analysing the tallest slice, assuming it to be unsupported by the rest to obtain a worst case scenario. Delocre's Furens dam design essentially followed this. Rankine (1872) supported this approach but recognised a number of underlying principles which no design should ignore. To develop a safe design the French used data from Spanish dams to calculate the likely maximum stress in the masonry, obtaining a range from 6.5-14.5 kg/cm^2. They used the lower figure which led to a relatively thick dam profile, therefore not particularly economic in its use of masonry. Later French designers tried to be more economic, using slenderer profiles. A taller, thinner profile was likely to require fresh consideration of lines of thrust and the middle third rule. There was a possibility that when the reservoir was full tensile stresses might develop in the water face near the top. There was also the question of sudden reservoir filling with an inadequate waste spillway. This was revealed in 1881 when the Habra dam in Algeria failed.

French engineers in particular were pursuing a 'rational design' for economy, focussing on maximum compressive stresses, and the profile of least resistance. As a result 'no tensile stresses' were not a design imperative, and the middle third rule was conformed to as result of other decisions. One can argue that looking at the safety of existing Spanish dams was far easier than designing safely masonry dams in a variety of locations. While Fife and other engineers in India may have felt themselves in the forefront of engineering science, there was a danger, if they overlooked Rankine's principles, they might be acting riskily. Sazilly's methods were difficult to follow, and Rankine's logarithmic profile may have intimidated practical engineers, however more satisfactory Rankine's general solution may have been. That may explain why Molesworth (1883) seized upon Bouvier's methods, which focussed upon calculating one peak stress point. This meant that one could design the air face and ignore the water face and the distribution of stresses between the two. Despite the shortcomings of the method it became mandatory in France after the Bouzey dam failure leading to very inefficient dam design there in the early 20th century. It was the method that was criticised by Pennycuick, and then forced upon him.

The Bouzey dam in France, designed in 1876, was beset by problems from the start (Smith (1994). Repaired in 1885 uplift was not taken into account, although, probably as a result of Habra, it was by Hawksley and Deacon at Vyrnwy reservoir by that time (Binnie, 1987; Deacon). The dam failed catastrophically on 27 April 1895. No account was taken of tensile stresses in either the original 1876 calculations or those for the 1888-89 rebuild (Langlois). The French Inquiry attributed the collapse to a shear failure, but Smith (1994) demonstrates that the middle third rule was disregarded and the greatest deviation was where the initial fracture took place.

The failure had an impact beyond French engineering circles. The most famous British commentator was W C Unwin (1896), who had taught at Cooper's Hill. He summarised dam design methods based on French theory, and earlier ideas based on designing against sliding and overturning at the downstream toe. These latter both implicitly assume uplift or water pressure from below as well as the retained water pressure. Sliding and overturning were discounted in the French methods. He realised, perhaps for the first time (Unwin p13-14) that if for any reason a tensile crack developed in the water face it could lead to a progressive failure as water pressure came to bear in that crack. By ignoring tensile stresses the French engineers were also ignoring the possibility of failure by overturning in the upper section of a masonry dam. Unwin calculated the line of resistance for the condition of the reservoir full and discovered it did not conform to the middle third rule, that tensile stresses could develop creating cracks, exarcebated by poor bond between the masonry and mortar, which uplift could the exploit. Unwin was accompanied in his site visit by G F Deacon.

Less well known but evidently pertinent was the May 1895 visit of George Kenneth Scott-Moncrieff, a Royal Engineer who was born and served in India. His report is an appendix to his *Water supply* (Scott-Moncrieff, 1896), a textbook intended for engineers training with the Royal Engineers at Chatham, still a major source for recruits for Indian service. Both his *Structural analysis* (Scott-Moncrieff, 1898) and *Water* contained design methods for masonry dams based on Rankine's principles, and one can conclude that engineers proceeding to India in the early 20th century were au fait with the lessons of Bouzey. Thus when Garrett (1913) designed Agar dam as a multiple arch dam in Rajputana in 1905-1906 he was aware of Bouvier, Unwin, and Pennycuick.

ANGLO-INDIANS OUTSIDE INDIA

As the British Empire expanded through the nineteenth century the colonies required civil engineers to develop the infrastructure. These civil engineers came not only from the British Isles but other parts of the Empire, particularly India. In Egypt, from 1883, Indian experience of masonry barrage and dam design and construction enabled (Sir) Colin C. Scott-Moncrieff and colleagues to successfully rebuild the Delta barrages, before moving on to Aswan and Asyut in the early twentieth century (Smith, 2002),

Engineers stationed in India went to Australia. When there were problems with the embankment dams built in Victoria to supply water to Coliban and Geelong, the Victoria Government turned to India (Harper, 1998; 1999). Lieutenant Colonel R H Sankey, Chief Engineer Mysore PWD, was asked to report. His recommendations included the appointment of an experienced water supply engineer (Sankey, 1871)) and George Gordon was appointed. His Indian experience, work on water supply under William Tierney Clark (Skempton, 2002), and education in Scotland, Germany, and at UCL, made him an ideal candidate.

Gordon, and Edward Dobson (Cross-Rudkin and Chrimes), resident engineer for the district, decided the simplest solution was to build a dam on a new site, a rock gorge, ideal for a masonry dam. He had taken advantage of a trip back to Europe to visit the Furens dam. He must have designed the dam in late 1872 or early 1873 as work began on site in February 1873, and the dam was completed in June 1874. He used a modified version of the Graeff and Delocre method of equal pressures (Gordon, 1875), which conformed to Rankine's middle third rule, without express reference to Rankine's paper of 1872. The dam was built with a curved plan of 91.5m(300 ft) radius, according to Dobson (1879) to abut better on the sides of the gorge, rather than following Rankine's recommendations. This suggests, as Harper hypothesises (Harper, 1998, 200x) that Gordon was aware of Rankine and others advice regarding tension in masonry, and had probably read Fife's translation of the French design method, but not the 1871-1872 reports. Dobson's explanation of the design and Gordon's own paper have led to suggestions this was the first gravity dam to take account of both French theories and Rankine's conditions for stability. The evidence is not explicit. The dam is also of great interest for its use of concrete. As built the dam was 16m high and 68m long, with a storage capacity of 631m litres. It was narrowly preceded in construction by Boyd's Corner in the USA and Perolles in Switzerland, both larger concrete gravity dams.

Later dams of interest in Australia show an independence of spirit. In Queensland Henry C. Stanley (Cross-Rudkin and Chrimes) designed the 75-miles dam, the 4th arch dam to be built in the nineteenth century, and possibly the first in concrete (1879-80)(Chanson, 1999). In South Australia the Beetaloo Dam (Jobson) was the highest concrete gravity dam in the world at 37m when built 1888-90, with the Australian, Christopher Jobson AMInstCE as Resident Engineer (Doherty, 2000).

More or less contemporaneously with Periyar, Australian engineers designed and built a series of thin concrete arch dams in New South Wales, 1896-1908 (Mackenzie, 1992; Wade, 1908). Under Moriarty, engineers of the NSW PWD had been designing circular service reservoirs through the 1880s (Darley, 1891). It seems likely that these were designed using a formula that had been in use throughout the nineteenth century for assessing the thickness of pipes for hydrostatic pressure. Such a method appears in a memorandum book probably owned by Thomas Telford, and can be found in works by Gregory, Moseley, and Rankine. Cecil West Darley (1900) who succeeded Moriarty in 1888 states that it was essentially the same formula, that was used for the design of the arch dams. Despite the Parramatta precedent, however, it seems it was the recent completion of Bear Valley Dam in the US that acted as a catalyst for the dams.

There was also an Indian influence in South Africa after the Boer War when (Sir) William Willcocks reported on the irrigation in the colony, and a new administrative system was established. William Strange (1853-1929) (McWilliam) the Indian dam expert was appointed first Director of Irrigation in Transvaal (1903-1907) and initiated a program of rural dam construction.

CONCLUSIONS

This paper has concentrated on masonry dams. It would be misleading to suggest that this material dominated dam construction in the Indian Empire, or indeed the British Empire generally. British embankment dam practice with puddle clay cores was very much in evidence at Bombay and Nagpur Waterworks. These were both the work of British engineers- Henry Conybeare and Alexander Binnie respectively, although Binnie spent some time in India (Cross Rudkin and Chrimes; McWilliam). The Red hill scheme for Madras was the work of a Madras Engineer- William Fraser (Madras), but also featured puddle clay cores. However, perhaps pioneered by Fife, it became more general in India to place selected material in compacted layers, more akin to modern methods of embankment dam construction (Strange; Bligh; Brown). Brown challenged the value of the central puddle wall and the function of the earth upstream, highlighting masonry walled structures at Foy Sagar and Kair Tank (Brown pp 77-78). Strange advocated a form of composite construction using earth and masonry, and prepared a major scheme at Maladevi in the late 19th century. All this reinforces a view that the scale and nature of civil engineering work enabled engineers working in India to develop design methods and practice independently of, and at least arguably in advance of their peers based in the UK.

It is clear from the debate at ICE in , when 4 papers on dams were discussed (Clerke, Jacob), including one by Franz Kreuter (1894), the leading German dam theorist, that Rankine was not necessarily disregarded through ignorance. The lively debate, in which Indian engineers played a full part, is indicative that Rankine and the French theorists were being challenged because their approach was overcomplicated in deriving a profile – as Molesworth claimed. Baker and others criticised all approaches as inaccurately modelling the great variety in strength of stone masonry. It was recognised as well that the relationship of the French approach to observation of Spanish dam profiles was not necessarily the best theoretical approach to dam design. It is also evident that Pennycuick and Hill, perhaps the most important of the Indian dam designers were on top of the mathematics, and in Pennycuick's case developing his own design through considerable thought. Kreuter's approach received a mixed reception, with stronger support from continental commentators than British engineers. The debate about masonry dam design continued into the twentieth century. The Bouzey failure meant in France that a very conservative approach stifled innovation in the early twentieth century. Concerns raised by theorists temporarily paralysed the first heightening of the Aswan Dam (Smith, 2002). The intellectual debate over uplift was a contributor to the tragic row between Terzaghi and Fllunger in the 1930s (Chrimes, 2008). Arch dam design was the subject of an intense research programme as recently as the 1950s and 1960s. As Leliavsky (1958) pointed out slow progress in adopting new ideas was in part the result of language barriers. It would also seem that in Britain risk-averse design and possibly a lack of theoretical understanding meant work in its colonies frequently astonished the home audience with its boldness. In tackling language barriers, debating theory, and adopting new materials the British in late nineteenth century India revealed themselves as true innovators. As A T Mackenzie (1894, 171) the chronicler of Periyar remarked:

"What was wanted to reduce their (masonry dams') proportions was faith – in the theory and in the material employed in constructing dams."

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