THE GEOFFREY BINNIE LECTURE 2008

The Binnie heritage in dam engineering

Dams and Reservoirs
2008 **18**, No. 3, 121–134
DOI: 10.1680/
dare.2008.18.3.121

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The 2008 Binnie Lecture, delivered at the 2008 British Dam Society conference, covers the worldwide achievements of Geoffrey Binnie himself and the firm that bears his name. It then traces the author's personal engineering history, touches on the earth-core versus concrete-faced rockfill dams debate, legal issues, and finishes with a personal view of the future of dam engineering in the UK.

Introduction

As senior partner of Binnie & Partners I was chairman of the British National Committee of the British Section of the International Commission on Large Dams (BNCOLD) when we launched the name BDS and I persuaded my partners to stump up the funds to sponsor the Geoffrey Binnie lecture.

It was anticipated that this biennial lecture would be given by a notable international dam engineer. You will have to ask our chairman what happened to him. I am, however, deeply honoured to stand in.

It gives me particular pleasure that the Institution of Civil Engineers' President, David Orr, is attending our conference. He is a fellow Ulsterman and graduate of Queen's, Belfast. I am the third generation of my family to graduate at Queen's and to become a water engineer. Both my grandfathers were involved in the development of water supplied from the Mourne mountains. One was chief engineer of the Belfast Water Commissioners at the time of the Silent Valley dam construction (Fig. 1.). The struggles to complete this dam make fascinating history, but it was notable that one of the contractors' engineers was the first lady chartered civil engineer, Dorothy Buchanan. Much earlier my paternal grandfather, a contractor, built the first reservoir in the Mournes (Fofany (Fig. 2)) and he drove the first tunnel from the Annalong Valley. His theodolite stands on the crest of the hill called Drinnahilly above Newcastle. It consisted of a masonry tower built above a shaft for plumbing to the tunnel below. The bearings for a reversible sighting telescope were bolted to the parapet of the tower, and it was possible to sight for back bearings at each portal some miles apart. The aquaduct and 2 mile (3·2 km) tunnel went into service in 1901 to bring Annalong and Silent Valley water to Belfast, some 35 miles (56 km) distant.

The Binnie background

In delivering the Geoffrey Binnie lecture for 2008 I feel justified in dwelling on the achievements of 'GMB' at some length because, although he will be a stranger to most of this audience, he was for most of my career the revered leader of the firm which bore his name.

Geoffrey Binnie was the third generation to head up the firm started by his grandfather Sir Alexander Binnie in 1901 (Fig. 3).[1] He joined the firm in 1932, was a partner in 1939 and returned after war service in 1945 to join his father, the famous W. J. E. (Willie) Binnie, who retired in 1948 at the age of 81 (incidentally an Ulsterman, born in Londonderry).

Geoffrey had a firm start in dam engineering, being a pupil of the famous Dr Gruner in Basel, working on hydropower projects. After joining the firm he worked on the design and then the construction of the remarkable Gorge dam in Hong Kong (Figs 4–5). This rockfill dam was 85 m high and had the distinction of being the highest dam in the British Empire. It was an early form of concrete-faced rockfill dam (CFRD) with the upstream reinforced concrete (RC) face being near vertical, supported on a mass concrete thrust block. The rockfill was uncompacted and the ongoing consolidation settlement was anticipated by the designers who incorporated a sand wedge between the thrust block and the rockfill and which could be flooded to maintain the support of the face in the event of rockfill deformation. The dam has been successful, and is now over 70 years old.

In common with most of the large dams designed by the firm in those days, Gorge dam was constructed by direct administration. The consulting engineers bought the plant and hired the labour on behalf of the owner. Geoffrey was responsible for engineering on site and inter alia made a number of hydraulic model tests to refine the design of the bellmouth spillway.

Although Binnies was first and foremost a water engineering firm, Geoffrey was primarily interested in dam engineering and hydraulics, whether for water

Fig. 1. Silent Valley dam

supply, hydropower or irrigation. He suffered from deafness and this inhibited him from taking an active part as expert witness in the promotion of schemes in the UK by Parliamentary bill. Fortunately for the firm this enabled him to concentrate his energies on overseas work.

Until the early 1950s the firm's dams had been principally headworks for water supply projects both in the UK and overseas. Such dams, masonry and earthfill, were generally under 50 m high (with the exception of the Hong Kong Gorge dam). Most were constructed by

Fig. 3. Geoffrey Binnie

Fig. 2. Fofany dam

Fig. 4 Gorge dam, Hong Kong

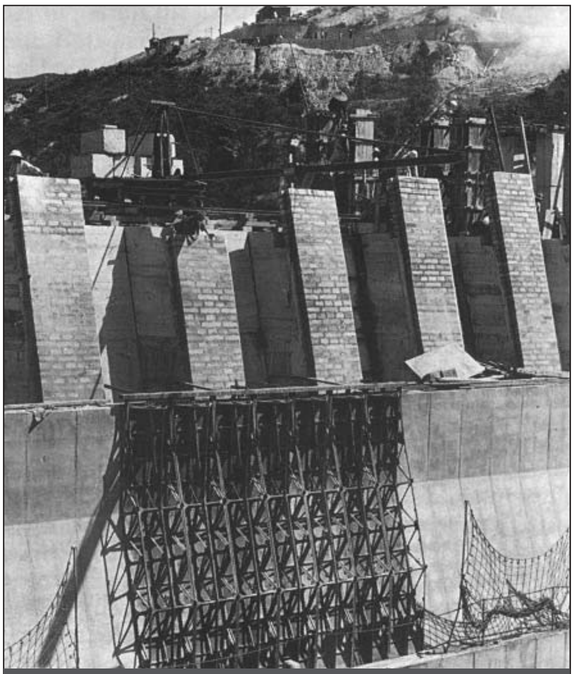

Fig. 5. Gorge dam, Hong Kong

direct labour. The list includes the Daer dam,[2] 41 m high, in Lanarkshire, the Gorge dam, Kalatuwawa in Ceylon, Pegu Yomas in Burma, Gunong Pulai dam in Singapore and a number of other smaller dams (Fig. 6).

The pupils of the late 1940s became graduates under agreement in the early 1950s. Site staffs, particularly on the direct labour jobs, were large and most graduates could expect to spend part of their agreement time on a dam site. This training in both design and construction established a great feeling of confidence among the staff of the firm.

Fig. 6. Gunong Pulai dam

Fig. 7. Dokan dam

It was from this platform that Geoffrey Binnie launched the firm in the large dam business in the field of river control, hydropower and irrigation worldwide.

Binnies developed the master plan for the conservation and control of water resources in Iraq – the Hydrological Survey of Iraq in 1950 – and this led eventually to the development of the ZAD schemes in 1954–1958: 9000 km^2 of irrigated land including the Kirkuk scheme and Dibbis dam.

Meanwhile in 1951 the firm was appointed by the Iraq government for the implementation of the 116 m high Dokan dam[3] in a gorge of the Lesser Zab river, a tributary of the Tigris river (Fig. 7). A design was developed for an arch dam of single curvature form to suit the profile of the gorge. Geoffrey had co-opted his friends in Imperial College, including Professor Pippard and a brilliant but highly eccentric mathematical lady – Letitia Chitty – to develop a stress analysis technique using relaxation methods and a rubber model to verify the design form. This was a significant advance on the laborious trial load method of the US Bureau of Reclamation (USBR) then in vogue, and was made possible with the use of early calculating machines. Construction took place between 1953 and 1959. The boldness of the design was admirable but Geoffrey's determination to overcome the geological difficulties of the site were the more remarkable.

The gorge was in limestone, heavily karstic at abutment level, rather more dolomitic and less fissured at foundation level in the river. Conditions were particularly bad in the left abutment spur (in my experience, the left abutment gives trouble in the Northern hemisphere), where a grout curtain 2 km long was constructed with upper and lower galleries. The galleries were equipped with bulkhead doors to allow future extension of the galleries for leakage reduction.

The primary use of the dam was for flood control and irrigation release. Power intakes and penstocks were taken through the base of the dam for a future 1000 MW power plant. For the first 30 years of its life there was significant leakage through karstic caverns beyond the end of the grout curtain, which contributed to the planned releases.

Fig. 8. Geoffrey Binnie on a visit to dams on the Tigris, Turkey, en route to Iraq

Fig. 9. Mangla spillway

Much later the firm was appointed to review the safety of the dam using modern finite element analysis. The stresses within the dam were found to be entirely satisfactory. During this work in 1986 Geoffrey made a post-retirement trip to Iraq and was able to see the Dokan bellmouth spillway discharging for the first time (Fig. 8). The gated tunnel spillway had of course been in regular use for smaller flood discharges. The power station was constructed in the late 1980s, and the left abutment gallery and grout curtain were safely extended.

Binnies continued in Iraq through the overthrow of the Iraqi monarchy in 1959, the rise of the Baath party, and were still very active at the time of the overthrow of the Saddam Hussein regime. They were responsible for the water supplies of Baghdad City and were involved in the problems of Mosul dam and the construction of the new Adhaim dam. A major project to provide high quality Tigris water to Basra and onward to Kuwait fell foul of Saddam's incursion into Kuwait and the first Gulf war.

Mangla[4]

Geoffrey was never able to explain how he secured the Mangla job for Binnies in 1957. At the time Binnies were building the Kalatawa dam for water supplies to Colombo, Sri Lanka, and had a history of work on dams in Burma, Singapore and Hong Kong. Geoffrey's grandfather, who founded the firm, had been in the Indian public works service, developing water supplies for the Central Provinces including the Nagpur dam in 1871.

During the 1950s and 1960s the world looked to the USA for guidance in the fields of soil mechanics and dam engineering, more specifically to the USBR and Corps of Engineers and of course to the doyen of soil mechanics, Professor Carl Terzaghi.

The Mangla feasibility study had been made by the American firm Tipton and Hill in 1952–54 at a time when storage on the Indus river headwaters was recognised to be vital for the new state of Pakistan, created in 1947. India and Pakistan nearly came to war over the Indus waters dispute. India could command the headwaters of the three eastern tributaries of the river, and could thus starve Pakistan of vital water for the irrigation of 10 million ha.

By funding the major storage reservoirs of Mangla on the Jhelum and Tarbela on the Indus, in 1960 the World Bank (IBRD), backed by the USA, Britain, New Zealand, Australia, Canada and Germany, was able to sponsor the Indus water treaty agreeable to both parties, and thus avoid certain conflict.

In 1957 Binnie and Partners were appointed by the Mangla dam organisation set up by the Pakistan government to carry out detailed investigation of Mangla and to submit a project report. They formed an association with Preece, Cardew and Rider for the electrical and mechanical work, and with Harza Engineering USA for design work on the spillway (Fig. 9). They reported favourably at the end of 1958 on a larger dam and reservoir than that proposed by Tipton and Hill. This was a huge project by any measure but in 1961 it was the largest civil engineering project in the world to be completed as a single contract. The tender price was £126·5 million (over £2 billion at today's prices), the dam height was 138 m, and the fill volume 106 million m^3.

The project was completed and the power station went online one year ahead of the contract completion date (Fig. 10). At that time it was the largest embankment dam in the world (Fig. 11). During the early phase of construction persistent low angle shear zones were encountered in the Swalik mudstones. These were thin bedding plane slips in which the mudstone shear strength was reduced to residual value by shearing to φ of 12 degrees. With advice from Professor Skempton, of Imperial College London fame, the designers called for extensive stabilising fills both upstream and downstream, and significant extra work on the spillway. There was

Fig. 10. Mangla intake dam

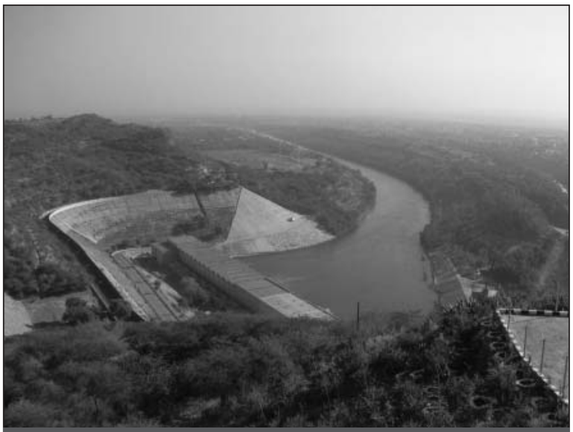

Fig. 11. Mangla powerhouse

some difficulty in persuading the advisory panel to accept the need for the extensive additional fill works. The gossip in the firm was that Geoffrey threatened to resign if the changes were not approved. He had his way.

The success of Mangla owed much to Geoffrey's personal drive and leadership, and to the good relationship which existed between the Pakistan water and power authority and Geoffrey's team, headed up by Gordon Eldridge and Ronald Gerrard. Most importantly, the management and construction skills of the American contractors, led by Guy F. Atkinson, enabled them to complete the works within budget and ahead of programme. During discussion on the Mangla paper at the Institution of Civil Engineers (ICE), the President of Guy F. Atkinson said that at an early meeting Geoffrey had said that he 'anticipated a jolly good show' – he got it!

The outcome of Mangla was that the firm was entrusted with major follow-up projects in Pakistan: the study and design in 1981 of the 80 m high Kalabagh dam, the Gazi Barotha hydroelectric scheme downstream of Tarbela dam (completed in 2000) and quite recently the raising of Mangla by 12·2m to bring it up to full development (Figs 12–13). The dam height is now 150 m, gross storage is 1184 km^3, installed power is 1000 MW, and the dam fill volume 153 million m^3.

Geoffrey retired at the end of 1972 but was appointed in 1974 to advise the contractor Impregilio, following the failure of the gate and tunnel lining of the Tarbela diversion tunnel.

Fig. 12. Gazi Barotha barrage

Fig. 13. Gazi Barotha power channel

During this period, despite the American lead, the Europeans were emerging as strong competitors for the many new large dam projects in the middle and far east. With the confidence gained from Mangla and Dokan, and many other smaller dams, Binnies were able to compete on equal terms with the world's leading consulting engineers or state organisations, winning consultancy appointments for dams in Saudi Arabia, Turkey, Greece, Malaysia, Algeria and Peru, while continuing to serve old clients in Hong Kong with Plover Cove (Fig. 14) and High Island (Fig. 15) dams.

My career in Binnies

My own career in Binnies began in 1951 and at the end of that year I was assigned as a site engineer to the Usk Dam,[5] then under construction on the headwater of the River Usk (Fig. 16). It was a direct supply reservoir for the water supply of Swansea, with a tunnel through the mountain and a pipeline to the city. The dam was 34 m high – an earthfill embankment with a puddle core – typical for the period. It was founded on boulder clay with a deep concrete-filled cut-off trench. A horizontal layer of silt within the boulder clay had to be drained by vertical sand drains, and to confirm satisfactory relief of excess pore pressure due to the loading of the dam, piezometers were installed in the silt layer. This was a very early use of piezometers, and some additional hydraulic piezometer tips were installed in the embankment fill, again boulder clay.

As a recent graduate who had been taught the rudiments of soil mechanics it was my duty to monitor the piezometer instruments. Imagine the consternation and initial disbelief when I reported back to the head office that the Bourden gauges were past full scale and the needles were bending on the stops. The actual r_u values were close to unity. They fell to 0·75 over the winter shutdown.

The position was confirmed for the sceptics by installing standpipe tubes and observing pore water overflowing 3 m above fill level. Arthur Penman, who sadly died recently, was the expert who made the installation.

On the advice of Professors Skempton and Bishop, horizontal drainage blankets were included in both upstream and downstream shoulders of the dam, and the improved drainage paths controlled the rise in pore pressure when fill resumed during the following summer. Without these measures a failure would have been inevitable.

Usk was one of the first embankment dams to be equipped with pore pressure monitoring instruments.

In 1953 I went to work in the jungles of Malaya, as it then was, on the survey and site investigation stage of the

Fig. 14. Plover Cove spillway

Fig. 15. High Island dam

Cameron Highlands hydroelectric scheme. This was an exciting and rewarding time for a young engineer, surveying in dense tropical rain forest in the course of the emergency in that country. What we would have given for GPS!

I went on in 1961 to be resident engineer on the Shek Pik dam on Lantau Island, Hong Kong (Fig. 17).[6] The island's catchments were being developed with an undersea pipeline to Hong Kong city. The dam had a complex grouted alluvium cut-off and was otherwise a conventional residual soil earth dam 60 m high. The clay core was formed from residual soil derived from weathered fine grained rhyolite, and despite being placed well wet of optimum, it became extremely stiff and brittle, probably due to chemical action during consolidation. The result was that the core could not

Fig. 16. Usk dam

Fig. 17. Shek Pik dam

Fig. 18. Brianne dam

deform as the bank settled and it cracked. The cracks were discovered when water flush was lost when drilling vertical holes for foundation piezometers.

Binnies' head office were greatly concerned about the risk of cracks reopening as the reservoir filled. I was required to report daily by telex to London on the progress of impounding, which was limited to 1 m/day, and to redesign the tunnel plug with blasting charges to blow a steel plate and allow rapid reduction of water level if there was adverse performance of the dam measured by seepage pore-pressures.

In fact, heavy rain amounting to 290 mm in 12 h, caused the reservoir to rise to spillway level in a few days. There was no evidence of crack propagation or seepage, and although I could not control the rate of rise, I didn't have to blow the charges.

My paper on this dam prompted a correspondence with Professor Casagrande, who was studying cracking in earth dams at the time. I concluded that cores should be placed well wet of optimum, and I followed that practice on the Brianne dam in Wales and on the many residual soil dams for which I was responsible in Malaysia.

Brianne

I was fortunate to be put in charge of developing a project to provide water supplies for the expanding industrial area of South Wales. This comprised an impounding reservoir on the headwaters of the River Towy, river regulation, abstraction at the tidal limit, tunnel and pipeline aqueducts, a terminal reservoir, removal of an 18th century 30 m high troubled earth dam and construction of a new dam on the same site, treatment plant and covered service reservoir near Swansea. The project was completed in 1972 (Fig. 18).

Such a comprehensive project gave much opportunity for innovative engineering. Brianne dam, 91 m high as built, is the highest dam in Britain. Built of slatey rockfill with a highly deformable wet clay core, the dam was the first large rockfill dam in the UK. Experience of use of relatively weak slatey cleaved rockfill was lacking. The deformation of the dam during construction was closely monitored for both stress and strain (Fig. 19).[7]

The results demonstrated how the soft core with high pore pressure and low shear strength was able to deform

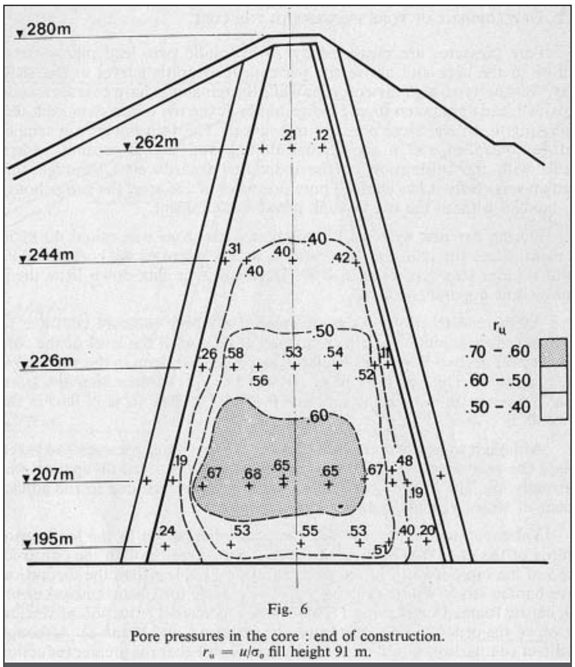

Fig. 6

Pore pressures in the core : end of construction.
$r_u = u/\sigma_v$ fill height 91 m.

Fig. 19. Brianne pore pressures[7]

with transfer of load to the rockfill shell without risk of cracking. The data was widely used in the development of finite element models for predicting strain in embankment dams with materials having non-linear stress strain characteristics. Now 35 years old, Brianne has behaved well. The dam was raised by 2 m in 1990 and a 5 MW hydropower unit was added.

Earth core versus CFRD

During construction I was visited by the late Barry Cooke, the American doyen of CFRD dams, and there began an argument which lasted for most our careers, over the relative merits of CFRD versus central core rockfill dams. Barry used to argue that CFRD was the ultimate safe dam type. It required little design effort and provided the details of the joints (particularly the perimetric joints) were correct, nothing much could go wrong. While I agree that for certain dams CFRD is the only choice because of the lack of appropriate fine-grained soil for the core, the advantage of the core dam is that it does not deteriorate if properly designed and constructed.

The membrane of an upstream deck rockfill dam will start to deteriorate from the first day in service. If it is an RC deck it will have joints which move, and some degree of stress cracking will be unavoidable. If the membrane is of asphalt concrete there are no mechanical joints, but weathering effect on the bitumen will age the deck in due course.

The earth core dam requires no post-construction servicing, provided that the core contact with the rock foundation has been properly treated with shotcrete and grouting and the downstream filters have been properly designed and executed. Placement conditions for the filter are critical.

Many very large CFRDs have been constructed and recent dams have exceeded 200 m in height, but they have not been without problems. Campos Novos (202 m) (Fig. 20) and Barra Grande (185 m) in Brazil, and TSQ1 (178 m) in China have all suffered severe compressive failures of the deck on filling to near top water level.

Fig. 20. Compos Novos in Brazil

Fig. 21. Bakun dam

Analysis predicts tensile stresses in the deck during reservoir filling, and on earlier dams this was the case. Most problems arose as a result of tension and shearing on the parametric joint. On the latest and highest dams the relatively stiff membrane has been unable to deform to compressive forces on the face as the reservoir fills.

In the case of Bakun dam (210 m) in Sarawak the deck was placed on the lower half, while rockfill continued on the upper half (Fig. 21). Completion of filling caused a rupture of the concrete sub-deck.

Partnership

I joined the partnership in 1972, taking over responsibility for establishing the firm in Saudi Arabia, Greece, Turkey and Jordan, and returning to Iraq.

Fred Hardy, our irrigation partner, had been in Riyadh to make a bid for flood control and irrigation work in Najran on the Yemen border. Sadly Fred fell dead when checking out of his hotel, having put in a bid for the Najran flood control project. We subsequently received a letter of award from the Ministry, but we in London had no copy of the offer put in by Fred. My first sally into Saudi was to thank the director of irrigation for the award, but to plead to be told what we had offered to do. Such an innocent approach seemed to appeal to his sense of honour, and we enjoyed the closest relationship throughout the project, which included the construction of the 71 m high Najran dam – the only major dam in the kingdom, completed in 1980 (Fig. 22).[8]

In those days close personal relationships between the firm's principals and the clients were the key to success.

Fig. 22. Najran dam

This was demonstrably true in Iraq, where I was able to establish a highly successful working relationship with the director general of water supplies. With my team I sat in his office in Baghdad through the first small-scale air raid of the Iraq–Iran war, both sides politely ignoring the racket. Our good relationship continued with a stream of large projects until the Gulf war in 1990 brought a closure.

The award of jobs became much more objective in later years, and competition for work in Greece and Turkey from the large international consultants was fierce. Nonetheless we were successful in Turkey in water supply and sewerage projects for Istanbul and Ankara, and eventually for the detailed design of the major hydro project of Ilisu and Cizre on the Tigris with a dam intended to be 140 m high. This project was begun but to date has not been completed. In Greece, as part of a powerful European joint venture, we were eventually successful in securing the design of the Arakthos project.

Retirement

I retired from Binnies in 1994, but was fortunate to be able to continue as a consultant in private practice.

My connections with federal and state authorities in Malaysia led to my appointment to review the design and construction of a number of important dams – in effect a one-man panel.[9]

I have been retained by Severn Trent Water on their dam safety panel to provide a critical review of the company's policy in this area. We initiated the proposals to reconstruct Ladybower dam to provide additional freeboard to counter the effect of progressive settlement (Fig. 23).

Roy Coxon, in the 2004 Binnie lecture, set out the case for panels. They are not always popular with designers, but I agree with Roy that they are essential. They do not challenge the authority of the design consultant, but they do provide the essential discipline that the design case has to be robustly presented for an objective review.

I served as chairman of the then Overseas Development Agency review panel on the Pergau hydro project in Malaysia which was completed in 1996.

Developed as a design and construct project by Balfour Beatty Cementation JV, the scheme is of great value to Malaysia as a peaking station when they are critically short of power. Balfour Beatty did a splendid job of introducing modern standards of health and safety in construction and in training local Malaysian operators.

The scheme fell foul of a political row over an arms deal and never got the credit it deserved.

Unique problems which were overcome by JV and their designers Knight Piesold were: very high rock temperatures at the underground power house level, geothermal hot waters and very low in situ rock stresses. My experience of the construction of residual soil dams in very wet conditions was of some value.

For the design review of the proposed 110 m high CFRD rockfill dam on Sungei Selangor for the water supplies of the Klang valley and Kuala Lumpur in 1999, a detailed review of the geological conditions of the intended plinth showed that it was impossible to define precisely the level at which sound rock would be found (Fig. 24). Because of the geometry of the intersection of face and plinth, the position in plan of the intersection is fixed at any level once the dam layout in plan is fixed. The plinth must be raised in height if further excavation of weathered or badly jointed rock is encountered. This has caused serious trouble on some dams, such as Winscar. For Sungei Selangor dam the designers were persuaded to revert to a central core rockfill. The core fill was excavated from the reservoir basin and from required weathered rock strip in the dam site. The dam was successfully completed and filled in 2005.

Legal

Legal cases are fortunately rare, but the role of expert witness can provide the opportunity for the retired engineer to use his experience to enable the case to be resolved.

Fig. 23. Ladybower dam

Fig. 24. Sunei Selangor dam

In Botswana the late Professor Knill and I were able to prove that the claimant's geotechnical interpretation of the drilling data for the Bokaa dam was wrong and their case against the designer flawed. They withdrew their claim to arbitration, which was to have been held in London before Professor Uff.

Later, Knill and I were brought in as expert witnesses in a case brought by the UK Ministry of Defence (MOD) over the Symvoulos dam in Cyprus. This dam, built on calc-siltite (similar to chalk) had developed catastrophic leakage through reactivated solution channels. Drastic modification of the sealing elements and high pressure grouting intensity number (GIN) grouting provided a satisfactory solution. The reservoir remains watertight. The legal case was settled.

I am presently engaged as design review consultant for the Betotan dam in Sabah, North Borneo, for water supplies of Sandakan (Fig. 25). Although modest in size, the dam is being built on very difficult foundations. The clay is described as a slump breccia. Pyroclastic volcanic ash was deposited in the Sula sea in the tertiary age. The land rose and present day North Borneo provided a rich area for planting rubber and now palm oil.

The clays are similar to our over-consolidated clays, although with many sheared and slickensided surfaces. The published results for Empingham dam (Rutland Water)[10] were relevant for the design process.

The dam is complete, and the slopes have remained stable. There have been some problems with the embankment spreading near the centre line, causing opening of the joints in the diversion and draw-off culvert, although it was founded in stiff clay well below original ground level.

The future of dam engineering in the UK

With the platform of the Scottish hydro schemes and dam engineering in countries with a strong colonial link, engineers of my generation were enabled to work in the international field of dams and to have a noticeable presence in the International Commission on Large Dams (ICOLD). How is this position to be sustained?

Fig. 25. Betotan dam

Britain has long had effective regulation of dam safety. More recently UK dam engineers have been in the forefront of risk assessment and safety management of old embankment dams because of the large stock of old dams in the Pennine area. Surprisingly, a similar state of affairs exists in the state of Victoria in Australia, where of a stock of over 200 referable dams, half were constructed before 1930, and many were puddle core dams built on the Pennine model to provide water for the gold rush works.

In 1994 the Office of Water Reform commissioned a review of headworks by Snowy Mountains Engineering Corporation (SMEC) supported by a panel of experts including Glenn Tarbox of the USA and myself. Essentially this was a screening process to build up a database, to rank the dams in order of condition, and finally to identify those which should be assessed for risk of failure using the risk assessment models developed by Bowles and Anderson from Utah.[11]

On any projection of climate change the UK is likely to have abundant fresh water. It may need to be transferred from areas of excess to areas of seasonal shortage. This is unlikely to need technology other than that available to and used by our grandfathers, but there certainly is scope for some significant water engineering.

There is no prospect of significant hydropower development. The UK is unique in never having built a dam on a major river in its mature course. This is undoubtedly due to the intense development during the industrial revolution when the Pennine reservoirs provided the water power for mills and major towns developed lower down in the flood plains of the main rivers Severn, Thames and Trent.

The only future productive hydropower development of significance will be tidal power, and of course the Severn barrage scheme is the most likely to be developed to increase our predictable renewable energy output. With installed power in excess of 8 GW the output could be 17000 GWh/year.

Binnie and Partners were appointed by the UK Department of Energy to study the scheme in 1978 and they presented their final report in 1981. Following that, there was a symposium in Cambridge in 1982, and since then several attempts at promotion by private groups. At the time of the Binnie study the scheme was found to be technically feasible, but uneconomical against the then market costs of alternative fuels. A negative point was the high investment of energy in the form of fossil fuel to construct the project. It is highly appropriate that the cost and environmental impact of the project are now to be reviewed with the rapidly changing costs of energy and construction.[12]

Any proposal to construct a Severn barrage will cause an outcry at the scale of the environmental impact. We have in Britain some of the finest estuarial wetlands. The Wash, Humber, Thames, Solway and many more lie on the migratory flyways to the northern and arctic breeding grounds.

Fig. 26. Nendrum tide mill

The Severn estuary is affected by the high tidal range of 13 m and the mobility of the sediments limits its value as a wildfowl habitat. The environmental impact of the scheme could indeed be positive by limiting the tidal range upstream of the barrage, and this could additionally reduce the risk of flooding due to predicted sea level rise.

In the history of tidal power there have been numerous medieval tidal power mills, including one at Eling on Southampton Water still in operation. Much earlier, in the 7th century AD, a tide mill was built at Nendrum in Strangford Lough in Northern Ireland (Fig. 26).[13] The mill dam is still visible and the vertical shaft turbine with its runner and blades in a wheelhouse has recently been very carefully excavated. From the mill dam a stone penstock led to a nozzle with the jet impinging on the horizontal turbine wheel. The vertical shaft extended to the millstones on the floor above.

What is so fascinating is the development of the horizontal turbine wheel. The first mill at Nendrum had a wheel with 18 flat paddles presenting an inclined face to the water jet (Fig. 27). This was approximately 72 cm in diameter and was dated by dendrochronology to 619–621 AD.

It was replaced by a second mill on the same site in about 789 AD in which was employed a much more sophisticated wheel with shaped paddle blades about 98 cm in diameter.

The tide mill is thought to have 1 KW of power to mill the grain for Nendrum monastery at mean spring tide level in the mill pond. The estimate of power available suggests that 50 t of coarsely milled barley could have been produced annually.

Although I am again plugging the Ulster connection, it is claimed that this is the earliest tidal power scheme in the world, and has been positively dated by dendrochronology. David Orr and I, although not claiming to be direct descendants of the monks of Nendrum, could offer advice to the next generation of Severn tidal power men.

There could be a future for more pumped storage hydroelectric power capacity to help stabilise the National Grid. The government is committed to the production of 20% of its energy from renewable sources by 2020. With 1·5% available from hydropower and the future of tidal power being so uncertain, it is clear that the bulk of the shortfall will be generated by wind power. To produce the required 70 TWh/year would require the installation of 20 to 30 GW from mostly offshore wind farms. The capacity will depend on the actual load factor. The current UK load factor for onshore wind turbines is 25% and in some proposals a factor of 30% is claimed for the future offshore farms.

The greatest experience is with the Danish wind turbines (known as their wind carpet) which is fully interconnected with the hydropower systems of Norway and Sweden. They have a load factor of 20% and experience rapid fluctuation of suitable wind speeds: 4m/s to 20 m/s (shut off at 25 m/s, force 9–10).[14]

The UK has no prospect of connection to European hydropower networks to store surplus wind-derived energy, or to balance the rapid fluctuations of output. The present UK wind energy capacity is less than 2GW. Finally, wind is unpredictable and must be backed up fully by thermal power. All of this will lead to extreme difficulty in controlling the grid.

Pump storage can help by traditional peak generation but equally valuable spinning reserve and frequency regulation.

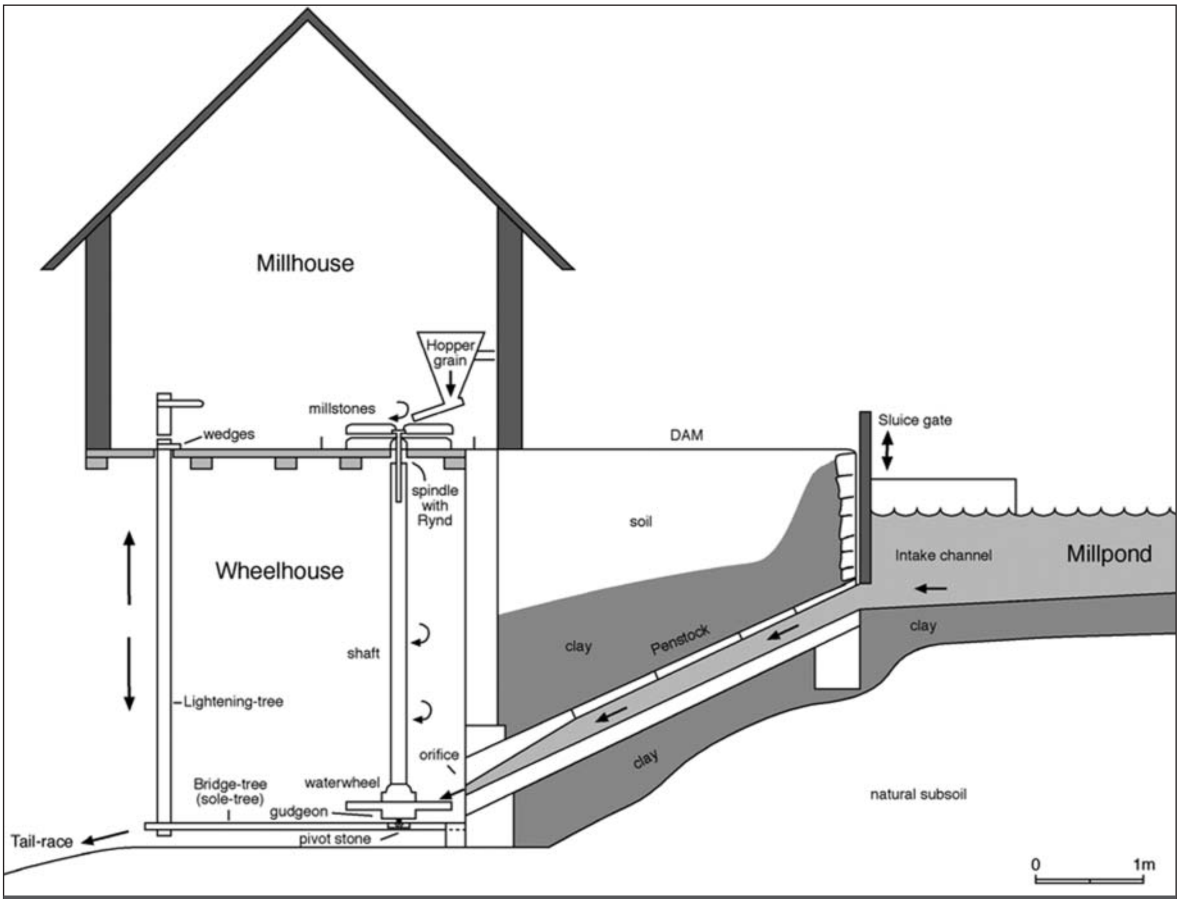

Fig. 27. Nendrum tide mill cross section

The UK has four pumped storage installations in operation: Cruachan and Foyers in Scotland, and Ffestiniog in Wales were built in the 1960s and 1970s and have installed capacity of up to 400 MW. A fifth pumped storage project, Camlough, was under construction in Northern Ireland but had to be abandoned in 1973 because of the security situation in the border area. All that is visible of the scheme today is a large steel bulkhead door in the mountainside.

In 1982 the much larger Dinorwic project was commissioned with a capacity of 1800 MW (Fig. 28).[15] It was designed by James Williamson and Partners in association with Binnie and Partners for the upper and lower reservoirs. Dinorwic is special in being the largest pumped storage plant in Europe and is capable of generation up to 1350 MW within 10 s from spinning reserve, with the turbine runners at grid frequency and the water in the turbine casing blown down by compressed air.

In 1982 a detailed study was made of a large pumped storage project in Scotland on Loch Lomond, but I understand that there are no plans to proceed. Of course, the first major pump storage gets the maximum credit for spinning reserve and frequency regulation.

Dinorwic provided the opportunity for some innovative engineering in the design of the upper reservoir, Marchlyn Mawr, and particularly for me, the responsibility of a major failure during the construction of the dam for the lower reservoir, Llyn Peris.

Fig. 28. Dinorwic: Marchlyn

Marchlyn Mawr was formed by the enlargement of a small moraine-dammed lake in a glacial cwm. To take advantage of the location of the rock bar, and to use the moraine as a part of the embankment, the dam was curved in plan. Although adopted for strictly utilitarian reasons, the curved shape of the dam, when viewed from afar as part of the magnificent landscape of the Glyders, appears to be part of the mountain. It was claimed by Frederick Gibberd and Partners as an ‘amazingly successful piece of landscape design’.[16]

The lower reservoir was formed by damming the existing Llyn Peris with a 4 m high embankment dam, operating from +2 m to -12 m relative to the original level of the

Fig. 29. Llyn Peris failure

lake. The low dam was constructed on a foundation of laminated sandy silts, sands and gravels with peat lenses. A partial cut-off was constructed by slurry trench diaphragm wall to a depth of 27 m below the original ground. The Afon Nant Peris is diverted around the lower reservoir by tunnel, thus isolating it from most natural inflow to preserve the capacity when pumped down ready for generation.

During construction it was necessary to lower the lake by floating pumping plant to enable the construction of the power station tailworks to be done in the dry and to allow the excavation of old quarry spoil tips from the lake. The foundation of the low dam and the cut-off works behaved as expected. However, a mass of peat in the old lake bed became unstable and slid out into the lake. The resulting slip of a 250 000 m^3 removed some of the rockfill dam and a small part of the top of the cut-off wall (Fig. 29).

It is at times like this when the designer is hurried to the site of the disaster, stands somewhat apart, and is asked: what do we do now? The experience should form part of any dam engineer's upbringing.

Fortunately the problem at Peris was solved by rebuilding the slope with the mass of slate rockfill which was being excavated from the old tips and dumped in the lake. The project has been so successful that Marchlyn dam has recently been raised with the construction of a crest wall to allow a 3·3 m rise in operating top water level. This will increase generating capacity from 9100 MWh to 10 260 MWh in a 5 h generating period.

CONCLUSION

Although there are obvious limitations to the opportunities for dam engineering in the UK, there will always be opportunities to offer bold, innovative solutions to difficult problems in the international field. The British dam engineering business is alive and well.

Malcolm Dunstan has established an enviable reputation as the consultant of choice in everything relating to roller-compacted concrete (RCC) dam construction. In association with Halcrow they are tackling a number of very large dams. MWH are consultants for a dam over 200 m high in Ethopia, and for Bashu, a large hydro plant in Pakistan with a 150 m high dam, following on their recently completed Jinnah scheme. Jacobs, having recently completed the Glendo hydro project in

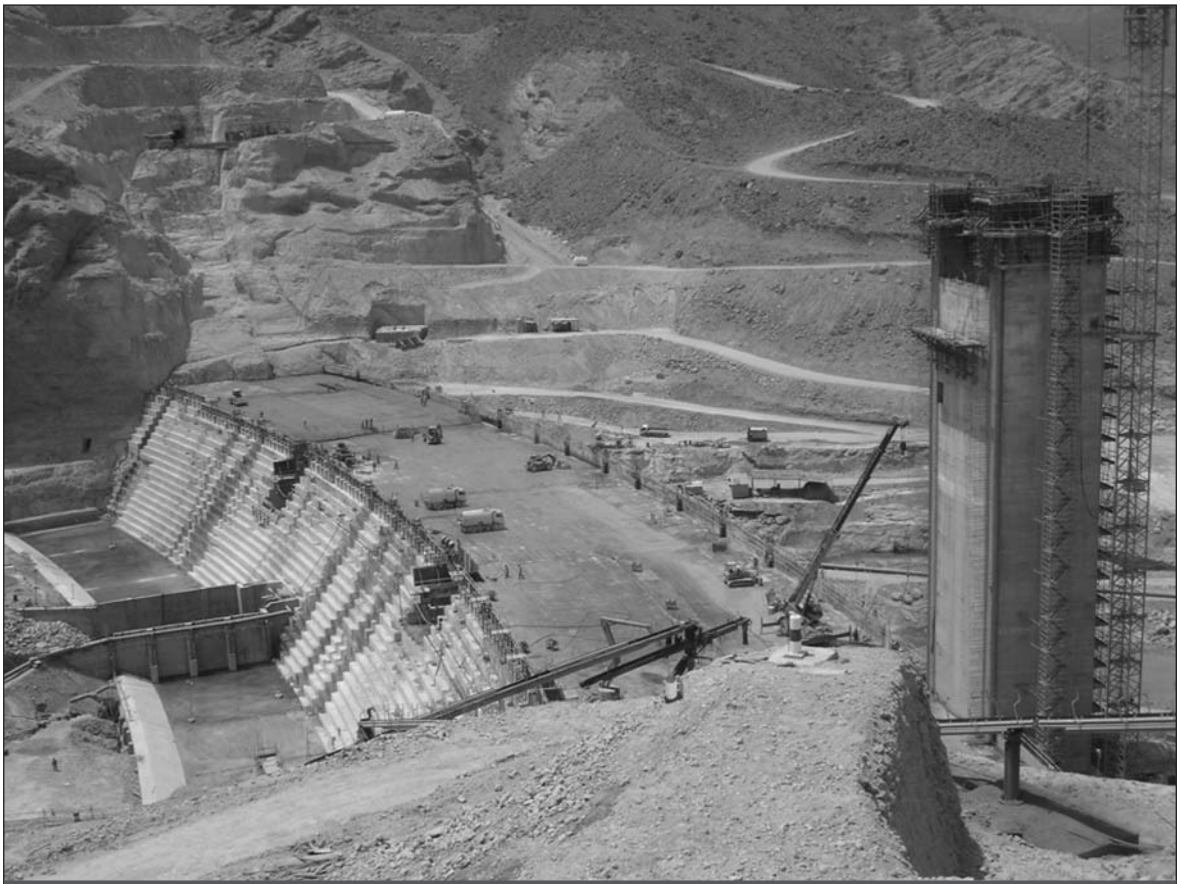

Fig. 30. Wadi Dayqah dam

Scotland, are engaged on a number of overseas dams. Mott MacDonald are engaged with Sogrea on the 180 m high RCC Bunji dam on the Indus in Pakistan, and with Coyne and Bellier on the 200 m high Karhanjkar CFRD in Iceland. They are also responsible for dams in Ethiopia, Laos and India. Binnie Black and Veatch (now Black and Veatch) were consultants for the recently completed raising of Mangla dam and for the completion of the Gazi Barotha hydropower scheme downstream of Tarbela on the Indus river, which was completed in the year 2000. They are now consultants for Wadi Dayjah, an 80 m high RCD in Muscat.

Figure 30 shows Wadi Dayqah dam—back where we started! It is a modern form of the Vyrnwy dam built in 1881 by Dr Deacon, one of the founders of Sir Alexander Binnie, Son and Deacon.

Acknowledgements

The author would like to thank the following individuals and companies for supplying images: Alan Cooper and the Water Service, NI (Figs 1 and 2), Andy Rowland and Black and Veatch (Binnie & Partners archive) (Figs 3–19, 22, 30), Ir. Ong Boo Say, SMHB Kuala Lumpur (Figs 20, 21, 24, 25), Ms. Gail Pollock, Environment & Heritage Service, NI (Figs 26 and 27) Bryn Williams, First Hydro Company, Dinorwig (Figs 28 and 29) and Neil Williams, Severn Trent Water Ltd (Fig. 23). The author is particularly grateful to Andy Rowland for the preparation of the presentation.

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