Some Aspects of Embankment Dams Constructed on the Mercia Mudstone

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SYNOPSIS. The Mercia Mudstone is a widespread stratum in the UK, underlying large swathes of the Midlands and North West England, and outcropping in locations as diverse as Devon, South Wales, Lincolnshire and Carlisle. Unsurprisingly, a number of reservoirs are constructed on this stratum, mostly impounded by earth-filled embankment dams, and many of them fall under the remit of the Reservoirs Act 1975. However, with the proposed change in legislation, it can be anticipated that many more such reservoirs constructed with and/or on this material will fall under the Act.

This paper deals with the geotechnical challenges posed by dam construction on the Mercia Mudstone. It highlights some of the essential features of this formation using examples from the site of a proposed new reservoir in Lincolnshire, but also from some historical dams.

INTRODUCTION

Anglian Water’s Lincoln Water Resource Zone is predominantly supplied by abstraction from local aquifers. However, forecast demand growth is predicted to result in a supply-demand deficit of 20 Ml/day by 2035. The proposed solution to address this issue is a new 20 Ml/day Water Treatment Works (WTW) to the west of the City of Lincoln.

The project is to consist of a river water intake from the River Trent, a new raw water storage reservoir (RWR), a new water treatment works and various water pipelines. Mott MacDonald has been commissioned by Anglian Water Special Projects to carry out firstly the preliminary studies and optioneering for the project, and subsequently the design of all components of the scheme. Design is under way, and construction is expected to commence later in 2012. However, the ground investigation, undertaken in 2011, revealed some unexpected and variable results. It was therefore considered worthwhile to undertake a broader review of some older embankment dam structures constructed on the Mercia Mudstone.

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GENERAL INTRODUCTION TO THE MERCIA MUDSTONE

The term Mercia Mudstone superseded the original name ‘Keuper Marl’ following a detailed review of Triassic strata by Warrington *et al* in 1980[1]. Whilst the engineering geology of the Mercia Mudstone is discussed in detail in the excellent review by the BGS[2], the subsequent BGS report of 2008[3] represents current thinking on lithostratigraphical matters. The current formational nomenclature is as follows:

Table 1. Current Formation Nomenclature for the Mercia Mudstone Group

Unit	Name	Dominant Lithologies
E	Blue Anchor Formation	Pale green-grey dolomitic siltstone, silty mudstone and siltstone [youngest].
D	Branscombe Mudstone	Red-brown mudstone and siltstone with reduction patches; gypsum/anhydrite in nodules and veins.
C	Arden Sandstone	Grey, green and purple mudstone interbedded with paler siltstone and sandstone.
B	Sidmouth Mudstone	Red-brown mudstone and siltstone with reduction patches; dolomitic siltstone; gypsum/anhydrite in nodules and veins. Thick halite in some areas.
A	Tarporley Siltstone	Interbedded micaceous siltstone, mudstone and fine sandstone; gypsum in small nodules [oldest].

The Mercia Mudstone Group ranges in age from Mid Triassic (Anisian) to latest Triassic (Rhaetian) (241 – 205 million years before present). It was deposited in a mudflat environment under four main depositional processes, as follows[3]:

- Settling out of mud and silt in brackish or hypersaline estuarine waters;
- Rapid deposition of sheets of silt / fine sand, transported by flash floods;
- Accumulation of wind blown dust on wet mudflat surfaces.
- Chemical precipitation of salts, principally halite & gypsum, from marine-sourced hypersaline water bodies.

Relevant Lithologies

As suggested above, the Mercia Mudstone Group comprises a number of different lithologies from clays and mudstones to sandstones and evapourites. Thin bands of dolomitic siltstone and fine sandstone, known as ‘skerries’ are common, as are gypsum veins, often found in association with the skerry beds. However, the dominant materials on which dams have been constructed are red/brown silty mudstones from Units B and D. Therefore this paper concentrates on these materials, although the influence of the other lithologies in the Group is also considered. In this paper the acronym 'MM' is used to refer to the mudstones of the Mercia Mudstone Group, whilst 'MMG' is used to refer to the Group as a whole.

ENGINEERING GEOLOGY OF MERCIA MUDSTONE

The engineering geology of the MM is given comprehensive treatment in the 2002 BGS report[2] and the CIRIA guide[4]. Some of the main properties of the MM that are of relevance to dam construction are discussed below.

Weathering

The MM comprises materials that vary from an engineering rock to an engineering soil. In some places it may be a jointed weak rock, whilst in others, due to the effects of weathering, it may have become a clay. Indeed, the degree of weathering is key to any assessment of MM in engineering terms. Chandler and Davis[5] introduced a scheme for describing the weathering of MM, a key feature of the MM is that a profile of decreasing weathering grade with depth should not always be expected.

Mineralogy

Clay minerals make up around 70% of the mudstone units, the major minerals being the detrital clays illite and chlorite. Authigenic clay minerals, such as smectite, palygorskite and sepiolite are also often present[1]. Of the non-clay minerals, quartz is the main silt and sand sized mineral. Dolomite and calcite are common cementing agents, while authigenic carbonates can fill pore spaces reducing both porosity and permeability. Calcium sulphate is commonly present as gypsum or anhydrite.

Index Properties

Research has shown that the clay minerals in the MM are typically aggregated so that particle size analyses give clay contents much lower than the true value obtained from mineralogical studies[1]. Index testing generally indicates that the MM is a very silty clay of low to intermediate plasticity[4]. However, the properties of the less weathered mudstones are influenced more by cementation, structure and lithology than by index properties. Moisture content unsurprisingly has a large effect on all physical properties.

Shear strength and stiffness

The significant variations in the fabric, structure and cementation of the MM result in highly variable profiles of strength and stiffness with depth. It is common for soft and hard bands to alternate, and whilst there is a reduction in strength and stiffness through weathering grades I to IV, lithological variations tend to cause greater scatter in the data than weathering alone.

Permeability

The permeability of all but the most weathered grades of MM is considerably higher than might be expected for a clay/mudrock. This is due to the presence of fissures, sandstone or skerry beds and cavities left by dissolution of materials such as halite and gypsum, which can increase the ‘mass’ permeability by orders of magnitude over the ‘intact’ permeability[1].

Chemical and other aspects

Deposits of minerals such as anhydrite and gypsum within the MM can cause engineering problems due to their potential for dissolution, and their ability to create aggressive conditions for buried concrete[1]. The MM has low shrink/swell potential due to the limited proportion of shrink/swell-susceptible clay minerals and the presence of intergranular cements[1]. Whilst it may be somewhat susceptible to frost action[4], it has low susceptibility to liquefaction due to the presence of cementing minerals.

OVERVIEW OF HISTORICAL DAMS ON MERCIA MUDSTONE

The authors have identified 58 statutory dams and reservoirs that are located either wholly or substantially on exposed Mercia Mudstone. There may be more but the criteria used here were that the dam should be founded on and should impound substantially over the Mercia Mudstone. The locations of all 58 dams are shown in relation to the outcrop of the MM in Figure 1. A table listing the highest dams in this group is given in Appendix 1.

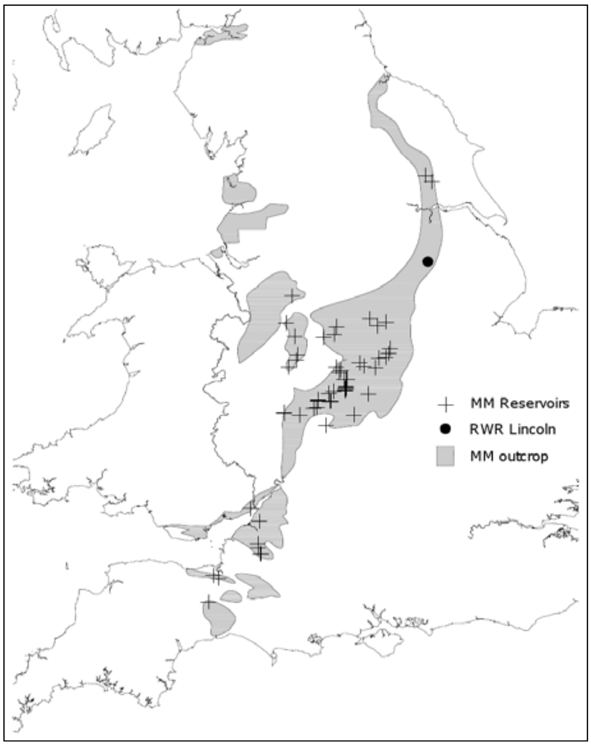

Figure 1. Locations of known dams on Mercia Mudstone

Nearly 90% of these dams are impounding dams; only seven are non-impounding. About half of the dams were built for primarily landscape / ornamental purposes, but these dams make up only 5% of the total reservoir capacity. In contrast, public water supply reservoirs account for only one fifth of the dams, but 85% of the total capacity. Another major contributor is canal feeder dams, making up 15% of the dams and 8% of the capacity.

In terms of age, the dams can be considered in three groups. One third of the dams (20 no.) date from the 17th and 18th centuries. These older dams are mainly the smaller dams, constructed for ornamental or landscaping purposes, and most have a capacity of less than 100,000m³.

With the coming of the industrial revolution, the functions of the dams changed and their size increased. Just under half of the dams (27 no.) were built between 1800 and WWII, and these included dams for canal feeder reservoirs, river flow compensation, and public water supply. These reservoirs have a median capacity of 200,000m³. The early dams were still of homogeneous construction and the earliest dam of this group to have a puddle clay core was Durleigh, constructed in 1839.

Only 19% of the reservoirs (11 no.) date from the post-WWII era, but these make up 70% of the total impounded capacity. These figures are strongly skewed by the two largest reservoirs in the whole group, namely Chew Valley Lake in Avon at 20.5Mm³ and Blithfield in Staffordshire, at 18.2Mm³, both public water supply reservoirs, and both built in the 1950s.

OBSERVATIONS ON HISTORICAL CASES OF EARTH FILL DAMS ON MERCIA MUDSTONE

Early Dams

The earliest dam in this group is **Park Meadow**, near Meriden, dated circa 1600. Dams designed by ‘Capability’ Brown, include **New Waters** at Warwick Castle Park (1765)[6], and **Coombe Pool** (1771)[7]. Binnie[8] notes that Brown left no details of his dam designs, but Hinde[6] claims that he constructed dams with a central clay core from around 1755. Thus, as their construction details remain a matter for conjecture, little can be learnt from these early dams other than that they remain functional despite their age.

Canal feeder dams

A number of canal feeder dams were constructed on the MM between the 1790s and the 1830s. An interesting case is **Belvide** dam in Staffordshire, owned by British Waterways. It was constructed c.1833, impounding Horse Brook to feed what is now part of the Shropshire Union Canal. The original dam, designed by Telford[8], had a height of about 10m, but by 1841 it had been raised by 4m using a steep brick lining to retain the upper part of the upstream face. An inspection report dated 1974, noted an “extensive and deep morass with water bubbling up under pressure” where the old stream course emerges from the toe of the dam. In the 1980s a hydrographic survey confirmed the existence of a ‘borrow pit’ at the upstream toe of the embankment, in line with the ‘morass’. Further studies concluded that seepage was occurring through the less weathered marls below the superficial layers, which had been excavated away[9]. Whether this ‘borrow pit’ was a feature from the original dam construction or from the dam raising, it appears to have had a damaging effect, leading to continuous leakage at the ‘morass’. The dam remains stable but as of March 2012, seepage at the morass continues to flow at a rate of around 8 l/min.

River flow compensation dams

The river flow compensation dams in this group are all part of a public water supply scheme near Bristol[10]. The Litton Dams, completed in 1850[11], show how problems are not necessarily related to dam height or slope angle. **Upper Litton** is an earth-filled dam with a crest only 120m long, wedged into a narrow, steep-sided valley. At 19m high, it is the highest dam on MM that has been identified. The downstream slope angle is 20°. After some grouting around the overflow in 1950, and core raising works in the 1960s, this dam has not required much repair work over the last 50 years. **Lower Litton** dam, at just 8m high, is a more modest affair. The valley here is broader and more gently sloping. The crest is 160m long, and the downstream slope angle gentler at 17°. A drawing from 1964 records a major grouting operation around the spill weir and along part of the dam crest. Significant cavitation must have been occurring both in the weathered MM and in the less weathered material below since heavy water losses and heavy grout takes are noted both above and below a line that divides “soft red marl” above and “hard red marl” below. These works were undertaken in 1963. Earlier grouting works had been carried out in 1950. Despite these previous works, problems of leakage still persist in 2012, and further grouting works are planned for later this year[11].

Early public water supply reservoirs

An example of public water supply reservoirs constructed on and with the MM is **Shustoke Lower** Reservoir, in Warwickshire, constructed in 1885 with a capacity of 1.921Mm³. This non-impounding reservoir is encircled by an embankment of total length of 1,860m. The bulk of the reservoir and dam are underlain by MM, but the western end is underlain by river alluvium. Record drawings indicate a puddle clay trench cut-off into the foundation material, a puddle clay core and general fill on the shoulders[12]. The dam has a maximum height of 8.6m, with slope gradients of 1 on 3.5 downstream and 1 on 4.5 upstream. The embankments have proved to be stable for over 100 years, but since 1972 there has been a very wet area at the toe of the SW slope. In addition, crest levels showed abrupt settlements of 20mm to 50 mm in the period 1989-1994 in the same area. Possible explanations for these movements included settlement in the alluvium, wash-out of embankment material due to leakage and mining subsidence. However, recent works have revealed a separate cause for the wet area, and leakage through the MM embankments is now not suspected.

20th century public water supply reservoirs

The two largest reservoirs in the whole group, namely Chew Valley Lake and Blithfield, appear to have similar construction details, with a puddle clay core and a concrete cut-off excavated into the underlying MM foundation. At **Chew Valley Dam,** the clay core tapers from 3.2m width at the base to 1.5m at the crest, and was extended down vertically in the centre of the dam where alluvial soils exist. The base of the puddle clay was keyed into the top of the concrete cut-off once the MM was reached. This dam has required little ongoing maintenance and has suffered no instability, although minor seepage is currently being investigated. One possible flow path is through the MM.

Summary of historical cases.

From the cases studied, there are no examples of major slope instability. Settlement has occurred in some cases, but this has been due to external influences, as at Shustoke Lower. No cases have been found of water quality problems related to the MM. However, leakage has been a recurring theme affecting a number of the sites. Leakage has been shown to be high through the less weathered, more structured MM of the dam foundations, as at Belvide and Lower Litton, but examples of leaks through well-formed embankments have been less easy to confirm. Examples such as Chew Valley Dam suggest that it is possible to construct reliable embankment dams with relatively low maintenance requirements using this material, provided suitable methods are used and adequate compaction is applied.

LINCOLN WATER TREATMENT WORKS RAW WATER RESERVOIR

Site Selection and Geological Context

The site selected for the RWR is on high ground just to the east of the River Trent near the village of Newton-on-Trent in Lincolnshire. The water intake is to be located some 500m to the north west, where the river cuts into the higher ground, forming a steep bank some 15m to 20m high, called Newton Cliff. The MM exposed here contains numerous veins of gypsum over 50mm thick within the mudstone sequence, and several skerry beds. In relation to the stratigraphical model discussed earlier, the site is believed to be in Unit D, the Branscombe Mudstone Formation, near the top of the MMG, which in this area is about 230m thick. At the reservoir site, the MM is overlain by a thin layer of wind blown sand of recent age. This is typically a loose clayey uniform fine to medium sand less than 1m thick.

Ground Investigations

Ground investigations (GI) for the RWR were carried out in May and June 2011, consisting of six cable percussion boreholes, two rotary drillholes and five static cone penetration tests. Groundwater monitoring showed that standing groundwater level in the MM was over 15m below ground level. In-situ testing in the boreholes comprised standard penetration testing and permeability testing. Laboratory work included classification, total and effective stress triaxial, compaction, point load and chemical testing.

Classification tests, grading and sulphates

The results of classification testing confirmed the MM at this site as a low to intermediate plasticity clay, as indicated in the literature. Moisture contents reduced with depth to about 4m depth, below which they were consistently below the plastic limit. Particle size testing showed a much higher fines content (c.90%) for Grade IV material than for Grades III and II (45%-60%) suggesting a lower degree of aggregation for a higher degree of weathering. Sulphate concentrations were low at ground level but increased significantly with depth.

Shear Strength

Values of undrained shear strength, c_u, were obtained from a number of different testing methods, both direct and indirect. Plots of c_u show a general increase with depth, but a huge range for any given depth. Weaker material often underlies stronger material. The literature[1,4] suggests that this is due to preferential weathering and lithological changes and the borehole logs support this. The strength values obtained fall between medium strength clay and weak rock, though the majority of material in the upper 6m was a clay of medium to high strength. From the effective stress testing the Grade IVa and III materials were assigned characteristic effective strength parameters of $c' = 3.7$kPa and $\phi' = 29°$, which are within the broad published ranges[4], though anomalies existed between the grades.

Permeability

Permeability testing conducted on the MM comprised in-situ falling head tests and laboratory tests on intact and reworked samples. The in-situ tests were interpreted firstly using the method set out in BS5930[15] for saturated soils. However, due to the low water table, this was not applicable in many cases so an alternative ‘soakaway’ methodology was used. The latter method calculates a ‘soil infiltration rate’, ‘f’, which can be compared to permeability ‘k’ values. The k and f values obtained are shown in Figure 2.

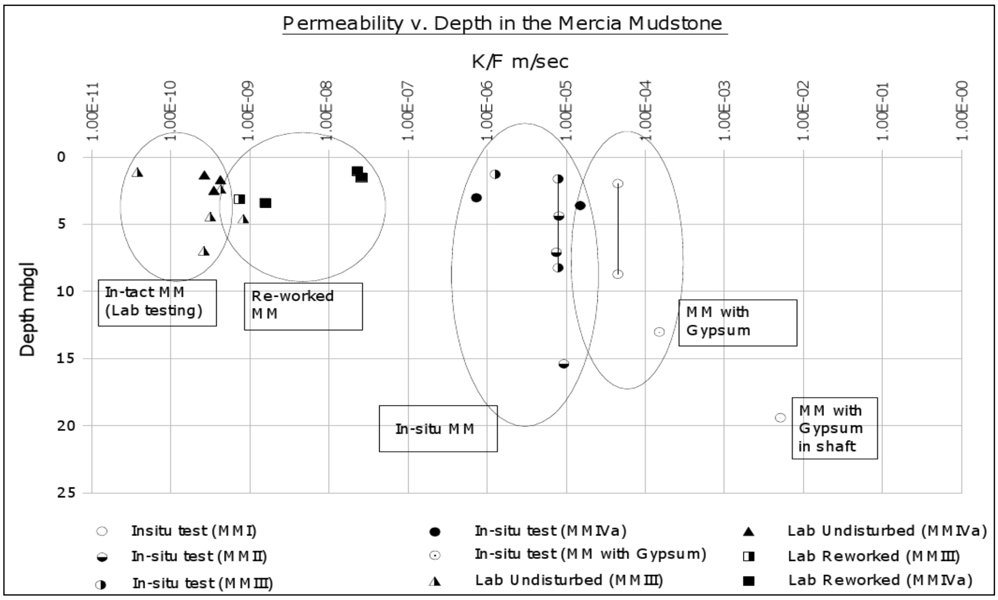

Figure 2. Permeability of the MM at the proposed Lincoln RWR site

The permeability of intact samples taken from the more weathered MM was very low, and that of samples of re-worked MM similarly so, although in two cases it was somewhat higher. However, the values recorded for the MM ‘en masse’ are three to four orders of magnitude higher. This is considered to be due to the effects of bedding, fissuring, lithological variations and so on, that do not affect small laboratory samples. The highest values of all were recorded over borehole test sections containing gypsum, the high values being attributed to bedding effects and possibly the dissolution of gypsum. These values are fully six orders of magnitude higher than that of the in-tact material. Even more startling results were obtained in permeability tests on the MM at the river intake site. In one test water could not be pumped into the borehole fast enough to raise the water level and in another the water level fell from 0.5m depth to 12m, only to rise again of its own accord to 8m. Such variable and strange test results were of considerable concern to the reservoir design team.

RESERVOIR DESIGN DEVELOPMENT

The initial stages of preliminary design focused on obtaining an earthworks balance for the 306,000m³ capacity reservoir within the constraints of the levels required for water processing at the WTW. The resulting cross section requires embankment heights of between 5m and 7m, with the maximum excavation depth being around 6m. The wind blown sand will need to be stripped off the entire area and will be used as general fill on the outside of the reservoir. A typical section is shown below in Figure 3.

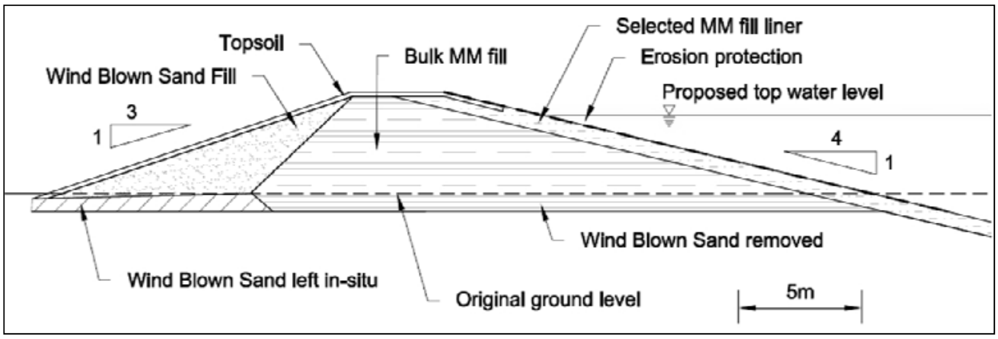

Figure 3. Preliminary section through proposed embankment at Lincoln.

Slope analyses have been conducted using conventional slope stability software for both undrained and drained cases, including rapid drawdown effects. Settlement analyses suggest maximum embankment settlements of 80mm, with implications for the design of the reservoir inlet and outlet. However, the most critical single element of the reservoir has been the waterproofing design. Various options were considered to address the risks posed by the variable in-situ permeability of the MM encountered during the GI. Seepage analyses calculated total leakage flows of between 1 and 20 l/s, depending on the extent and nature of the lining system. However, the most cost-effective option proved to be an in-situ reworked clay liner, on the upstream face. Therefore it is currently proposed that a 0.6m thickness of re-worked Grade III and IV MM is placed over the entire water retaining area of the reservoir. This specially selected reservoir liner material will be reworked at a moisture content above optimum to achieve a permeability in the area of 10^{-9}m/s. Practicality dictates that this material is placed on an internal slope formed at a relatively shallow angle. The surface of the inner slopes will be protected by a bitumen-impregnated erosion mat system.

DISCUSSION

A ground investigation for a new reservoir to be formed on and constructed with weathered mudstones of the Mercia Mudstone Group has revealed significant variations in lithology, strength and, more than anything else, permeability. Whilst these findings are consistent with data published in well known texts about this stratum, they are not helpful to the designers. A review of some historical cases of earth fill embankment reservoirs on Mercia Mudstone has helped to confirm how some of these characteristics affect the performance of embankment dam structures in the long term. The lesson appears to be that whilst stability is not often a major concern, the prevention of leakage is. In this regard it is encouraging that other studies, notably that by Vaughan[15], have concluded that a low permeability can be reliably achieved in stiff clay and mudrock fills through proper compaction. Vaughan et al. state that:

> "The permeability of in-situ clays and soft mudrocks is strongly affected by slightly open fissures. It is difficult to prove the absence of open fissures and low bulk permeability. However, field experience is that when these materials are placed as fills using modern plant, a uniform low permeability results."

A specific concern at the Lincoln site was the very high permeability apparently associated with the presence of gypsum beds, both at the reservoir site, but especially at the water intake site. However, geological factors suggest that the highly gypsiferous beds exposed in the river bank are thankfully at considerable depth below the reservoir site.

CONCLUSION

It is concluded that a review of previous cases, in combination with a site-specific investigation has helped to provide the necessary confidence in material properties to develop an economical earth-fill embankment design for this reservoir. Although none of Vaughan's specific case studies were in this stratum, it is also concluded from this study that the general sentiments of Vaughan's paper, as stated above, also apply to the Mercia Mudstone.

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REFERENCES

1. Warrington, G. *et al* (1980). *A correlation of Triassic rocks in the British Isles*; Special Report of the Geological Society No. 13.
2. British Geological Survey (2002). *Engineering geology of British rocks and soils – Mudstones of the Mercia Mudstone Group*; BGS Research Report RR/01/02, BGS, Keyworth Nottingham.
3. Howard, A.S. *et al* (2008). *A Formational framework for the Mercia Mudstone Group (Triassic) of England and Wales*. Research Report RR/08/04, BGS Keyworth, Nottingham.
4. Chandler, R. J. and Forster, A. (2001). *Engineering in Mercia Mudstone*. CIRIA Report C570, CIRIA, London.
5. Chandler, R.J. and Davis, A.G. (1973). *Further Work on the Engineering Properties of Keuper Marl*. CIRIA Report 47.

6. Hinde, T. (1986). *Capability Brown, the story of a master gardener*. Hutchinson, London

7. Warwickshire County Council. (1986). Coombe Pool SSSI Citation ref. W/S/10.

8. Binnie, G.M. (1987). *Early Dam Builders in Britain*, Thomas Telford, London.

9. Brown, D. (2012) British Waterways, Personal communication.

10. Heaton-Armstrong, C.W.P. (1984) Floods and Spillways of the Mendip Supply reservoirs of the Bristol Waterworks Company. *Proc. BNCOLD Conference, University of Cardiff*, 1984, pp 21-35

11. Hunt, C. (2012) Bristol Water plc, Personal communication.

12. Mills, D. (2012) Severn Trent Water plc, Personal communication.

13. Hodgson, A. (1991). *The Story of Bristol Water Works Company 1939-1991*. Bristol Water Works Company 1991.

14. BS5930:1999 + A2:2010. *Code of Practice for Site Investigations*.

15. Vaughan, P.R. *et al* (2006). The effect of compaction on the bulk permeability of stiff clay and mudrock – field experience from embankment dams. *Proc. 5th ICEG Environmental Geotechnics*, Thomas Telford, London.

KEY TO TABLE IN APPENDIX 1

* = Information estimated

- = Not Known

The table contains Environment Agency information

Appendix 1 - Table of basic data for dams over 8m high on Mercia Mudstone

Dam	Year Built	Primary Function	Dam Type	Height (m)	Length (m)	Capacity (m^3)
Upper Litton	1850	River Flow Compensation	Earthfill Embankment	19	120	459,100
Tardebigge	1822	Canal feeder	Gravity & Earthfill	18	460	396,640
Blithfield	1953	Public Water Supply	Earthfill Embankment	16	856	18,172,000
Cropston	1870	Public Water Supply	Gravity & Earthfill	15	600	2,528,000
Bittell Upper	1832	Canal feeder	Earthfill Embankment	15	255	1,022,400
Belvide	1833	Canal feeder	Earthfill Embankment	14	1,025	2,196,000
Leigh	1889	Public Water Supply	Gravity & Earthfill	13	300	120,000
Chew Valley Lake	1957	Public Water Supply	Earthfill Embankment	12	470	20,457,000
Thornton	1854	Public Water Supply	Gravity & Earthfill	12	500	1,320,000
Chew Magna	1850	River Flow Compensation	Gravity & Earthfill	12	98	113,650
Swithland	1894	Public Water Supply	Earthfill Embankment	11	406	2,227,540
Durleigh	1839	Public Water Supply	Gravity & Earthfill	11	430	959,000
Lawton Hall Lake	1760*	Fishing	Earthfill Embankment	11	-	127,000
Church Wilne	1971	Public Water Supply	Gravity & Earthfill	10	2,220	2,790,000
Westwood Gt Pool	1870	Landscape	Gravity & Earthfill	10	270	400,000
New Waters	1765	Landscape	Gravity & Earthfill	10	-	110,000
Washing Pool	1750*	Landscape	-	10	-	38,010
Hundred Pool	1750*	Landscape	-	10	-	27,300
Shustoke Lower	1885	Public Water Supply	Earthfill Embankment	8	1,950	1,921,000
Bittell Lower	1811	Canal feeder	Gravity & Earthfill	8	260	196,400
Lower Litton	1850	River Flow Compensation	Gravity & Earthfill	8	160	109,100
Ragley Hall Lake	1625	Landscape	Gravity & Earthfill	8	100	55,000