GEOTECH-YEAR 2000
Developments in Geotechnical Engineering
27-30 November 2000, Bangkok, Thailand

Four decades of development of British embankment dams

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SYNOPSIS

In 1950 to 1990 a large number of embankment dam projects were constructed in Gt. Britain. Of 137 large dams, 69 were embankment designs, with most having clay cores and clay foundations. The period has seen tremendous growth and development of geotechnical engineering, and many significant examples of dams and geotechnical engineering are described.

1. INTRODUCTION

The four decades of 1950 to 1990 cover a busy period of dam projects in Great Britain when 137 large dams (i.e. over 15m in height - ICOLD Register) were constructed to form impounding and pumped storage reservoirs. Of the dams completed since 1953, 68 were concrete and 69 were embankment designs, and of these 54 have clay cores or in some cases clay fills or clay foundations.

These decades have seen the tremendous growth in Great Britain of geotechnical engineering including soil mechanics, rock mechanics and engineering geology. The first University Professor of Soil Mechanics was Professor A W Skempton at Imperial College in 1955. Now there are over 20 geotechnical professors in the country. It is now inconceivable that an earth dam project would be designed and constructed without experienced post graduate engineers on the staffs of the site investigation contractor, the testing laboratory, the consulting engineer and the civil engineering contractor.

The position before the 1950's can be summarised in a quote from a lecture by G M Binnie:
"From the beginning of this century up to the end of the second world war, the design and construction of earth dams followed traditional lines based on more than a century of recorded practical experience.

Following a slip during construction of Chingford Reservoir in 1938, Professor Terzaghi was called in to advise and after the war Terzaghi's concepts were welcomed with enthusiasm by the post war generation of British Engineers. Whilst experience and judgement still remain very important factors in the investigation and design of dams, the empirical methods of the past have now been superseded by methods based on analysis and scientific logic."
(Binnie, 1976)

This period of 1950 to 1990, which has included many well known embankment dams, can be considered as a modern golden age of British dam history, and with arguably one major exception, the period is also a major success story. Many technical papers have been published covering work in this period, and reference can be made to published references, including, amongst many others, Skempton (1989), Knight (1989), Rowe (1970), etc. Aspects of a few of the earth dams constructed in the period are described in the following sections.

2. FROM 1950 - 1960

At the 33m high Usk Dam, in South Wales, in 1950 a lens of silt was found in the glacial drift foundation. As the silt was sealed by boulder clay above and below, no consolidation of the silt could occur when loaded by the embankment and the consulting engineers, following proposals by Dr A D M Penman and the Building Research Station, decided that it was economic to introduce a row of sand drains as an alternative to removing the silt and the ground above the silt. The drains proved so effective that scarcely any excess pressures developed in the silt during construction. The Building Research Station also proposed to take the opportunity to install piezometers in the clay fill shoulders of the embankment. These instruments showed positive pore pressures, and in fact pore water was found to rise up standpipes above the level of fill. Studies by Dr Penman led to Professor Skempton and Dr Bishop being consulted and analyses showed that building could not safely continue without a modification in design, and that the most expeditious method of achieving adequate stability was to introduce drainage blankets before adding the second, and then the third season's earth fill.

The work at Usk led Professor Skempton and Dr Bishop, to realise that drainage blankets in clay fills as well as sand drains in soft clay foundations, could provide

"a valuable feature in the hands of an engineer designing an earth dam under conditions where clay had to be used and where there was substantial rainfall. What had at first been considered an expedient to overcome a difficult situation was now showing itself as a feature which could with great advantage be incorporated in earth dams at the outset of design".
(Skempton, 1957)

The 36m high Selset Dam, where construction commenced in 1955 became a classic example of this. The design using boulder clay fill in the shoulders incorporated drainage blankets in the shoulder fill from the beginning.

Additional foundation site investigation, early in the contract at Selset, showed the extent and depth of the soft clay foundation and extensive sand drains were immediately designed.
(Kennard & Kennard; Bishop & Vaughan, 1962).

The dissipation of pore pressure in boulder clay fill in the wet climate at Selset, between both horizontal and vertical drainage blankets was observed by arrays of hydraulic piezometers. Although both layouts were effective, horizontal blankets were subsequently used due to less obstruction during fill placing. Following this, dam drainage blankets in clay shoulders have subsequently been incorporated in over 20 British embankment dams.

The performance of the Selset embankment during construction was monitored and analysed continuously, so that the factor of safety during the critical stage, as full height was reached, was known at all times.

In the Usk and Selset Dams, the clay cores were of puddle clay as in a large number of older British dams, but the experience of rolled clay in the shoulders of the Usk and especially Selset Dams, with extensive pore pressure, shear strength and permability data, enabled British engineers to have confidence in rolled clay, and most of the later embankment dams have rolled clay cores.

3. FROM 1960 - 1970

The long-term performance of clays used in clay embankments, especially of weathered London Clay, Oxford Clay, and Weald Clay, all in Southern England was not so well known and documented as the boulder clays in Northern England. As these materials were used in larger embankments a certain conservatism was required, especially with regard to spacing of drainage blankets and long-term softening of the clay.

At the 27m high Diddington Dam, now Grafham Water, (completed in 1964) the initial design had a provisional spacing of the drainage blankets at 3.2m centres. After consultation with Professor Bishop and Binnie & Partners a more conservative approach to the problems of long-term softening was adopted, with the blankets mainly at 1.6m centres. The analyses included the stability of the upstream slope against shallow draw-down slips under the extreme condition of rapid drawdown with the shoulder material fully softened. The cross-section is shown on Fig. No. 1.
(Hammond & Winder, 1967).

There is probably evidence however that blanket spacing in some dams of modest height constructed in the drier parts of the country has been unduly conservative, but the engineer does not always have the advantage of hindsight in making design decisions.

The need to consider critical surfaces, and also the need to review the design after the initial design, is shown by 58m high Llyn Celyn Dam (completed in 1965) where computer analyses with circular slip surfaces were initially carried out, leading to a conventional 1 in 3 upstream slope. Non-circular failure surfaces were subsequently investigated, particularly in connection with foundation failure. Re-assessment of the stability for the upstream foundation was made when, shortly after construction had started, investigations of other dams founded on similar clay cast doubt on the long-term strength of the upstream foundation. As a result, the original uniform upstream 1 in 3 slope was replaced by a toe term extending 64m upstream, a 6m wide berm 12m higher and a 1 in 5 slope in between. (Crann, 1968).

At the 36m high Derwent Dam, completed in 1966, a combination of geological and geotechnical conditions led subsequently to a design incorporating sand drains in the foundation, a base drainage blanket, an upstream open cut clay cutoff, a base clay blanket, drainage blankets in the fill, flat slopes and relief drains. (Rowe, 1970). The constructed cross-section, on which Professor Rowe advised, involved extensive changes from the original design, including changing from a central puddle core design as considerable information became available during construction of the cut off and foundation. The changes at Derwent probably represent the end of many aspects of the early British empirical designs to a cross-section based on the best principles of geotechnical expertise applied to a very difficult site. The cross-section is shown on Fig. No. 1.

Scammonden Dam, an 80m high rockfill dam with a sloping upstream rolled clay core is a combined motorway embankment/dam structure, and was constructed in 1966 to 1970 to serve both purposes of a reservoir and a 6-lane motorway. Considerable trials were carried out on excavation and compaction techniques for the relatively soft sandstone fill. To reduce post-construction settlement and its effect on the motorway road surfaces, the clay core was located upstream. The embankment was some 11m higher than was necessary to form the water supply reservoir. Significant economic advantages were obtained by combining the two functions of a dam and a highway embankment. Recently, consideration has been given to both widening the motorway, and raising the reservoir top water level.

4. FROM 1970 TO 1980

At Empingham, now Rutland Water, completed in 1975, a 40m high bank on Lias Clay also illustrates how sophisticated geotechnical investigation, testing, analyses, and constructional control and modification enabled a difficult site to be utilised. Pumped storage schemes such as Empingham, Draycote, and many others, have led to larger reservoirs and higher dams than if sites had only been used to store water from their own catchments. This introduces problems of scale not previously encountered. The dam foundation is Upper Lias Clay extensively sheared and brecciated by valley bulging and periglacial disturbance. The weak foundation was the controlling factor in design and made a wide cross-section with extensive berms necessary. Because determination of the reliable strength of foundation was difficult, it was confirmed by a trial bank placed early in the construction which was incorporated into the embankment cross-section. The flat cross-section makes a simple cross-section illustration difficult. The dam was designed by T & C Hawksley, and Dr Vaughan. (Bridle, Vaughan & Jones, 1985).

At the 52m high Kielder Dam, completed in 1982, with glacial till or boulder clay, foundation and fill, a cross section with slopes similar to the early standard design was used, but with an upstream base clay layer as a seepage control measure. This made the critical slip surface pass through the centre of the 6m thick base clay layer which was to the same specification as the clay core. No limiting rate of construction was specified, and the results of on-going stability analyses at two day intervals showed a drop in FOS from 2.5 to 1.4 in only one week. Fill placing had to be suspended a few weeks before the end of 1979 earth moving season. If fill placing had continued, it would appear that failure could have occurred. This shows the importance of continually assessing the stability of a design based on pore pressures and comparing the design pore pressures with those measured in piezometers as the work proceeds. At Kielder during the winter shut-down, further boreholes were sunk and samples tested. The core and blanket material was found to have strength parameters which were lower than had been anticipated. Use of these lower parameters reduced the calculated factors of safety even further. The cross-section is shown on Fig. No. 1.

Subsequent analyses indicated that if the high rates of construction were to be maintained for the 1980 season a modest stability berm would be required at one section. During this final season close monitoring of core and blanket piezometers was maintained, and the FOS fell to 1.28 when the fill was more than 7m below crest level. At this stage a modest toe berm was placed and this increased the FOS to 1.80 and at completion of the bank it was 1.5. At the commencement of impounding it had increased to 1.7.
(Millmore & McNicol, 1983).

5. FROM 1980 TO 1990

Construction of the 35m high Carsington Dam commenced in 1981 and the cross-section included a widened base (boot) section of the rolled clay core.

The contractors were unhappy about certain aspects of the foundation and embankment and after failing to get a meeting with the Engineers to discuss the design, instructed their consulting engineer to report on the situation, when there was still about 5m of fill to be placed. I, together with Professor E N Bromhead, rapidly prepared a report, using as the base the Engineer's published design parameters, and found that:

(1) the most critical slip surfaces had not been analysed
(2) the factor of safety was less than quoted and less than generally acceptable factors of safety
(3) foundation design parameters were not available
(4) instrumentation data tended to show a developing slip zone and
(5) the shear strength parameters of the clay core, used in the original design, were known to be too high, and even the revised known ø' was probably too high. A revised design was considered to be essential so that the embankment (then 12m below final level) could be completed with safety and confidence.

No discussions were subsequently held on the report, and no effective action was taken by the Engineers or the owner. The upstream slope failed catastrophically some six months later (on 4 June 1984). After three days the tension crack extended to 500m with a drop of some 10m and a forward movement of the upstream embankment toe of some 13m.

The failure was the subject of extensive investigations, analyses (including advanced finite-element analysis) and reports. An official governmental report by Mr R E Coxon (1986) concluded, in respect to the design, the following:

"(1) The early analyses do not appear to locate the critical slide surface for a circular analysis. Had this been located, or had non-circular surfaces been analysed, factors of safety lower than 1.69 would originally have been identified.

(2) The computations by the Engineers using later measured shear strengths and actual pore pressures gave lower factors of safety than originally computed. Had c' been taken as zero the figure would have been close to unity. In my view these factors of safety should have led to a re-examination of the original design.

(3) The contract cross-section of Carsington cannot be considered to be obviously conservative.

(4) It is clear that there were shortcomings in the process of design."

These conclusions effectively confirmed the views of the pre-failure report, and therefore showed that the failure could have been avoided, and that acceptable geotechnical standard methods were available to show that the original design was unsatisfactory. Reliance on computer printout needs the basis of realistic shear strenths, pore pressures, and slip surfaces, which unfortunately were lacking in this particular case.

The dam has been satisfactorily re-designed and re-constructed and has now been used to store water for some years. Professors A W Skempton and P R Vaughan, with others, were extensively involved in the post-failure investigations and re-design. The successful design generally has flatter slopes, and a less critical clay core cross-section than the original (failed) cross-section as shown in Fig. No. 1 of the original and reconstructed dam cross-sections.

6. INTERNAL AND FOUNDATION SEEPAGE

There have been significant changes from early designs with a relatively thin puddle clay core and deep concrete filled cut-off trenches, to rolled clay cores with downstream filters, and reliance on clay strata and blankets, and grouting.

An example of the change in philosophy in the development of cut-off measures is Cow Green Reservoir. The watershed area between the proposed reservoir in the River Tees valley and the adjacent valley, comprised several limestone strata, and within the area extensive barytes mineral workings of shafts and long adits. When the site was considered in the mid 1950's, a view was expressed that because limestone strata were involved with a lower level outlet in the adjacent valley, a considerable cut-off problem existed with the possible need for a grout curtain all around the reservoir. Consideration of the site was therefore abandoned in 1956 in favour of an alternative reservoir site. However increasing industrial water demands led to a further look at the site in the mid 1960's, and Dr (now Professor Sir) John Knill re-assessed the situation and considered that there was evidence that the ground water table in the col area between the two valleys was at a sufficiently high level for there to be a natural water cut-off to the proposed reservoir. Extensive site investigation with ground water observations in standpipe piezometers proved this to be the case. (Kennard & Knill, 1968). Although the opposition argued the case in Parliamentary Committee proceedings that extensive grouting may still be required, the scheme was approved and construction began. No grouting or cut-off measures were constructed, and the reservoir has been satisfactory with no known leakage problem.

7. CONSTRUCTION CONTROL AND INSTRUMENTATION

In British conditions regarding variability of geotechnical materials, and climate, the control and supervision of construction, including instrumentation, are essential for the satisfactory performance and safety of dams. The instrumentation of embankment dams, especially of pore pressures of clay foundations and fills, ground water levels, and internal and surface displacements has made great advances and has generally become standard practice.

Earlier construction control specifications limited clay fill specifications to matters such as layer thickness and descriptive use of rollers.

In the post war period, specifications have covered such aspects as moisture content and relative density, thickness of layers, type of roller, non use of certain excavating plant which might lead to wetter clay fill, watering of cores and fill, outward sloping surfaces, etc. Later developments include shear strength specifications for clay cores in which an acceptable range has been stated and the method has enabled the required properties of a non-cracking and plastic clay core to be readily tested. (Kennard, Lovenbury, Chartres & Hoskins, 1978)

Alongside this, measures to increase the water content of clays have been developed by contractors at different sites, and with a range of different clays, to achieve the required shear strength. Examples of the range of shear strength specified, include 70 to 110 kN/m2 at Derwent; 50 - 100 at Empingham and 60 to 140 at Kielder. Below 60 kN/m2 there would be problems of rutting of clay with rubber tyred plant.

Space precludes a wide coverage of this topic of construction control, but over the years the considerable use of site investigations, site laboratory testing, instrumentation, checking of design parameters, plotting of results, continuing analyses of stability, based on observational techniques and post construction performance studies have all made significant advances and developments which are well covered in the literature.

8. CONCLUDING REMARKS

The history of the last four decades of British embankment dams is much more than the few examples described, but they are sufficient to show some of the developments that have occurred in this period from early empirical designs and how British dams have been constructed in accordance with state-of-the-art principles developed, especially on British geotechnical experience and performance.

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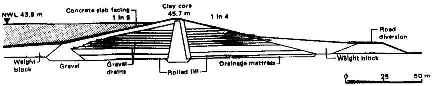
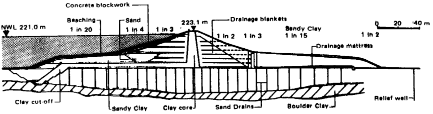
FIG.No.1 TYPICAL CROSS SECTIONS



DIDDINGTON DAM



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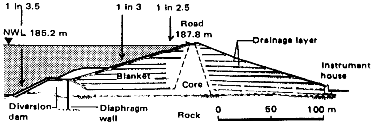

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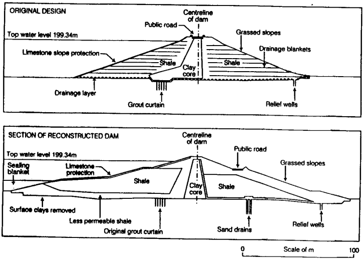

CARSINGTON DAM