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Ground Investigation through London's raised reservoirs with a summary of ground investigation risks and recommendations, citing techniques used at two sites.

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SYNOPSIS Thames Water operates and maintains thirty raw water reservoirs across London and the Thames Valley, supplying water services to nine million customers. Most of these reservoirs are retained by a perimeter embankment with a puddle clay core that extends down into the underlying London Clay Formation bedrock. These reservoirs were built with selected material placed downstream of the core to act as a filter, but with no drainage system to monitor; therefore non-intrusive geophysical surveys are regularly carried out by Thames Water to identify areas of excess leakage or seepage, with remediation works being carried out afterwards.

Ground investigation through puddle clay cores is notoriously challenging with a number of key risks; this paper uses two projects as case studies to provide a summary of the ground conditions and associated risks which may be expected at the various reservoir sites around the capital. This paper also summarises the various techniques used for investigating the dams to mitigate these risks and support the construction and remediation of the structures, with a particular focus on the requirements of British Standards and best practice, and the practicality of using these techniques in the field.

INTRODUCTION

Thames Water operates and maintains 30 raw water reservoirs across London and the Thames Valley, supplying water services to 9 million customers. The majority of these reservoirs are raised above the surrounding land and comprise soil embankment dams with a watertight puddle clay core. Puddle clay core embankments were the preferred method for constructing dams in the UK for well over a hundred years before being replaced by the rolled clay core methodology (Reeves & Cripps, 2006). A survey of embankment dams cited in Charles (1989) suggested that, of the 2000 embankment dams in the UK, 65% of them had puddle clay cores. As these reservoirs are now up to or over 100 years old, and due to drawdown during World War Two, defects are occurring within the cores. These defects are being identified by both physical evidence (i.e. ponding at the toe of the embankment) but more recently through geophysical methods which allow for the early identification of seepage before external evidence occurs.

Ground investigation (GI) through puddle clay cores is notoriously challenging with a number of key risks; this paper provides a literature review setting out what to consider when investigating puddle clay cores (with a particular focus on the requirements of best practice and British Standards, and the practicality of using these techniques in the field) and uses two projects as case studies to provide a summary of the ground conditions and associated risks which may be expected at the various reservoir sites around the capital.

The reservoirs selected for discussion in this paper are Island Barn Reservoir and King George V Reservoir; both of which are located on similar natural ground comprising bedrock of London Clay Formation, overlain by River Terrace Deposits and Alluvium. Locally derived soils were typically used for constructing the dams and as such, the two reservoirs' embankments are constructed using similar materials, including London Clay Formation or Alluvium derived puddle clay, and embankment shoulder material largely comprising River Terrace Deposits. From a review of historical case studies, it is expected that the majority of Thames Water's embankment dams are composed of similar material.

PUDDLE CLAY CORES AND THEIR DEFECTS

Puddle clay can be described as 'natural clay of high plasticity reworked and compacted into place to remove all natural fabric or structure [such as sand layers, fissures etc.] and so is a homogeneous material of low hydraulic conductivity' (Reeves & Cripps, 2006). The purpose of the puddle clay core is to create an impervious barrier through the dam and, more often than not, beneath it, therefore it is keyed into the underlying impermeable bedrock. Typically, an embankment with a puddle clay core is less than 15m in height (although some were built as high as 34m), has an upstream slope of 3h:1v, a downstream slope of 2h or 2.5h:1v, and a narrow central core of puddle clay which is keyed into the underlying bedrock strata through the cut-off trench (BRE, 1999). The core itself was constructed in typically 150 to 200mm thick layers and ranges in width (BRE, 1999).

Typically, the clay that was used for the core depended on the materials available close to the dam, with local borrow pits within the reservoir footprint itself often used. In some cases, the as-dug material was used and, in other cases, materials were mixed, again typically with other local materials. In London, the cores are typically formed of reworked London Clay Formation.

Freshly laid puddle clay has the consistency of very soft clay (colloquially likened to toothpaste) and an undrained shear strength of around 8 to 10kPa. It is noted though that the consistency and undrained shear strength will generally increase with time due to settlement and a reduction in water content. Long term undrained shear strength in excess of 20kPa is typical (Reeves & Cripps, 2006). The water content of puddle clays derived from London Clay Formation is generally between 40 and 50%; water contents less or more than this may be a sign of defects within the core. Defects within the puddle clay core may occur due to a variety of factors, including:

- Construction methodology: Potential contamination of the core from poor construction practices, such as the use of timber shoring, may create voiding enabling seepage pathways.
- Construction methodology: The installation of pipes or culverts may lead to a 'cold joint' between the core and the structure which may create a seepage pathway.
- Construction methodology: Differential settlement following construction may cause fracturing (or 'cracking') of the core and develop associated seepage pathways.

- Drawdown of the reservoir: Desiccation of the core during a period of prolonged drawdown (as ensued occurred World War Two) may ensue, leading to fracturing (or 'cracking') of the core with development of associated seepage pathways.
- Vegetation: Tree roots which penetrate the core may cause desiccation of the clay leading to fracturing (or 'cracking') of shrink-swell prone clay cores and creating associated seepage pathways.

Once defects enabling seepage pathways occur in the core, the bulk permeability increases and effectiveness of the core decreases exponentially. Furthermore, the physical movement of water through the seepage pathways, or the chemical weathering associated with it, may cause the fractures or voids to increase in size, join up and potentially cause a failure of the dam. This is the worst case, however Charles (1989) notes that the rate of seepage through a core is generally small and therefore chemical weathering is limited.

GROUND INVESTIGATION THROUGH PUDDLE CLAY CORES – INDUSTRY REQUIREMENTS AND BEST PRACTICE

In order to adequately and efficiently inform the design of the defect remediation, and where possible, investigate the cause and extent of the defects, ground investigation will be required to be undertaken. The nature and extent of the defect may be investigated through the use of non-intrusive methods, i.e. geophysics, but to obtain geotechnical parameters for use in design, intrusive investigation through the use of boreholes and cone penetration testing is often the best course.

It is imperative that the integrity of the dam is safeguarded during any intrusive GI in order to reduce the risk of puncturing the reservoir core and enabling dam failure. Therefore, various organisations (most notably the BRE in the United Kingdom) have provided industry best practice and guidance associated with this activity. Recommendations that are relevant for undertaking GI though puddle clay cores are summarised below. It is noted however that although the information provided below is 'best practice' there may be situations where the recommendations below may not be applicable and alternative methods may be required. BS 5930:2015 'Code of Practice for Ground Investigations', as well as the 'International Levee Handbook' (CIRIA, 2013) provide useful summaries of intrusive and non-intrusive techniques.

Experience

BRE (1996) notes that it is essential that GIs are carried out under the supervision of a geotechnical specialist (i.e. engineering geologist or geotechnical engineer) acting for the client, who is experienced in investigations through dams. This specialist can then ensure the clients objectives are met, including ensuring the safety of the dam is not impaired by the investigation; and confirming that the standard of work is as expected and that the required technical information is gained from the investigation. The Federal Energy Regulatory Commission Division of Dam Safety and Inspections (FERC) (2016) builds upon this and provides recommendations for the minimum qualifications required for the client's specialist, noting that the specialist should be qualified by a combination of education, training, and experience. FERC (2016) also recommends that borehole/drill rig operators must have a minimum of five years of experience in undertaking boreholes and be able to demonstrate clearly on their CV that they have embankment dam experience.

Managing Risks for Dams and Reservoirs

Intrusive Works

Vertical boreholes are a common method of investigation through puddle clay cores; the verticality of the borehole must be monitored throughout advancement to reduce the risk of deflection and the possibility of puncturing the core, which can have serious consequences with regards to dam stability (BRE, 1996).

Rotary drilling using air flush should be used with extreme caution and is not advised in or near to a narrow puddle clay core as high air pressure may be inadvertently generated which may fracture the core (BRE, 1996); it is also the author's opinion that the logistics associated with flush disposal may also make this method unachievable on an embankment dam.

FERC (2016) suggests that cable percussion (or tool) boring is the preferred method of boreholes through embankment dams as it does not need to use any lubrication in the form of air mist or water and therefore has a low potential of causing fracturing. In smaller height embankments, windowless sampling methods may also be suitable. Keeping the general stability of the dam should be the primary concern of the works; with this in mind, the ability of the crest to support heavy plant should be reviewed beforehand (BRE, 1996), especially when undertaking works through the core itself given its low strength properties. This may also include plant or methods of investigation with high vibration. Cable percussion and windowless sample rigs have a light structure and are low vibration techniques so fulfil this requirement well.

Earth pressure can squeeze puddle clay into an uncased borehole, therefore it is required that all boreholes are cased; furthermore, this provides additional stability reducing the risk of hole enlargement and possibly dam collapse. Note though, even where a borehole is cased below a critical depth, usually about 20m, puddle clay can squeeze into the base of the cased borehole. To control this squeeze, the borehole may be supported by filling with water; note though that if the support pressure (i.e. the water in the borehole) is too high, then hydraulic fracture may be induced – it is therefore recommended not to exceed the height of the reservoir water. Note also that when a borehole contains water, the recovered material can be highly disturbed, so care needs to be taken in interpretation and testing (BRE, 1996).

Cone Penetrometer Tests (CPTs) are another commonly adopted technique due to the quick nature and low impact to the dam integrity; casing and maintaining a water head is not required with this method and it also has low vibration. It is also able to provide a near-continuous vertical profile of the soil (but is unlikely to identify specific defects) and can be used to derive a number of geotechnical parameters.

The main risk with CPTs is that they are typically truck or lorry mounted, but may be tracked, and exert pressure on to the ground through stabilisers in order to push the cone rods through the underlying stratum and undertake the test. This pressure on the dam may have significant consequences on the local stability of the dam (BRE, 1996). The pressure of the CPT plant is associated with the capacity of the equipment and its ability to penetrate through various stratum and associated stiffnesses. The equipment capacity needs to be sufficient for the ground conditions being investigated to ensure the required information is obtained. That being said, if there are restrictions on the pressure of the plant, then the required capacity of the CPT equipment may not be reached and the required information not gained.

Reinstatement

Following the completion of the GI, properly designed and carefully executed reinstatement of the ground is important to avoid changes in strength or voiding within the core and to maintain the global integrity of the dam (BRE, 1996). Reeves and Cripps (2006) recommend backfill in puddle clay cores to be approximately 20% solids (bentonite grout) but generally the backfill should mimic or be more permeable than the surrounding ground. Note that stiffer backfill in the form of bentonite pellets may be more suitable for the London Clay Formation bedrock portion of the borehole. Backfilling should be undertaken using a tremie pipe from the base of the borehole to avoid the formation of voids and the subsequent creation of preferential seepage paths (FERC, 2016).

CASE STUDIES

Introduction

Thames Water routinely undertakes geophysical surveys on their reservoir embankments, including Island Barn Reservoir and King George V (KGV) Reservoir. The results of such surveys at both reservoirs highlighted areas within the dams where seepage was likely to be occurring and thus required remediation. It is noted that neither of these reservoirs showed external signs of leakage, such as ponding, hydrophilic vegetation or slope movement, so the geophysical survey identified the seepage at the sites before surface expression occurred. Typically, the seepage was believed to be occurring at the interface between the puddle clay core and the underlying London Clay Formation – this is a common occurrence and has been cited in a number of historical case studies for London-based reservoirs.

Recommendations from the geophysical survey contractor was for the identified areas of seepage to be remediated as per timescales provided within Thames Water's internal risk assessments. It was decided by Thames Water and the appointed Qualified Civil Engineer (QCE) that undertaking remediation directly, as opposed to taking the time to investigate and confirm the seepage pathways, was the preferred way forward. Furthermore, it was deemed unlikely by the Designer that clear evidence of the seepage would be observed during an investigative GI, particularly where a balanced head is being maintained which may reduce the quality of cores and samples from boreholes.

It was therefore requested by Thames Water that a review of possible remediation options be undertaken; and it was decided by the Designer and agreed by Thames Water and the QCE that, for these reservoirs, remediation would comprise the installation of sheet pile cut-off walls through the puddle clay core of the embankments and into the underlying London Clay Formation bedrock. It was agreed that this method would meet the dam safety, effectiveness, buildability, cost, maintenance, and environmental requirements of the schemes (Rettura *et al.*, 2018). In order to suitably design the remediation options and the associated enabling works, GIs were undertaken at each of the sites. The aims of the GIs were to confirm the dimensions of the core, identify the top of the London Clay Formation, confirm the construction of the embankments (by comparing the results against as-built drawings), and to provide geotechnical parameters for use in sheet pile design.

For both projects, Thames Water was the Client and Principal Designer who engaged AtkinsRéalis (previously Atkins Ltd.) as Designer for both schemes; as part of this role AtkinsRéalis designed and supervised the GI's, meeting the Client's and reservoir safety requirements. Following this, AtkinsRéalis also undertook remedial design work and supervised the installation of the sheet pile cut-off walls.

To manage the health and safety of the projects, Thames Water employed the same QCE to cover both projects; the QCE directly inputted in to and reviewed the scope of the GI, to ensure reservoir safety was protected, and provided support during the investigations.

The Principal Contractors were Costain Group (Costain) at Island Barn Reservoir and MWH Treatment (MHWT) at KGV. The Principal Contractor's role was to manage the safety of the site activities, including having an action plan in place in case any stability issues arose.

Industry guidance notes the importance of utilising a GI Contractor who has a good level of experience of undertaking works in dams and, although not explicitly stated, it is inferred that having prior experience in GI through puddle clay cores is a necessity. For Island Barn Reservoir, tenders were sent out to Thames Water approved suppliers requesting this level of experience, but the project team were unable to find a contractor that met this criterion in full. Instead, all parties of the project agreed that selecting a specialist GI contractor that demonstrated suitable years' experience on Thames Water sites as a whole was acceptable, providing they were closely monitored by the Designer's on-site supervisor. The supervisor, with the support of the QCE, had a clear understanding of the issues associated with GI through puddle clay cores and the controls needed to be in palace to mitigate risks associated with the limited experience of the available GI contractors. The same GI contractor was employed at KGV due to the experience they gained at Island Barn.

It is noted that the following case studies focus on the exploration of the puddle clay core only. Further GI's were undertaken at both sites to support ancillary works and assessment of slope stability, but these aspects are not the subject of this paper.

Island Barn Reservoir

Island Barn Reservoir is a 0.5km^2 reservoir located in East Molesey, Surrey. The height of the embankment dam is between 6 and 8m and has a crest width of typically 4.6m, with a 2.5h:1v slope on the landward side (downstream) and a 3h:1v reducing to 4h:1v slope on the reservoir side (upstream).

Despite opening in 1911, good as-built drawings showing the dimensions of the core with widths and heights were available. The drawings showed the puddle clay core to be 1.5m wide at the top of the embankment, widening to approximately 2.7m at the base of the embankment. The puddle clay core was indicated to extend thr ough the natural superficial deposits (Kempton Park Gravel Member (local river terrace deposits), and Alluvium) and keyed by 0.9m into the underlying "sound London Clay". Below the original ground level, the core was shown to be approximately 1.8m wide thinning to 0.9m at the base.

In 2016, the Designer designed a GI in order to corroborate the as-built drawings and to obtain relevant geotechnical information – most importantly the stiffness of the underlying London Clay Formation, as the Giken Silent-Piler was to be employed to install the piles. At the time of the works, this type of hydraulic push piler was only suitable for installing piles in ground with an undrained stiffness of approximately 100 kPa. The puddle clay was expected to have a low strength which would have been sufficient for the piler, but the London Clay Formation could have had a strength in excess of 100 kPa.

Boreholes were undertaken at three locations around the reservoir which were identified as leaking from the geophysical survey. The investigation included seven 150mm diameter, fully cased cable percussion boreholes (Figure 1) which were undertaken through the core to depths of up to 24.5m below ground level (bgl).

In advance of undertaking the boreholes at the top of the embankment, hand-dug inspection pits were undertaken to the top of the puddle clay core to identify the depth of the core and confirm the absence of services; two additional inspection pits were also dug on either side of the initial pit to determine the edges, and confirm the width, of the core. This would inform the positioning of both the boreholes and the cut-off wall through the centre of the core – this was imperative to confirm the thickness of the core and to avoid pushing through it.

During the drilling of the boreholes through the core, a balanced head of water was always maintained just below the reservoir level. This is more cautious that the approach given in BRE (1996) and was undertaken in order to: to reduce the risk of squeezing of the puddle clay at the base of the casing (typically being required for holes deeper than 20m); and to reflect that the borehole may intercept the leak and thus balance water pressures would prevent a sudden surge). This was deemed to be a safer method of working, as agreed with the QCE.

As casing was installed for boreholes through and adjacent to the core, the inclination of each section was monitored using a spirit level as it was pushed into the ground, to reduce the risk of the borehole tilting and puncturing the core below ground. Standard penetration tests (SPTs) were also undertaken at 1m intervals to 10m bgl, then every 1.5m. Further *in situ* and laboratory geotechnical testing was also undertaken.

The embankment and reservoir water level were monitored throughout each day by the Designer's site representative, in order to identify any anomalies associated with dam instability or leakage. None was observed during the works.

Figure 1. Cable percussion borehole through Island Barn embankment dam.

The GI corroborated the information provided in as-built drawings. The crest of the embankment was between 4.6m and 4.9m wide; the top of the puddle clay core was between 0.8 and 1.1m deep and between 1.2m and 1.5m wide. The puddle clay was found to be generally 'soft' with an undrained shear strength of typically 20kPa. The London Clay

Formation was found to be ‘firm to very stiff’ with stiffness and undrained shear strength increasing with depth (typically 57+6z kPa (where z is top of the stratum)). This is in line with industry expectations and meant a cost-effective sheet pile solution could be undertaken. Whilst the shear strength of the puddle clay was as expected, the water content was slightly lower than anticipated (at 19 to 44% as opposed to published values of 40 to 50%). Given the results of the lab testing and *in situ* testing, it was considered that the need to maintain a balanced water head in the holes did not affect the *in situ* nature of the materials.

To conclude, at Island Barn Reservoir, the work was completed with no issues reported with regards to quality of geotechnical results and dam safety. The parameters for the puddle clay obtained during the GI generally matched those provided in published literature, as did that of the London Clay Formation, allowing for the subsequent successful installation of three sheet pile cut-off walls using a Giken Silent-Piler. The success of the investigation was attributed to a number of factors including: preparation of strong scoping and works information documents which took into consideration best practice for safely investigating puddle cores in reservoir dams; the over-sight and advice provided by the QCE; the use of competent drillers and engineering geologists who took care to understand the associated risks; and supervision of the GI by the Designer.

King George V Reservoir

KGV is located in Enfield and is part of the Lee Valley Reservoir Chain. KGV is the largest reservoir in London with an embankment dam of over 6.5km long. Due to its size, the reservoir has been split into two cells, the ‘northern cell’, and the ‘southern cell’ which is separated by a windbreak embankment running east to west across the centre of the reservoir.

The height of the embankment is around 9.4m from the toe to the crest, and the width of the crest varies across the site from 3.5 to 5.0m. The gradient of the downstream slope of the embankment dam is approximately 2.5h:1v and the upstream slope is 3h:1v at the wave wall and 4h:1v towards the toe.

Historical drawings provided by Thames Water presented the Puddle Clay core as being 1.5m wide at the top of the embankment, widening to approximately 2.7m at the base of the embankment. The core was indicated to extend through the natural superficial deposits and is keyed by 0.9m (300mm) into the underlying ‘sound London Clay’. Below the original ground level, the core is shown to be approximately 1.8m wide thinning to 0.9m at the base.

The geophysical survey procured by Thames Water showed that the dam was leaking through its foundation at a localised section of the northern cell. By comparison to historical drawings, it was determined that the leak coincided with the original path of the River Lea which was diverted northwards during the construction of the reservoir in 1912 (Figure 2).

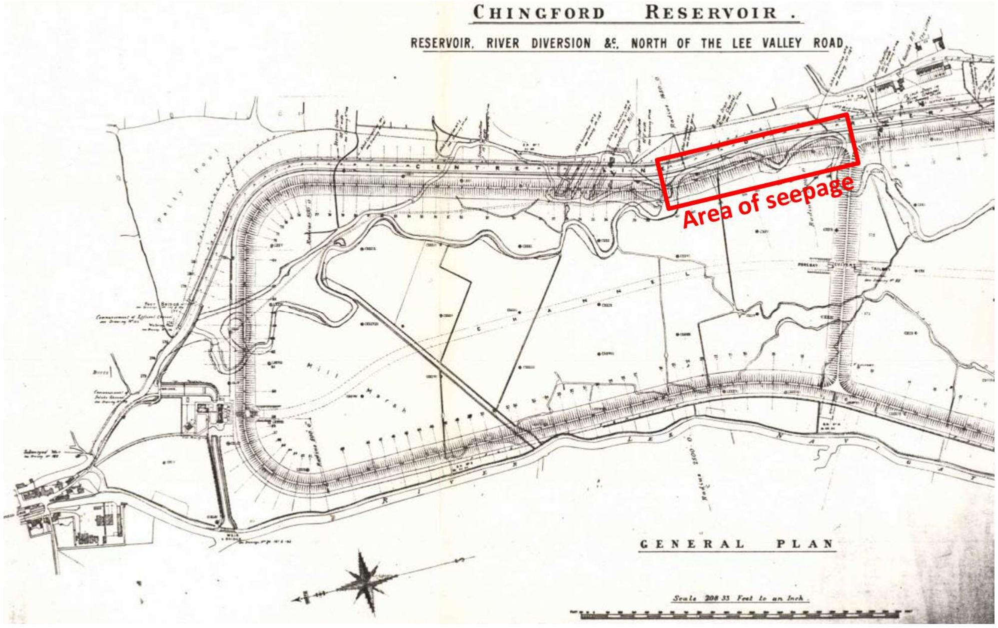

Figure 2. Historical plan of KGV.

A number of historical GIs had been undertaken on the site prior to the Designer's involvement (in 2021), which corroborated the as-built drawings. Following the recommendations in the geophysical survey report to remediate the seepage, the Designer designed a limited GI to confirm relevant geotechnical information to support the use of the Giken Silent-Piler to install a sheet pile cut-off. Two 150mm diameter fully cased cable percussion boreholes (to depths of 20m) were scheduled.

Following the success of Island Barn Reservoir GI, whilst a different Principal Contractor was involved, the same GI contractor was appointed to undertake the works at KGV (Figure 3).

Figure 3. Cable percussion borehole through KGV embankment dam (provided by MWHT).

During the drilling of the first borehole through the core, the driller did not maintain a balanced head of water and this was not identified by the Designer's representative on-site. Significant water ingress was encountered at approximately 15m bgl, a depth roughly consistent with the base of the puddle clay core (Figure 4); this water was under pressure (suggesting it likely came from the reservoir itself as opposed to natural groundwater) and rose up the borehole at a significant rate. The representative on site informed the named Investigation Supervisor who instructed for the hole to be plugged immediately to stop further ingress (also informing the Principal Contractor, the Client and the QCE.)

The base of the hole was plugged using bentonite pellets. The remainder of the hole was backfilled using a bentonite/cement mix slightly thicker than the puddle clay consistency (in order to displace the water in the borehole). For the duration of the remaining works, the borehole was monitored for any evidence that water ingress had continued – no further ingress or other issues with this hole were recorded and therefore no further action was called for by the QCE.

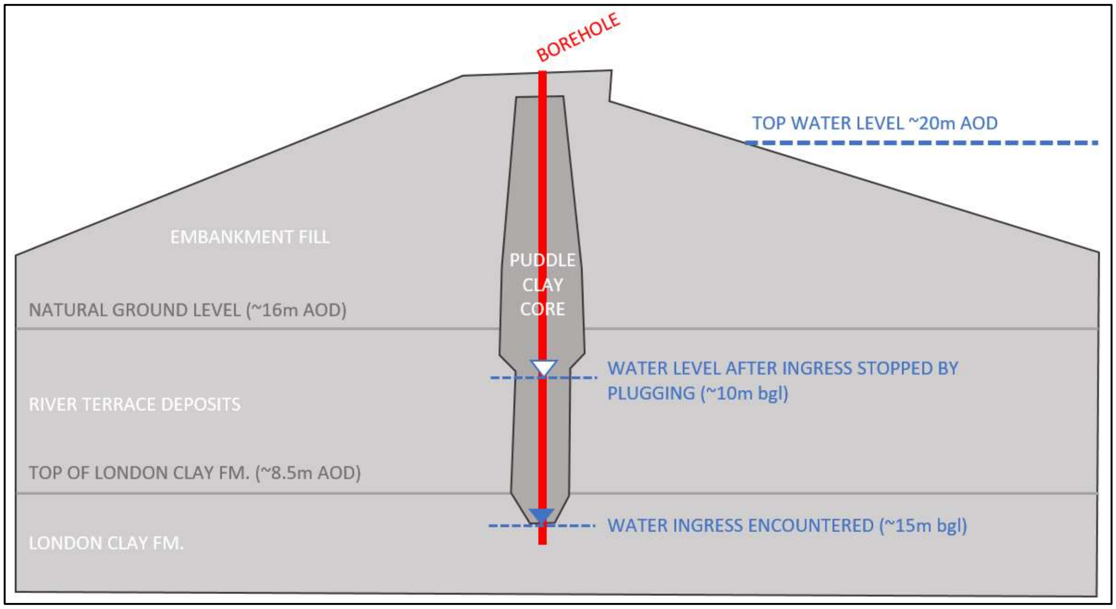

Figure 4. Schematic cross-section of the KGV embankment dam and water ingress incident.

A subsequent investigation into the cause of the incident found that, whilst the same GI contractor was engaged, a different drilling team (from that which undertook the works at Island Barn) was employed due to availability. It had been assumed that the new team had been suitably briefed regarding the specification for the works and the need to maintain a balanced head for dam safety but it had not. Furthermore, the methodology for undertaking the borehole was changed by the GI contractor without notifying the Designer or the QCE (and this was also missed by the Designer's site representative).

Following the incident, the GI contractor was not confident in their own ability to safely continue with the second borehole, even if the original methodology (successful at Island Barn) was followed. In order to limit delays to the programme (relating to demobilisation and procurement of an alternative GI contractor), an open discussion between all parties was arranged. It was agreed that changing the remaining borehole to a static piezocone CPT was suitable (given the available historical GI data) and was suitably low risk for the GI contractor.

The CPT was undertaken using a 3.5 tonne track mounted CPT rig, progressing from the base of a hand-dug inspection pit to 14.82m bgl (approximately 1m into the London Clay Formation). During penetration, the CPT rig was also able to monitor the inclination of the probe to manage the risk of pushing out of the core.

The full depth of 20m was not reached due to the restrictions on pressure on the embankment dam; this was a known and accepted risk (again there was sufficient historical and published information to produce a reasonable design).

The results of the GI generally confirmed the ground conditions expected as per the as-built drawings and historical GI – the crest of the embankment was between 3.3 and 5.1m wide; the top of the puddle clay core was between 0.8m and 0.9m deep and was around 1.65m wide. The puddle clay was found to be generally 'soft' with an undrained shear strength of typically 45kPa which is slightly higher than would be expected based on published values. The water content of the puddle clay was also higher than expected (52% to 75% as opposed to published values of 40% to 50%.

With regards to the London Clay Formation, in the limited GI undertaken, it was found to be 'stiff' with a maximum undrained shear strength of 214kPa. To combat this stiffness, an allowance for lubrication during the installation of the sheet piles was included (although during the installation of the piles, lubrication was not required).

Lastly, with regards to the old course of the River Lea, no evidence of this feature was gained due to the limited depth of the GI. Undertaking another borehole (rather that CPT) may have yielded the required evidence of the presence of the relict river channel, but this information was not essential to the development of the design for a sheet pile cut-off.

In summary, for the KGV Reservoir project, best practice was again scoped but was not fully undertaken, therefore water ingress within the borehole occurred. This could have caused significant embankment stability issues had the borehole not been cased and, whilst instigating the issue, the drillers were sufficiently competent to facilitate backfilling. Furthermore, the need for maintaining a constant balanced water head within the hole was proven as not just being important for stopping puddle clay from 'squeezing' up the base of the hole, but would have reduced the risk of pressurised water ingress.

Through collaboration between all parties, suitable alternative methods were adopted providing a reasonably good set of geotechnical results for sheet pile design; the drawback was the lack of results for the London Clay Formation, resulting in the reliance on published values and slightly conservative design.

The most important lesson to be learnt from this investigation is that, even if the GI contractor (as a company) is experienced in undertaking this specialised type of GI, it cannot be assumed that drilling crew will have had that experience. It is therefore important to ensure all site personnel are fully briefed on the requirements and sensitivity of the GI (with the site supervisor from the client/designer side being constantly alert to changes in approach which may affect safety).

CONCLUSION

Best practice guidance with regards to undertaking ground investigation through puddle clay cores while maintaining dam safety is generally good, and can be summarised as follows:

Managing Risks for Dams and Reservoirs

- It is essential that GIs are carried out under the supervision of a geotechnical specialist and that those undertaking the works are suitably experienced.
- Vertical, low-vibration percussive boreholes are the preferred method, however these need to be fully cased and, where required, a balanced water head below the reservoir water level maintained.
- CPTs are also recommended and provide a wide range of geotechnical parameters, but the ability of the dam to support heavy plant should be reviewed beforehand and the consequence of not obtaining suitable bedrock information risk-assessed.

Experience from the projects discussed in this paper show that best practice must be recognised, communicated and followed in order for geotechnical information to be gained whilst maintaining reservoir safety. The experience of the drillers and engineers must be taken into account together with that of the client/designer representative. The transfer of knowledge between these teams, both on the contractor and the design side, is imperative for the successful and safe completion of ground investigations through puddle clay cores.

There are situations where on-site geotechnical information must be sacrificed in order to ensure safety. In these cases, as-built information and published literature may be used but under the direction of a suitably qualified engineering geologist or geotechnical engineer.

Lastly, as evidenced from the case studies presented in this paper, when investigating leaks it is necessary to maintain a head of water in line with the reservoir level rather than starting to maintain a balanced head once the boreholes have exceeded approximately 20m bgl (and thus only being applicable for embankments over 20m in height) as per BRE (1996). This is because the recommendations in BRE (1996) largely refer to squeezing of the puddle clay, but do not account for any seepage or leakage pathways which may cause rapid water ingress into the borehole, as observed at KGV. Maintaining a balanced head earlier on in the advancement of the hole would reduce the risk of the significant water ingress and its associated risks.

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