Highways England: A303 Amesbury to Berwick Down Project, Development Consent Order Application

Scheme Reference: TR010025

Comments on Written Representations and Additional Submissions to Examining Authority

submitted by Deadline 2

Prepared for

The Stonehenge Alliance (Reference No. 2001870)

by Dr. Simon Temple, Dr. Kate Fielden

and Dr. George Reeves

Stonehenge Alliance Comments on Written Representations and Additional Submissions submitted by Deadline 2

1. Introduction

1.1 This document contains comments on Written Representations submitted by Deadline 2, relating to:

- Cultural Heritage; and
- Traffic and Transport (general transport planning and economics);

and Additional Submissions submitted by Deadline 2 relating to

- Flood risk, groundwater protection, geology and land contamination.

1.2. The name of the person commenting on behalf of the Stonehenge Alliance (SA) is given in each instance.

2. Cultural Heritage: Historic England/HBMCE Written Representation

(Document ref. REP2-100)

2.1. *Response to Written Representation REP2-100, specifically on the subject of Outstanding Universal Value (OUV)*

Comment by Kate Fielden for SA

2.1.1. The Stonehenge Alliance notes some confusion concerning **the concept of OUV** in the Written Representation (WR) of Historic England/HBMCE, REP2-100, pp. 48–49. We refer to the concept of OUV in our own WR on Heritage and the Historic Environment (REP2-136, Section 1.2) which should, please, be read in conjunction with our views expressed here.

2.1.2. Para 5.7.1. of REP2-100 comes under the heading “Outstanding Universal Value and attributes”. It is, perhaps a typographical error that outstanding universal values are referred to in the plural in this paragraph, since OUV is normally referred to in the singular. We agree with Historic England/HBMCE that “*Understanding OUV . . . is central to the consideration of any proposed developments that have the potential to impact on it.”*

2.1.3. It should be emphasized that features outside the WHS may be relevant to or associated with the OUV of the WHS but they are not attributes of OUV and the WHS is of OUV without their inclusion.

2.1.4. Para. 5.7.3 of REP2-100 states that OUV is comprised of three “pillars”:

- Meeting the criteria (WHC.17/01 para, 77);
- Authenticity and Integrity (WHC.17/01 para. 79-95); and
- Protection and Management (WHC.17/01 para. 96-119).

2.1.5. Common sense dictates that this is an impractical suggestion. UNESCO's *Operational Guidelines for the implementation of the WH Convention* to which these three "pillars" are referenced (http://whc.unesco.org/en/guidelines/), set out procedures for the inscription of WH properties, their protection and conservation, and the granting of international assistance and mobilization of international support if needed (*ibid.,* Introduction, Section 1A). The *Guidelines* indicate that the three "pillars" are, in fact, *requirements* or *conditions* that must be in place for a WHS to be nominated and accepted for designation and for that designation to be maintained.

2.1.6. In response to what is said in para. 5.7.4. of REP2-100, we suggest the criteria for OUV are not the same as the second requirement(s) for inscription (authenticity and integrity) which might be said to validate OUV, or the third requirement(s) of protection and management which should sustain it. All three requirements must be present nowadays *for a WHS to be designated*. Adequate measures of authenticity and/or integrity are closely associated with the criteria for OUV but protection and management cannot sensibly be included within the *concept* of OUV; nor do we find any indication in UNESCO documentation that UNESCO "regards protection and management as an integral part of OUV itself."

2.1.7. It is clear that there are WHS properties which do not have an adequate management system and protection regime but they retain their WHS designation and OUV unless or until the WH Committee de-Lists them. Liverpool Maritime Mercantile City, for example, is on the List of WH in Danger and threatened with de-Listing owing to current failure of its protection regime – but the Site retains its OUV. Deep concerns have been expressed by the WH Committee about other WHSs, including the Palace of Westminster and Stonehenge.

2.2. *Response to Written Representation on the subject of the A303*

Comment by Kate Fielden for SA

2.2.1. Historic England/HBMCE, at REP2-100, para. 5.7.7, refer to the impact of the A303 on the WHS in the SoOUV, under the provisions for protection and management. Adverse impact of the A303 is mentioned in a number of other places in REP2-100, for example:

> "*The A303 continues to have a detrimental impact on the integrity of the SAAS WHS, effectively cutting the southern part into two and also has a detrimental visual and aural impact. Whilst its presence did not prevent the SAAS WHS inscription, its removal remains an important opportunity for enhancement*." (p.23, para. 4.7)

> "*HBMCE agrees that the existing A303 has an adverse effect in respect of all 7 Attributes, in addition to the Integrity and Authenticity of OUV*." (p.62, para. 6.10.17)
>
> "*HBMCE considers that the Scheme offers a once in a generation opportunity to address the harm currently being caused to the Attributes, Integrity and Authenticity of the internationally important SAAS WHS by the presence of the existing A303*." (p.131, para. 8.10)

2.2.2. HBMCE also refers to the current impact of the A303 in its SoCG with Highways England:

> "*HBMCE states that the existing A303 trunk road has a substantial adverse impact on the Outstanding Universal Value (OUV) of the WHS and they accept the need to improve the road between Amesbury and Berwick Down*." (REP2-013, Table on p.9)

2.2.3. The National Trust, in its WR makes similar comments about the A303, e.g.,

> "*Currently, the busy A303 road cuts through the WHS, having a major adverse impact on its OUV, monument settings, and tranquility*" (REP2-115, p.5, para. 4.1.1)

2.2.4. The Stonehenge Alliance refers, in our WR on Heritage and the Historic Environment (REP2-136), section 1.3.4.1, to other such statements about the A303 made by Highways England in the DCO application: we ask that that section of our WR is considered along with our comments made here. We point out that the WHS was designated of OUV in 1986 with the A303 in place when no specific mention was made of it creating an adverse impact on the Site or its OUV. There has been no development of the A303 since then – only in the amount of traffic on it. We see no justification for saying that the A303 has a substantial adverse impact on the OUV of the WHS.

2.2.5. We have the following additional comments to make, on statements made by Historic England/HBMCE in REP2-100, concerning the A303.

2.2.6. The volume of traffic on the A303 makes it dangerous at times to cross to the south of the A303, where public byway access is possible. It appears that almost all the land south of the A303 is unlikely to be open access in future. If crossing the road were a serious concern, it could be addressed with a footbridge or pedestrian crossing.

2.2.7. The sweeping statement that "the A303 affects all seven attributes of OUV" is evidently incorrect. It should also be borne in mind that the presence of the A303 has enabled artists, writers and many others to experience and enjoy the OUV of the WHS. Again, the problem is not the A303 but the traffic.

2.2.8. A generation is around 25-30 years. Around half a generation ago (in 2004) a 'once in a generation' 2.1km bored tunnel scheme considered by English Heritage (now Historic England) to be 'the best we can get' was proposed for the A303 at Stonehenge. The scheme was abandoned owing to unforeseen costs. Could a tunnel longer than c.3km be proposed within a generation?

2.2.9. Historic England/HBMCE suggest that the A303 is not only harmful to all seven attributes of OUV but also the "Integrity and Authenticity of OUV". This goes well beyond what is agreed in the WHS management Plan and in the SoOUV.

2.2.10. In respect of "Authenticity" of WHSs,

> *"The ability to understand the value attributed to the heritage depends on the degree to which information sources about this value may be understood as credible or truthful. Knowledge and understanding of these sources of information, in relation to original and subsequent characteristics of the cultural heritage, and their meaning as accumulated over time, are the requisite bases for assessing all aspects of authenticity."*
> (UNESCO*, Operational Guidelines for the implementation of the World Heritage Convention*, 2017, para.88. http://whc.unesco.org/en/guidelines/)

There is no suggestion in the Management Plan or SoOUV that the A303 affects the authenticity of those elements that contribute to the OUV of the WHS or the information sources that provide confidence in their authenticity. (See *WHS Management Plan*, p.28. http://www.stonehengeandaveburywhs.org/assets/2015-MANAGEMENT-PLAN_LOW- RES.pdf)

2.2.11. "Integrity" is described by UNESCO as follows:

> "*Integrity is a measure of the wholeness and intactness of the natural and/or cultural heritage and its attributes. Examining the conditions of integrity, therefore requires assessing the extent to which the property:*
>
> *a) includes all elements necessary to express its Outstanding Universal Value;*
>
> *b) is of adequate size to ensure the complete representation of the features and processes which convey the property's significance;*
>
> *c) suffers from adverse effects of development and/or neglect.*
>
> *This should be presented in a statement of integrity"* (UNESCO, *op. cit.,* para. 88)

2.2.12. A retrospective SoOUV (such as that for the SAAS WHS),

> *" . . . should reflect, the OUV of the property at the date on which it was inscribed on the World Heritage List, based on the decision of the World Heritage Committee at that time, supported by the evaluation undertaken by the Advisory Body and the nomination prepared by the State Party."*

> (ICCROM *et al*., 2010, *Guidance on the preparation of retrospective Statements of Outstanding Universal Value for World Heritage Properties*, p.5 https://www.iucn.org/sites/dev/files/import/downloads/whouven.pdf)

2.2.13. Under "Protection and Management", UNESCO Guidelines say:

> "*Protection and management of World Heritage properties should ensure that their Outstanding Universal Value, including the conditions of integrity and/or authenticity at the time of inscription, are sustained or enhanced over time.*" (UNESCO, *op. cit.*., para. 96).

Historic England/HBMCE agree that "*The condition of the property at the time of inscription together with the SOUV provides the baseline against which the effects of change (positive and negative) can be assessed*." (REP2-100, p.55, para. 6.9.3)

2.2.14. Guidance on authenticity and integrity in compiling an SoOUV states that:

> *"The conditions for integrity and authenticity should be documented at the time of inscription if such assessments were undertaken and if they are still relevant today. Where neither was specifically assessed at the time of inscription (and this will be the case for the integrity of cultural properties inscribed before 2005) or where vulnerabilities associated with integrity and/or authenticity are now known (such as through State of Conservation Reports or the World Heritage Committee), then the conditions should be assessed as of the date of the draft Statement*." (ICCROM *et al., op. cit.,* p. 8)

2.2.15. The conditions of authenticity and integrity for the SAAS WHS were effectively provided in summary form in the 1986 Nomination Document. At that time, the A303 was not considered to be detrimental to the WHS and there has been no development or change to the road since then, apart from reconfiguration of Longbarrow Roundabout in 2013 and removal of the A344 junction (neither achieved by the date of the SoOUV). It is for this reason that considerable care was taken in drafting the retrospective SoOUV for the WHS in order not to introduce changes to the description of the Site at designation.

2.2.16. In terms of the roads at Stonehenge, the 1986 Nomination Document describes the situation at designation, under the heading "State of preservation/conservation", as follows:

> "*Future work will involve the conservation of the surrounding landscape and monuments, and the re-routing of road, paths, the provision of car-parks, shops, etc*." and *"Existing arrangements which include a car park, light refreshment and toilets, explanatory notices and guidebooks are currently under intensive review and it is hoped to produce major improvements within the next few years."* (HBMCE for the DoE, WHS Nomination Document, n.d. [1986]).

"Rerouting of road" is understood to mean the A344 which has now been partially removed and stopped up (2013).

2.2.17. The Statement of Integrity in the (retrospective) SoOUV is as follows:

> *"The presence of busy main roads going through the World Heritage property impacts adversely on its integrity. The roads sever the relationship between Stonehenge and its surrounding monuments, notably the A344 which separates the Stone Circle from the Avenue. At Avebury, roads cut through some key monuments including the Henge and the West Kennet Avenue. The A4 separates the Sanctuary from its barrow group at Overton Hill. Roads and vehicles also cause damage to the fabric of some monuments while traffic noise and visual intrusion have a negative impact on their settings. The incremental impact of highway-related clutter needs to be carefully managed.* (WHS Management Plan, p. 27.

http://www.stonehengeandaveburywhs.org/assets/2015-MANAGEMENT-PLAN_LOW-RES.pdf)

Thus, the retrospective SoOUV is careful not to be too prescriptive in its description of the Integrity of the WHS, mentioning nothing not already present at the time of inscription. The 'busy main roads' may now be busier than in 1986 but their physical presence in the WHS has not changed, except for the change to the A344 proposed in the Nomination Document. Thus the 'adverse effects of development or neglect' which must be recorded in a Statement of Integrity could only be related to increased traffic (and archaeological damage by vehicles) in respect of the roads: issues which could be dealt with – and not necessarily by removal or part-removal of roads.

3. Devon County Council Written Representation

(Document Reference: REP2-085 [TR010025-000697])

Comment by Simon Temple for SA

3.1 *Stonehenge Alliance comment:* Devon County Council set out similar arguments for the full A303/A358 Corridor programme to those of the Heart of the South West Local Economic Partnership. They note that "the delivery of the A303 Amesbury to Berwick Down scheme alone will not solve the connectivity issues between the South West and South East". Once again, this emphasises the importance of understanding the overall impacts of the corridor programme, before any consent is given for this project.

3.2 Devon County Council refer to the alleged wider economic benefits of the project, based on the 2013 Parsons Brinckerhoff "A303 A358 A30: Corridor Improvement Programme: Economic Impact Study". As we showed in our Written Representation on Transport Planning and Economics Issues (REP2- 129, paragraph 3.7.2) there are serious methodological problems with this work, which means that the results are biased and unreliable. Parsons Brinckerhoff have now re-analysed their data in a refresh of the study, completed in January 2019. This used data from the original survey on the impact of the A303/ A358 programme on the turnover of respondents' businesses and then expanded this to make an overall estimate that the full programme would generate £40 billion of economic benefits. In addition to the issues highlighted in our Written Representation, this estimate is dependent on respondents (a) being able to accurately assess the impact on their business and (b) providing unbiased answers. Clearly transport access is only one factor affecting turnover and the A303/A358 programme is only one aspect of this, so it would be very hard for any business to assess its impact reliably, particularly in the context of a short business survey. There is also a severe risk of policy response bias, where respondents exaggerate the impact to achieve the outcome they desire, especially given that the entire survey was about the corridor programme.

4. Highways England Updated Funding Statement

(Document Reference: REP2-005 [TR010025-000772-4.2] Funding Statement (Rev 1))

Comment by Simon Temple for SA

4.1 This document purports to show that £1.7 billion is available to fund the project, so that it could proceed without delay if approved. However it contains an important caveat that means that this cannot be relied on. In paragraph 3.1.9, Highways England quote paragraph 5 of the latest Budget Statement as follows "The government is still committed to pursuing these projects [A303 and Lower Thames Crossing], subject to scrutiny of the relevant business cases which are still in development." As we argued in our Written Representation on Transport Planning and Economics issues, the business case for this project is very weak and subject to significant uncertainty, therefore there must be considerable uncertainty about the availability of funding.

5. Highways England Additional Submissions (AS-014–AS-019)

on flood risk, groundwater protection and land contamination, specifically concerning *Rock Quality, Groundwater, and Tunnelling methods (including use of slurry/grouts*); and the *creation of an extensive "Groundwater Dam".*

Comment for SA by Dr. George M Reeves CGeol CEnv PhD MSc BSc FGS FIMMM,
HydroGEOtecH Consultants, Lybster Caithness, Scotland. www.hydrogeotech.co.uk
See Additional Biographic Note at end of text.

Executive Summary

In relation to publication of the reports on groundwater modelling and monitoring by Highways England, included in documents AS-014 to AS-019 submitted on 5th April 2019, the following observations on this work have already been made to the Planning Inspectorate by the Stonehenge Alliance (letter to Richard Price dated 17th April 2019; REP2a-003): *"In the absence of any public availability of the original site investigation reports and data relating to much of the reported 2018 work (specifically, borehole record data on drilling, logging and testing, plus geophysical logging in these 2018 boreholes), it is impossible to consider much of the observations, conclusions and interpretations included in these documents. Indeed the 2018 site investigation reports are not referenced anywhere at all, previous work is incorrectly referenced and attributed, significant appendices are missing (notably from report TR010025-000571) and therefore little independent assessment can be made of any of this work, the reports, their interpretations and conclusions."*

These comments are further discussed in the light of the Environment Agency/Highways England Statement of Common Ground (REP2-012) apparently accepting these reports as a good assessment of groundwater conditions and predictions.

Further details of the Chalk bedrock strength, degree of fracturing, high permeability and rapidity of disintegration, after recovery of cores from a number of boreholes (especially in the phosphatic chalk successions - see Appendix 1) demonstrate that the use of a closed, bentonite-based slurry full-face tunnelling machine (TBM) will be essential, possibly backed up by grout injection from additional boreholes drilled from surface. The principles of such operations, together with details of typical grout additives and the extent of invasion of grout and component additives into surrounding strata can be seen in Appendix 2 (Reeves, Sims and Cripps, 2006: *Clay Materials used in Construction*: Chapter 12 – "Specialised Applications").

Drilling techniques, using the triple-tubed wireline core drilling methods are also discussed. Core drilling methods, developed in 1976 by Soil Mechanics Ltd. for Severn Trent Water Authority's "Nitrates in Groundwater" research project (Lucas and Reeves 1980), have produced the best possible undisturbed and uncontaminated rock core recovery.

With particular reference to rock core drilling methods, Rock Quality Designation (RQD) values, and the integrity of bedrock at Stonehenge (in both 2002/4 and the latest drilling campaign-from 2016 to 2018), as seen in recovered cores (see Appendix 1), the highly fractured nature and poor quality of Chalk bedrock in large sections of the proposed tunnel line can be easily demonstrated, especially if earlier "Off Line" site investigation information is included in a 3 dimensional model of the Stonehenge area.

5.1 Groundwater Reports

5.1.1. The following reports were prepared by Highways England groundwater consultants, the AmW consortium:-

1.TR010025-000574-AS-HEng-Stage 4:-Groundwater monitoring 2018-2019 Conceptual Model Review.pdfHE551506-AmW-EWE-SW-GN-0000-ZZ-RA-WR-0104 (Examination Document AS-019)

2. TR010025-000571-AS-HEng-Stonehenge Area Pumping test 2018 Interpretative Report.pdf. HE551506-AmW-EWE-SW-GN-0000-ZZ-RP-EN-0001-P02 (Examination Document AS-016)

3. TR010025-000572-AS-HEng-Stage 4: Implications of 2018 Ground Investigations to the Groundwater Risk Assessment (Working Draft)HE551506-AmW-EWE-SW-GN-0000-ZZ-RP-EN-0102-P04 (Examination Document AS-017)

4. TR010025-000573-AS-HEng-Stage 4: Supplementary Groundwater Model Runs to Annex 1 Numerical Model Report (Working Draft) HE551506-AmW-EWE-SW-GN-0000-ZZ-RP-EN-0103-P02 (Examination Document AS-018)

5.1.2. These reports, as they currently stand in the Examination document database are incomplete, incorrect in many basic elements, and are far from being any kind of comprehensive and authoritative documentation on groundwater conditions in the Stonehenge area.

The basic data behind all these reports is still not publicly available, nor are included, despite being referenced, in these reports.

These missing data are the original site investigation reports relating to much of the reported 2018 site investigation work (specifically, borehole record data on drilling, logging and testing, groundwater information plus the geophysical logging of these 2018 boreholes).

It is therefore impossible to consider and critically assess much of the observations, conclusions and interpretations in these documents. Therefore, the validity of the Highways England/Environment Agency "Statement of Common Ground" (specifically groundwater related issues) published in the Examination documentation listing on May 7th 2019, can be called into question.

Indeed the 2018 site investigation reports are not included anywhere by Highways England, previous work is incorrectly referenced and attributed, significant appendices are missing (notably from report TR010025-000571) and therefore little independent assessment can be made of any of these reports, their interpretations and conclusions.

5.2. Geotechnical Properties of the Chalk Bedrock (Seaford and Newhaven Formations) along the Proposed Tunnel Line. (with additional reference to the zones of Phosphatic Chalk)

5.2.1. The drilling, logging and testing techniques applied in the earlier (2002 to 2004), and the more recent (2016 to 2018) site investigation (SI) works seem to be generally of the highest quality; particular credit should be given to the extensive use of wireline geophysical logging methods for thorough down-hole investigations.

5.2.2. As outlined above, however, not all the recent basic data has been made publicly available.

It is now evident that poor ground conditions are more extensive, especially where the Phosphatic Chalk is encountered. Rock Quality Designation (RQD) values of less than 20%, and quite commonly less than 10% have been observed and recorded on borehole logs during both drilling campaigns.

(RQD is a means of describing "Good=100% intact core", and "Poor, i.e. highly fractured; 0-10% RQD score", where core is fragmented to lengths of less than 100mm in length).

Wireline recovery 146mm triple tube drilling methods, when properly and consistently applied, can produce high quality core recovery, inside the inner Mylar (rigid plastic) liner tube within the core barrel. Then RQDs can be accurately and consistently reported.
This technique was developed by Soil Mechanics Ltd. in conjunction with Severn Trent Water Authority during 1975 and 1976 in the STWA "Nitrates in Groundwater" Research project in the Sherwood Sandstone aquifer of North Nottinghamshire (Lucas and Reeves, 1980).

5.2.3. From examining the records of Borehole R501, drilled near Chainage 8700 near the centre line of the proposed tunnel in February 2017, a surprising set of core box photographs can be seen (see Appendix 1). The first ones were taken at the rig side shortly after recovery of the cores from the borehole on Tuesday February 28th.

The same core boxes were photographed the following day (on Wednesday March 1st at the works compound) and showed signs of severe deterioration (especially in the Phosphatic Chalk zones).

A further photograph, taken a week later on 9th March, showed extreme disintegration of the cores. The borehole was abandoned at 36.50m depth due to the poor quality of the Phosphatic Chalk.

5.2.4. This remarkable core degradation demonstrates the high degree of weakness in some of the Chalk bedrock along the proposed tunnel line, and defines the tunnelling method that will, of necessity, have to be deployed. This is with the use of a closed, full face, slurry shield TBM using a bentonite (plus lubricating additives) -based formation supporting grout system.

(See Appendix 2: from Chapter 12, "Specialised Applications" - in Reeves, Sims and Cripps, 2006, *Clay Materials used in Construction*: The Geological Society - Special Publication 21).

5.2.5. In constructing a 13m diameter pair of twin tunnels, across a 3km stretch of Chalk aquifer, at right angles across the mainly southerly flow pathways of current groundwater movement, considerable disruption of the natural movement of groundwater is to be expected.
What will be created, if such construction goes ahead, is a massive groundwater cut-off, or "groundwater dam", that will cause the current groundwater flow patterns (generally southwards towards the River Avon) to be profoundly affected.

5.2.6. If grout/slurry take-up calculations are made, it can be argued that possibly up to 50 metres of depth, along the whole 3 kilometre run of the proposed tunnel, from west to east portal could be affected by the creation of a low permeability groundwater diversion feature.
Such conditions are likely to affect existing vulnerable groundwater abstractions, as well as local and regional groundwater resources and groundwater quality, permanently.

5.2.7. The modern approach to assessing such variable geotechnical (and hydrogeological) features over such a large volume of rock is to use a 3-D Ground Model (as extensively documented and described on the British Geological Survey website: https://www.bgs.ac.uk).

Using such an approach (which is now common to complex ground conditions with extensive SI databases) complex changes in rock strength, fracturing and quality, alteration (for example areas of phosphatic chalk), and groundwater flow and chemistry, can all be visualised in a large

3 dimensional volume of rock. (Examples can be seen on the BGS website: Search for "3 D visualisation systems".)

5.2.8. Such approaches have been successfully used in the Elgin area of Moray, Scotland, the Dounreay Site in Caithness, the LLWR site in Cumbria, the Greater Manchester area, London tunnelling projects and Glasgow City areas, amongst many other locations. Such approaches are far more powerful and useful than any number of 2-D sections.

Highways England have categorically denied the usefulness of this approach.
(Mr. D Parody: Letter to Mr. R Price dated 18th April 2019: "*No 3-D model has been produced, as this is not required or necessary for the purposes of EIA or in order to develop the design for the DCO application. Conceptual 2-D ground modelling has been carried out, as per the Preliminary GI Report*" (REP1-017 Highways England Deadline 1 Submission - Response to Stonehenge Alliance).

5.3. Ground Vibrations, Voids Migration and potential Archaeological Damage

5.3.1. In running a 13m diameter closed-face TBM across the Stonehenge section (twice; west to east, then the return, east to west tunnel bores) it is possible that vibration from such activities will be generated upwards towards the ground surface.
No specialised engineering geophysical combined surveys and interpretive techniques are understood to have been applied along the proposed tunnel line to investigate features or void spaces, either shallow or targeted to the proposed tunnel depth.

5.3.2. A thorough investigation, using modern digital combined surface geophysical survey techniques, with 3-D modelling of the combined output (from, inter-alia, Ground Probing Radar, Engineering Seismic Surveys, Electrical Resistivity and E/M, gravity and magnetics surveys) would be a modern, informed approach on such an area of ground, prior to any major project which would involve ground disturbance and especially tunnelling. It is suggested that, in view of the extreme archaeological sensitivity of the Stonehenge landscape, such a survey be considered essential prior to any decision on the DCO application.

Dr. GM Reeves 19.05.19

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Note: The author of this Response would be happy to amplify and discuss any aspects of the above interpretations and opinions.

Appendices

Appendix 1: Borehole R501: Selected Core Box Photographs: from Structural Soils SI Report to Highways England: "Factual Report on Ground Investigation"; December 2017.

Appendix 2: Excerpt from Chapter 12, "Specialized Applications", in Reeves, GM, Sims I and Cripps, JC (Eds), 2006, *Clay Materials used in Construction*. Geological Society of London, Engineering Geology Special Publication 21.

References

Lucas, J L and Reeves G M., “An Investigation into High Nitrate in Groundwater and Land Irrigation of Sewage”. *Water Science & Technology*, 13 (6), pp 81-88. Jan.1981.

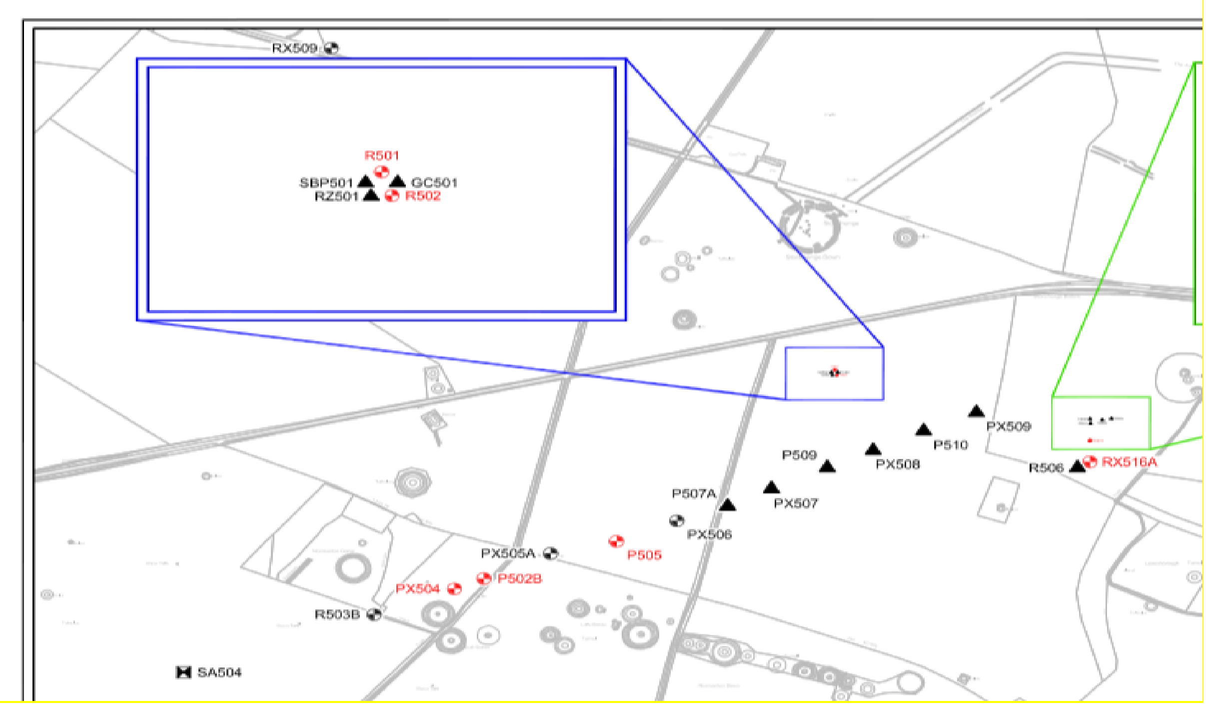
Reeves, GM, Sims I and Cripps, JC (Eds) 2006. *Clay Materials used in Construction.* Geological Society of London, Engineering Geology Special Publication, 21. ISBN 10: 1-86239-184-X

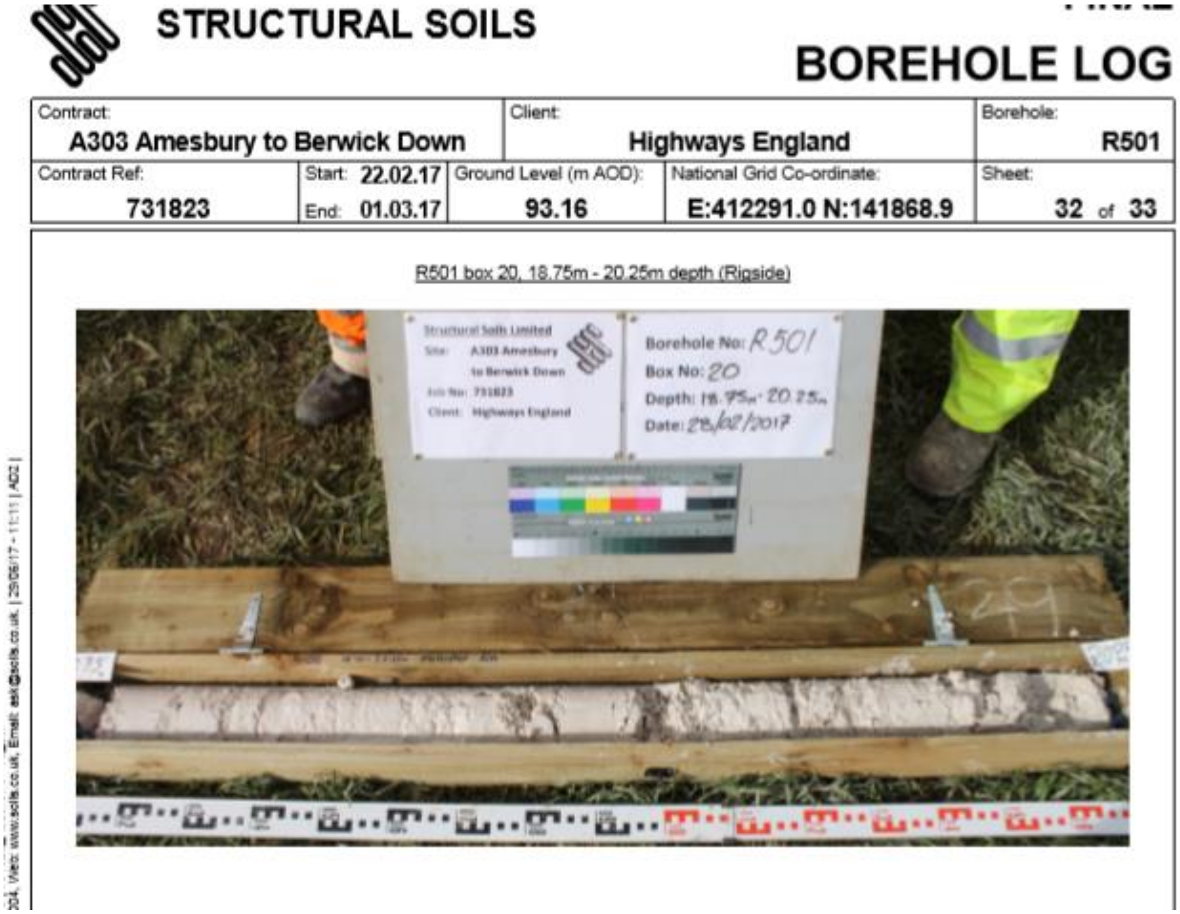
Additional Relevant Biographic Information

George Reeves is an experienced Engineering Geologist and Hydrogeologist.
He represented the Stonehenge Alliance case against the Highways Agency in 2004, presenting the arguments that poor ground conditions (highly fractured rock), groundwater control, plus the need to prevent contamination from tunnel operations in the event of an in-tunnel pollution incident (involving, for example, a tanker spillage), would all contribute towards spiralling costs for the tunnel as proposed in 2004.
Prior to working for Atomic Energy of Canada, Research Company in 1981, he worked as a hydrogeologist for Severn Trent Water Authority (now the EA), and developed the triple tube drilling techniques, in association with Soil Mechanics Ltd. for the “Nitrates in Groundwater” project in N. Nottinghamshire (Reference 1).
He then worked for two years as a geologist, hydrogeologist and geotechnical engineer for a drilling and SI company, Strata Surveys Ltd. both in the UK and overseas.
He subsequently took up the post of Assistant Manager with Robertson Research Engineering Services Ltd. (now Robertson Geologging) where he acted as geological and hydrogeological consultant, helping to develop the company’s wireline geophysical logging developments into down-hole digital logging systems and contracts.

On returning to the UK in 1986, he helped to run, then took over as Course Director of the Newcastle University, Department of Geotechnical Engineering, taught the MSc Advanced Course in Engineering Geology, remaining in post for nearly 20 years. He was also involved in teaching and research supervision on the Rock Mechanics, Soil Mechanics and Environmental Geotechnics MSc courses, as well as PhD and MSc Research supervision.
He was awarded a PhD degree (under staff regulations, after a 24-year period of extended research) in 2005 in hydrogeophysics with his submitted thesis “The Application of Borehole Geophysical Logging Techniques to Geotechnical and Hydrogeological Investigations” by the then Newcastle University Chancellor, Christopher Patten.
He now runs his consultancy, HydroGEOtecH Consultants, and has worked for UK and overseas governments, NGOs and many private and public organisations as geological, hydrogeological and geotechnical advisor.

APPENDIX 1: Borehole R501: core Images





STRUCTURAL SOILS

BOREHOLE LOG

Contract: **A303 Amesbury to Berwick Down**		Client: **Highways England**		Borehole: **R501**
Contract Ref: **731823**	Start: **22.02.17** End: **01.03.17**	Ground Level (m AOD): **93.16**	National Grid Co-ordinate: **E:412291.0 N:141868.9**	Sheet: **32** of **33**

R501 box 20, 18.75m - 20.25m depth (Rigside)

004, Web: www.soils.co.uk, Email: ask@soils.co.uk, | 29/06/17 - 11:11 | AD2 |

R501 boxes 20 - 21, 18.70m - 21.00m depth (Compound)

R501 boxes 20 - 21, 18.70m - 21.00m depth (logging area)

R501 boxes 25 - 26, 24.00m - 26.00m depth (Rigside)

R501 boxes 25 - 27, 24.00m - 27.50m depth (Compound)

R501 boxes 25 - 27, 24.00m - 27.50m depth (Logging area)

R501 boxes 30 - 31, 30.50m - 33.50m depth (Compound)

R501 boxes 30 - 31, 30.50m - 33.50m depth (Logging area)

Core Box Photographs:

First Example:- Depth: 18.70m-21.00m

28th February 2017/1st March 2017/9th March 2017

Second Example:- Depth: 30.50-33.50m

APPENDIX 2:
please see file sent separately

Extract from**:** Reeves, GM, Sims I and Cripps, JC (Eds) 2006. *Clay Materials used in Construction.* Geological Society of London, Engineering Geology Special Publication, 21. ISBN 10: 1-86239-184-X, Chapter 12, pp. 347–363 and references.

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Clay Materials Used in Construction

Edited by
G. M. Reeves, I. Sims & J. C. Cripps

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12. Specialized applications

12.1. Principles

12.1.1. Scope of chapter

This chapter essentially covers the specialized uses of clay in construction not included in the more routine applications covered in other chapters. There is a very wide range of such specialized applications, so none can be treated in great depth in this book. In addition, some of the applications, especially in the areas of environmental engineering, are undergoing rapid development. Readers interested in particular applications should therefore consult the appropriate references given and be prepared to search for more recent publications.

The applications discussed in this chapter may be divided into two main categories, though there is some overlap between the two. The first category includes the use of clay slurries in drilling, piling, diaphragm wall construction and tunnelling. In most cases the slurry is used as a construction expedient to provide fluid pressure, support soil particles in suspension to prevent sedimentation, and to act as a medium of transport for excavated material. In some cases the slurry may be left in place to form an impermeable barrier; in such cases the clay slurry may be mixed with natural soil and/or cement to achieve a semi-solid final state. Clay or clay/cement slurries may also be used as grouts to seal permeable natural ground for either short- or long-term purposes.

The other principal category includes uses where plastic solid clay is employed to form impermeable barriers or waterproof layers, most commonly in the construction of engineered landfill facilities or for the containment of hazardous solids or liquids. In these cases the applications are making use of the low hydraulic conductivity of clays, which is maintained even when the material is deformed, due to the clay's ability to strain plastically without cracking. A traditional form of such material is 'puddle clay', widely used in the past for lining canals and forming the core of earth embankment dams.

In the great majority of cases the clay used in these applications is bentonite, although attapulgite (syn. palygorskite) has occasionally been used for slurries mixed with salt water. The nature, origin and properties of bentonites are covered in Chapters 2 to 4, while important aspects of their behaviour in the context of this chapter are covered in the next three sections. In some cases, natural locally occurring clays may be employed instead of processed bentonite; such clay will usually be of high plasticity and have a significant content of bentonite-type minerals.

12.1.2. Bentonite

The name bentonite is popularly used for a range of natural clay minerals of the smectite group, principally potassium, calcium and sodium montmorillonites derived from the weathering of feldspars. The name derives from the discovery of large deposits near Fort Benton in Wyoming, USA. Because of the chemistry and microstructure of the clay particles, they have a strong ability to absorb water and are able to hold up to ten times their dry volume by absorbtion of water. Montmorillonite (after Montmorillon, southwest of Paris) consists of very thin flat crystalline sheets of clay minerals which are negatively charged and are held together in 'stacks' by positively charged sodium or calcium ions in a layer of adsorbed water. In particular the soil particles comprising a stack of sheets of sodium montmorillonite form extremely small and thin platelets, being typically of the order of 1.0 μm or less in length and 0.001 μm thick. The ability to absorb water comes from the relatively low bonding energy of the sheets, which allows water molecules to be adsorbed onto the internal and external sheet surfaces. Calcium ions provide a stronger bond than sodium, so that calcium montmorillonite swells less readily than sodium montmorillonite. Potassium ions provide much stronger bonding between clay sheets as the potassium ion is of exactly the right diameter to fit between atoms in the sheet structure with negligible gap between the clay sheets. A similar material to montmorillonite but with potassium bonding is the non-swelling clay mineral known as illite. The substitution of sodium by calcium or potassium ions in montmorillonite greatly reduces the ability of the clay structure to hold water.

The very small particle size of bentonites results in an extremely low hydraulic conductivity for intact clay, with a coefficient of permeability of typically less than 10^{-10} m/s. This allows the clay to be used to form 'impermeable' or 'waterproof' layers and sustain high hydraulic gradients across thin layers with negligible water flow. The swelling property is also important in such applications, since should water permeate a layer of dry bentonite it will swell even against high pressures and tend to seal any crack or fault which might otherwise develop into a leakage path. The volumetric swelling of particles can be up to 13%, but that of an agglomeration of particles is somewhat less depending on their packing.

Many applications of bentonite involve the use of slurry. Mineral particles in a slurry generally carry electrical charges, the nature and intensity of which vary

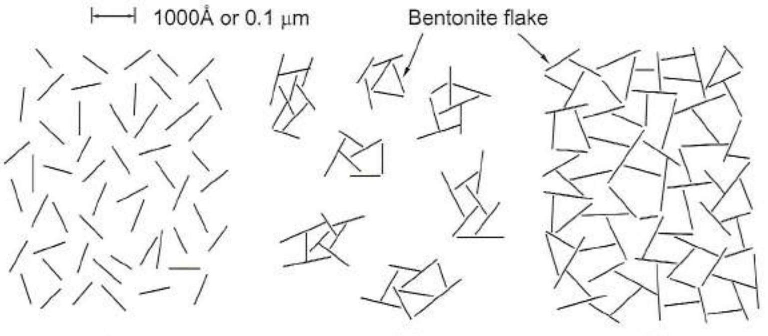

FIG. 12.1. Structures of bentonite slurry: (a) dispersed, (b) flocculated, (c) gel.

with the particle surface characteristics and the chemistry of the liquid phase. Polar water molecules may then be adsorbed on to the particle surface, forming a layer of 'bound' water surrounding each particle. The result of the two effects is to produce repulsive forces between particles, which are greater than attractive Van der Waal's forces except when the particles are very close together. The particles in a slurry therefore tend to keep apart from each other in a 'dispersed' condition (Fig. 12.1a). The effects are most noticeable with small particles (clay/silt rather than sand/gravel, and in practical terms only with finer clay particles) since the relative surface areas are much larger, and gravitational forces are much smaller. Under some conditions the plate-like particles of clay minerals may have different charges on the edges and faces of the particles, and are able to clump together in a 'flocculated' structure (Fig. 12.1b). The large flocs settle out of the slurry much more readily than the small individual particles.

Some slurries demonstrate the effect known as thixotropy, whereby they 'set' into a gel if left undisturbed, but revert to a viscous fluid (sol) when sheared. The alternation between sol and gel may take place any number of times. The phenomenon is well known in 'non-drip' paints. A gelled 'house-of-cards' type of structure with edge to face connections is illustrated in Figure 12.1c; gels of thin clay particles may contain only a few per cent of solid material. The gelled structure is also able to support larger soil particles and prevent them from settling out. Bentonite slurries are thixotropic and typically form a gel at concentrations of a few per cent by mass in water; this is an important property of bentonite slurries in many applications. For a more detailed discussion of the nature and properties of bentonite slurries see Jefferis (1992).

Bentonite clays occur, and are mined and processed commercially, in many parts of the world. Some natural deposits, notably those from Wyoming, have a high proportion of sodium. These tend to produce slurries with high viscosity but relatively low gel strength. The deposits mined in the UK, near Woburn, are mainly of the calcium form, and these are converted by ion exchange to the sodium form by ball-milling with sodium carbonate. These materials tend to be less dispersive and give lower viscosities for the same slurry density, but higher gel strengths. As natural products, bentonites vary widely around the world in quality and content of other minerals, even after commercial processing, and these variations must be taken account of in their specification and use.

Bentonite is available commercially in a variety of forms, but nearly always in a dry state, as powder (in bulk or bags, like cement), pellets or blocks. For applications in construction it will usually be hydrated, although in some waterproofing materials the hydration is allowed to occur *in situ*. For use as a slurry, the bentonite is mixed with water at a rate of a few per cent of solids by mass. The aim is normally to produce a slurry in which the bentonite particles are well dispersed and fully hydrated. For good mixing and rapid hydration, a high-shear colloidal mixer (shear rate >900/s) should be used, and the slurry then left to stand for some time while the clay particles hydrate. The quality of the slurry obtained depends on the hydrogen ion concentration (pH) of the water used in mixing; saline or acidic water or water containing impurities may cause the clay particles in the slurry to flocculate. This may initially cause the slurry to 'thicken', but there will then be a tendency for the flocculated particles to settle out of suspension and form a sludge. However there is not normally a practical problem with seawater coming into contact with a slurry, provided the slurry cannot mix freely with the seawater and has previously been fully hydrated with fresh water. Deliberate flocculation with flocculating agents may be used to help remove bentonite from suspension when the slurry is no longer required or has become too contaminated with cement, clay or silt. A combination of low hydraulic flow into the slurry (so long as hydraulic heads are low), and long diffusion times for salt compared with exposure times, usually causes few problems in the presence of seawater.

Bentonite is also used in combination with other materials, in particular other soil materials and Portland cement. At one extreme a small quantity of bentonite may be added to a concrete mix to produce highly plastic concrete able to undergo quite large deformations without cracking; while a small quantity of cement in a bentonite

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slurry can produce a hardening slurry with a small shear strength. Natural clay, silt and sand may be used as 'fillers' to produce cheaper material while keeping most of the benefits of the sealing ability and low permeability of the bentonite. Gleason *et al.* (1997) found that about 5% of sodium bentonite and 10–15% of calcium bentonite had to be added to fine sands to achieve a sand–bentonite mix with a permeability of less than 10^{-9} m/s. Hardened bentonite-cement slurry mixes containing 180 kg/m^3 of cement and 60 kg/m^{3}of bentonite had permeabilities of about 10^{-7} m/s with calcium bentonite and 10^{-8} m/s with sodium bentonite. These mixtures are discussed further below in relation to various different applications. Small quantities of polymers and other chemical additives may also be used to enhance or modify the properties of bentonite slurries for particular applications. These are also discussed further below.

12.1.3. Interaction of slurries and natural ground

The interaction of slurries with the ground is considered in this introductory section because it is important in many different applications. It may be required for a slurry to permeate the ground when it is being used as a grout to reduce the permeability or increase the strength of the ground. On the other hand, the slurry may be required to seal the ground at the interface so that the fluid pressure of the slurry may be transmitted to the soil particles within the natural ground and provide support. Penetration of slurry into the ground, or lack of it, is controlled by two principal effects known as pore blocking and rheological blocking. Pore blocking is the mechanical effect whereby, as the slurry tries to infiltrate the ground, agglomerations of particles from the slurry become wedged in the pore channels of the ground, thereby blocking the channels and preventing further inflow of slurry. Rheological blocking occurs when slurry has penetrated more deeply into the ground, until the pressure gradient becomes too small to maintain flow of the slurry through the pore channels, the slurry gels, and no further flow can occur. In practice the two effects act together and their relative importance depends on the nature of the slurry, the nature of the ground, and the pressure difference applied.

Penetration of slurries has been studied in relation to grouting of soils by Raffle & Greenwood (1961). They quote the expression:

$$s = \frac{\Delta p \cdot \alpha}{2.0\tau_s}$$

where s is the penetration distance, α is the average minimum pore size (1/10 of the average minimum particle size), τ_s is the shear resistance of the slurry, and Δp is the difference between the slurry pressure p and the ground water pressure u. The German Standard DIN 4126 1986 substitutes d_{10} for α for tunnelling, where d_{10} is the particle size such that 10% by mass of soil is of smaller size, but this is not consistent with experience from grouting applications. Jancsecz & Steiner (1994) produced a similar formula but with the number 2.0 replaced by 3.5, giving almost half the penetration distance, more consistent with grouting experience. The penetration seems likely to be influenced by soil density, grading and particle shape as well as by d_{10} particle size. Jefferis (1992) provides an expression which includes the porosity of the soil n:

$$s = \frac{\Delta p \cdot d_{10}}{\tau_s} \cdot \frac{n}{(1-n)} \cdot f$$

where f is a factor to take account of the geometry and tortuosity of the flow paths within the soil, and may be about 0.3. With clean bentonite slurries, typical values of Δp, and typical shear strengths of the slurry of 20 to 50 Pa, penetrations of several metres result in soils coarser than medium sand. However, if the slurry contains larger particles of cement, silt or fine sand, which help to block the pores, penetration is greatly reduced.

The influence of cement on the shear resistance of hydrated bentonite slurries can be judged from Figure 12.2. The curve for 0% bentonite represents neat cement grouts. Even small additions of bentonite to grouts increase their shear resistance dramatically, thus reducing their ability to permeate fine soil pores. The suspension/cement rates approximating to the shear resistance minima are typical of diaphragm walling and piling hole support slurries. The minima arise relative to clean bentonite (shown as higher suspension/cement ratios) because of the degrading of the bentonite by free calcium from the cement. Thus the supporting capacity of bentonite for soil particles is reduced causing increased sedimentation and 'bleed' of clear water.

Where the slurry is required to support the ground by fluid pressure, it is best if the interface is effectively sealed so that the fluid pressure is transmitted with a large pressure gradient within the natural ground. This is achieved by the formation of a 'filter cake', a thin layer of highly impermeable bentonite 'caked' or 'plastered' on to the interface (Fig. 12.3). This occurs when (as usually) there is a range of particle sizes in both soil and bentonite; the coarser particles in the slurry filter out in the finer pore sizes of the soil. As long as some flow continues into the coarser pores of the soil the filtration also continues, gradually thickening to cake the soil surface with a mixture of silt sized particles in a matrix of bentonite clay from the slurry. This occurs with clean bentonite slurries in sand and silt; in coarser soils the slurry will dissipate into the ground without forming a filter cake, while in clays there will be insufficient inflow for a thick cake to be formed (and support pressure may be provided simply by water without need for a slurry). Filter cake formation in coarser soils may be encouraged by inclusion of silt and clay particles in the slurry to act as pore-blockers.

High molecular weight long-chain polymers may also be incorporated in the slurry to perform a blocking function; the long molecules also act as reinforcing fibres in the filter cake and help to form a net to hold the clay particles. A slurry of high density (around 1.2 Mg/m^3) containing some fine sand and polymer can effectively seal sand-free fine gravels or sandy cobbles.

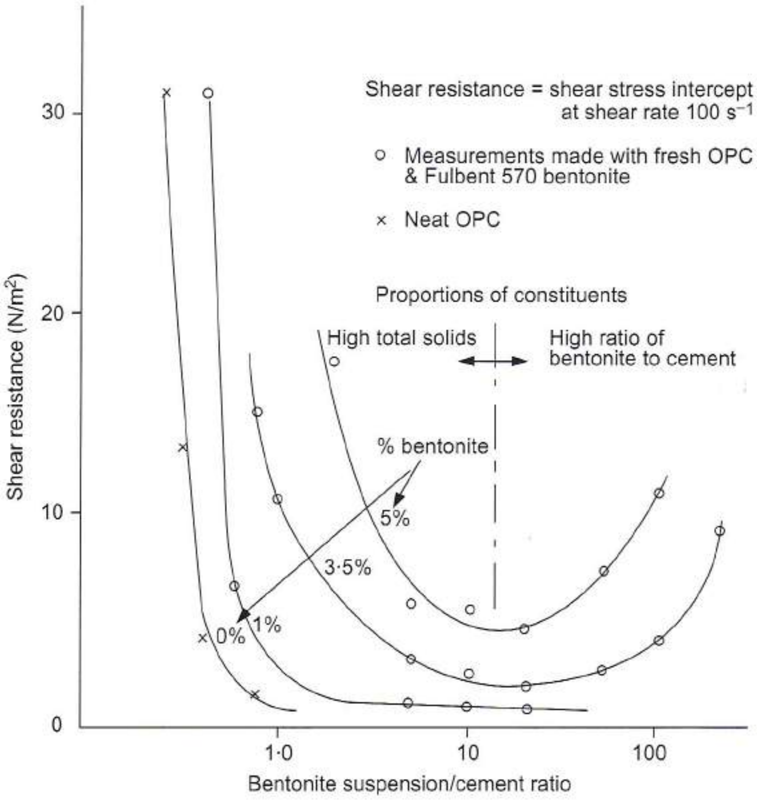

FIG. 12.2. Shear resistance of bentonite/cement grouts and slurries. Measurement by Cementation Research Ltd.

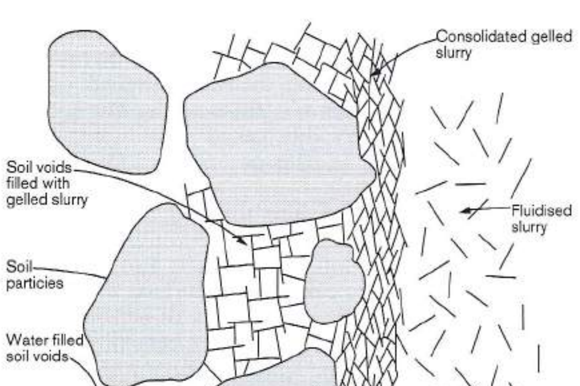

FIG. 12.3. Formation of filter cake.

Under favourable conditions, a filter cake will form very rapidly, for instance during the rotation of the cutter head in a tunnelling machine or the cut of a diaphragm walling grab. A typical thickness might be less than 1 mm with high-quality bentonite and up to 5 mm with bentonite of lower quality. If a differential pressure is maintained across the filter cake it will gradually increase in thickness, at a reducing rate, due to filtration of the slurry through the cake (see Text Box on p. 351). If the filter cake is insufficiently impermeable, the fluid loss through it may contribute significantly to increasing the pore pressures in the ground (or reducing negative pore pressures induced by excavation) and allowing localised swelling and softening at the contact with soils with significant clay content. The best filter cake in most cases is therefore one that is thin but highly impermeable; however under less onerous conditions the thicker, more permeable filter cake formed by lower quality (calcium) bentonite may be perfectly satisfactory.

12.1.4. Test procedures

A number of test procedures are used to categorize the quality and performance of bentonite slurries. These relate to the viscosity, gel strength, density, sand content, pH, and filtration characteristics of the slurry. Many of the tests used have been developed by the oil industry in relation to drilling of deep wells with bentonite (mud) flush. They are covered by American Petroleum Institute

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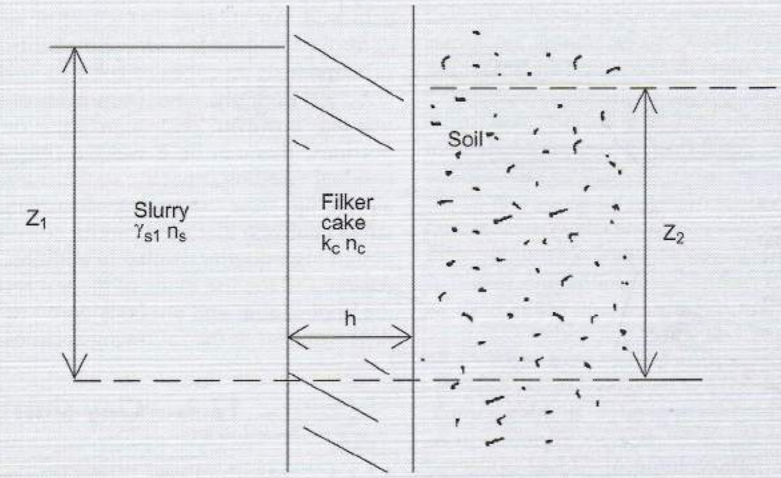
Formation of filter cake



Consider a filter cake layer of porosity n_c, and thickness h varying with time t, building by filtration against the wall of a trench or pile. By equating the rate of build up of the filter cake to the rate of loss of solids from the slurry by water permeating through the filter layer due to the difference in pressure head between the slurry in the trench and the water in the ground, the following equation is obtained:

$$h=\left(\frac{2k_c(1-n_s)(\gamma_s z_1-\gamma_w z_2)}{(n_s-n_c)\gamma_w}\right)^{1/2}\sqrt{t}$$

where n_s and γ_s are the porosity and unit weight of the slurry, k_c is the permeability of the filter cake, γ_w is the unit weight of water, z_1 is the depth below the surface of the slurry and z_2 the depth below the groundwater surface. Since the pressure differential across the filter cake is constant, the flow rate will reduce in inverse proportion to the thickness of the filter cake, and will thus decrease with the square root of time.

(API) Publication RP 13B, and are also described in detail by the Federation of Piling Specialists (FPS 2000). Details of the tests are not repeated here, but the purpose and limitations of the tests are discussed.

It is not normal to explore the full rheological behaviour of a slurry over a range of shearing rates. It has been found generally acceptable to treat a slurry as a Bingham fluid with thixotropic properties. A Bingham fluid is one in which the viscosity rises linearly with shear rate from an initial non-zero value at zero shear rate (Fig. 12.4). The initial value is known as the yield strength and the rate of increase with shear rate as the plastic viscosity. Both can be derived provided measurements are made of viscosity at two different rates of shear. This is most conveniently done with a Fann viscometer. The relative performance of slurries is often checked on site using a Marsh funnel, in which an apparent viscosity may be determined by the rate of flow of slurry from a standard funnel. Its main use is as a quality control test, to check that slurry being used on site is consistent.

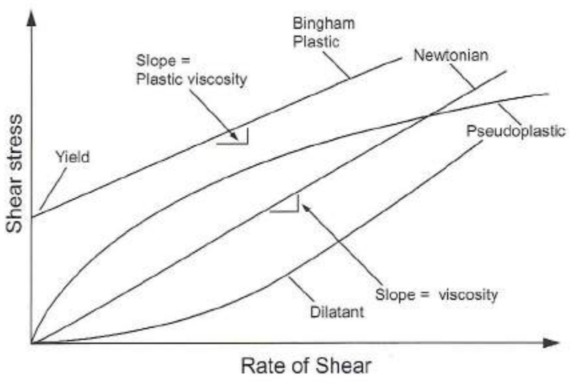


FIG. 12.4. Models of viscous behaviour.

The density of a slurry is measured simply using a 'mud balance'; the density is important both in its own right, by creating hydrostatic pressures somewhat in excess of groundwater pressures, and as a controlling factor in many of the other aspects of slurry performance. While it is common to allow some silt and sand to remain in the slurry, to improve pore blocking and filter cake formation, excessive amounts of sand lead to problems with material settling out and in excessive wear of pumps and other equipment. The sand content is measured by screening out the sand from a small sample of the slurry using a 75 micron sieve.

Bentonite slurries disperse best in neutral or alkaline conditions, and it is sometimes necessary to increase the alkalinity artificially. Values of pH in the range 9 to 12 are generally considered satisfactory, and may be measured using a glass-electrode meter or, less accurately, with pH papers. Higher pH values are usually the result of Portland cement contamination, which can have a severely deleterious effect on slurry behaviour.

The ability of a slurry to form a filter cake and the rate of fluid loss through the cake is measured in a test developed by API using a fluid loss apparatus. In this a sample of slurry contained in a cell is pressurized and forced through a filter paper. The volume of filtrate collected after 30 minutes and the thickness of the resulting filter cake are measured. The test was devised for drilling fluids and the applied pressure of 100 lbf/in^2 (690 kPa) is high for civil engineering applications, with the result that specifications may be unnecessarily onerous.

Grouts are sometimes tested for bleeding, the tendency for water to separate from a grout due to settlement of the solids. The tendency for bentonite–cement grouts to bleed will be partially or wholly offset by the setting process, depending on the depth of the sample tested, and results of bleed tests need to be interpreted with caution. Grouts also need to be tested for set time and increase of viscosity with time, since these control the period for which it is possible to inject the grout. Set time may be difficult to define for grouts which have a gel strength immediately after mixing which then increases with time until a fully hardened state is reached.

Hardened strength of bentonite–cement may be measured in unconfined compression tests, or in triaxial tests with a confining pressure. The former is a useful quality control procedure, but gives no indication of the stress–strain behaviour of the material in use, when there will nearly always be confining stresses. Drained tests carried out in a triaxial cell allow the long-term stress–strain behaviour to be investigated; typically the behaviour will be brittle at low confining pressure and ductile at higher pressures. Hydraulic conductivity may also be measured in a triaxial cell; it often reduces significantly with time and it may be necessary for tests to be continued for several days when the results are critical.

Specifications for testing are required to cover three different aspects of the materials to be used: the quality of the raw materials as supplied; the behaviour of the newly mixed materials in a fluid or plastic state; and for permanent installation the long-term properties affecting performance. The second of these aspects may cover either the suitability of the material for immediate construction purposes, or as an indicator of the long-term behaviour (or in some cases both). Results of tests for long-term performance will not normally be available until it is too late for them to be used to control construction; their purpose will be to confirm that adequate properties have been achieved. An anology is the use of slump tests as a site control procedure for concrete quality followed by compression tests on cubes or cores to confirm that adequate concrete strengths have been achieved. It must be commented, however, that, depending on the mixture proportions, this can be a weakly cemented material with residual swelling capacity, so there are many issues (such as curing time, sampling disturbance, and effective stress changes) that need careful consideration in order to obtain high-quality results. In addition, the necessary test regime and the use made of the test results will vary with the application, and are considered further in relation to different uses in the following sections.

12.2. Clay slurries

12.2.1. Introduction

Clay slurries are most commonly used as construction aids in the formation of diaphragm walls, bored piles, vertical and horizontal boreholes, tunnels, pipe jacks and caissons. The slurry may be required to seal permeable ground to prevent water inflow and/or allow fluid pressures to be applied to the ground; it may be needed to 'hold' excavated spoil, prevent it settling out and allow it to be transported away from the point of excavation; or it may be used to provide lubrication. In many cases the slurry may be required to do several or all of these things, and the ideal specification of the slurry may be different for each. The slurry design will nearly always be a compromise between different technical requirements, with the usual addition of the need for the process in which it is used to be as economical as possible. For instance, a decision may be required between cleaning the slurry of accumulated sand and silt for re-use or dumping it and supplying fresh slurry. In the following section the main applications are considered in turn.

12.2.2. Applications

12.2.2.1. Diaphragm walls and piles. In these applications the slurry is used to support the sides of the excavation for a diaphragm wall or uncased bored pile (Fig. 12.5). The slurry pressure must exceed the groundwater pressure and the excess pressures must be transmitted via a filter cake to the soil to provide sufficient additional effective stress to maintain stability of the trench or pile sides. The slurry must also be able to keep particles of soil in suspension so that they do not settle to the base of the trench, yet must be fluid enough to be easily displaced by concrete placed by tremie pipe and not to adhere to the reinforcement to an extent that would impair the bond between reinforcement and concrete. With some types of excavator using reverse circulation

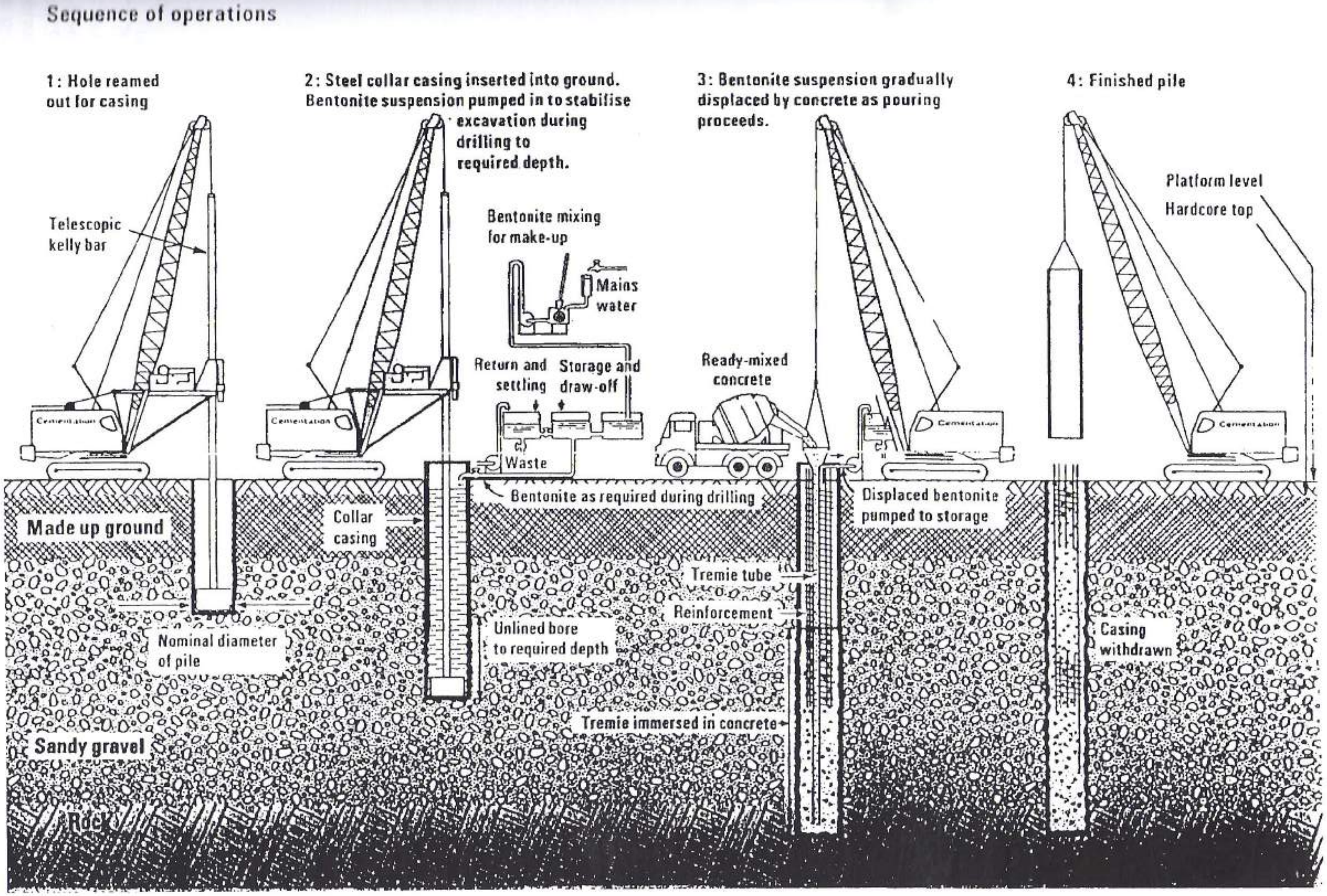
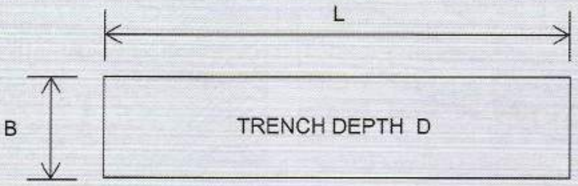


FIG. 12.5. Construction of bored pile using bentonite slurry. Figure courtesy of Cementation Foundations Skanska Ltd.

Effect of finite trench length on stability



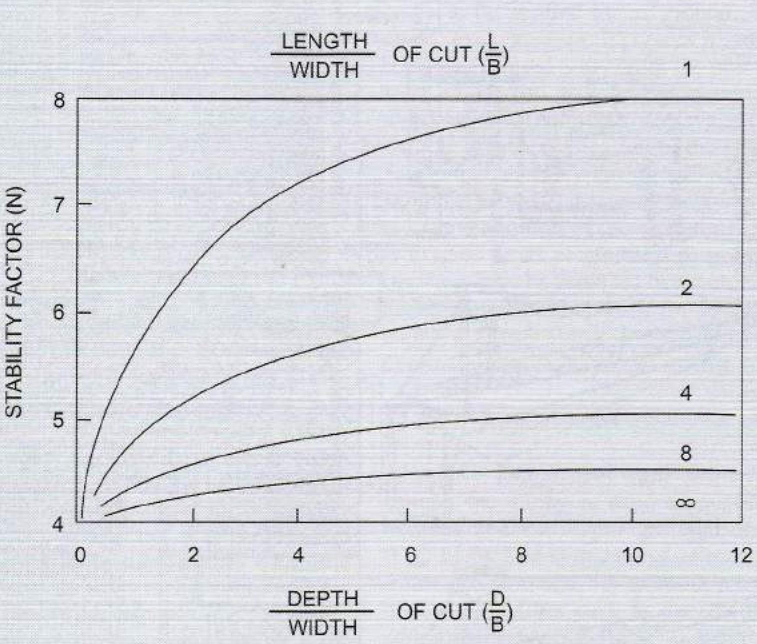
For cohesionless soils, after Huder (1972), the pressure required to maintain stability of the trench wall is the sum of the ground water pressure and the effective active earth pressure, with the latter multiplied by a factor *A* given by:

$$A = \frac{1 - e^{-2nK_a \tan\phi}}{2nK_a \tan\phi}$$

where $n = D/L$, D is the depth of panel, L is the length of panel. For cohesive soils, after Meyerhof (1972), the factor of safety F against collapse of the trench is given by

$$F = \frac{N_c \cdot c_u}{H(\gamma - \gamma_f)}$$

where N_c is a bearing capacity factor given in the plot below, γ is the total unit weight of the soil and γ_f is the unit weight of the slurry.



cutters the slurry is also used to transport the cut material to the surface.

The technique has been in use since the 1950s, and a major milestone in its development in the UK was the conference on diaphragm walls and anchorages held at the Institution of Civil Engineers in 1974 (ICE 1975). At this conference, Sliwinski & Fleming (1975) provided an overview of practical considerations affecting the

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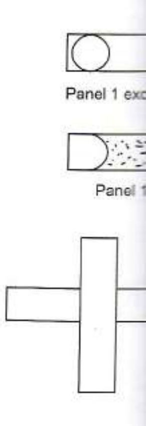


FIG. 12.6. Constr

construction of diaphragm walls, while Hutchison *et al.* (1975) discussed the properties required of bentonite slurries and their control. Many of their comments are still relevant, though improved equipment has allowed the use of the technique to be extended; for instance more powerful excavators can now cope with very stiff soils and soft rocks. Diaphragm walls may be routinely formed to a depth of 60 m and thickness 1.2 m, and in special cases to a depth of 120 m and thickness of 2.0 m.

Practical limitations on the use of the method are:

- in soil with permeability of greater than about 10^{-3} m/s loss of slurry may be excessive;
- cavities in the ground may lead to sudden loss of slurry;
- in very weak strata, with shear strength less than about 10 kPa, the ground may not be able to withstand the pressure of fresh concrete and a casing may be needed;
- water pressures under artesian head cannot be controlled.

Apart from these limitations, the conclusions of CIRIA Report PG3 are that the use of bentonite slurry has no significant adverse influence on eventual pile performance, provided that the technique is properly understood and good materials and workmanship are employed.

In the UK, use of the technique is usually required to be in accordance with the Specification for Piling and Embedded Retaining Walls (ICE 1996). This document requires that the slurry level is kept at all times a minimum of 2.0 m above groundwater level in pile bores and 1.5 m in diaphragm wall trenches (the reason for this difference is not clear). The excess fluid pressure will not normally be sufficient to provide the full active pressure required to support the sides of a long trench, and stability can only be achieved by taking advantage of the reduction in required support pressure due to horizontal arching around panels of relatively short length in plan (see Nash 1974*a,b*) (see Text Box on p. 354). Depending on ground conditions, typical panel lengths are in the range 2 to 7 m. Curved panels or panels with T, L or X shapes in plan are also possible (Fig. 12.6).

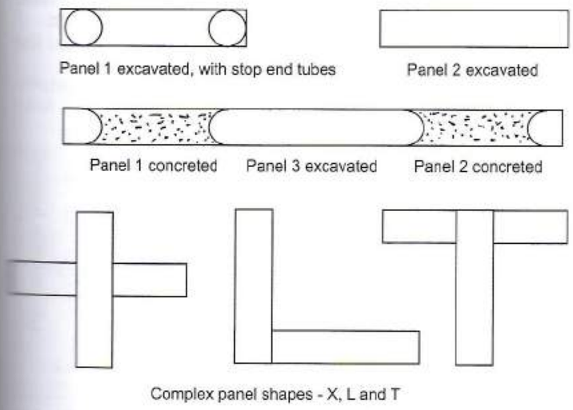


Fig. 12.6. Construction of diaphragm walls (in plan).

In the Guidance Notes to the ICE specification, it is suggested that a slurry with the required properties is likely to contain between 3% bentonite for natural sodium montmorillonite and 7% or more for some manufactured bentonites, with a figure of 5% appropriate for activated (ion exchanged) calcium montmorillonite of UK manufacture. In this application, the thickness of the filter cake is not usually of great importance and the thicker layer resulting from the use of activated rather than natural sodium bentonite is acceptable. The bentonite is required to be of a quality in accordance with Publication 163: *Drilling Fluid Materials* of the Engineering Equipment and Materials Users Association, last reprinted in 1988. An alternative is the API Specification 13A, 15th edition, May 1993, Section 6 (OCMA grade bentonite). There are some differences between these specifications, which are discussed in detail by the Federation of Piling Specialists (2000).

A table is provided in the ICE Guidance Notes (reproduced in Table 12.1a) giving suggested test procedures and compliance values for the slurry as supplied to the pile or trench, and as sampled from the pile or trench immediately prior to concreting. Similar but generally less restrictive criteria are included in the draft European Standards for bored piles and diaphragm walling, prEN 1536 and 1538 respectively—see Table 12.1b. The restriction on the density and viscosity of the slurry in the trench or pile bore, especially at the base, immediately prior to placing concrete is to ensure that the fresh concrete is able to displace the slurry without trapping any of it. A simple device is used to take samples of the slurry from the required depth. More detailed requirements used by one of the main companies specializing in diaphragm walling in the UK are given in Appendix 12.1, along with some comments on the tests used. The values quoted are based on the use of UK manufactured bentonite and might have to be modified for other types. Further guidance on the use and limitations of bentonite slurry in these applications is given in CIRIA Report PG3 and by the Federation of Piling Specialists (2000).

Successful formation of piles or diaphragm walls under slurry requires the use of a suitable concrete mix, one that is sufficiently fluid to displace the slurry at the base of the trench when placed through a tremie pipe, but is also cohesive and not prone to segregation. Requirements for concrete mixes are given in the ICE Specification for Piling and Embedded Retaining Walls. Typically the minimum cement content will be 400 kg/m^3, the water/cement ratio below 0.6, and the aggregate will be naturally rounded sand and gravel, well graded with maximum aggregate size 20 mm and with about 40% sand content. Slump will be in excess of 175 mm, and workability therefore best measured using a flow table, with a target flow of 500–600 mm.

12.2.2.2. Slurry tunnelling. In this application, slurry is pumped to a chamber in the head of a tunnelling shield, where it has two main functions: to apply pressure to the excavated soil face and thereby help to maintain its stability and reduce ground movements into the tunnel; and to act as a transport medium back to the ground surface

TABLE 12.1(a). *Tests and compliance values for bentonite support fluids (from ICE 1996)*

			Compliance values at 20°C	
Property to be measured	API RP13* Test method and	Section No.	As supplied to pile	Sample prior to placing concrete
Density	Mud balance	1	< 1.10 g/ml	< 1.15 g/ml
Fluid loss (30 min test)	Fluid loss test (low temperature)	3	< 40 ml	< 60 ml
Viscosity	Marsh cone	2	30–70 s	<90 s
Shear strength (10 min gel strength)	Fann viscometer	2	4 to 40 N/m²	4 to 40 N/m²
Sand content	Sand screen test	4	<2%	<2%
pH	Electrical pH meter	9.5 to 10.8	9.5 to 11.7	

* American Petroleum Institute: *Recommended practice standard procedure for field testing water-based drilling fluids.*

TABLE 12.1(b). *Characteristics for bentonite suspensions (from prEN 1538:1996)*

	Stages		
Property	Fresh	Ready for re-use	Before concreting
Density in g/ml	< 1.10	< 1.25	< 1.15
Marsh value in s	32 to 50	32 to 60	32 to 50
Fluid loss in ml	< 30	< 50	n.a.
pH	7 to 11	7 to 12	n.a.
Sand content in %	n.a.	n.a.	< 4*
Filter cake in mm	< 3	< 6	n.a.

n.a., not applicable. Requirements for prEN1536 are similar but omit requirements for filter cake.

* Sand content may be increased to 6% before concreting in special cases. Sufficient gel strength is required, and may be checked with rotational viscometers or other suitable equipment.

for the soil material cut from the face (Fig. 12.7a). For the latter purpose the slurry is continuously circulated and carries the excavated material in suspension. Since relatively large volumes of excavation are involved, except in short tunnels of small diameter, it is usually economic to separate the excavated material from the slurry on the surface, and recirculate the cleaned slurry.

In naturally cohesive ground, the 'slurry' may initially be pure water. When returned to the surface, this is only partially cleaned, leaving some clayey material in suspension. Where there are fissures or more permeable zones of ground, some larger sand-sized particles will also be left in suspension to act as pore-blockers in the formation of a filter cake. However excessive quantities of sand in the slurry cause excessive wear to the pumps used to circulate the slurry. In cohesionless soils, or ground containing inadequate amounts of clay to form a natural slurry, a slurry based on bentonite is required. Again this is usually allowed to retain some of the excavated material; the quantity of suspended material may gradually build up until it becomes necessary to dispose of some of the slurry and replace it with fresh bentonite. The original concentration of bentonite may range between zero (pure water) and about 6 or 7%, giving a slurry density of 1000 to about 1040 kg/m³, while the maximum slurry density still capable of being pumped is 1400–1500 kg/m³. Small quantities of polymer, typically about 0.5% by mass of

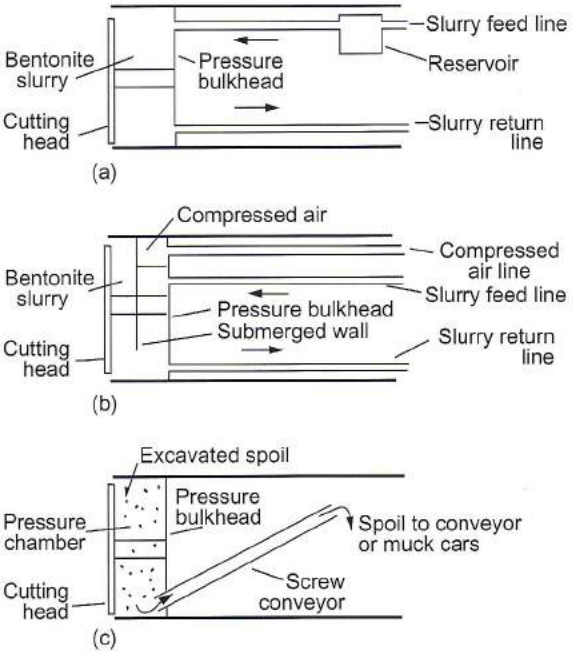


FIG. 12.7. Tunnelling shields (schematic): (a) slurry shield; (b) hydroshield; (c) earth pressure balance shield.

slurry, may also be included to help with filter cake formation; suitable long-chain polymers are sodium carboxy methyl cellulose (CMC), polyanionic cellulose (PAC) or polyacrylamides and their derivatives.

Support of the tunnel face requires formation of a filter cake as an impermeable layer, then sufficient fluid pressure to oppose any groundwater pressure and provide a positive effective pressure on the soil skeleton sufficient to maintain stability of the ground. The extent to which a filter cake has time to form during active tunnelling is debatable, since the face is cut back two, three or more times (depending on the cutter head design) for each revolution of the cutter head. However, excessive penetration of the slurry must be avoided, otherwise large quantities of slurry may be lost into the ground. A slurry that very rapidly (within a few seconds) forms a thin, highly impermeable cake is therefore preferred. Face support is particularly critical when the tunnelling machine is stationary. For long tunnels it is usually necessary to get access to the cutter head on one or more occasions during the drive to change cutter tools for varying ground conditions or replace worn tools. One way of achieving this while maintaining face support is to replace the slurry pressure by compressed air, in which case the filter cake must be effective enough to transmit the air pressure to the ground without excessive losses. Workmen are then able to access the face through an air lock in the shield or tunnel. In some slurry tunnelling machines a ‘bubble’ of air is trapped in the shield to provide an elastic cushion which helps to minimize changes in pressure caused by variations in tunnelling and slurry pumping rates (Fig. 12.7b).

Penetration distances for slurry into the ground are discussed above in Section 12.1.3. In practice slurry shields are best adapted for use in reasonably well-graded sands and gravels (Fig. 12.8); more open ground will allow excessive penetration of the slurry, though appropriate use of polymer additives may allow this range to be extended. In finer-grained soils, problems arise in the sufficiently rapid removal of the excavated material from the slurry in the separation plant, and in the tendency for the more plastic clays to clog the openings in the cutter head. The maximum size of particle that can be transported is limited by the diameter of the slurry pipes, and the cutter head openings are often limited to exclude particles too large to be handled by the machine. Alternatively a crusher unit can be fitted just ahead of the spoil intake to reduce cobbles and boulders to sizes with which the machine can cope.

The slurry may also have a lubricating action on the cutter tools and cutter head face, reducing wear and the power required to drive the head. Small quantities of natural oils such as palm or jute oil may be added to the slurry to increase its lubricity.

When acting as the medium for transporting the spoil back to the surface, the slurry must be sufficiently viscous to stop material falling to the bottom of the machine head chamber or settling out in the pipes, and have sufficient gel strength to hold material in suspension if slurry circulation is halted for any reason. High concentrations of bentonite, of up to 12 or even 15%, may be used. However excessive gel strength may make it difficult to restart circulation after a stoppage, while excessive viscosity increases power requirements for pumping. A natural Wyoming bentonite may be preferred, its superior properties for this application justifying its greater cost over an activated bentonite.

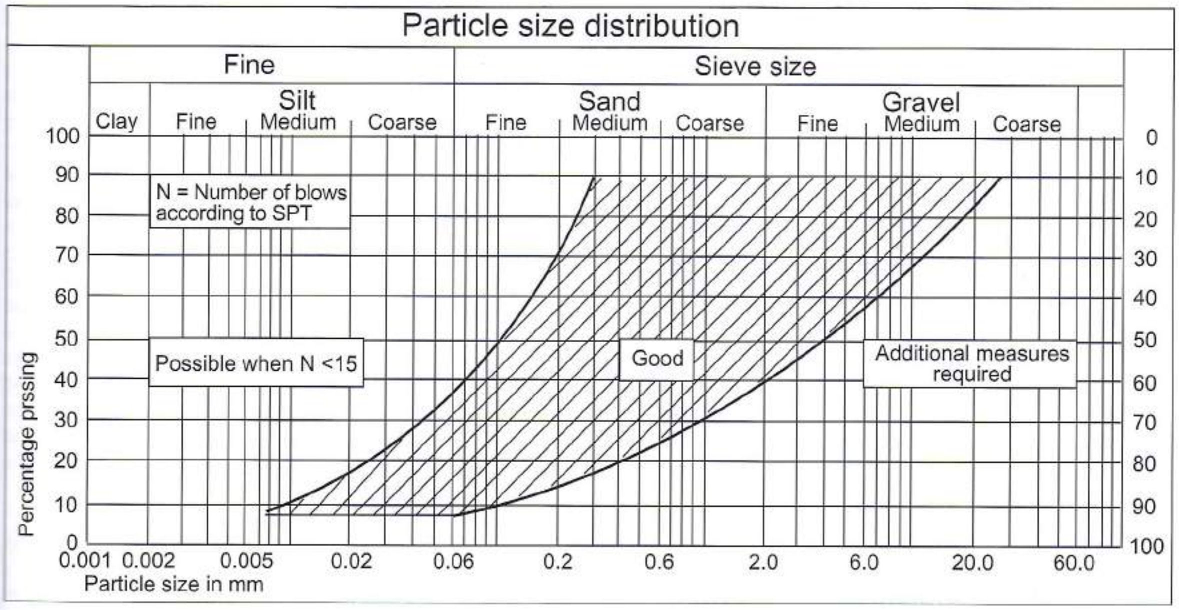


FIG. 12.8. Soil grading for slurry tunnelling.

12.2.2.3. Pipe jacking and microtunnelling; shaft sinking. Pipe jacking is the technique of forming tunnel linings by pushing a 'string' of pipes in behind the tunnelling shield, additional pipes being added at the launch pit as excavation proceeds at the shield (Fig. 12.9). The term 'microtunnelling' is variously used, in the USA to describe all types of pipe jacking in which the tunnelling process is remotely controlled from the surface, but in the UK the term is normally restricted to tunnel diameters too small for man entry (and therefore perforce remotely controlled), or less than about 1.0 m internal diameter.

Pipe jacking and microtunnelling often use slurry tunnelling machines, for which the same comments apply as for large scale machines. However slurry is often also used as a 'lubricant' to reduce the frictional resistance to forward movement of the pipe string and hence limit the total jacking force which has to be supplied by the hydraulic rams, resisted by the back wall of the jacking pit, and transmitted through the pipes.

The tunnel bore is usually excavated to a slightly larger diameter than the outside diameter of the pipes, the 'overcut' being typically 10 to 20 mm on diameter. In stable ground, including all except very soft clays and fine sands above the water table supported by capillary suction, the pipes are then able to slide along the bottom of the bore. In unstable ground, particularly sands and gravels below the water table, the ground will collapse on to the pipes and generate large frictional resistance to jacking. The use of lubricant slurry within the overcut can have three effects (Milligan & Marshall 1998). The first, and most important, is to support unstable ground. This it does by the same process as at the face of a slurry machine, by creating a filter cake and then transmitting radial stresses to the ground. The pressure required to maintain stability is not greatly in excess of the groundwater pressure (see Text Boxes on p. 360 and p. 361). The second effect is that the pipe becomes more or less buoyant within the fluid; small, relatively thick-walled microtunnelling pipes may not become fully buoyant, while larger diameter reinforced concrete jacking pipes may become positively buoyant, contacting the ground at the crown rather than invert of the tunnel. In either case the contact forces between pipe and ground are greatly reduced, and the frictional resistance correspondingly lessened. Finally, the slurry may reduce the coefficient of friction between pipe and ground, though this effect is generally the least important of the three. Overall, the jacking resistance may be reduced by over 90% in unstable sand and gravel, and by typically about 50% in stable ground.

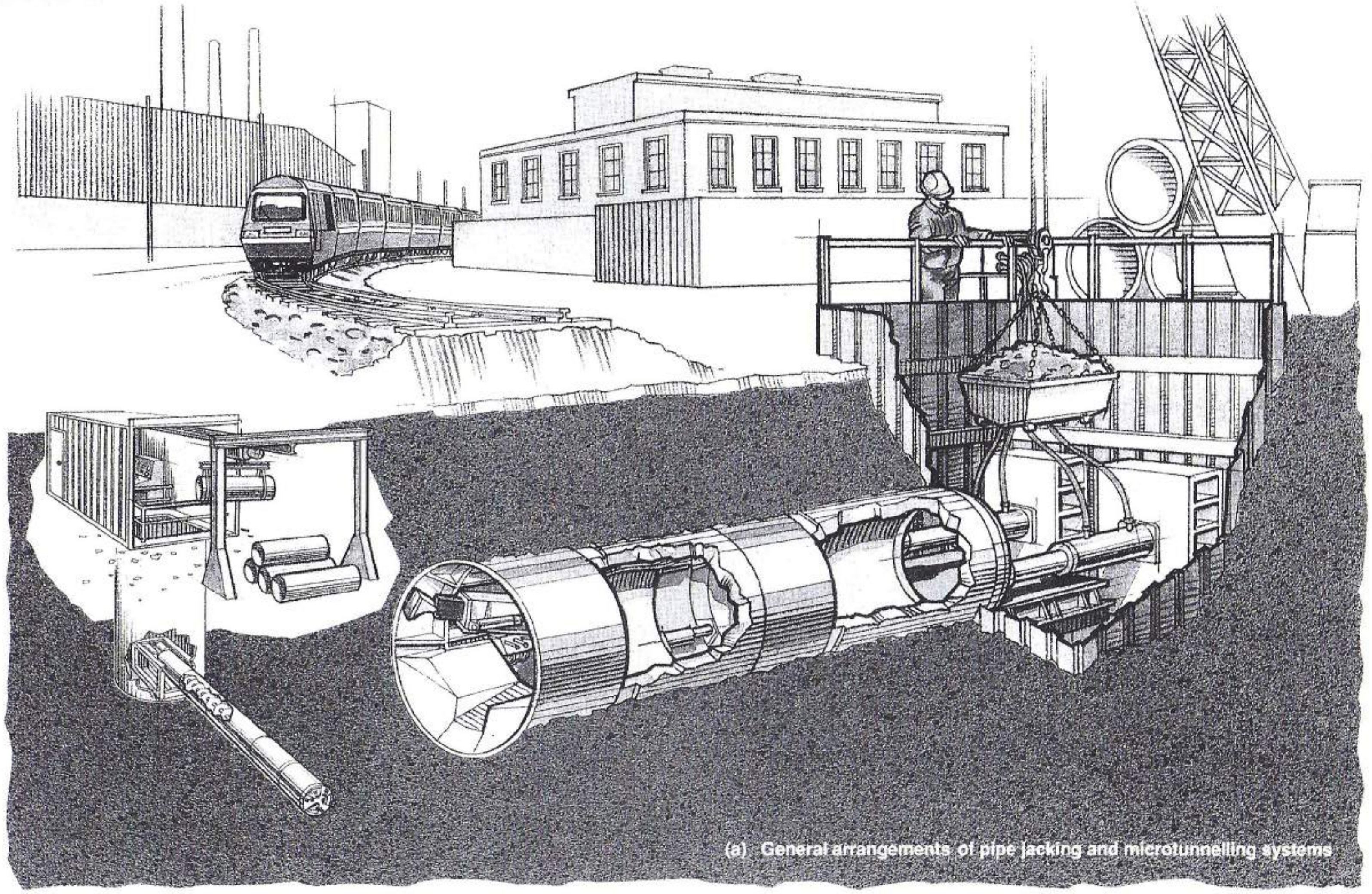
In swelling clays, the use of simple bentonite slurry for lubrication may be counter-productive. The ground takes in water from the slurry and swells, 'squeezing' on to the pipes and increasing the jacking resistance substantially, even though the interface friction coefficient may be very low. In these cases a slurry designed to inhibit swelling may be used; this is achieved either by the incorporation of potassium salts such as potassium chloride, causing ion-exchange with the swelling clay minerals and rendering the near-surface soil non-swelling, or by including a polymer such as partially hydrolysed polyacrylamide (PHPA) which is highly anionic, binds to the clay particles, and prevents water penetration of the clay mineral. Polymers are however considered environmentally harmful in the oil industry, especially when used in aquatic environments (see Sections 12.3.1 to 12.3.3).

Slurries may similarly be used as stabilising and lubricating agents around the outside of caissons being sunk to form vertical shafts. In this case the excavation takes place at the base of the shaft. In soft soil the weight of the caisson may be sufficient to penetrate the bottom edge into the ground ahead of excavation, but in stronger soils the excavation is made slightly larger than the outside diameter of the shaft, leaving a small annulus which is filled with slurry. The action of the slurry is very similar to that in pipe jacking lubrication.

12.2.2.4. Soil conditioning in earth-pressure-balance tunnelling. An earth-pressure-balance machine (EPBM) is an alternative to a slurry tunnelling machine. It has a working (pressure) chamber immediately behind the cutter head in which the excavated soil is remoulded into a plastic mass which provides the support to the tunnel face provided by the slurry in a slurry machine (Fig. 12.7c). The pressure is maintained by balancing the shield advance rate, the excavation rate and the rate at which spoil is removed from the pressure chamber, usually by a screw conveyor. The EPBM has the advantage over the slurry machine of not requiring a separation plant and of producing spoil in a condition suitable for disposal as normal landfill. However EPB shields only work effectively in reasonably fine-grained soils which remould to a soft plastic consistency and have sufficiently low permeability to control inflow of water through the working chamber and screw conveyor. Typically this requires a fines content (<63 μm) of more than 30%, and less than 30% greater than sand-size (2.0 mm). The natural water content of the ground needs to be such as to give a liquidity index in the range 0.4 to 0.75. EPB shields were mainly developed during the 1970s in Japan, where natural ground conditions were often close to ideal.

For coarser or dryer soils the excavated soil must be 'conditioned' by the addition of water, clay or other material such as polymers or foam to provide the required consistency. Bentonite slurry is suitable for this, sometimes improved by the addition of polymers; a relatively small quantity gives a substantial increase in plasticity and reduction in permeability of the spoil. It is best injected through ports in the cutter head, so as to have the maximum chance to mix thoroughly with the excavated material, but as an emergency measure may also be injected into the screw conveyor. The former requires the presence of hydraulic slip rings to deliver slurry to the cutter face.

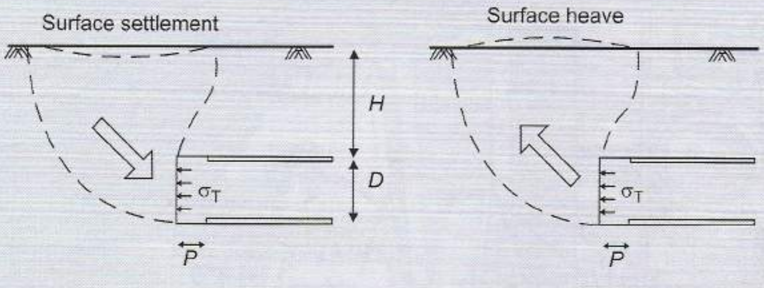
12.2.2.5. Vertical and horizontal (directional) drilling. Bentonite slurries (muds) have for long been used as a stabilizing, lubricating, cooling and spoil transport medium in drilling both vertical boreholes and near-horizontal bores for pipes and ducts. The action of the



(a) General arrangements of pipe jacking and microtunnelling systems

FIG. 12.9. Pipe jacking and microtunnelling. Figure courtesy of The Pipe Jacking Association.

Slurry pressures required for tunnel stability

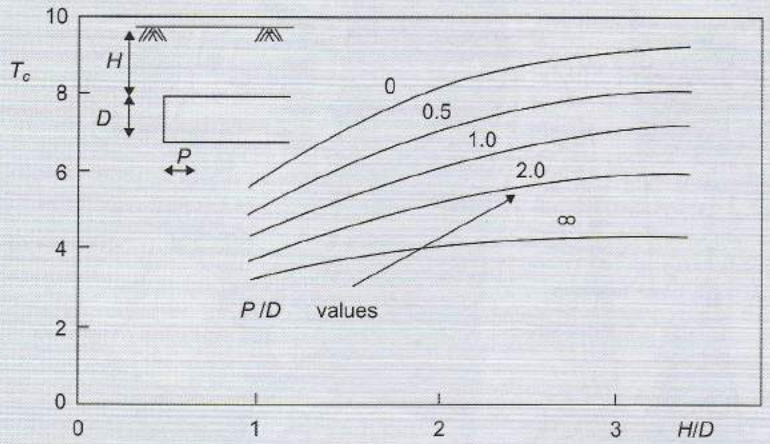


(a) collapse (b) Blow-out

In cohesive soils the slurry pressure σ_T must lie between the limits given by

$$\gamma(H + D/2) - T_{cC_u} \le \sigma_T \le \gamma(H + D/2) + T_{cC_u}$$

where H is the soil depth above the tunnel, D the tunnel diameter, c_u the undrained strength of the soil, γ the unit weight of the soil, and T_c a stability number given in the plot below from Atkinson & Mair (1981). The value of T_c depends on the value of P, the unsupported length of tunnel ahead of the tunnel lining. The lower and upper limits of the slurry presure given in this expression are for tunnel collapse and blow-out respectively. To assess a safe range for σ_T, with acceptably small ground movements, a factor of safety of 2 is usually applied to the soil strength. For a long unsupported bore, as may occur during a pipe jack, the appropriate stability number is that for an infinite value of P.



In cohesionless soil, the assessment of face stability is more complex, though analytical and numerical solutions have been presented by Anagnostou & Kovari (1996) and Leca & Dormieux (1990). Solutions for a long tunnel applicable to the pipe jack condition have been obtained by Atkinson & Potts (1977). For a deep tunnel, the pressure required to prevent collapse is

$$\sigma_T \ge \gamma D T_\gamma$$

and for a shallow tunnel with a significant surcharge on the ground surface

$$\sigma_T \ge \sigma_s T_s$$

where σ_s is the surcharge pressure and T_γ and T_s are stability numbers given by the plots below. Note that T_γ is independent of depth, and that both these solutions apply to dry soil. Below the water table, water pressure must be added and the buoyant weight of soil used in these equations.

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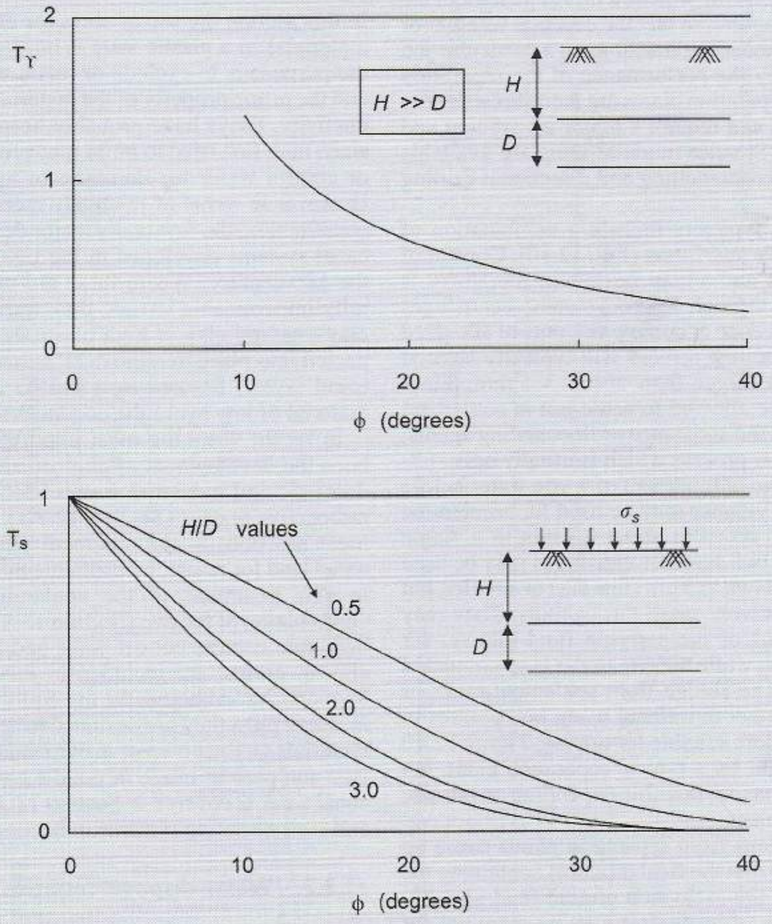
Slurry pressures required for stability continued



slurry is essentially the same as in other applications considered above, but the performance requirements may be considerably more onerous where boreholes penetrate to considerable depths through variable strata. The oil exploration industry has developed a wide range of additives to and replacements for simple bentonite slurries, which have had a major impact on drilling rates. Some of these are gradually finding their way into the construction industry, but are beyond the scope of this report. More conventional bentonite-based slurries used in horizontal drilling differ somewhat from those used in vertical drilling. In vertical drilling the cuttings are returned to the surface using a combination of high viscosity and high flow rates in the slurry, and because of the large depths to which drilling sometimes occurs the density of the slurry and the pressure head generated are important. In horizontal drilling the flow rates are much lower, excessive viscosity is unacceptable as the resulting pressures may become excessive at shallow depth leading to danger of blow-out, but gel strength is necessary to prevent settlement of excavated material in the bore. In cohesionless soils the drilling fluid is required to form a filter cake and support the ground in the same way as described for pipe jacking and microtunnelling.

12.2.3. Re-use and disposal of slurries

Where relatively small quantities of slurry are required, it will normally be used until it no longer fits its purpose, and then removed from site for disposal. However slurries are becoming increasingly difficult to dispose of, particularly when affected by cement or contaminated soil. It is therefore better practice whenever possible to clean the slurry on site for re-use. With piling and diaphragm walling the slurry is used in batches, and provided sufficient space is available for storage tanks the cleaning of the slurry is an off-line process and the rate at which it can be carried out is not critical. However in a large-volume continuous usage such as slurry tunnelling it is necessary to process most of the slurry on a continuous basis, the rate of which may well be a limiting factor in the rate of tunnelling progress. In fact the decision whether or not to use a slurry tunnelling machine on a particular job is often controlled by the performance of the separation plant. Large-scale separation plants are therefore a feature of slurry tunnelling, and require a major investment and considerable space. Smaller modular units are available for pipe jacking, microtunnelling and directional drilling projects.

Separation plants typically include a combination of screens, settling tanks and filters (Fig. 12.10). Control of the amount of sand and silt to be left in the slurry is usually by passing through hydrocyclones; centrifuges may be required to reduce excessive amounts of silt-sized particles. Simple vibrating screens will typically be used to remove particles larger than about 3–5 mm. Finer material may then be allowed to settle out in settlement tanks, probably with the assistance of flocculating agents; however this is a slow process which is usually only suitable for the final stage of treatment of waste water before disposal to drains. Cyclones may be used for accelerated removal of particles down to about 0.1 mm in a single stage or 0.02 mm in two stages. Centrifuges may be used to remove particles down to 5 µm (fine silt) or smaller, but can only handle relatively small throughputs. They may be used to clean part of the carrying fluid (slurry) for re-use in the machine, while the remainder is re-circulated without treatment. The sludge from settlement tanks or cyclones may be further dewatered using belt presses to produce a material more suitable for tipping. Figure 12.10 shows a flow diagram for a typical separation plant, but considerable variations are possible depending on the size and nature of the project.

The coarser fractions from separation plants cause no problems in disposal, but the final products containing the finer fractions from the excavated ground (and possibly significant quantities of bentonite) may be marginal for disposal as land fill. The residual water content of the filter cake material from belt presses may still exceed 100%, although the material may seem drier if flocculants have been used. Gradual degradation of the flocculant may allow free water to be released and the material to become more fluid again. Criteria for the acceptability of spoil may not be well defined, and lead to conflict with owners of landfill facilities or environmental agencies. Simple criteria combining minimum shear strength and minimum solids content have been suggested (Fig. 12.11), in which material with shear strength in excess of 10 kPa and solids content greater than 35% would be considered acceptable.

Highly contaminated slurry may be treated with Portland cement or lime to produce a mix stiff enough to be transported by lorry. However there is an increasing tendency for such mixtures to be treated as special wastes, with the attendant high costs of disposal. For further discussion of the cleaning, re-use and disposal of bentonite slurries, reference should be made to the Federation of Piling Specialists (2000).

12.3. Plastic clay

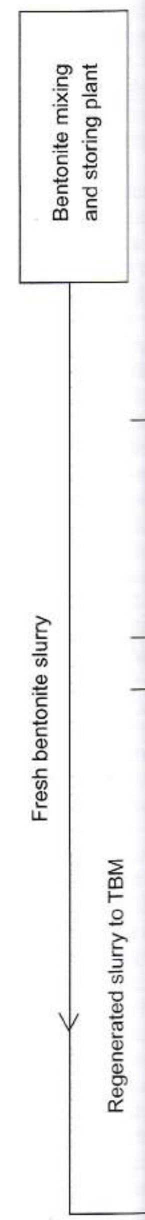
12.3.1. Introduction

In this section the use of clays (or clay mixed with other materials) in a plastic state is considered. In most cases the purpose is to exclude or retain water or other fluids, and the prime property of the material is its hydraulic conductivity. Clays have probably been used in these ways since man first tried to build rain-proof shelters or collect or control water for domestic or agricultural purposes. However in terms of relatively recent large scale use in construction, the first really major development was in the canal systems developed in the UK and elsewhere from the 18th century. Where these did not run through naturally impermeable terrain, they were lined with 'puddle clay', natural clay of high plasticity reworked and compacted into place to remove all natural fabric or structure (sand layers, fissures etc.) and so create homogeneous material of low hydraulic conductivity.

In recent years the most important applications have been the development of engineered waste facilities, for domestic and industrial wastes (Section 12.3.2), and for radioactive wastes (Section 12.3.3). A parallel development has been in the treatment of previously contaminated land for re-use, by containment of the contaminants, *in situ* treatment of the contaminated ground, or a combination of the two (Section 12.3.4). The formation of bentonite-cement cut-off walls and piles, and the use of clay in grouts, are included in this section rather than Section 12.2. Although the materials may initially be used in slurry form they are designed to set and form structural materials on their own or in combination with the ground. Past and present usage of puddle clay for dam cores and canal work is covered in Section 12.3.5, and other sealing and waterproofing systems in Section 12.3.6.

12.3.2. Waste disposal facilities

12.3.2.1. Landfill liners and covers. The use of clay in landfill liners and covers is a vast subject, which can only be covered briefly here. The principle is straightforward and now generally accepted in developed countries; any waste material to be disposed of that is not naturally inert and non-hazardous is to be encapsulated in engineered landfills to control aqueous and gaseous emissions and prevent them from polluting the environment. It is not necessary or possible to reduce emissions to zero, but they should be reduced to such levels that with the help of natural dilution and attenuation they pose no threat to plant, fish or animal life (including of course humans). The complexity of the subject arises from the wide range of materials to be disposed of and the potential pollutants produced by them, the various interactions between pollutants and the environment and the materials used to contain the waste, and the variations in regulations and waste management strategies in different countries. Jessberger (1994) provides a useful suite of papers on geotechnical aspects of landfill design and construction, based mainly on German practice, while Street (1994)



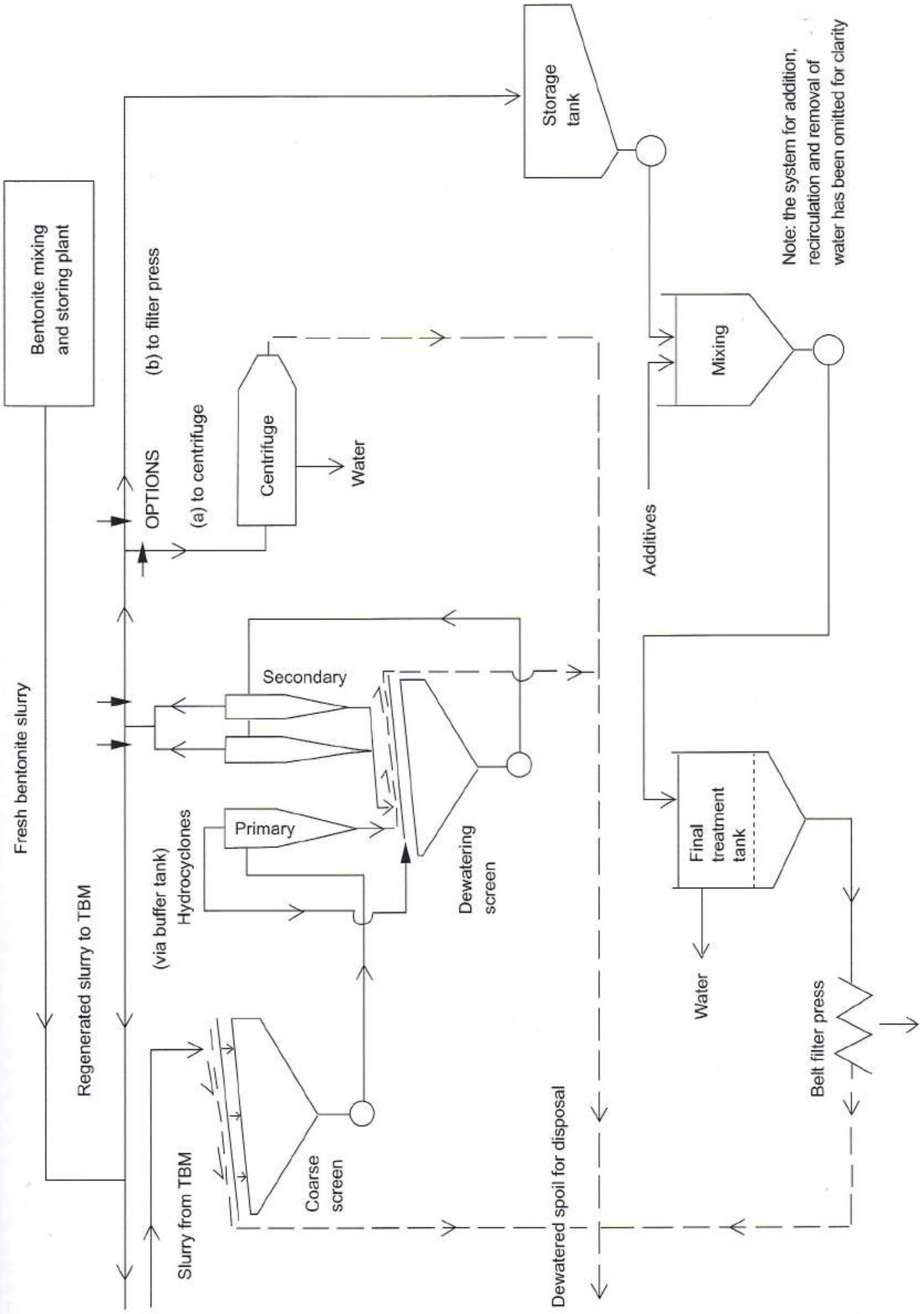


FIG. 12.10. Simplified flow diagrams for typical separation plants: (a) using vibrating screens, hydrocyclones and centrifuge; (b) using a belt filter press in place of a centrifuge.

4.2 The method of working the clay shall be agreed by the Engineer before work commences. Whatever means are adopted they shall produce a continuous plastic mass of puddle clay effectively free from voids, laminations or imperfections which could affect its water retaining properties.

4.3 The clay shall be placed in horizontal layers not exceeding 150 mm consolidated thickness and compacted by an approved method to an air void content not exceeding 5%.

4.4 Unless agreed otherwise with the Engineer, the type of compaction plant and number of passes shall conform with the requirements of Clause 608 and Tables 6/1 and 6/4 for material class 7C (selected wet cohesive material) of the DoT Specification for Highway Works Part 2.

4.5 Before placing a further layer of puddle, the surface of the previous layer shall be cleansed of all slurry and surplus water and the surface prepared to ensure that the clay to be placed shall be integrated with that already placed. Preparation of surfaces between successive layers shall be formed by frequent non-continuous spade cuts into the upper surface of the clay to a depth of 75 mm.

4.6 Where puddle clay is to be joined with existing clay puddle, the existing clay shall be cut back and stepped to form a good key between the existing and new clay puddle over a distance to be agreed by the Engineer, but not less than 1000 mm. All trace of junction marks shall be wholly eliminated.

4.7 Precautions shall be taken to ensure any puddle clay awaiting placing, puddle which has been placed and any puddle clay in dry areas shall be kept continuously wet to prevent it drying out, and covered by waterproof sheet to protect it from rain damage. Precautions shall be taken to prevent the material freezing.

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