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REPORT ON

GEOTECHNICAL ASPECTS OF THE STABILISATION OF SILBURY HILL

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Report on Geotechnical Aspects of the Stability of Silbury Hill

1. Introduction and Terms of Reference

I am employed, through ICON (IC Consultants Ltd.), to advise English Heritage on the geotechnical aspects of the stability of Silbury Hill, near Avebury, Wiltshire. The stability of the Hill is being investigated following the collapse, in 2000, of the infill to a shaft that was originally drilled in 1776 to investigate the Hill.

As part of this investigation extensive geophysical and geotechnical studies of Silbury Hill have been carried out. The geophysical investigation involved the drilling of five boreholes through the full height of the Hill, using down-hole geophysics which was interpreted using tomography. Following the geophysical investigation it was decided to investigate areas of possible loose chalk or voids by direct drilling. Two further boreholes were drilled, No. 6, close to the shaft, and No. 7 in the shaft itself to check the state of the shaft backfill.

This report is based on Skanska's Geotechnical investigation of Silbury Hill (R/03/C2001) dated April 2003, during which boreholes 6 and 7 were drilled, and should be read in conjunction with that report. Other information used in this report has been provided by English Heritage. Manuscript information is referenced in the text, while published information is detailed in the List of References at the end of this report.

2. Shaft collapse in 2000

The shaft collapse in May 2000 exposed the original sides of the shaft to a depth of 10 m. The plan area of the shaft was square, about 1.7 m x 1.7 m. At the base of the open length of shaft there was a cavity to the side of the shaft. The volume of the latter void, discounting the shaft volume at this depth, was about 24 m^3. This volume is equivalent to approximately 8 m depth of shaft, so that the volume involved in the collapse is equivalent to a shaft depth of about 18 m.

A further collapse occurred in December 2000, when the sides of the shaft at the surface fell into the existing cavity. It is not known if a further subsidence of the shaft fill was involved on this occasion.

3. Results of Skanska recent boreholes: BH 6 and BH 7

Borehole 6 was drilled to investigate a less dense area or possible void at depth in Silbury Hill, and to obtain samples for density and water content (or moisture content) measurement. These measurements were made so that comparison might be made with modern earthworks composed of chalk fill. This borehole achieved 100% core recovery, indicative of continuous (no voids) and competent material. Soft material was encountered from19.50 m to 24.35 m depth, and the central peat-stack core of the Hill was found between 25.27 m and 30.15 m. The original in-situ chalk beneath the Hill occurred from 30.60 m, and the borehole was terminated at 34.70 m.

Borehole 7 was drilled to investigate the state of the backfill of the shaft. It was anticipated that there might be some voids in the backfilled shaft, though in the event none was found until the borehole encountered the Atkinson Tunnel. It appears that loose debris was encountered at the tunnel floor, but not in-situ chalk. Baffle plates were found (and drilled through) at the crown of the Atkinson tunnel, which would have been sufficient to prevent shaft infill material from collapsing into the tunnel. However the backfill just above the baffle plates was extremely loose, almost the equivalent of a void. The shaft backfill was in general much less compact than the chalk fill in borehole 6, and the core recovery was much reduced. The Appendix lists several observations which suggest that the shaft backfill subsided on a number of occasions in the past. A series of layers, including buried topsoil, found at relatively shallow depth in borehole 7 support this suggestion.

3.1. Density of the chalk fill in Silbury Hill. The results of density determinations on samples recovered from boreholes 6 and 7 are shown in Figure 1. Comparison with modern specifications for compacted chalk fill show that most samples are significantly less dense (*e.g*. Lord *et al*., 2002) than would now be the case. The density measurements are doubtless biased towards more dense material since less dense samples would be unlikely to be sufficiently competent for the measurement technique used, namely determining volume and mass. The sampling process itself may also have resulted in some densification. Thus it is probable that the average density of the chalk fill of which much of the Hill is composed is less than these test results indicate.

3.2. Slope stability. The inclination of the side slopes of Silbury Hill is variously reported as 27½° to 34°, averaging 32° (Petrie 1924). During construction, the maximum slope is unlikely to have been greater than the angle of repose, the angle at which loosely tipped material will stand. Petrie (1924) observed with the chalk fill that he excavated the angle of repose was 33° 50′.

Assuming the chalk of which the Hill is composed to have a frictional strength of 33° (Skanska Report C100975/CR1), then a 'dry' slope (one in which water pressures are zero) will just stand at that angle. Two factors, however, operate to enhance the slope stability. One, disturbed chalk with the passage of time tends to 're-bond' due to precipitation of calcium carbonate, and even a small proportion of rebonding will significantly improve the stability. Two, the chalk is not truly dry, but in fact has a relatively high water content. Below the water table the pressures in this water will be positive. Above the water table, as is the case for all the chalk-fill portion of the Hill, these pressures are negative, and are often referred to as 'suctions'. These suctions will also improve the stability.

The suctions exist in part because the soil is incompletely saturated; that is, there is air present in the chalk fill. During periods of heavy rain surface layers of the chalk fill will become wetter, the suctions reduce, and the slope become less stable. In spite of this there are no features on Silbury Hill that suggest that landslips have occurred in the past.

It is, however, no surprise that subsidence of the shaft occurred in 2000 after a period of notably wet weather, as was also the case with some of the Merewether tunnel collapses. No doubt these were all triggered by reduced suctions in the chalk fill.

4. Timetable of events of geotechnical significance

The Appendix lists the events known to the writer that are of geotechnical significance. Taken together, it seems likely that:

1. The excavation of the Merewether tunnel in 1849 removed spoil from the base of the shaft, causing further subsidence from that time.

2. The construction of the Atkinson tunnel adjacent to the Merewether tunnel reinitiated subsidence into that tunnel.

3. The use of the support encountered in borehole 7 in the roof of the Atkinson tunnel would have prevented shaft backfill collapsing into the tunnel after 1969.

5. Ground water conditions

The physical behaviour of Silbury Hill as described in Section 3.2 above requires knowledge of the groundwater conditions in and below the Hill. Ground water was encountered towards the base of boreholes 1 to 3 and in borehole 5, which showed the groundwater table to in the in-situ chalk beneath the Hill. Groundwater observations in these boreholes were made on 06/12/01, and are given in Table 1 below.

Borehole No.	**Depth to water, m.**
1	42.0
2	37.4
3	29.5
5	41.5

Table 1. Ground water observations in Silbury Hill.

The groundwater table recorded in the boreholes is reflected in water levels observed in the "moat" which surrounds the Hill, which generally largely dries out in summer and floods in winter.

Two observations apparently conflict with the concept of a water table below, rather than within Silbury Hill. A number of reports from people who entered the Merewether tunnel in the early 1900s reported the tunnel floor to be wet and slippery, and at least one reports a "stream" in the floor of the tunnel, though it is clear from the account that this stream only occupied part of the tunnel length (Sandell *in litt*. to Atkinson, 03/10/67). The general dampness would be consistent with the anticipated high humidity in the tunnel, while the reference to a stream suggest that, at least occasionally, infiltration from rainfall (perhaps coming down the shaft) reached the tunnel.

The second observation is that of the single rotary borehole drilled in 1968 (Appendix), which was recorded as reaching 86' 6" (26.4 m) where the "ground was saturated with water". It seems most unlikely that the ground water table was encountered, particularly as the Atkinson tunnel was concurrently being excavated below this depth apparently without encountering any water. The most likely explanation seems to be that the rotary borehole was drilled using water as a flushing medium, and that at this depth the chalk fill in the Hill became (at least locally) sufficiently dense for the flush water to return to the surface, a condition usually interpreted as a result of the ground being saturated.

6. Possible remedial schemes

Skanska (April 2003) list possible solutions:

- Leave Silbury Hill in its current state and undertake no further work.
- Utilise directional drilling and grouting to fill existing cavities.
- Re-excavate the existing Atkinson and Merewether tunnels, re-support and make safe.
- Re-excavate the 1776 shaft, re-support and make safe.
- Install a temporary cap over the shaft and allow progressive settlement.

I will deal with each of these in turn. Though interconnected in more than one sense, the shaft and the tunnels can be considered as separate problems and could be dealt with as separate exercises if required. It must be emphasised, however, that stabilisation of the tunnels is a necessary prerequisite to stabilising the shaft.

6.1. Leave Silbury Hill in its current state. The history of periodic, albeit relatively small, collapses of the 1776 shaft and of the Merewether and Atkinson tunnels, show that similar collapses can be expected to occur over time, particularly if there are protracted periods of wet weather. It is possible that the Hill could be left in its present state for a few years, perhaps even for tens of years, without further major deterioration. However every collapse represents further weakening of the structure, perhaps with the loss of valuable archaeological data. It must be appreciated that the Hill is in a less robust state than prior to 1776, and may have deteriorated more since 1776 than in its entire pre-1776 history.

I believe that leaving it for more than a few years without some repair works is unadvisable.

6.2. Grout to fill existing cavities There is no doubt that drilling and grouting could be used to fill the existing cavities, both the two tunnels and the shaft. It is also a technique that could be used to consolidate the weak ground within which subsidence is known to have occurred, such as around the shaft, particularly near the top of the Hill, and above the entrances to the tunnels where there have been several episodes of subsidence since 1915.

At first examination this is a promising technique. There are, however, two major matters for concern. First, it is difficult to control grout penetration, and there can be no guarantee that the grout would go where required. Second, since any repairs will have to enable future generations to enjoy Silbury Hill, consideration must be given to any possible long term chemical effects of grout material in the Hill.

6.3. Re-excavate and make safe the existing tunnels Two possibilities exist. Either re-excavate and support one or both tunnels with sufficient lining to eliminate any possibility of further collapse, or re-excavate and completely backfill one or both tunnels. The former would have the advantage of allowing future entrance to the tunnel(s) for archaeological purposes. The latter would, if compacted local chalk were used to backfill the tunnels, potentially put the Hill back to its pre-1776 state.

6.4. Re-excavate and make safe the 1776 shaft It is clear that the 1776 shaft has subsided periodically since being backfilled in (presumably) 1777. It is almost certain that at no time would the backfilling would have involved more than tipping some of the spoil from the shaft back down the shaft. The 2000 collapse involved the equivalent of about 18 m depth of shaft. Since the base of the shaft is known to have been sealed by the support at the crown of the Atkinson tunnel, and since borehole 7 exhibited no voids except perhaps just above the crown of the Atkinson tunnel, it appears that there was (pre-2000) a void or voids totalling about 18 m at depth in the shaft. Usual mining practice until around 1960-1970 was, when backfilling shafts, to block the shaft perhaps 10 m down and then tip in the backfill.

That some spoil remained at the crest of the Hill for many years demonstrated the looseness and/or incompleteness of the backfill, as did its propensity to subside periodically, particularly after periods of unusually wet weather. The likelihood of subsidence was increased after the excavation of the Merewether tunnel when it is clear that spoil was removed from the base of the shaft.

Re-excavation of the shaft is certainly feasible once the tunnels are made safe. A drawback is that the state of the chalk fill around the shaft is uncertain, and re-excavation (as discussed below) may involve more than just the shaft itself.

6.5. Cap (temporarily) the shaft and allow progressive settlement The exact mechanism of subsidence is uncertain. In particular it is not known if it was solely a plug of backfill within the shaft that subsided, either as a whole or in separate sections, or if the settlement of the shaft backfill was accompanied by collapse of material adjacent to the shaft. Such a collapse could have occurred at any stage in the past since there must have been significant open lengths of shaft.

The subsidence event of 2000 certainly involved collapse of the shaft sides. It will be prudent, therefore, to assume that the chalk adjacent to the shaft is disturbed and may have voids anywhere over its full depth. This could also result in difficulties in re-excavating the shaft if this were to be done.

For this reason there may be benefit in delaying treatment of the shaft, which could be done safely as the shaft is now known to be completely backfilled, albeit of rather loose material. Consequently, once the tunnels have been made safe, it will be impossible for the shaft infill to collapse into the tunnel.

Temporary capping of the shaft is thus potentially beneficial, since careful monitoring of the extent of any future shaft subsidence in the future will provide information on the nature of the shaft collapse mechanism. Providing the tunnels are made safe, future subsidence can reasonably expected to be minor. It may be that this could be a long-term strategy, but if this is so it is essential that the situation at the crest of the Hill be reviewed on a regular basis.

7. Conclusions

● Almost certainly Silbury Hill has suffered more damage since the sinking of the shaft in 1776 than at any other time in its 4,500 year history.

● With regard to the Merewether and Atkinson tunnels I agree with Skanska that there is now sufficient information to enable decisions to be made regarding the treatment of the tunnels.

● The tunnels can be made safe, either by (i) providing support to allow future access to the tunnel(s), or by (ii) complete backfilling using local chalk, carefully and thoroughly compacted.

● A decision needs to be made as to whether (i) or (ii) above is to be carried out.

● Making safe the tunnels will ensure against all but minor subsidence directly associated with the tunnels. It will also go a long way to eliminate the possibility of a significant collapse of the shaft backfill since there will no longer be any major voids into which such a collapse could occur. Consequently making safe the tunnels is an essential first stage to any remedial works.

● If the tunnels are properly made safe, then remedial works to the shaft could be delayed. If the latter course were followed, the behaviour of the shaft and its backfill should be carefully monitored on a regular basis, and the results of the monitoring should be reviewed after two - three years, with a view to making the shaft safe at that stage.

● A temporary cap in the form of a steel bulkhead with an inspection hatch as suggested by Skanska could be installed. This would be best done after removal of the polystyrene blocks, perhaps placed on compacted (local) chalk and then buried at shallow depth for safety reasons and to deter vandals. It would then be possible to remove the existing temporary fencing. Any instrumentation should also be buried, again to deter vandals.

● If the decision is made to monitor the shaft performance, simple instrumentation (*e.g.* borehole extensometers or even surface movement points) could be used.

● I recommend that the settlement hollows above the Merewether and Atkinson tunnel entrances should be backfilled with local, hand compacted chalk. The objective is to reduce the risk of local rainwater infiltration which could result in further subsidence.

● For similar reasons every effort should be made to minimise infiltration to the shaft and the surrounding disturbed area. This might be achieved by a very slight doming of the summit (with a fall of about 1:30) and the avoidance of any low points would allow the accumulation of water.

● Apart from the points discussed above, it appears from the recent investigations (including the near surface studies on the north side of Silbury Hill) that the general body of the Hill is otherwise stable. There is no apparent need for any remedial works other than those discussed above.

R.J. Chandler

8. List of References

Atkinson, R.J.C., 1967. A Digest of Information on Silbury Hill. Ms., Department of Archaeology, University College, Cardiff. 7pp.

Lord, J.A., Clayton, C.I.R. and Mortimore, R.N., 2002. The Engineering Properties of Chalk. *CIRIA Publication C574.*

Petrie, W.M.F., 1924. Report of diggings in Silbury Hill, August 1922. *Wilts. Arch. Mag.*, **XLII**, 215-218.

10. Appendix

List of known events of geotechnical significance at Silbury Hill

- Construction: *c.* 4,500 BP

- March 1743 Trees planted on summit, with presumably relatively shallow excavations. (Stukeley 1723; 1743)

- 1776/7 Shaft excavated by Duke of Northumberland and Colonel Drax. Mounds of "earth" at the crest of the Hill reported present by Merewether in 1849 (still present in about 1887 (Pass 1887)) demonstrate that shaft was at best only incompletely backfilled in 1777.

- 1849 Merewether tunnel excavated. Base of 1777 shaft found to be very loose. Roof totally unsupported since 1849 (Atkinson *in litt.* to Taylor 15/01/1969). "Lucis sketch" of this date shows crater at crest. Only the tunnel entrance was sealed at the end of Merewether's investigations.

- 1887 Entrance to Merewether tunnel collapsed, allowing entry. Blocked again in 1923.

- 24/03/1915 Merewether tunnel collapse (Atkinson *in litt.* to Taylor 01/01/1969). "exposed a hole in the hill about 12 feet above where it formerly was." (ms notes, A.D. Passmore).

- 1916 Hole at summit at site of shaft. (Wernham *in litt.* to Atkinson 18/10/67).

- 1922 A section dated 1922 shows top of shaft open. Still present *c.*1924 (Petrie 1924).

- 1922 "a tunnel was cut 20ft. eastwards" (Petrie 1924). [Nothing seems to be known about this tunnel; indeed, it may not have been a true tunnel. Perhaps this should be researched further?]

- 1968 Rotary borehole drilled through hill. Hole stopped at 86' 6" (26.4m) where "ground was saturated with water ... as it was approaching a tunnel being dug at the base of the hill." (Pugh *in litt*. to Atkinson 07/08/68; Pitt 29/07/68).

- 1968-70 Atkinson Tunnel excavated. Filming for BBC in 1968 & 1969; external excavations only in 1970.

- about 24/12/68 Merewether tunnel collapse. (Atkinson *in litt*. to Taylor 01 & 15/01/1969). Followed "exceptionally heavy rainfall during the weeks before Christmas" (Atkinson to Mensbridge, *in litt*., 17/04/69).

- 10-11/01/1968 "Minor subsidence" of Atkinson/Merewether tunnel (Atkinson *in litt*. to Taylor 15/01/1969).

- May 2000 Shaft collapsed.
- December 2000 Further collapse of shaft.

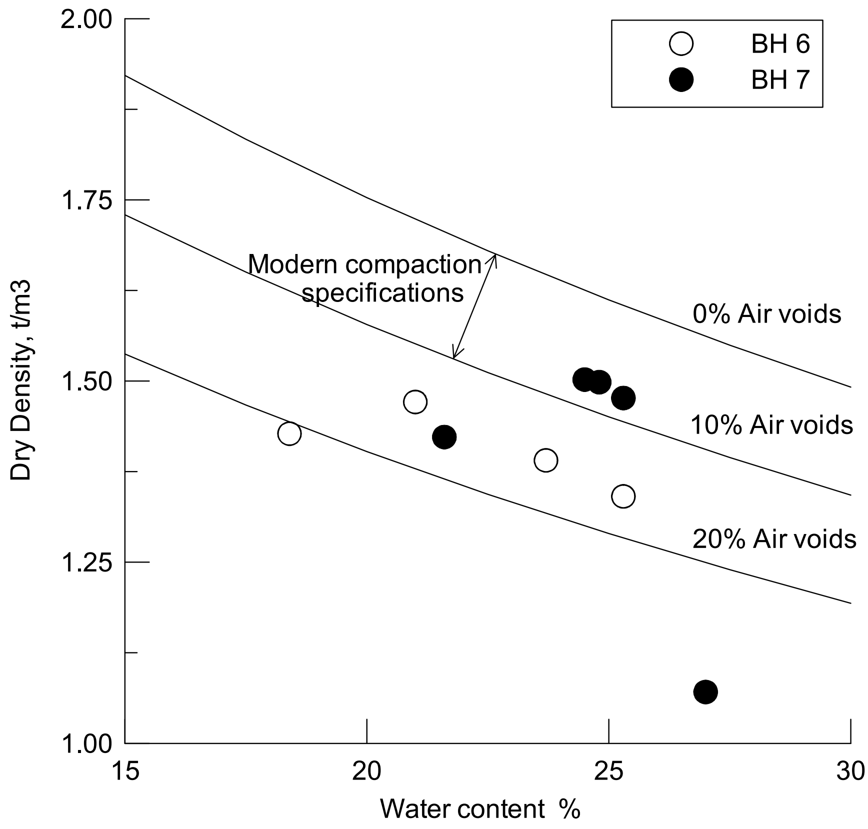

Figure 1. Relationship between dry density and water (moisture) content for the chalk fill recovered from boreholes 6 and 7.