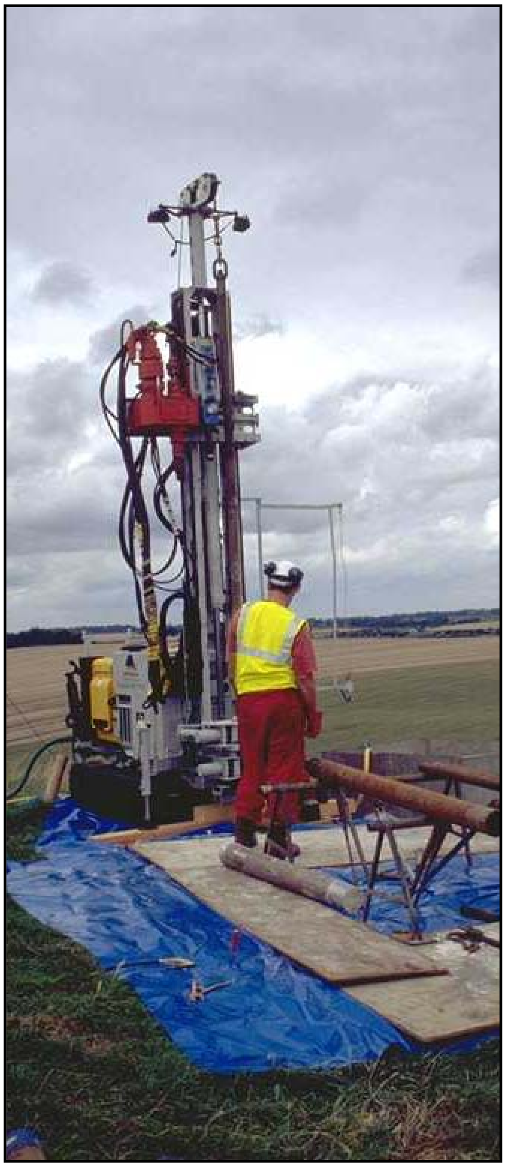
Silbury Hill Review



Interpreting the seismic tomography data

By Professor Michael Worthington

And

Silbury Hill: geotechnical work and investigation of voids

By Professor Richard Chandler

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SUMMARY

Interpreting the seismic tomography data

Professor Michael Worthington

Seismic tomography has proved to be a very effective imaging tool in many applications. However, it is very important to appreciate that the seismic velocity images should be interpreted and not simply accepted as unambiguous evidence of sub-surface structure. Interpretation requires some understanding of the limitations of this exploration method. There are three essential requirements for a successful seismic tomographic survey;

1. Good ray coverage between the source and receiver positions over the region of interest.
2. High frequency (short wavelength) data relative to the size of the buried structures that it is hoped will be imaged.
3. Good data signal to noise ratio.

If ray coverage is approximately uni-directional, then images will be very blurred with poor resolution in the direction of the ray paths. Regions of poor or zero ray coverage can result in false anomalies in the velocity image. Velocity images should always be compared with ray coverage plots. At the very least, one should be cautious if there is an obvious correlation between these two plots.

Virtually all tomographic imaging schemes offered by commercial organisations will be ‘ray-based’. This means that the data are reduced to one measurement: the first arrival travel-time. By so doing, a lot of information in the recorded waveforms about the sub-surface structure is discarded. However, the data analysis becomes comparatively straight-forward. If the seismic wavelength is large relative to the size of the structures that are to be imaged, then the waves will diffract around the structures and there will be little or no evidence of their presence in the first arrival time data.

Finally, good data signal/noise ratio is essential. If the first arrival travel times cannot be reliably picked, then input to the data processing procedure will be rubbish and so, of course, will the output. Unfortunately, it is not always easy to predict the data quality of any particular survey before it is carried out.

The Silbury Hill seismic survey was well designed. Ray coverage was quite sufficient to enable the key questions about the internal structure of the mound to be answered. Some additional crosshole paths would have been an advantage. But this would only have been achieved by peppering the hill with more boreholes. In the sections of the mound where good quality crosshole data were recorded, the frequency content was high enough to provide image resolution of approximately 2 metres. However, the major short-coming and disappointment of the survey was the quality of the crosshole data above the water table, due to extremely poor coupling between the hydrophones and the chalk hill.

Silbury Hill: geotechnical work and investigation of voids

Professor Richard Chandler

Introduction

The following summarises the engineering findings regarding the stability of Silbury Hill. The investigations were instigated following subsidence at the crest of the Hill in May 2000, with the aim of establishing the present-day stability of the Hill, and to examine if there is a need for any remedial works to be carried out.

More important events of geotechnical significance at Silbury Hill

Events in the history of the Hill which have a bearing on its stability are as follows.

- Construction: *c.* 4,500 BP
- March 1743 Trees planted on summit, with presumably relatively shallow excavations.
- 1776/7 Shaft excavated by Duke of Northumberland and Colonel Drax. Mounds of "earth" on the crest of the Hill reported in 1849 and still present in about 1887 suggest that the shaft was incompletely backfilled in 1777.
- 1849 Merewether tunnel excavated. Base of 1777 shaft found to be very loose. Only the tunnel entrance was sealed at the end of Merewether's investigations, so tunnel roof totally unsupported since 1849.
- 1887 Entrance to Merewether tunnel collapsed, allowing entry. Blocked again in 1923.
- 1915 Merewether tunnel collapse "exposed a hole in the hill about 12 feet above where it formerly was".
- 1916-24 Hole at summit at site of shaft.
- 1968-70 Atkinson Tunnel excavated. Filming for BBC in 1968 & 1969; external excavations only in 1970.

- 1968 — Merewether tunnel collapsed following exceptionally heavy rainfall in December. A minor subsidence in January 1969.
- May 2000 — Shaft collapsed following wet weather.
- December 2000 — Further collapse of shaft.

Investigations since 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 exposed depth of shaft there was a cavity to the side of the shaft. The total volume of the collapse (cavity plus shaft) was 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.

Following the collapse of the shaft in 2000, the stability of the Hill was investigated in two stages, geophysical work being followed by a geotechnical study to amplify the geophysical findings. The geophysical investigation involved the drilling of five boreholes through the full height of the Hill. One of these boreholes encountered Atkinson's tunnel, showing that it had not been backfilled.

Geotechnical work and results

Following the geophysical investigation it was decided to investigate areas of possible loose chalk or voids within the Hill by direct drilling. Two further cored boreholes were drilled, No. 6 close to the shaft, and No. 7 in the shaft itself.

Borehole 6 was drilled to investigate a less dense area or possible void at depth identified in the geophysical investigation, and to obtain samples of the chalk of which the Hill is composed for density and water content measurement. This borehole achieved 100% core recovery, indicative of continuous (*i.e.* no voids) and competent material. Less dense 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. Loose debris was encountered at the tunnel floor, where the borehole was terminated. In-situ chalk was not reached. 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. The shaft 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 results of density determinations on samples recovered from boreholes 6 and 7 showed that in comparison with modern specifications for compacted chalk fill most samples are comparatively loose, but not exceptionally so.

Conclusions on the overall stability and condition of Silbury Hill
Taking the results of the investigations together with the history of the Hill leads to the following general conclusions.

- Almost certainly Silbury Hill has suffered more damage as a consequence of the intrusive investigations commencing with the sinking of the shaft in 1776 than at any other time in its 4,500 year history.

- The general body of the Hill is basically stable, but there will be a slow deterioration of the condition of the Hill if the existing open tunnels and the backfilled shaft are not treated in some way.

- 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.

- Making safe the tunnels will ensure against all but very minor subsidence directly associated with the present largely unsupported tunnels. It will also 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.

Options for remedial works
- 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/Merewether tunnels, re-support and make safe.
- Re-excavate the 1776 shaft, support and make safe.
- Install a temporary cap over the shaft and allow progressive settlement.

These options will be discussed in sequence .

Leave Silbury Hill in its current state With the presence of the open tunnels in the Hill, further and continuing subsidence within the Hill can be expected. This will be at a slow rate, though it may accelerate in periods of particularly wet weather. There will be associated internal “archaeological” damage.

Grout to fill existing cavities Drilling and grouting could be used to fill the existing cavities, both the two tunnels and the shaft, and could be used to consolidate the weak ground where subsidence has occurred, such as around the shaft and above the entrances to the Merewether and Atkinson tunnels. There are at least two major matters for concern with this proposal. First, it is difficult to control grout penetration, and the grout may not go where required. Second, consideration must be given to any possible long term chemical effects of grout material in the Hill.

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 access to the tunnel(s) for inspection/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. Once the tunnels have been made safe it will be impossible for the shaft infill to collapse into the tunnel.

Re-excavate the 1776 shaft, support and make safe The exact mechanism of subsidence of the shaft backfill is uncertain. In particular, it is not known if it was solely a plug of backfill within the shaft that subsided, or if the settlement of the shaft backfill was accompanied by collapse of material adjacent to the shaft. Since the subsidence in 2000 involved collapse of the shaft sides it is possible that the chalk adjacent to the shaft is disturbed and/or contains voids, though the geophysical investigation suggests that large voids are unlikely.

If the shaft collapse involved collapse of the shaft sides re-excavation may not be entirely straightforward.

Cap (temporarily) the shaft and allow progressive settlement Temporary capping of the shaft could therefore be potentially beneficial, since careful monitoring (with appropriate instrumentation) of any future shaft subsidence will provide information on the nature of the shaft-collapse mechanism. This could be a long-term strategy, but only if the situation at the crest of the Hill is reviewed on a regular basis. Providing the tunnels are made safe, future subsidence can reasonably expected to be minor.