

# SILBURY HILL

WILTSHIRE



English Heritage's Investigations into the Collapse  
at the Top of the Shaft and the Stability of Silbury Hill.

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## 1 INTRODUCTION

- 1.1 The purpose of this report is to provide a summary of the investigations carried out by English Heritage resulting from the collapses at the summit of Silbury Hill in May and December 2000 and more general concerns as to the stability of the Hill. Its production comes at a time when English Heritage has completed a programme of geophysical and geotechnical investigations, archival research and on-site archaeological work, and has also carried out temporary works to stabilise the area of collapse at the top of the shaft, sunk in 1776 on behalf of the Duke of Northumberland.
- 1.2 English Heritage's investigations have revealed that there are, within the Hill, areas connected with earlier archaeological investigations which have not been backfilled or where the fill is poorly compacted. Although this may lead to the continued upward migration of the tunnels and further slumping of the shaft infill, we know from the geophysical investigations that Silbury Hill is a robust structure which is very unlikely to suffer from major catastrophic collapse.
- 1.3 The results from the on-site investigations were assessed and the findings reported to the English Heritage Advisory Committee (EHAC) in September 2003 ( Harding, 2003 ) along with recommendations for

further work. Subsequently, the Board has developed the options for remedial work and assessed the conservation risks associated with the implementation of each option. Following discussion with the wider archaeological community, a further report has been prepared for EHAC ( Bewley,2005 ) which seeks their advice on the best option for stabilising Silbury Hill.

- 1.4 Alongside the geophysical and geotechnical investigations, much has been learnt about the archaeology of the Hill, especially through the survey work, limited excavations and sampling of the cores extracted from the boreholes sunk to the centre of the mound. This knowledge is only referred to in this report inasmuch as it is relevant to English Heritage's response to geotechnical problems relating to the conservation of the Hill. Extremely interesting discoveries relating to the dating and development of the Hill and to the environmental conditions pertaining to the time of construction, have been uncovered. The results to date have been published in a range of documents ( see bibliography for Canti et al, Cromwell, Field, Linford, Martin and McAvoy ).

## **2 GENERAL BACKGROUND**

- 2.1 Silbury Hill is the largest artificial pre-historic mound in western Europe and perhaps the most well known example of a rare Neolithic feature now classified as a 'Monumental Mound'. The Hill was one of the first

monuments to be given protection under the Ancient Monuments Protection Act 1882.

- 2.2 At the time of the first collapse in May 2000, Silbury Hill was in the ownership of Lord Avebury. It was a designated Scheduled Monument (SM 21707) and as such, was statutorily protected under the Ancient Monuments and Archaeological Areas Act 1979. The Monument was in the guardianship of the Secretary of State for the Department of Culture, Media and Sport who had delegated this role to English Heritage. English Heritage had in turn entered into a Local Management Agreement with the National Trust, who managed the nearby Avebury Stone Circle, for them to take day-to-day responsibility for the maintenance of the Hill, designated car park and viewing point. In August 2000 the National Trust asked for the Agreement to be revoked and day-to-day management reverted to English Heritage.
- 2.3 Silbury Hill is a key component of the Stonehenge and Avebury World Heritage Site. In addition, it is a Site of Special Scientific Interest given statutory protection under Section 28 of the Wildlife and Countryside Act 1981.
- 2.4 Fuelled by unanswered questions as to the identity of its original builders and the purpose of its construction, the Hill has long been the subject of intensive antiquarian and archaeological investigation. The first known occasion was the sinking of a shaft on behalf of the Duke of

Northumberland in 1776 recorded as being 8 feet (2.44m) square and 100ft ( around 35m ) deep. Another major intervention took place in 1849 when the Reverend Merewether supervised the digging of a tunnel which extended to the centre of the Hill and out from there in diverse directions ( McAvoy, April 2001 – fig. 5 ).

2.5 In 1968-70, Professor Richard Atkinson supervised the excavation of a second tunnel. This followed a similar line to the centre of the Hill as the Merewether tunnel but with two laterals and a central chamber. Surface investigations were also carried out ( see Whittle, 1997 ). More minor investigative work is known to have been carried out in 1867, 1886, 1922 and 1959.

2.6 Prior to the collapses in 2000, it was thought, on the basis of the records of Merewether's excavations, that the shaft had been infilled either deliberately or through collapse. It was known that the Merewether tunnel had been left open and that the Atkinson tunnel had been backfilled, but not how effectively.

### **3 ENGLISH HERITAGE'S INVESTIGATIONS INTO THE COLLAPSE TO THE TOP OF THE SHAFT AND THE STABILITY OF THE HILL.**

3.1 On the 29<sup>th</sup> May 2000 a roughly square shaped hole, recorded as approximately 2.25m wide and 10.3m deep, appeared on the top of Silbury Hill. In response, two days later, English Heritage erected a

scaffold and corrugated steel structure to create a secure capping. The aim was to prevent the weathering of the sides of the collapse and stop rainwater collecting and causing further instability. It was also necessary to provide protection to members of the public.

- 3.2 A video camera survey of the collapsed area was carried out and a desk-based assessment of the potential for archaeological recording and investigation was completed in July 2000 ( McAvoy, July 2000 ) This desk-based assessment identified two principal aims for further research work:

Aim 1: To advance our knowledge and understanding of the extent and nature of antiquarian investigation at Silbury Hill.

Aim 2: To advance our knowledge and understanding of the construction and use of Silbury Hill.

- 3.3 The assessment noted that assumptions about the infilling of the shaft were obviously incorrect. At least the top 10m of the shaft had been left open and capped. It was this capping which appeared to have collapsed but it was not known whether this collapsed material lay above either backfill or a further void.

- 3.4 Following completion of the assessment, a field evaluation was carried out on 9 August 2000. With the assistance of consultants specialising in rock mechanics and confined space working, further photographic

recording was carried out and a small number of soil samples taken. It was also possible to undertake a general characterisation of the visible archaeology, and investigate and report on the cause of the collapse.

- 3.5 The specialist consultants found evidence that an upper infill to the 1776 shaft had collapsed into a cavity below. It was proposed that the collapse may have been triggered by the shearing away of the shaft wall below the infill.
- 3.6 Over the following months, a considerable amount of work was undertaken using a wide range of non-destructive survey techniques ( summarised in Harding, 2001.p.4 ). The results of the magnetometer, earth resistance and ground penetrating radar surveys were published in Linford and Martin, 2001 and Linford, 2001. In addition, two small trenches were opened up on the summit of the Hill ( McAvoy, May 2001 ) and extensive archival research was carried out. The Centre for Archaeology recorded the shaft location and the deposits exposed in the sides of the crater. These, when related to information gleaned from archival research, showed that the shaft had re-opened and been filled on a number of earlier occasions ( McAvoy, April 2001, fig. 4 ). The results of the Archaeological Investigation analytical earthwork survey, including archival documentary research and the results of past investigations, were later published in Field 2002.

- 3.7 The more problematic issue was devising a scheme of remedial work. In December 2000 a further collapse occurred to one side of the hole and the geophysical surveys carried out in February 2001 highlighted the instability of the sides of the collapse ( see photographs in McAvoy, April 2001 ). The temporary capping was rendered ineffective by this further collapse and it was feared that it was concentrating rainwater onto the perimeter of the area of fresh collapse to the detriment of the stability of the sides of the hole. It was, therefore, removed and replaced by a fence which was erected around the crater under archaeological supervision ( Cromwell, 2001 ).
- 3.8 The difficulty in devising a repair solution arose from a number of factors. First, the uniqueness of the construction of Silbury Hill and the fact that there were no standard, tried-and-tested repair solutions. Secondly, there were concerns that a standard solution such as grouting could have an adverse chemical reaction with material in the Hill, that it would not be reversible, that there would be no way to control its flowpath and no way to test its effectiveness in consolidating the mound. Thirdly, there were concerns that if the hole at the summit were to be simply filled with chalk then the weight of the new fill could precipitate further collapses into unknown voids below. Fourthly, English Heritage had no clear idea as to the compactness of material and presence of voids deep in the Hill.
- 3.9 To address these concerns English Heritage took the following steps:

- (i) It drew up a brief for geophysical investigations ( McAvoy, April 2001 ) and sought tenders from suitable contractors to achieve the objectives of the brief which were defined as:
- To locate, and map in three dimensions:
    - a) any significant air-filled voids within the make-up of the mound.
    - b) the present position of the Merewether and Atkinson tunnels.
    - c) any other zones of structural weakness within the make-up of the mound (e.g. infilled voids, zones of low density and/or water saturation).
    - d) any planes of weakness (e.g. slip or shear planes) within the make-up of the mound. These should include planes of differential compaction such as those that might exist between the less well compacted filling of the 1776 shaft and its surroundings.
  - To provide some correlation between the pure geophysical information obtained and the material properties of the make-up of the mound.
  - If feasible to locate, and map in three dimensions, any structural features contemporary with the construction of the mound (e.g.

features cut into underlying solid chalk subsurface, the overlying turf core, interfaces between subsequent layers of make-up, revetments of chalk blocks, concentrations or layers of sarsen boulders).

- (ii) It engaged Professor Michael Worthington, Professor of Geophysics at the School of Mines, Imperial College London to provide expert advice to the project team including helping assess tender submissions.
- (iii) It set up a Project Board chaired by the Regional Director, Dr Kevin Brown, to provide a focus for decision-making and to ensure that the necessary resources were made available.
- (iv) It established a set of criteria for the design of remedial works against which any proposals would be judged ( Harding, 2001 )

3.10 Cementation Skanska, a company with considerable geotechnical experience, won the tender for the geophysical investigations. Their proposal was for the execution of a seismic tomography survey. The theory behind this technique is that seismic energy travels through different materials at different velocities. This enables the interior of a volume to be reconstructed by interrogating this region with an energy source and examining the transmitted and scattered wavefields. This technique had not been used before to look deep within a structure

such as Silbury Hill to help determine its stability and possibly reveal its archaeological history. It was recognised, however, as the only technique which might be able to do so and which it was felt could, if successful, have significant potential.

3.11 Skanska's method for executing the survey was to drill four boreholes from the plateau at the top of the Hill. Cross-hole data would then be collected utilising an airgun source and in-hole hydrophones. In-hole to Hill slope surface source data would be collected utilising an airgun source and surface geophones ( Skanska, 2001 ( note – all Skanska Cementation reports were written by M.A. Kirkbride ))

3.12 Skanska commenced work in August 2001. As part of their commission they were asked to carry out works to temporarily infill the hole which had resulted from the shaft collapse. The purpose of this work was to stabilise the sides of the collapse and to protect both the top of the Hill and the shaft from the on-coming winter weather. It also ensured that the drilling operations and vibrations occurring during the tomographic survey did not destabilise the sides of the collapse. The infilling was achieved by lining the collapse with a geo-membrane, filling this with polystyrene blocks and capping the hole with a layer of chalk ( see McAvoy, 2005 fig. 6 ).

3.13 During the drilling operation, one borehole penetrated the western lateral from Atkinson's tunnel. Drilling was stopped and a downhole

CCTV camera lowered down to the lateral. This revealed that the roof of the lateral had collapsed and partially filled the tunnel ( see McAvoy, 2005 fig. 14 ). A fifth borehole had then to be sunk to complete the seismic survey. Geotechnical logging and archaeological examination of the earth cores recovered from the boreholes were carried out at English Heritage's Centre for Archaeology. Skanska published their tomographic survey report in November, 2001. The report includes the geological logs, seismic data record sheets and seismic images.

3.14 Skanska's principal findings were that significant anomalies were located at the site of some, but not all, of the areas disturbed by Merewether's and Atkinson's tunnels and the earlier shaft. They also drew attention to a number of "significant low velocity anomalies", in particular one in the central "core" of the Hill, corresponding with the surroundings of the 1776 shaft and the 1969 tunnel excavations, and one rising up the northern slope ( see Skanska, 2001, fig.s H3 to H9, H15 to H19 and H21 to H24 ). These, they considered, should be investigated further. Laboratory testing showed that the mound material had typical strength and angle of friction values for reconsolidated chalk. There appeared to be no significant risk of severe slope instability but Skanska highlighted the risk of continued upward migration of voids, resulting in further surface collapse.

3.15 Following Skanska's on-site investigations, there was intensive correspondence between English Heritage's adviser on geophysics,

Professor Worthington, and Skanska regarding the method and detail of the processing of the collected data and the conclusions to be drawn. Professor Worthington assessed the tomographic images produced by Skanska and requested further details regarding particular technical aspects of the data analysis.

3.16 In studying Skanska's findings, Professor Worthington concentrated on two recorded anomalies, those to the north slope and the central "core" (Worthington, January, 2002). With regard to the northern anomaly, he felt that the ray coverage was good and found that the interpretation of the travel times was consistent with the presence of an anomaly. He felt, however, that further investigation was necessary to confirm the existence and identify the precise nature of this anomaly. With regard to the central "core", Professor Worthington considered the ray coverage inadequate and the travel times unreliable. As such, he considered that, to date, there was no evidence for the existence of a low velocity zone at the base of the central core of the mound between the boreholes. He recommended that another crosshole survey should be conducted to investigate this region.

3.17 Physical features on the northern aspect had been identified by the Archaeological Investigation Team as a result of their topographic and analytical survey (Field 2002). In order to test the anomaly highlighted by Skanska and by extension the validity of their results, the Project Board decided to carry out further investigations in this area. These

were progressed in two ways. First, Skanska were asked to undertake a surface-based refraction survey on the Hill adjacent to the northern anomaly ( see Skanska, April, 2002 ) Secondly, the Centre for Archaeology was asked to take a series of cores across the anomaly ( see McAvoy, 2002, fig. 3 ).

3.18 The results of the refraction survey confirmed, in Skanska's opinion, their earlier findings of a northern anomaly ( Skanska August, 2002 ). The Centre for Archaeology's report on the northern anomaly was published in September 2002 ( McAvoy, 2002 ). As a result of their cores, the Centre for Archaeology found marked contrasts in the nature of the deposits on this part of the Hill, with 'soil' deposits found to a greater depth in the area of the possible platform already highlighted by the earlier topographical survey ( Field 2002 ). Chalk and subsoil 'mound' deposits comparable to those in earlier Skanska cores were, however, seen in all the CfA cores.

3.19 Skanska's data, collected during the tomographic survey ( Skanska, November 2001 ), relating to the core of the mound were considered inconclusive due to poor transmission and, after trials, Skanska returned to site in April 2002 to resurvey the area using additional equipment. They again concluded ( Skanska, June 2002 ) that there were a number of low velocity anomalies, the most significant of which were located below the stabilised crater, to the northern slope and to the 1969 tunnel portal. Other significant anomalies were located in the

central lower “core” and between this and the overlying crater zone The results of Skanska’s three reports from November 2001, April 2002 and June 2002 were combined in their final report published in August 2002 ( Skanska, August 2002 ).

- 3.20 Professor Worthington in his report ( Worthington, October 2002) considered the degree of confidence that could be placed in the seismic velocity images within the central core” of the mound between the four boreholes (having dealt with the borehole to surface images in his earlier report ( Worthington, January 2002) ). He identified two relevant possible causes of error in such images. The first was travel-time picking error and he considered the error estimates to be over-optimistic for source and receiver depths of less than 20 metres. He therefore argued that a low level of confidence needed to be attached to the smaller, anomalous, low velocity features. The second possible cause of error looked at by Professor Worthington was uneven ray coverage. As a result of the paucity of ray paths in certain areas, he considered that there was doubt as to the existence of the vertical elongated low velocity anomalies which appeared to run parallel to the shaft. Professor Worthington did, however, consider that the anomaly at a high level associated with uncompacted material at the top of the shaft and the anomaly in the region of the chalk bedrock and the bottom of the mound material were well resolved. He concluded, “My overall impression of what can be deduced from this survey is that the mound is essentially rather homogeneous”.

3.21 In October 2002 the Silbury Hill Project Board considered the results of geophysical investigations up to that date. They were assisted by Professor Worthington and also by Professor Richard Chandler, Professor of Geotechnical Engineering at Imperial College London and a chartered civil engineer. He was employed by the Board to advise on the interpretation of the geophysical investigations and the design of any possible remedial work. The Project Board decided to execute further sampling to the area of the shaft and one of the vertical elongated low velocity anomalies running parallel to the shaft and later referred to as a “chimney type feature” ( Skanska, August 2002, fig. 1, anomaly A2 ).

3.22 The brief for this work ( Harding and McAvoy, 2002 ) identified the objectives for the geotechnical investigations to the shaft as being:

- to check there are no large voids at the base of the shaft or at intermediate levels.
- to locate, record and assess any significant air-filled voids which do exist in or adjacent to the shaft.
- inform the design of long-term remedial works to this area.

It identified the objectives with regard to the investigations to the chimney type anomaly to be:

- to assess the validity of the hydrophone investigations to this area and, by analogy, to other areas of poor or zero ray coverage.
- to provide further information on the make-up of the ground in the defined anomaly and the presence of any voids.
- to locate, record and assess any significant air-filled voids within this anomaly .

3.23 The brief required the drilling of two vertical boreholes in total to the areas concerned, the recovery of columns of continuous, undamaged material for archaeological study and the execution of geotechnical testing of the cores to determine water content and bulk density.

3.24 Skanska responded with the submission of a proposed methodology ( Skanska, November 2002 ) which was agreed by English Heritage and work commenced on site in March 2003. The borehole to the shaft encountered, at its base, the steel support to the Atkinson tunnel and a significant cavity below. A CCTV borehole inspection camera was lowered and the cavity inspected. The Atkinson tunnel was found to be in reasonable condition, 1.64m high and continuing as a cavity for at least 4 to 5m along the tunnel ( McAvoy, 2005, fig. 15 )

3.25 Skanska presented the results of their investigations in April 2003 ( Skanska 2003 ). Those from borehole 6, through the possible chimney

type anomaly, showed reasonably consistent barrel penetration and recovery rates with material similar to that recovered in the first five boreholes.

- 3.26 With regard to the low velocity anomaly identified on the tomographic survey, Skanska proposed that this anomaly could reflect “subtle variations in the material properties of the Hill, which could include changes in the saturation state and in-site material parameters”.
- 3.27 By contrast, borehole 7, down the centre-line of the shaft, encountered significantly different material including some very soft layers and a particularly poorly compacted zone above the steel arch of the Atkinson tunnel. Significantly higher moisture contents were also recorded in this borehole.
- 3.28 The Project Board asked Professor Chandler to review Skanska’s findings and make recommendations as to possible remedial schemes ( see Chandler, 2003 ). In his report, Professor Chandler discussed Skanska’s conclusions and noted that the density of the chalk fill was less than that required in modern specifications. He also considered the slope stability of the Hill and, while noting that it was close to the angle of repose, argued that it would have been improved by the process of ‘rebonding’ of the disturbed chalk by precipitation of calcium carbonate and by ‘suctions’ caused by the negative water pressure in the chalk-fill proportion of the Hill.

3.29 Professor Chandler looked at various possible remedial schemes including:

- leaving the Hill in its current state.
- grouting of voids from the surface.
- re-excavating the tunnels and either supporting or backfilling them.
- backfilling to the settlement hollows above the entrances to the Merewether and Atkinson tunnels.
- re-excavating and capping the shaft.

He concluded that, apart from the areas of the shaft and tunnels, “ It appears from the recent investigations .... that the general body of the Hill is otherwise stable. There is no apparent need for any remedial works other than those discussed above”.

3.30 The Project Board prepared a report for the English Heritage Advisory Committee (EHAC) on progress to date which asked them to consider supporting further research into the feasibility, benefits and disadvantages of re-excavating the tunnels and properly backfilling them ( Harding, 2003 ).

3.31 In discussions prior to the committee meeting, EHAC members Professor Martin Bell and Professor Tim Champion stressed that English Heritage should carefully consider the effects that re-opening the Atkinson tunnel would have on the turf stack at the centre of the Hill. Analysis of the cores from the boreholes by the Centre for

Archaeology had shown that biological material within the primary mound was excellently preserved ( Robinson, D.E. 2003 and Robinson, M., 2003 ). It was felt that the cores had the potential to tell us a great deal about the natural environment at the time the Hill was first constructed, construction processes and the Hill's chronology.

3.32 The Committee endorsed the recommendations of the report and the Project Board subsequently developed a research strategy to provide, as far as possible, answers to questions regarding the various options for conserving the Hill. The results of this work were presented to a seminar held at Devizes in September, 2004 attended by invitees from the wider archaeological community and interested local bodies.

3.33 Besides a version of this document, papers were presented by Professor Worthington entitled " Interpreting the Seismic Tomography Data " ( Worthington, 2004 ) and by Professor Chandler on " Silbury Hill : Geotechnical Work and Investigations of Voids " ( Chandler, 2004 ). Campbell and Canti presented a report on " Site Formation, Preservation and Remedial Measures at Silbury Hill " ( Canti et al, 2004 ). This paper, as well as reviewing the results of the examination of material arising from exploratory interventions, looked at the impact on environmental remains of the different possible remedial options.

3.34 A further paper by McAvoy drew on this work and developed it to provide, as a draft for discussion, " An Assessment of the Conservation

Risks and Possible Responses Arising from Antiquarian and Archaeological Investigations Deep into the Hill “ ( subsequently revised as McAvoy, 2005 ). This assessed the condition and extent of known or predicted voids, looked at what damage they might cause and sought to model the nature, extent and possible rate of such damage. Having done so, the report looked at the impact of such damage on the archaeology of the Hill. Finally, the report identified the possible responses to the threats to the Hill’s archaeology and weighed up the possible conservation benefits and risks of each response before assessing them against the conservation principles set out at the inception of the project ( Harding, 2001 ).

- 3.35 At the seminar, a range of views were expressed as to how English Heritage should proceed. Three key points could be drawn from the contributions made. Firstly, there was little support for the idea of remotely filling the voids by grouting. Secondly, there was however considerable support for the idea of reexcavating the tunnels and refilling them and thirdly, if such an intervention was to take place, it should, on this occasion, be accompanied by the highest level of archaeological recording and investigation.
- 3.36 In the month following the seminar further investigations were carried out at the entrance to the Atkinson tunnel ( McAvoy, 2004 ). These established that this tunnel had been comprehensively backfilled close to the surface.

3.37 Following on from the seminar, a further paper has been prepared for the English Heritage Advisory Committee seeking the Committee's advice on the best option for stabilising Silbury Hill ( Bewley, 2005 ). A range of options are outlined in the paper and the associated risks and benefits discussed.

## SILBURY HILL

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