Assessment of the results of a seismic tomographic survey at Silbury Hill, Wiltshire.

M.H.Worthington
Imperial College Consultants (ICON Ltd)

For English Heritage

Seismic contractor: Cementation Skanska

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Introduction

The aim of this assessment and report is to provide English Heritage with an appreciation of the uncertainties associated with the Silbury Hill tomographic image. Uncertainty or ambiguity is essentially related to three factors;

(1) error picking the travel times (normally because of poor signal to noise ratio)
(2) ray coverage
(3) resolution issues relating to the Fresnel zone of the propagating wave.

Although a number of small anomalous velocity zones can be seen in the 3-D tomogram, two quite major low velocity anomalies, one in the central core of the hill and the other on the Northern flank, are listed as principal findings in the conclusions of the Cementation Skanska report. Both of these anomalies could be associated with quite large regions of relatively uncompacted soil and possibly voids. This report is specifically concerned with an investigation of these two major anomalies. Very little ambiguity arises from considerations of resolution related to Fresnel zone radius (item 3 above) simply because of their relative size. The important matters to consider are;

(1) How accurate or uncertain are the travel times with which the images are constructed?
(2) Is the ray coverage adequate to enable a reliable image to be constructed?

The North slope anomaly

Figure 1 shows the locations of the geophones superimposed on the plan view through the tomographic image at 155 metres (30 metres below the summit of the mound).

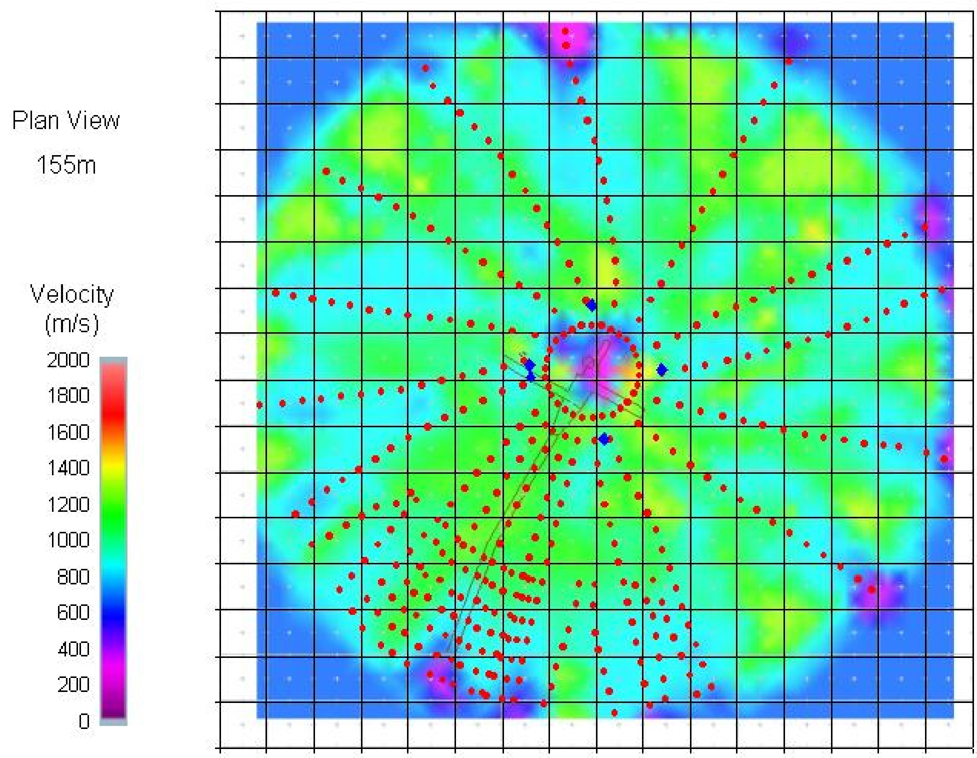

Figure 1: Plan view of tomographic image with positions of surface geophones (red dots) and boreholes (blue diamonds).

Note that at the outer fringes of the image, there is a correlation between the velocity image and the location of the geophone lines (or spokes as they will be referred to below). This is not at all surprising. Seismic data recorded at the end of the spokes will normally have the lowest S/N ratio. There is a tendency to pick travel times late if S/N ratio is poor because the first arrival can often be small relative to events at later time. Consequently, I am not surprised to see regions of low apparent velocity at the tips of some of the spokes, particularly as ray coverage at these points is sparse and uni-directional. There is no ray coverage at all between the spokes on the outer fringes of the image. These regions are therefore totally unconstrained by the data and so the petal-like fringe to the image results. However, the low velocity north slope anomaly associated with spoke 19 (see figure 7 for labelling of spokes and borehole) is too large to be dismissed as an image edge artefact.

The ray coverage defining the anomaly from holes 1, 2 and 3 into spoke 19 is good. I have examined the data quality and have checked a selection of travel-time picks to ensure they are consistent with the image as presented. Figure 2 shows the topography of the slope along spoke 19. The in-plane positions of holes 1 and 2 are also shown.

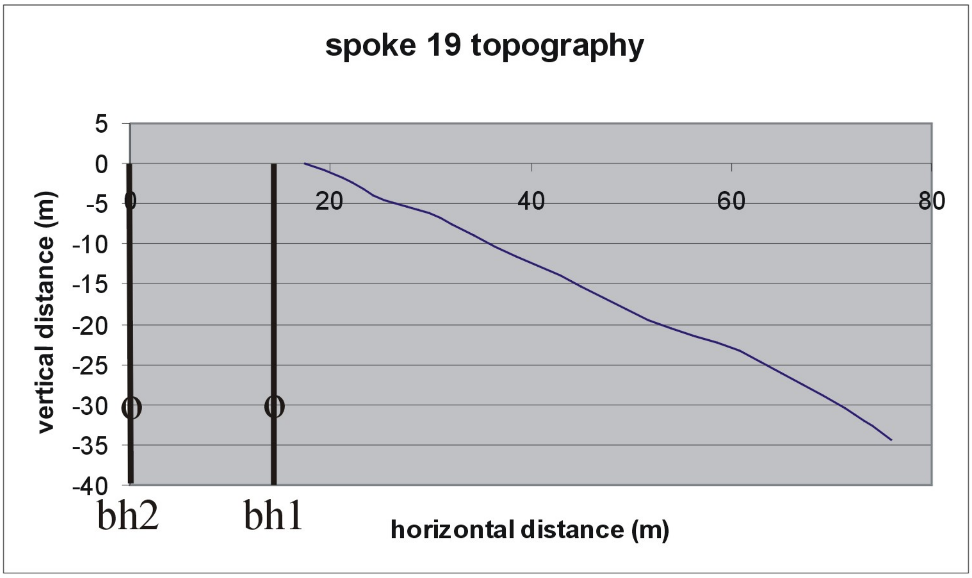

Figure 2 :Topography of the slope along spoke 19. The in-plane position of holes 1 and 2 are also shown. A circle in the holes at 30 metres depth marks the source position discussed in the text.

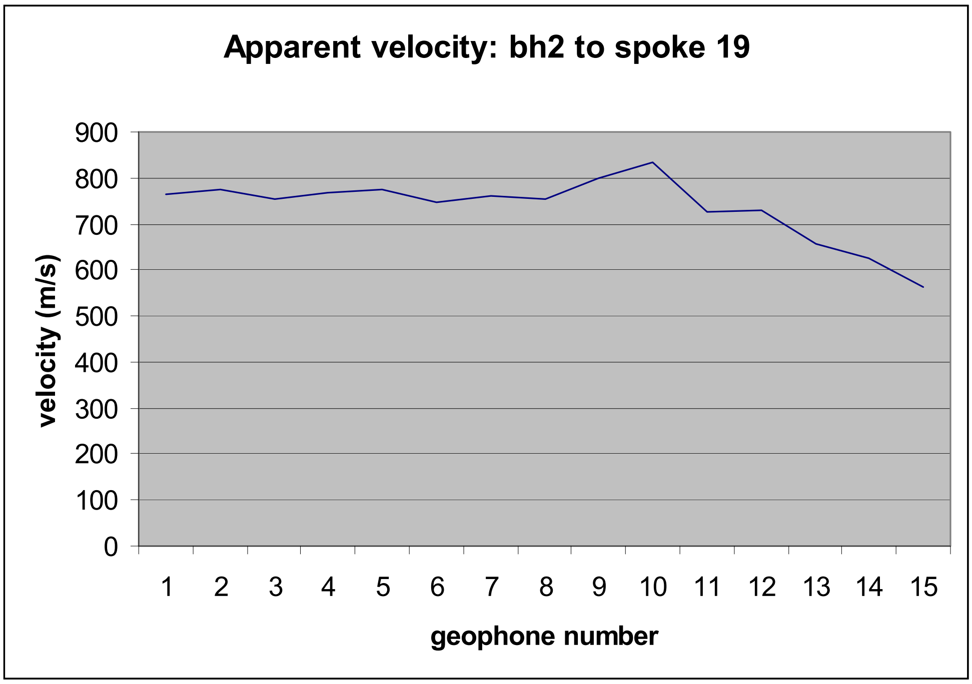

Figure 3 : Apparent velocities calculated from travel-time picks of the spoke 19 common shot gather with shot at 30 metres depth in hole 2.

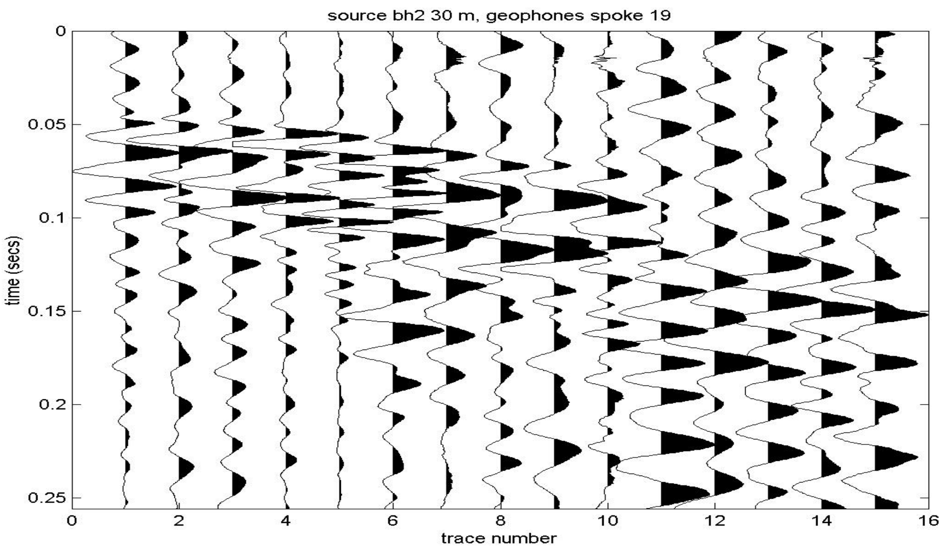

Figure 4 : Common shot gather from a shot at 30 metres depth in hole 2 into spoke 19.

Figure 4 shows a common shot gather from a shot at 30 metres depth in hole 2 into the geophones of spoke 19. Note how the data quality (S/N ratio) reduces rather abruptly at and beyond geophone position 11. This effect is generally observable in all spoke 19 gathers. Figure 5 shows another example for a shot in hole 1. Here the relatively abrupt transition in data quality occurs at geophone position 13. For comparison, I also have included (figure 6) the gather from a shot at 30 metres depth in hole 2 into spoke 25. Note the good data quality for all traces compared to the outer traces of figure 4.

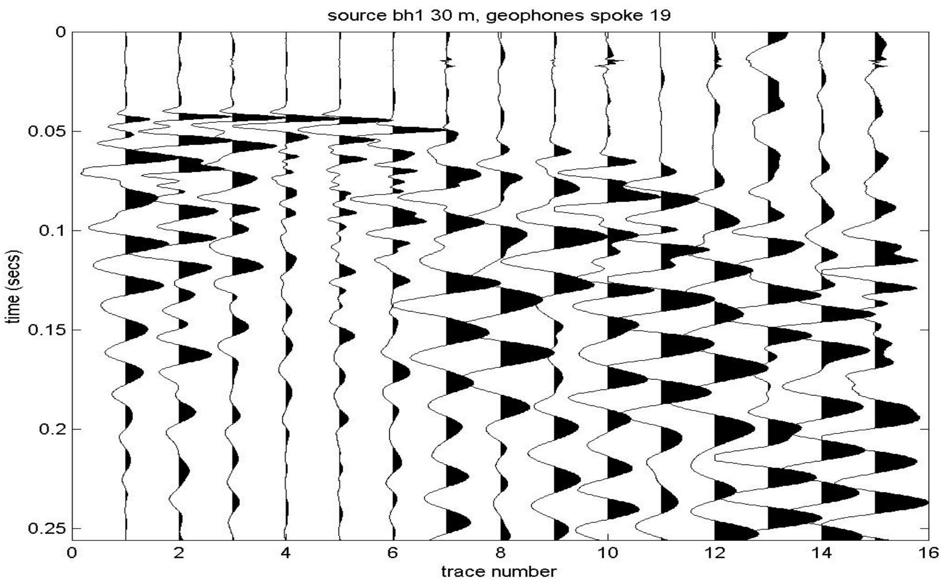

Figure 5 : Common shot gather from a shot at 30 metres depth in hole 1 into spoke 19.

Figure 3 is one result of a simple test to check that a selection of observed travel-times are consistent with the velocity image. It shows the apparent or average velocities calculated from my travel-time picks of the data in figure 4, assuming simple straight ray paths from shot to receiver. I would normally consider traces 11 to 15 to be un-pickable. But forcing myself to pick something, I have picked late. The average velocity from the first ten traces is consistent with Skanska's quoted average velocity for the mound. The onset of lower average velocity or alternatively poor data quality coincides with the location of the low velocity zone. I emphasise that this is only a

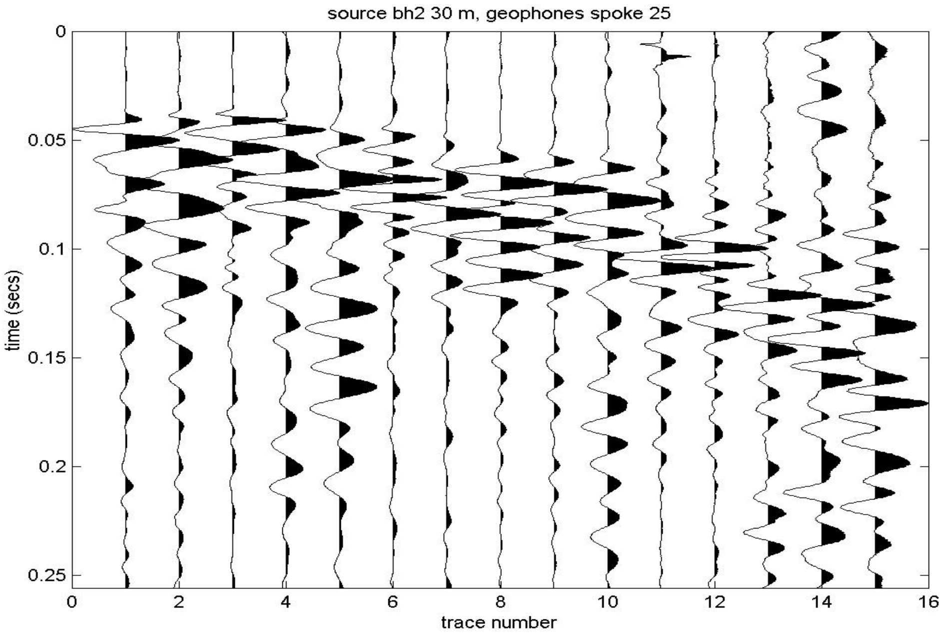

Figure 6 : Common shot gather from a shot at 30 metres depth in hole 2 into spoke 25.

simple check. The Stanska inversion takes account of any ray bending and averages the results of a large number of picks. However, the comparison of travel-time residual (or apparent velocity) plots with the final image is a standard procedure and is a good rough check on the validity of the result.

This exercise is a good illustration of a common cause of ambiguity. A region of uncompacted ground will normally have a relatively low seismic velocity but is also likely to have a high seismic attenuation coefficient. Consequently, it is difficult to accurately image the low velocity zone because the data quality is poor, precisely because the rays are passing through an uncompacted zone. So I am persuaded of the existence of the north slope anomaly as much by the quite clear evidence of a localised region resulting in poor data quality as I am by the actual value of velocity in the final image. There remains the possibility that the poor data quality is simply due to poor geophone coupling. Alternatively, the low velocity anomaly could be an artifact resulting from the difficulty of picking noisy data but that the data are noisy because of seismic scattering due, simply as a wild guess, to the abundance of flint boulders in the mound in this region. I conclude that further experimentation is required to confirm the existence of a zone on the north slope that is cause for concern. Fortunately, the obvious additional experiments are simple and relatively inexpensive. I would recommend a simple surface refraction (time-term) survey up the slope in the vicinity of spoke 19 and at one or more other radial positions for comparison.

The central core anomaly

The major issue here is ray coverage. Figure 7 shows the geophone and borehole locations. The following geophone data were recorded:

Shots in hole 1 into spokes: 11, 13, 15, 17, 19, 21, 23
Shots in hole 2 into spokes: 17, 19, 21, 23, 25, 27, 29
Shots in hole 3 into spokes: 1 ,2, 3, 4, 5, 6, 7, 23, 25, 27, 29
Shots in hole 4 into spokes: 1, 2, 3, 4, 5, 6, 7, 9, 11, 13, 29

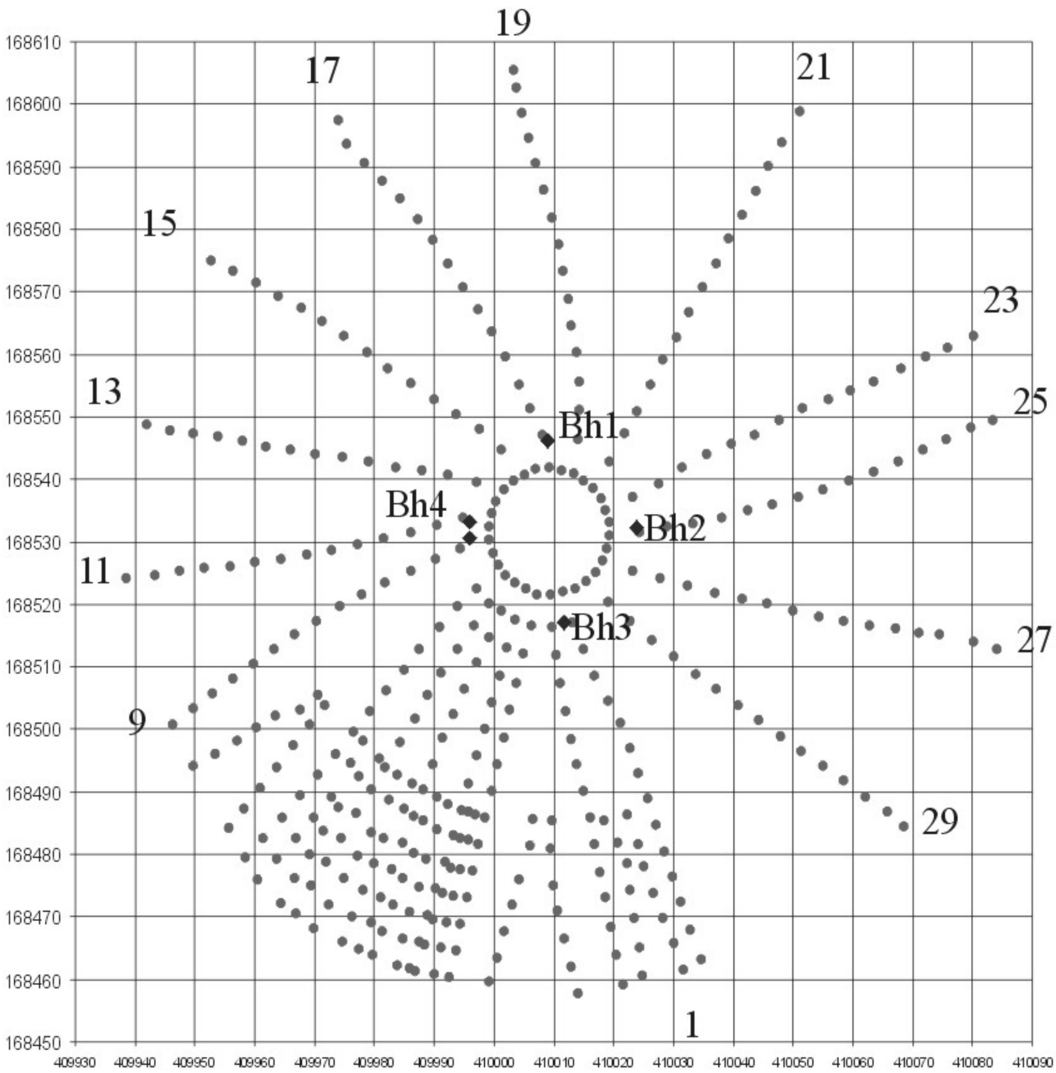

Figure 7 : Borehole and geophone locations.

In addition, all shots were recorded at the two central rings of geophones at the top of the mound. Note that no ray path from the shots to the spoke geophones crosses the region between boreholes. This is entirely sensible survey design, since the hydrophone data were supposed to cover this region. The region between the holes is partially covered by ray paths from shots to the two central rings of geophones. Figure 8 shows these ray paths. Note that no ray passes through the lower triangular region below the red lines labelled 'NO DATA'. This region is, in fact a cone in three dimensions. It corresponds quite closely to the central core velocity anomaly.

The only data that constrains or defines the central core anomaly are the crosshole hydrophone data. Unfortunately, the only hydrophone data that were considered of suitable quality to be picked were five shots in hole 1 at depths 26, 28, 30, 32 and 34 metres depth, recorded in hole 3 at twelve depths from 22.8 metres to 44.8 metres. This is a very sparse dataset but should at least provide evidence of any anomalous low velocity.

Figure 9 shows the hydrophone data from a shot at 28 metres depth in hole 1 recorded by hydrophones from 22.8 to 44.8 metres depth in hole 3. These are the data that were provided by Skanska before the final presentation meeting as an example of

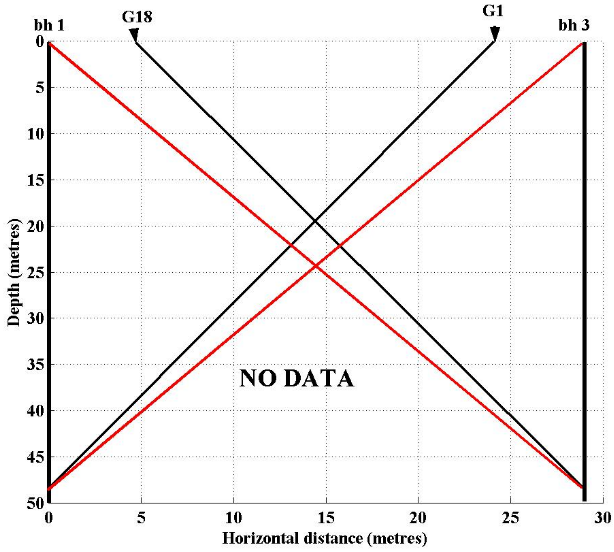

Figure 8 : Ray paths from the deepest shots in holes 1 and 3 into geophones in the inner (black) and second (red) central rings.

interpretable hydrophone data. Picked times were identified and the time increased from trace 1 to trace 12. The two arrows in figure 9 mark the approximate beginning and end time of these picks.

A similar event to the one shown in figure 9 is recorded for shots at 26, 30, 32 and 34 metres depth. Above and below this depth, the event disappears and no evidence of

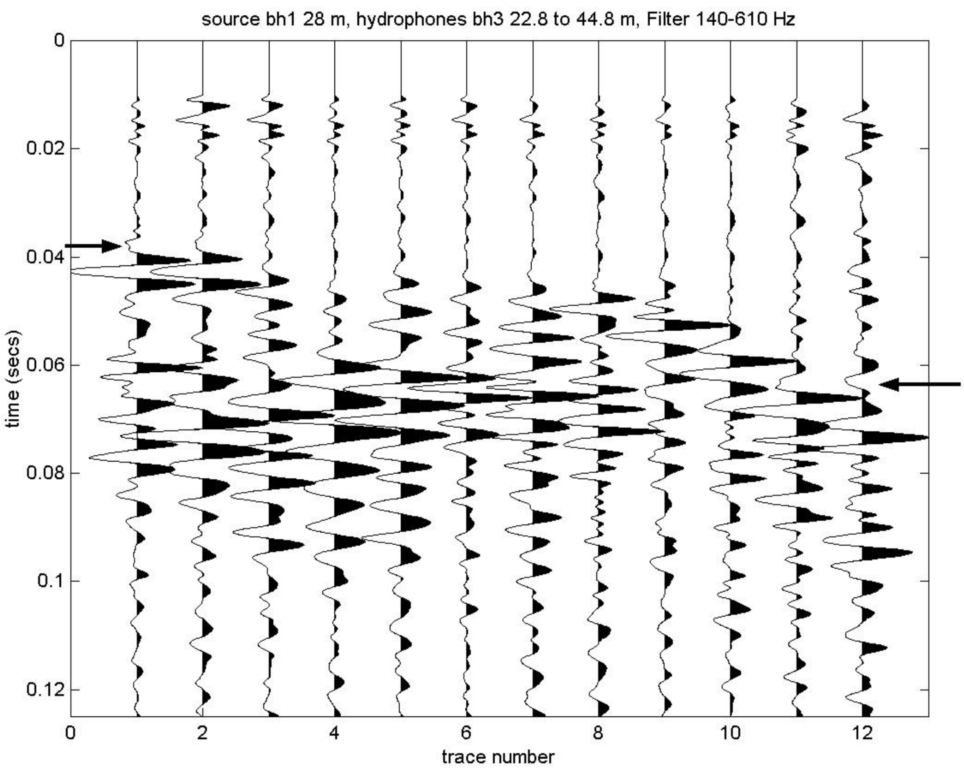

Figure 9 : Common shot gather from a shot at 28 metres depth in hole 1 into hydrophones in hole 3 from 22.8 to 44.8 metres depth at 2 metre intervals. A band pass filter has been applied to the raw data. The two arrows mark the approximate beginning and end points of the travel-time picks provided by Skanska.

any event that might have been generated by the shot can be identified. This is worrying. The fact that no other similar high frequency, high quality event could be identified in any of the other 201 hydrophone shot gathers is reason for caution. One might reasonably expect the minimum travel time to appear opposite the source depth at 28 metres which corresponds to trace 4, rather than at trace 1. In addition, the form of the event (relative travel times from trace to trace and shape of the waveforms) is similar for the five shot gathers. However, there is a mean travel-time difference for the different shot gathers. This is illustrated in figure 10. Common receiver gathers are shown for hydrophones at 22.8, 32.8 and 40.8 metres depth Note that the five signals in any one receiver gather are approximately similar. Note also that the relative time shift between traces in a gather is the same for all three gathers.

These data cannot be explained in terms of the travel-times one might reasonably expect between parallel shots and receivers. Essentially, we have five recordings of approximately the same event, differing only by a static time shift. It would be attractive to postulate that it is secondary scattered energy from some point diffractor and the time shift represents the travel-time from source to diffractor. Unfortunately, I fail to envisage any configuration of shot, diffractor and receiver array that would result in the travel-time shifts shown in figure 10. I can think of only two possible explanations:

(1) It is a spurious noise event that happens by chance to have been caught in the recording time window. Alternatively, the noise event might have something to do with the shot but the time delay between shot and noise event is random.
(2) A diffracted event is directly causally connected to the shot but the seismograph trigger is operating erratically.

I am not particularly satisfied with either of these explanations. I can only add that I have been doing crosshole surveys using hydrophone strings for over twenty years and this is not the first time I have puzzled about and failed to understand the cause of spurious events. However, I am completely certain that travel times from these five hydrophone gathers should not be included in the tomography data.

I conclude that there is no evidence at all for a low velocity anomaly towards the bottom of the central core of the mound between the boreholes. This region can only be investigated by attempting another crosshole survey, having established the cause of the failure of the previous survey.

Conclusions

Two significant velocity anomalies, which could be associated with quite large volumes of relatively uncompacted soil, were identified in the 3_D tomographic image. Those parts of the total seismic data that would have given rise in these two anomalous features have been analysed in some detail.
I conclude;

(1) there is evidence for an anomalous zone in the region of geophone spoke 19 on the North slope of the mound. However, further surface seismic tests are recommended to determine the precise nature of the anomaly.
(2) there is no evidence at all for the existence of a low velocity zone at the base of the central core of the mound between the boreholes.

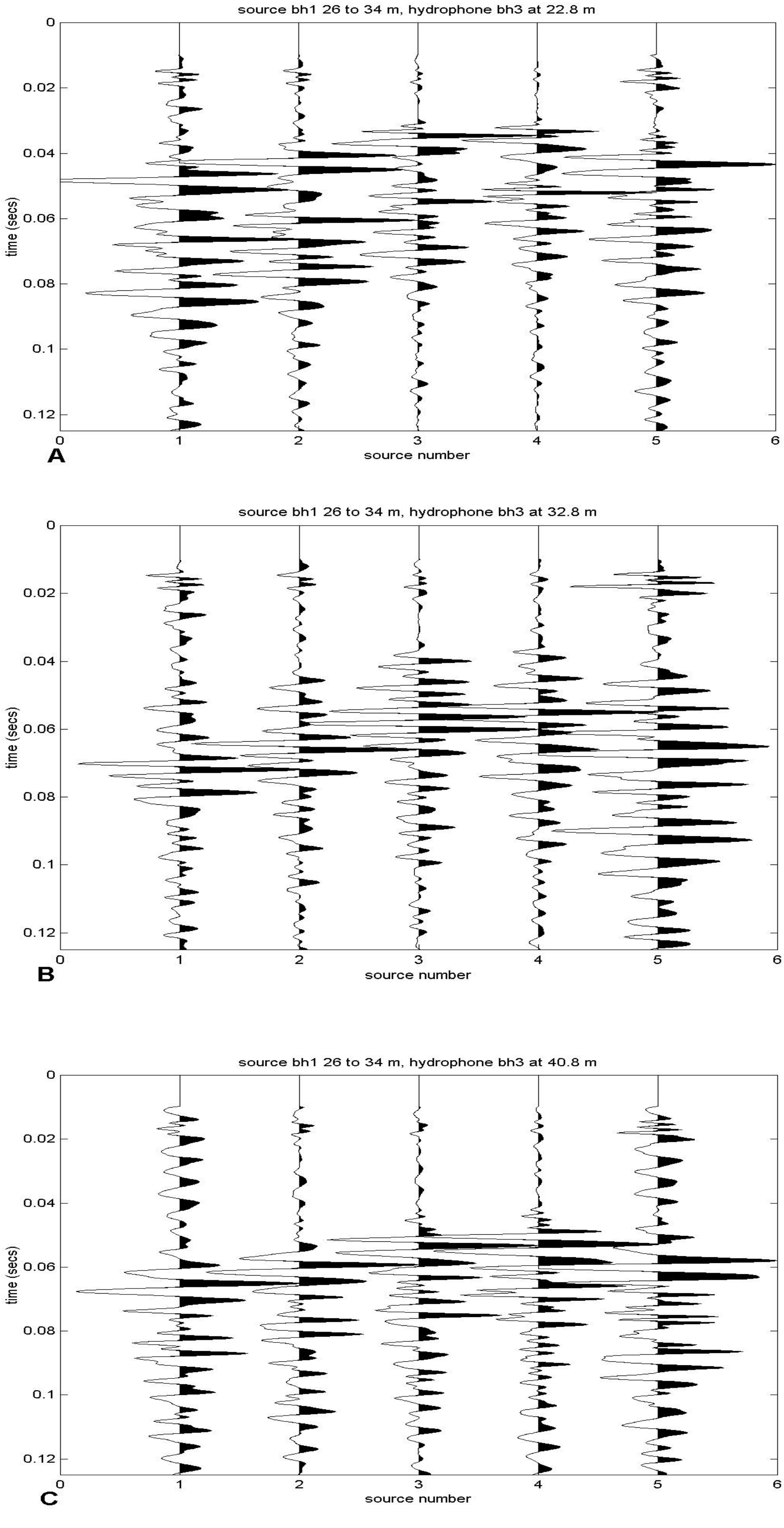

Figure 10 : Common receiver gathers for shots at depths 26, 28, 30, 32 and 34 metres depth in hole 1 recorded by hydrophones in hole 3 at depths, A: 22.8 metres B: 32.8 metres C: 40.8 metres.