The use of ground penetrating radar in the investigation of masonry retaining walls

Prepared for Quality Services, Civil Engineering, Highways Agency

J Kavanagh, K H Bowers and K C Brady
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Executive Summary

Scope of project
Masonry faced retaining walls are commonplace in many areas of the UK. The majority of these structures were constructed in the 19th and early part of this century and consisted typically of dry-stone walling. The stability of dry-stone walls and their derivatives cannot generally be determined satisfactorily from methods of analysis currently used for the design of modern types of earth retaining structures.

The objective of this project is to provide information on the stock of masonry retaining walls on the trunk road and motorway network in the UK, together with details of the inspection, assessment and maintenance techniques employed by the various Maintaining Agents. It will also determine current levels of maintenance expenditure.

Summary of report
This report assesses the use of ground penetrating radar (GPR) as a means of non-invasive investigation through its application to six masonry retaining walls. It provides details of the equipment and procedures employed, together with an appraisal of GPR as an investigative tool for such walls. Conclusions and recommendations for further work are also provided. The results of the investigations of the walls are presented in separate appendices to the report.

The retaining walls examined showed two distinct forms of structure. Typically behind the facing of the walls there was an ‘outer zone’ consisting of an irregular formation, backed by an ‘inner zone’ of a much more uniform formation. Using GPR alone it is not possible to determine the exact nature of the material within each zone. However the acquisition of physical data by (for example) drilling, the calibration of the GPR using adjacent wall parapets or abutments or through construction or maintenance records, does allow a better interpretation of the data.

The use of GPR as a non-invasive tool in the investigation of the internal structure of masonry retaining walls has much to offer. Combined with a visual inspection, GPR can be used to identify sections of wall which are at risk from failure. This could improve the effectiveness of inspection routines and enable maintenance expenditure to be better targeted.
1 Introduction

The objective of this project is to provide information on the stock of masonry retaining walls on the trunk road and motorway network in the UK, together with details of the inspection, assessment and maintenance techniques employed by the various Maintaining Agents. It will also determine current levels of maintenance expenditure.

This report assesses the use of ground penetrating radar (GPR) as a means of non-invasive investigation through its application to six masonry retaining walls. It provides details of the equipment and procedures employed, together with an appraisal of GPR as an investigative tool for such walls. Conclusions and recommendations for further work are also provided. The results of the investigations of the walls are presented in separate appendices to the report.

2 Methodology

2.1 Theory

Ground penetrating radar utilises electromagnetic waves typically in the frequency range of 1 to 1000MHz. Electromagnetic energy is pulsed into the formation under examination and is reflected at boundaries between materials of differing electrical properties. The reflected energy is captured and can then be interpreted to discern the structure of the formation. In the context of masonry retaining walls, areas with large voids, areas of wet material, and buried objects (such as pipes), do have sufficiently different electrical properties within a dry and well constructed wall to enable them to be detected.

2.2 Equipment

The system used throughout this investigation was a ‘pulseEKKO 1000’. As shown in Figure 1 the electromagnetic transmitter and receiver (antennae) are held in a frame that can be moved manually over the face of the structure of interest. The computer, via the console, controls the acquisition and storage of data.

During the course of this investigation, three frequencies of antennae were used – 250, 450 and 900MHz. The lower the frequency the greater the depth of penetration, but the higher the frequency the better the resolution of the structure of the formation. The choice of frequency is, therefore, a compromise between these competing requirements.

2.3 Application

A survey usually consisted of at least one horizontal scan along the entire length of the wall, at a height of about one and a half metres above ground level, and a number of vertical scans at selected positions. Additional scans were undertaken over any particular areas of interest, as identified by particular external features or from the results of the initial scans.

Individual scans can be electronically marked, for example at every metre length. The ‘pulseEKKO 1000’

Figure 1 GPR equipment set-up (Sensors & Software, Canada)
system designates the first marker ‘f1’ and subsequent markers as ‘f2’, ‘f3’ and so on. Thus identical markers on different scans of a structure do not refer to the same location. The system also permits points of particular interest to be electronically marked - these are indicated on the scans by the marker ‘PMB’.

Where it was possible, a number of 40 mm diameter holes were drilled through the wall to determine the thickness of the stone facing, to examine the backfill, and to confirm the presence of voids behind the facing. This information helped in the calibration and interpretation of the results of the GPR scans.

3 Details of the walls

The masonry retaining walls were selected for examination on the basis that they were showing signs of distress (e.g. bulging, leaning, cracking etc.) or indeed parts of them had failed. Six walls were examined:

1. A523 retaining walls to Hug Bridge, Cheshire.
2. A646 Halifax retaining wall, South Yorkshire.
3. A30 West Coker retaining wall, Somerset.
4. Addlewile Lane retaining wall, Somerset.
5. Millbank retaining wall, Gloucestershire.
6. Burdon Court Farm retaining wall, Gloucestershire.

Descriptions of the walls are given in the appropriate appendix along with a summary of the surveys and their interpretation.

4 Analysis of the field data

The subsoils behind a typical masonry retaining wall do not generally have features of markedly different electrical properties. Usually such soils will have open pores and so large voids will not necessarily be distinct. Similarly, water is likely to be present within the soils and so saturated areas may not be clearly identifiable. Nonetheless, as can be seen in Appendices A – F, differences in the sub-surface formation can be detected and interpreted. However it is useful to have some knowledge of the nature of the subsoils, obtained by drilling or from construction or maintenance records, to aid the interpretation of the GPR scans.

The GPR scans for the six retaining walls have a similar form. A typical scan, which can be found in any of the appendices, consisted of an initial series of contrasting black and white lines that reduced in intensity until it became a continuous, reasonably uniform medium. As stated in Section 2.1, electromagnetic energy is pulsed into the structure and is reflected at boundaries between materials of differing electrical properties. It is probable that the separate black and white lines are due to reflections of the electromagnetic energy at stone-air interfaces within the stone facing and immediately behind it. Behind the facing, the black and white lines may become quite curved; this is consistent with a coarse stoney fill with large voids. The uniform shading, where there is little or no reflection, is consistent with a more uniform material, such as a fine grained well compacted fill or bedrock.

The results and interpretations of the GPR scans for each wall are provided in the appropriate appendix.

5 Discussion

For all the walls examined in this investigation, it is probable that the non-uniform outer formation represents a coarse stoney fill with large voids. The thickness of the outer formation varies considerably, but it was at least 3 m thick at the Addlewile Lane wall.

It should be noted that the uniformity of the ‘inner zone’ formation is not necessarily associated with stability or good condition. The survey of the wall at Halifax revealed a clear correlation between areas of instability and the proximity of the formation to the wall facing. This contrasts with the findings of the surveys at, for example, West Coker and Millbank, where the proximity of the formation to the surface of the wall was associated with good physical condition. This is not surprising as the wall at Halifax is thought to retain fine grained fill, whereas the ones at West Coker and Millbank are thought to retain bedrock.

The importance of conducting a visual inspection of the external condition of the wall cannot be over emphasised. There was a good correlation between surface features such as bulges and the internal features determined by the GPR. Through calibration of the GPR results it is possible to produce an ‘hazard map’ which would aid the identification of potential trouble zones. This has implications concerning the management of maintenance routines and associated budgets, as it may permit the more efficient targeting of resources. Furthermore because GPR can identify voided areas behind a wall it can also be used to assess whether or not grouting could be used to stabilize a structure.

6 Conclusions

The retaining walls examined showed two distinct forms of structure: there was an ‘outer zone’ consisting of an irregular formation, backed by an ‘inner zone’ of a much more uniform formation. Using GPR alone it is not possible to determine the exact nature of the material within each zone. However the acquisition of physical data by (for example) drilling, the calibration of the GPR using adjacent wall parapets or abutments or through construction or maintenance records, does allow a better interpretation of the data.

The use of GPR as a non-invasive tool in the investigation of the structure of masonry retaining walls has much to offer. Combined with a visual inspection, GPR can be used to identify sections of wall which are at risk from failure. This could improve the effectiveness of inspection routines and enable maintenance expenditure to be better targeted.
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8 References


Appendix A: A523 retaining walls to Hug Bridge, Cheshire

A1 Location
The bridge and retaining walls are located on the A523, between Macclesfield and Leek; the structure lies at approximately grid reference SJ 931636. The bridge, situated about 2 km north of Rushton Spencer, crosses the River Dane which flows in an approximately easterly direction. To the north of the river, the east and west retaining walls of the structure are located in Cheshire whereas the east and west retaining walls to the south of the river are located in Staffordshire. The investigation focused on the east and west retaining walls to the north of the River Dane.

A2 Description of site
The structure comprises four masonry retaining walls acting as wing walls to a masonry arch bridge over the River Dane in Cheshire. It is constructed of sandstone blocks, which were probably obtained from a quarry adjacent to the site. A number of concrete blocks have been used to repair the bridge parapet, which had been damaged by vehicle impacts. The structure has elements of various ages but appears to have been originally built as part of a turnpike road in the second half of the 18th century.

The total length of the structure is approximately 90 m, including the 15 m span over the River Dane, and retains a maximum height of approximately 6 m. Figure A1 shows a view of part of the north-east retaining wall and Figure A2 a part of the north-west retaining wall.

Figure A2 shows the distortion of the north-west retaining wall, which was due to settlement of the foundations – mainly during or immediately following construction. The parapet does not show the same level of distortion; this implies that it was added some time after the retaining wall had been constructed. Five buttresses support the north-west wall and there are noticeable bulges in the lengths between the buttresses. Of the five buttresses, four are of similar design and have been constructed such that the stonework is pitched downwards towards the wall (see Figure A4). The fifth is of a different design and has horizontal masonry courses. The pattern of the distortion suggests that the external buttresses were added following the construction of the lower part of the wall: it is possible that the buttresses (or at least four of them) were added as it became apparent during construction that the wall had not been founded on competent ground. Given its proximity to the River Dane, it is likely that the wall was founded on loose alluvial or organic sediments in the river channel.

The north-east abutment has no external buttressing. As shown in Figure A3 it shows substantial distortion. A ditch runs down the side of the north-east retaining wall and discharges into the River Dane.

Figure A1 View of north-east retaining wall at Hug Bridge

Figure A2 View of north-west retaining wall at Hug Bridge, showing two of the five buttresses: note the pattern of distortion of the wall and the orientation of the stonework of the buttresses

Figure A3 View of north-east retaining wall at Hug Bridge
The bridge, shown in Figure A5, appears to have been constructed in two sections. A longitudinal construction joint is visible from under the bridge; steel ties have been inserted at some time to brace the sections together, but some of these appear to have corroded through.

Cracking of the supported pavement was evident in January 1998 but this had been repaired before the survey work was undertaken in August 1998.

Since the completion of the survey, the north-east and north-west retaining walls have been supported by the placement of fill against their faces. It should be appreciated that it is difficult to estimate the factor of safety against collapse of the distorted walls: an objective of this project is to determine how best safety could be evaluated and also the best means of obtaining data to complete such an evaluation (through for example GPR surveys).

A3 Results of survey

The structure was surveyed between 24th and 28th August 1998. A sample of the GPR scans from the north-east retaining wall is presented in Figure A6. The upper three plots in the figure are the results of scans from three vertical passes down the wall. The lower plot shows data acquired from a horizontal traverse along a section of the wall, at a height of approximately 1.5 m above ground level: the locations of the vertical scans are marked on this plot. (Note that the scan between locations f1 and f10 did not differ from that between f10 and f12, so this section has been omitted for brevity and clarity).

The markers on the horizontal scan (f11 through f15) refer to the locations of columns of survey reflectors attached to the wall by the Maintaining Agent to monitor movement of the structure. (Note that the direction f11 to f15 is proceeding towards the bridge).

Interpretation of the GPR results is aided by observations made from three drill holes. The first, located approximately 30 m from the foot of the masonry arch and 1.5 m above ground level, showed that the stone facing was 270 mm thick and it also encountered a sizeable void which extended a further 190 mm beyond the stone facing. The second hole was directly below the first but 300 mm above ground level; the stone was penetrated to a depth of 840 mm. The third hole was located approximately 6 m from the foot of the masonry arch and 300 mm above ground level; here stone was penetrated to a depth of 900 mm.

The results indicate a marked change in the internal structure of the wall between points f14 and f15. Up to location f14 the scans indicate the presence of a non-uniform formation behind the wall but, beyond f15, the GPR indicates the presence of a much more uniform internal formation. It is probable that the irregular formation, between locations f1 and f14, comprises a coarse stoney fill with large voids, whilst the uniform structure, found beyond location f15, comprises competent sandstone blocks.

The change in internal structure is also apparent from an examination of the vertical GPR scans. The results obtained at location f15 suggest the presence of competent sandstone blocks over most of the height of this section. (The maximum depth of penetration of the drill hole at this location is indicated on the figure). The GPR scans for locations f11 and f13 suggest the presence of a coarse, voided fill along the full height of the wall to a depth of approximately 1.0 m at f13 and 1.2 m at f11.

Figure A7 presents a GPR scan of the under side of the north-west masonry arch. The scan runs from the top of the arch (f1) to the footings (f8/f9), and shows a diagonal reflection running between the markers f2 and f5. The feature runs at its highest extent (f2) from about 1.0 m behind the face of the arch to (f5) about 0.6 m behind the face of the arch. This feature is likely to be a vertical internal wall constructed to retain the backfill to the arch.
Figure A6 Radar scans for the north-east retaining wall at Hug Bridge
Figure A7 Scan of north-west soffit to arch of Hug Bridge
Appendix B: A646 Halifax retaining wall, South Yorkshire

B1 Location
The wall is situated on the A646 west of Warley Road in South Yorkshire, about 3.5 km to the west of Halifax. At this location the A646 runs in an approximately SW-NE direction and the wall lies to the NW at, approximately, grid reference SE 058242.

B2 Description of site
The wall, which is about 380 m long and has a maximum height of about 6 m, is constructed of sandstone blocks. It borders a footpath to the SE and retains land occupied by houses and gardens, together with a pedestrian access way, to the NW. Figures B1 to B4 give views of the wall.

The wall is generally in good order but two sections have been repaired. One (A) is approximately 2.5 m wide and some 2 m above ground level, and is situated at the mid-point of the wall. The repair has been effected using mortared sandstone blocks. The other (B) is located approximately 50 m from the Halifax end of the wall and consists of some re-pointing of the original stonework at and around a substantial bulge in the wall.

B3 Results of survey
The structure was surveyed on the 16th October 1998. Owing to the presence of services within the wall, it was...
not possible to drill through it to confirm its structure. However it was possible to calibrate the GPR by using it to measure the thickness of the stone parapet to the wall. The irregular formation evident to a maximum depth of about 2.2 m is a fairly open formation and in all probability is a coarse stoney fill with large voids.

Figure B5 provides the results of a GPR survey for about a 10 m length of the wall. This section is located mid-way along the wall, and includes one of the repaired sections (A) which is about 2.5 m long. The scan is a horizontal traverse conducted about 1.5 m above ground level. The scan shows two distinct zones behind the face of the wall. From the surface to a depth varying between about 1.1 m and 2.2 m the scan indicates a disturbed, non-uniform formation. Behind this, the scan indicates a more consistent uniform formation.

Figure B6 gives a more detailed scan around the repaired section (A). The lower plot presents the results of a horizontal traverse, conducted at a height of approximately 1.5 m: the upper plots are the results of two vertical scans, conducted from the top to the foot of the wall - one of them was conducted through the repaired area and the other outside it. The scans show that the disturbed non-uniform formation exists to depths varying between 1.1 m and 2.2 m.

Figure B7 gives the results of a GPR survey of a 50 m length of the wall located at the Halifax end of the wall, which included the repaired section (B). The lower plot presents the results of a horizontal traverse conducted at a height of about 1.5 m above ground level, whilst the upper plots give the results of two vertical scans conducted from the top to the foot of the wall. Again one of the vertical scans was conducted through the repair area and one outside it. The scans show a disturbed non-uniform formation to a depth of between about 1.6 m and 2.2 m.

Without additional information it is difficult to identify the more uniform formation. However examination of Figures B5, B6 and B7 shows a correlation between the repaired areas and the proximity of the uniform formation to the face of the wall. The horizontal scan in Figure B6 shows that the uniform formation, within the repaired area, extends to within about 1.1 m of the front of the wall, compared to a typical depth of about 2.0 m outside the repaired area. A comparison of the two vertical scans also indicates that the uniform formation is found closer to the face of the wall in the repaired section. The scan of the vertical section within the repaired area (B) shows that in the bottom one-third of the wall the uniform formation is found about 1.6 m to 1.2 m (at the foot) from the wall face. An examination of the scan of the vertical section outside the repair area indicates a distance of about 2.0 m to 1.6 m (at the foot).

Given that the proximity of the uniform formation to the wall face appears to be related to instability, it is more likely that the formation is a finer grained or more compacted backfill rather than a competent bedrock. It would seem, unsurprisingly, that the areas of instability occurred where the wall facing was thinnest.
Figure B5 Scan for Halifax retaining wall including repaired section (A)
Figure B6 Scans for Halifax retaining wall including repaired section (A)
Figure B7 Scans for Halifax retaining wall including repaired section (B)
Appendix C: A30 West Coker retaining wall, Somerset

C1 Location
The retaining walls are situated on the A30, about 1km west of West Coker in Somerset, at about grid reference ST 504135. At this location the A30 runs in an approximately SW-NE direction with each of the walls retaining land adjacent to the carriageway. However only the retaining wall lying to the SE of the carriageway was surveyed.

C2 Description of site
The wall, constructed from sandstone blocks, forms an irregular retaining structure interspersed with exposures of in situ rock. The wall retains land occupied by a number of cottages, gardens and a farm (together with an access road) and also forms the SE abutment to a road bridge over the A30. The overall length of the wall is about 200 m and it has a maximum retained height of about 4 m. Only two sections of the wall were surveyed. The first was about 50 m long and terminated at the road bridge over the A30. The second was about 60 m long, starting at the junction between the A30 and the access road to Target Farm behind the retaining wall. Figures C1 and C2 show views of the wall.

C3 Results of survey
The structure was surveyed on the 11th November 1998. A single hole was drilled to obtain information about the internal structure of the wall. Additionally, the section of the wall that bordered the access road to Target Farm was used to calibrate the GPR.

A sample of the GPR scans, acquired from the first section of the retaining wall, is presented in Figure C4. The upper four plots in the figure are scans from four vertical passes down sections of the wall (top to bottom). The lower plot is a horizontal traverse along a 20 m length of the wall, at a height of about 1.5 m above ground level. The locations of the vertical scans (at chainages 5 m, 10 m, 15 m & 16.5 m) relative to the horizontal scan are indicated. The scans show two relatively distinct formations behind the face of the wall. To a depth of between about 0.5 m and 1.0 m the scan indicates a disturbed non-uniform formation. Behind this the scan indicates a more consistent uniform formation. Generally speaking, this section of the wall is in a good condition although in places mortar is missing and the stonework is dirty. The exception is a length, between chainages 9 m and 13 m, over which the mortar is in very poor condition with irregularly sized stones. In particular between chainages 9 m and 11 m the mortar is very soft and the condition of the wall is highly variable. Areas of dry, clean stone, pointed with competent mortar, alternate with areas of damp, dirty stone with very friable, or even missing, mortar. Over much of the length of the wall, there is evidence of water penetration with moss/lichen growth visible, and at two locations water was observed seeping through the wall. Sections of the wall are also obscured by a heavy growth of vegetation and, in places, large roots/branches penetrate the wall. The second surveyed section included both a large bulged area where there was visible seepage and, also, a recently repaired section of a failure that occurred in December 1995 (Figure C3).
stone surface is friable, indicative of water being retained behind the wall. The horizontal scan between chainages 9 m and 13 m shows a formation that is disturbed to a greater depth than in the adjacent sections of wall. The vertical scans do not show this difference in structure to the same extent, but the scan at chainage 10 m does indicate the presence of a non-uniform formation towards the bottom of the wall and to a depth of about 1.2 m. The non-uniform formation is also present towards the bottom of the wall in the two adjacent sections (chainages 5 m and 15 m) but, noticeably, to a much lesser extent. The vertical scan at chainage 16.5 m was across a bulge in the wall and it indicates a non-uniform formation to a depth of about 1.3 m behind the wall, for the entire height of the wall.

Figure C5 shows the GPR scans for the initial 45 m run of the second section of the wall. The lower plot is from a horizontal traverse conducted at a height of about 1.5 m. The results of five vertical scans (top to bottom) of the wall at chainages 5 m, 10 m, 15 m, 40 m and 45 m are also given on the figure. Although of small scale, the horizontal scan differentiates between the disturbed non-uniform formation immediately behind the wall and the more consistent uniform formation at depth. The figure also shows how variable the internal structure is with the thickness of the non-uniform formation behind the facing varying from perhaps as little as 0.1 m to about 1.5 m. Note that the vertical scan at chainage 40 m was conducted over the centre of a bulge in a wet section of the wall: the marker ‘PMB’ indicates the centre of the bulge. This point coincides with the greatest thickness of the non-uniform formation recorded along this length of the wall. It is also evident, from an examination of the horizontal scan, that at the ‘bulged’ area the non-uniform formation extends to some depth behind the wall.

The lower plot of Figure C6 is a horizontal traverse along the second length of the wall, between chainages 45 m and 60 m, at a height of about 1.5 m above ground level. The results of two vertical scans (top to bottom) at chainages 50 m and 55 m are also presented. The figure is demarcated into zones according to details recorded in the visual inspection of the wall. It is evident that the area of wall where seepage is visible also has the greatest thickness of non-uniform formation.

The disturbed non-uniform formation is probably a coarse stoney fill with large voids. As the sandstone was observed to outcrop through the wall at a number of locations, the uniform formation identified behind the face of the wall is probably sandstone bedrock.

It is evident that the lengths of the wall that exhibit external signs of distress, such as bulging, seepage or generally poor condition of stone, coincide with the locations where the coarse stoney fill has the greatest thickness, as indicated by the GPR.
Figure C4 Scans for A30 West Coker retaining wall section 1
Figure C5 Scans for A30 West Coker retaining wall section 2
Figure C6 Scans for A30 West Coker retaining wall section 2
Appendix D: Addlewell Lane retaining wall, Somerset

D1 Location
The wall is situated within the southern perimeter of Yeovil at, approximately, grid reference ST 558155. At this location, Addlewell Lane runs in an approximately north-south direction and the retaining wall, forming the western boundary to Addlewell Lane, retains the eastern edges of the carriageway to Park Street and Taunusstein Way.

D2 Description of site
The wall is approximately 160 m long and retains a maximum height of backfill of about 3 m (in addition there is a 1 m free-standing parapet). The wall is of masonry construction with mortared joints and is of variable condition. At the junction with the main road the wall is badly cracked and, in places, the stone facing is highly weathered. Some parts of the wall support the growth of mature vegetation, which penetrates the wall, and at others there are noticeable bulges. It is evident that a number of repairs have been carried out to the wall. Figures D1, D2 and D3 show views of the wall.

D3 Results of survey
The structure was surveyed on the 12th November 1998. Two holes were drilled into the wall. The first, at chainage 21 m, showed that the facing comprised two stones about 200 mm and 300 mm thick. The second hole, at chainage 2.5 m, penetrated a single stone about 200 mm thick before entering the backfill. Visual inspection of the wall showed a void extending 600 mm into the wall at chainage 161 m and another extending 700 mm at chainage 125 m.

A sample of the GPR scans, from a horizontal traverse along a 150 m length of the wall, at a height of about 1.5 m above ground level, is shown in Figure D4. The scan differentiates between a disturbed non-uniform formation which exists immediately behind the wall to depths varying up to about 1.5 m, and a more consistent uniform formation at depth. Figure D5 provides scans for a 10 m length mid-way along the 150 m length. The lower plot is a horizontal traverse and the three upper plots are from vertical traverses (top to bottom) at chainages 72 m, 75 m and 79 m. This section of the wall exhibited two noticeable bulges, and the horizontal scan shows a greater depth of the disturbed non-uniform formation at the two bulged sections than at the adjacent lengths. The vertical scans at the bulged sections show that the disturbed non-uniform formation exists to depths behind the face of, typically, 1.6 m. This compares to a typical thickness of 1.3 m within the non-bulged sections.

It is difficult to determine the thickness of the stone wall from the GPR scans, but typically the scans indicate a thickness of between 300 mm and 500 mm. It seems that the disturbed non-uniform formation detected by the GPR is a coarse stoney fill with large voids. Although there is insufficient evidence to identify the exact nature of the uniform formation it is worth noting from Figure D5 that it occurs close to the face between the two bulged lengths. This suggests that the formation is a reasonably competent material.
Figure D4 Scans for wall at Addlewell Lane, Yeovil
Figure D5 Scans for wall at Addlewell Lane, Yeovil
Appendix E: Millbank retaining wall, Gloucestershire

E1 Location
The wall is situated within the town of Nailsworth in Gloucestershire at, approximately, grid reference ST 850996.

E2 Description
The wall is about 60 m long and retains a maximum height of about 3 m; there is also a 1 m free-standing parapet. The wall and parapet are of dry-stone construction and the coping stone is mortared into place on top.

The wall is curved in plan and retains a carriageway. The height of the wall varies from 1.7 m, at one end, to about 3 m at the other. Above the carriageway there is a large house and below the wall there is a new housing estate. According to local knowledge, the new development is sited on gardens that once belonged to the large house and it was also suggested that a tunnel, running underneath the carriageway, once connected the two plots of land. The access to the tunnel appears as a small recessed area and resembles an old well. Whether the tunnel existed and, if so, whether it has been in-filled, could not be confirmed. Figures E1, E2 and E3 give views of the wall; the ‘recessed’ area is clearly evident in all the figures.

Figure E1 View of Millbank retaining wall, Nailsworth

Although in a generally good and clean condition, a number of areas of the wall show signs where seepage has occurred and some of the stones are severely weathered. Along an 8 m section of the wall a supporting buttress has been constructed at some time and there is a noticeable bulge at one point. There is some vegetation growth on the wall and some thick roots grow through the wall face, more frequently towards the top of the wall. At the high end of the wall, a 9 m long concrete plinth has been constructed at the base of the wall; the plinth incorporates two 150 mm diameter weep holes and eight clay pipes, acting as weep holes, have been added to the wall at about 500 mm above ground level. Also at the high end of the wall, a small stream runs from beneath the wall, turns through 90 degrees and then runs underground through the garden of a private house.

Figure E2 View of Millbank retaining wall, Nailsworth

Figure E3 View of Millbank retaining wall, Nailsworth

E3 Results of survey
The structure was surveyed on the 13th November 1998. The wall was not drilled but the GPR scans were calibrated using the wall parapet.

Figure E4 shows a sample of the GPR scans from a horizontal traverse of a 42 m length of wall, starting some 7 m from the low end, at about 1.5 m above ground level. To a depth behind the wall face of between 0.5 m and 2.8 m, the scan indicates a non-uniform formation. Behind this the scan identifies a more consistent uniform formation. The figure shows the wide variability of the material behind the wall.

At all locations along the wall where seepage was recorded (including the bulged section) the non-uniform formation appears to extend the full depth of the survey, a distance of about 2.8 m behind the face of the wall. At the
recessed area the non-uniform formation only extended to a depth of about 1m: the GPR survey did not identify the presence of a large void.

Figure E5 shows GPR scans of vertical sections of the wall conducted (top to bottom) at chainages 34 m and 39 m. The wall shows extensive seepage at chainage 34 m and the GPR scan shows that the non-uniform formation is much thicker here than at chainage 39 m.

It is probable that the irregular internal structure found to a maximum depth of 2.8 m represents a coarse stoney fill with large voids. It is difficult to identify the exact nature of the more uniform formation but examination of Figures E4 and E5 shows a correlation between the wall sections suffering from seepage and the depth of the coarse stoney fill. This suggests that the uniform formation is more competent than the stoney fill. At chainage 45 m, where a small stream was observed to be flowing from under the wall, the GPR scans indicate the presence of the uniform formation at depth and above the stream. This suggests that the uniform formation is reasonably competent rock. It is also interesting to note from Figure E4, at the location of the stream, the presence of a series of long, straight reflections to a depth of about 1 m within the wall; this is consistent with a lintel constructed to support the road over the stream.
Figure E4 Scan for horizontal traverse of retaining wall at Millbank, Nailsworth
Figure E5 Scans for vertical traverse of retaining wall at Millbank, Nailsworth
Appendix F: Burdon Court Farm retaining wall, Gloucestershire

F1 Location
The wall is situated close to Burdon Court Farm, to the east of the village of Tresham in Gloucestershire at, approximately, grid reference ST 796909. The wall retains the southern extent of an undesignated carriageway (off the A46) which, at this location, runs in an approximately east-west direction.

F2 Description of site
The wall, approximately 20 m long and 2 m high (including a 0.5 m high parapet), is of dry stone construction except for a 5 m length where a replacement mass concrete retaining wall was constructed following a partial collapse in February 1998; a view of the collapse is shown in Figure F1. The debris from the collapse was used to provide a masonry face to the front of the concrete wall. Three 100 mm diameter weep holes were incorporated into the base of the concrete. The stones were regularly sized and generally in good condition with some algae growth occurring in the bottom 100 mm to 200 mm. Details of the repair to the collapsed and bulged sections are shown in Figure F2. The wall appeared to be generally sound, although a small section, to the west of the failure, contained a separate bulge: this section is shown in Figure F3.

F3 Results of survey
The structure was surveyed on the 13th November 1998. Two holes were drilled into the wall to examine the internal structure. The GPR scans were calibrated against the wall parapet. Additional information was obtained from the repaired length (see Figure F2).

Figure F4 presents a sample of a GPR scan from a horizontal traverse along the full length of the wall and at a height of about 1.5 m above ground level. Also given are five vertical scans (top to bottom) at chainages 5 m, 7.5 m, 8 m, 10 m and 16 m. The scans show two different formations. To a maximum depth behind the wall facing of, typically, 0.5 m the scans indicate a non-uniform formation. Behind this there is a more consistent uniform formation.

There is a noticeable difference in the scans between the original and the repaired sections, with the latter having a much more uniform structure. There is, however, no discernible difference in the scans from the bulged section of the wall and the sections adjacent to it. It is probable that the non-uniform formation is a coarse stoney fill with large voids. There is insufficient evidence to identify the uniform formation but it is likely to be a granular soil rather than bedrock.

The GPR scans do not indicate any relation between the bulged section of the wall and the internal structure of the wall at and around that location. It seems possible therefore that failure of the wall may have been triggered by some intermittent disturbing force, such as heavy rainfall, the evidence of which is now not obvious, or through imperceptible variation in the weathering of the stone face.

Figure F1 View of failure of Burdon Court Farm retaining wall in February 1998

Figure F3 Bulge in Burdon Court Farm retaining wall
Figure F2 Details of Burdon Court Farm retaining wall failure and repair
Figure F4 Scans for retaining wall at Burdon Court Farm, Tresham
Abstract

This report assesses the use of ground penetrating radar (GPR) as a means of non-invasive investigation through its application to six masonry retaining walls. It provides details of the equipment and procedures employed, together with an appraisal of GPR as an investigative tool for such walls. The report shows that the use of GPR as a non-invasive tool in the investigation of the internal structure of masonry retaining walls has much to offer. Combined with a visual inspection, GPR can be used to identify sections of wall which are at risk from failure. This could improve the effectiveness of inspection routines and enable maintenance expenditure to be better targeted.

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