Application of ground-penetrating radar to investigate the effects of badger setts on slope stability at St Asaph Bypass, North Wales

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Abstract

At the St Asaph Bypass, surface cracking developed along the crest of a modern highway cutting, above a cluster of badger setts excavated in the sandy soils of the cutting slope. This prompted concerns about the extent of the underlying tunnel systems and the possible existence of deep cavities lacking surface expression that might cause a potential slope instability problem. The full threat posed to the integrity of the cutting and to the safety of road users remained uncertain. In addition, intrusive investigations were deemed inappropriate and a non-invasive solution to the problem was required.

Ground-penetrating radar was used along a 50 m stretch of the cutting to determine the full extent of the badger setts beneath the surface. The geophysical survey identified 324 m of tunnels and demonstrated that the tunnel network was generally shallow (*c.* 0–2 m). Pronounced radar reflections characteristic of air voids were identified in the data and interpreted as the badgers' access tunnels and living and nursery chambers whereas the more subdued features were interpreted as collapsed and abandoned diggings. This case history illustrates the benefits of using ground-penetrating radar to provide an understanding of slope stability and local ground conditions in areas of environmental sensitivity when non-intrusive investigations are required to provide reassurances in relation to public safety.

Keywords: badger setts, case history, radar, geophysics, highways, slope stability

Introduction

Animal diggings pose a common problem wherever poorly consolidated sandy soils form the slopes of embankments and cuttings along transportation corridors. Engineered slopes with well-drained, firm and undisturbed ground frequently combine with landscaped areas of broad-leaved woodland that adjoin open pasture-land to create ideal habitats for a wide variety of burrowing animals in general and badgers in particular (Cresswell *et al.* 1990). The engineering geological concerns relating to animal diggings principally involve their potential to induce ground movements that may adversely affect roads, railways, buildings and flood-defences, with potential consequences for neighbouring communities and the local economy.

Constructed in 1970, the A55 St Asaph Bypass includes a major earthworks cutting, 500 m in length (Figs. 1 and 2) (Nichol 2000). The site lies some 0.6 km north of St Asaph and at the northeastern end of the cutting [National Grid Reference SJ 040750]. Here, the slope profile contains numerous entrances and spoil heaps associated with badger setts. The presence of these diggings together with the development of longitudinal cracks along the crest of the slope prompted concerns about slope instability and the potential threat posed to the highway.

Badgers are a protected species under the Protection of Badgers Act, 1992. It is an offence to disturb or destroy a badger sett, even if this action is unintentional. It was therefore necessary to remotely assess the true scale of the problem before recommending whether physical intervention, such as sett relocation was required.

The use of ground-penetrating radar (GPR) techniques has become well established for highway engineering applications and the potential for GPR mapping of tunnels excavated by fossorial species was identified by Stott (1996) in describing experiments to investigate the structure of rabbit warrens near Adelaide, South Australia. However, as far as can be determined, the use of GPR techniques to map extensive, complex tunnel systems within engineered slopes along transportation corridors has not previously been attempted. In this paper non-invasive GPR investigations were carried out to determine the extent of excavation and redistribution of the soil by badgers within a major road cutting and also to provide a better understanding of the potential for future ground movements.

Geological setting

Geologically, the central feature of the district is the down-faulted rift valley of the Vale of Clwyd (Warren *et al.* 1984). Within the graben tract at St Asaph, the local bedrock consists of sandstones, siltstones and mudstones of Upper Carboniferous (Westphalian) age that crop out between the two Permo–Triassic basins around St Asaph. The rockhead strata are overlain by heterogeneous till deposits associated with the last

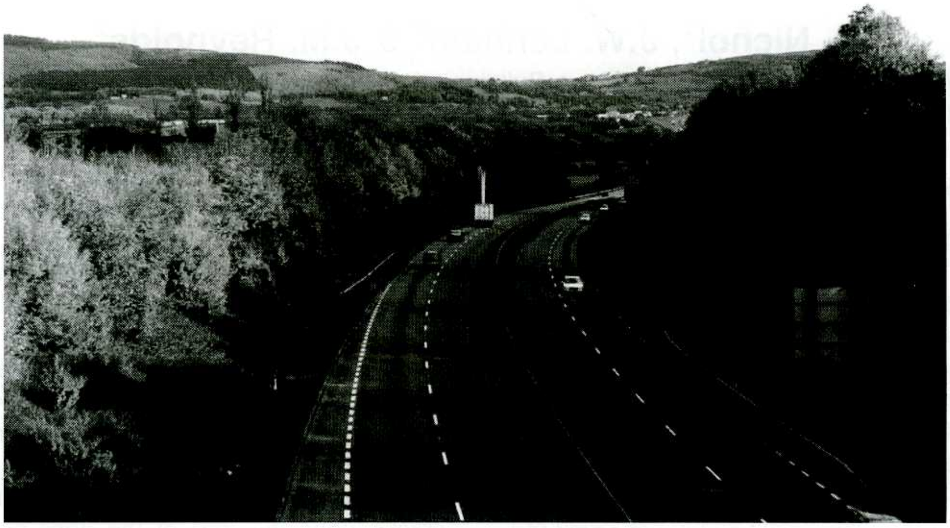

Fig. 1. A55 St Asaph Bypass cutting. View looking eastwards.

glaciation affecting the area during Late Pleistocene (Devensian) time.

Between the rivers Clwyd and Elwy the A55 highway passes in deep cutting through an intervening ridge. The principal glacial deposits forming the ridge are clayey tills, sands and silts.

The site

The site adjoins the A55 eastbound carriageway and comprises the earthworks slope of the highway cutting and a platform area above the crest. The slope has been planted with deciduous trees at regular 1.5 m spacing, whilst the platform has been left bare. The tree canopy effectively restricts growth of ground cover across the site. The cutting slope has an average gradient of 24° and a mean down-slope length of 15 m and the flat platform at the top of the slope varies from 3–6 m wide and is bounded to the north by a fence bordering an open field.

The geological profile of the site consists of pale brown heterogeneous sandy and silty soils overlying brown clayey soils. Descriptions and engineering properties of the soil units are summarized in Table 1. The particle size distribution of a representative sample of the spoil material is presented in Figure 3, indicating the characteristics of the ground in which the badgers have tunnelled.

The surface expression of the badgers' workings appears restricted to a 50 m stretch at the eastern end of the cutting. Most of the diggings are situated along the upper part of the slope, where flattened trackways between the trees link entrances, foraging patches and latrines. Several smaller entrances also exist on the level platform at the top of the slope but no surface indications of badger activity were noted in the adjacent field. On the slope, excavations by badgers have created conical spoil mounds measuring up to 3 m wide and 1.5 m high. Typically, each spoil mound surrounds a single entrance but, in places, individual mounds have coalesced to form larger heaps (Fig. 4), resulting in localized slope steepness of up to 38°. Anecdotal evidence from local badger conservationists suggests that there may have been a sett in this area for over 100 years and certainly, the site has been relatively undisturbed since 1970. Conceivably, the underground tunnel system has evolved over a long period of time and could be more complex than suggested by the distribution of features on the ground surface at the present day.

Ground-penetrating radar survey

Introduction

In GPR applications, radio-frequency pulses are transmitted vertically into the subsurface from an antenna placed on the ground. The subsurface propagation velocity and attenuation of radar waves are a function of soil conductivity, which is controlled by bulk composition and moisture content. Interfaces between media of differing dielectric properties give rise to partial reflection of the down-going radar wave; these reflections return to the surface where they are received and digitally recorded. The amplitude and time delay of reflected energy arrivals provide quantitative information on the composition and structure of the ground. Radar systems measure the two-way-travel time (TWTT) elapsed between transmission of the down-going pulse and

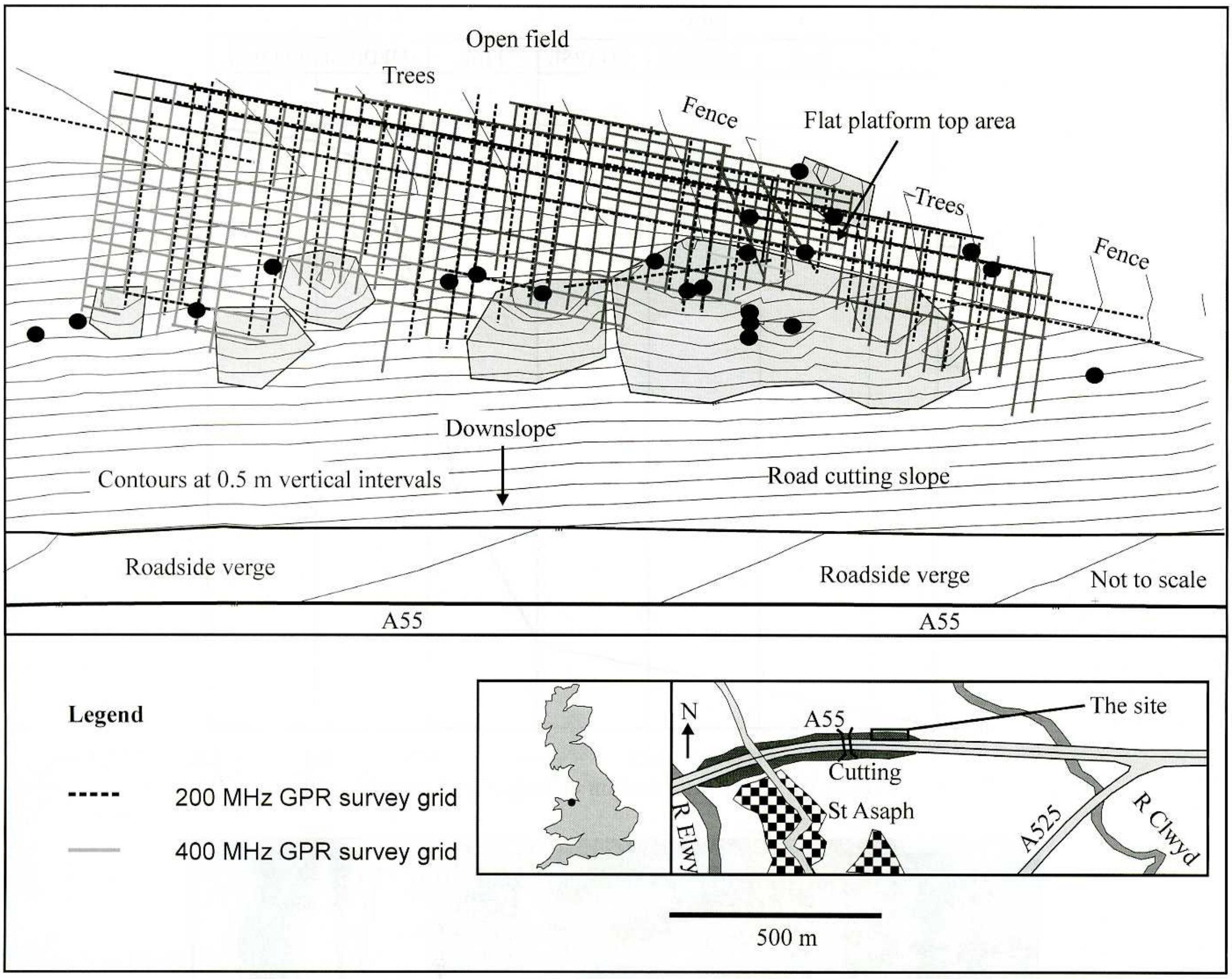

Fig. 2. Location of survey site and grid for 200 MHz and 400 MHz GPR investigations. Solid black circles denote positions of sett entrances.

Table 1. *Soil profile and representative engineering properties.*

Depth (m)		Soil type	Physical properties					Mechanical properties		Engineering geological property
from	to		Water content (%)	Dry density (g cm $^{-3}$)	Liquid limit (%)	Plastic limit (%)	Plastic index (%)	Cohesion (kPa)	Friction angle (°)	
0	1.9	Silty medium SAND	9	2.27	—	—	—	5	38	Good
1.9	3.5	Sandy CLAY	17	2.22	19	13	6	5	36	Fair
3.5	8.0	Silty CLAY (till)	19	1.86	25	17	8	25	22	Good

surface reception of reflections. By moving the antenna at a steady known rate across the ground surface, a pseudo-continuous 2-D section can be acquired, plotting TWTT against sample offset. Reynolds (1997) describes this technique in greater detail.

The GPR survey employed a GSSI SIR-2 radar system, alternately coupled with 200 MHz and 400 MHz monostatic antennae. Lines were set out with ropes (Fig. 5), facilitating rapid and accurate acquisition of data across the grids. Hard copy data profiles were produced and analysed in real time, allowing continuous survey grid adaption in response to the structures discovered. Digital data were subsequently processed and interpreted in Interpex Gradix, a PC-based GPR data visualization package.

The survey was designed to provide gridded transects at 0.5–2.0 m line spacings, with the closer spacing adopted in areas where features suggesting excavation,

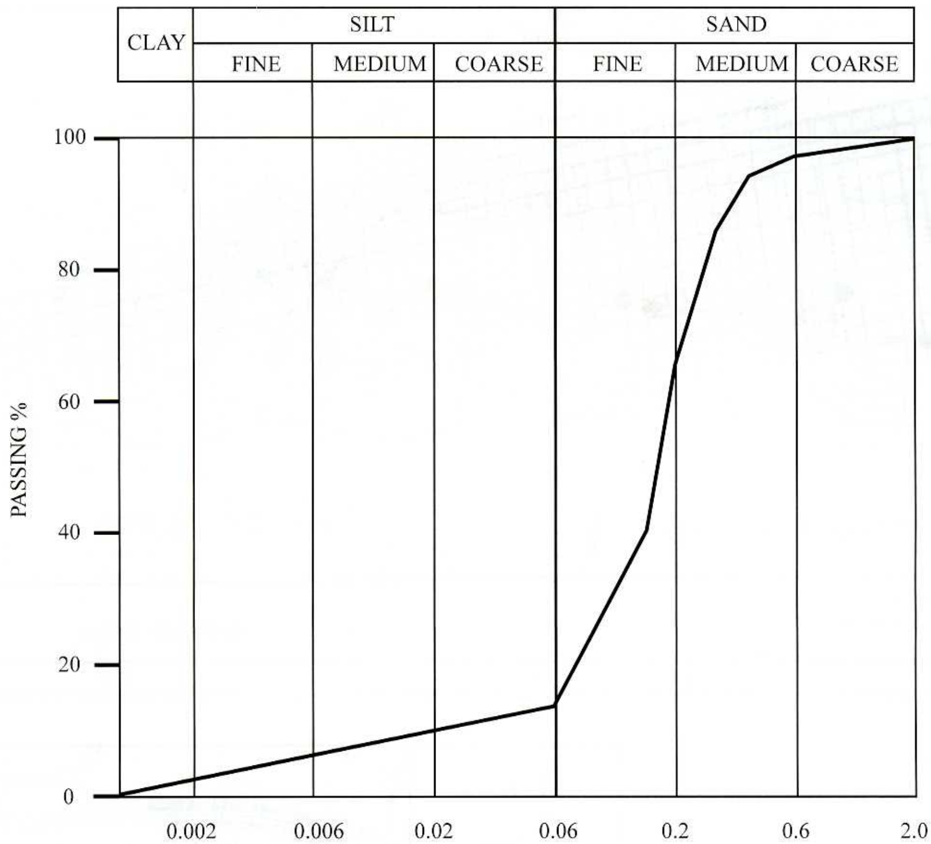

Fig. 3. Particle size distribution of badger spoil material.

Fig. 4. Excavation and deposition of soil in spoil mounds has produced oversteepening of the slope in the highway cutting.

such as spoil mounds, cracking and sett entrances predominate. An initial grid spacing of 1.0 m was adopted, with grid lines oriented perpendicular and parallel to the slope. Following field interpretation of the data, the survey area was then enlarged to investigate areas where tunnels extended beyond the initial grid margins (Fig. 2). In places, the grid spacing was reduced to 0.5 m in order to resolve areas of tunnel complexity. In addition, an EDM surveying instrument was used to map the distribution of spoil heaps, entrances and cracks.

System calibration

Engineering applications of GPR almost invariably require determination of subsurface radiowave velocities

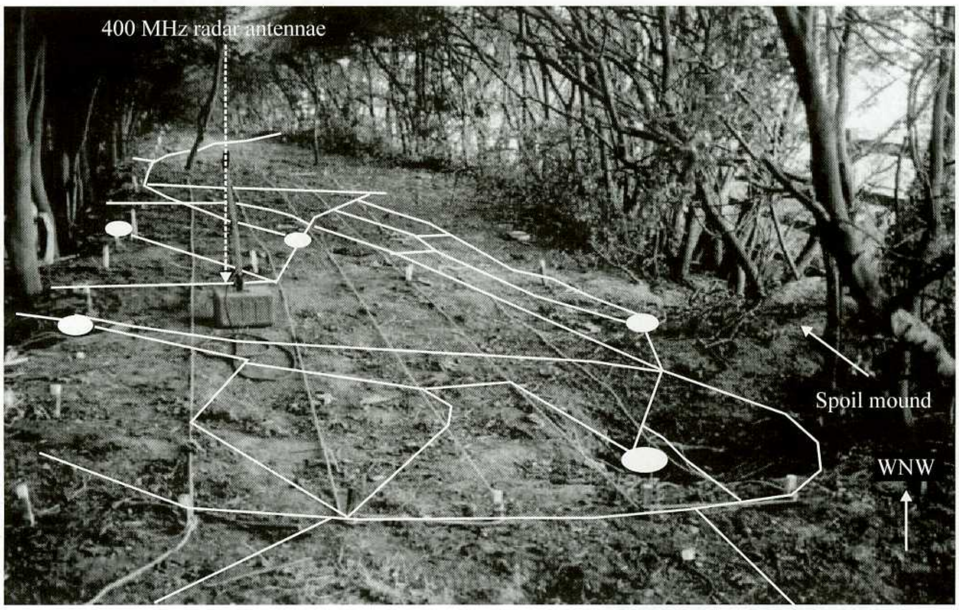

Fig. 5. Demonstration of line arrangement during 0.5 m spacing, 400 MHz survey on the platform at the top of the slope, with simplified 2-D interpretation of underlying tunnels linking the sett entrances. View looking westwards.

so that TWTT data can be depth-converted. In highway surveys along carriageways, velocities are generally obtained by calibrating reflection travel times against depth measurements obtained from as-built drawings. However, in this instance calibration was achieved by comparing the TWTT data with direct measurements taken at two positions close to sett entrances on the platform area. A thin rod was inserted through the ground above the tunnels until visible from the sett entrances and the precise depth to the roof of each tunnel was measured. GPR profiles at both 200 MHz and 400 MHz frequency were then acquired across the measurement points and perpendicular to the estimated tunnel headings (Fig. 6). Radiowave velocities calculated from the TWTT data and measured depths to roofs yielded a mean velocity of 0.11 m/ns.

The calculated radiowave velocity was used to estimate the vertical resolution of the GPR data, based on the quarter wave criterion (Reynolds 1997). Using the locally determined radarwave propagation velocity, the vertical resolution of the 200 MHz and 400 MHz data was calculated as 0.14 m and 0.07 m respectively. Spectral analysis of the radar reflection data indicated that the true dominant frequency of the arrival events ranged between 100 MHz and 400 MHz with a mean value of around 200 MHz. Accordingly, the best true vertical resolution between 0 m and 2 m is unlikely to be consistently better than 0.14 m.

Additional calibration information was acquired to assist in qualitative assessment of the local ground disturbance. Dual frequency trial profiles were acquired at the western end of the site in an area lacking surface signs of badger activity. During interpretation, background noise from this area was compared with areas of ambiguous reflection characteristics in the main survey grid to assist in differentiating collapsed tunnels from insignificant features unrelated to badger activities.

Data interpretation

Annotated examples of radargrams produced during the survey are shown in Figures 6, 7, 8 and 9. Interpretation of these radargrams requires consideration of the change in radarwave velocity and wavelength in sandy soils and in the tunnel air void. A radiowave passing from a slow to a fast dielectric medium (as in soil to air in a tunnel) produces a phase shift in the waveform that results in a large reflection coefficient, manifested as a strong reflection event. Furthermore, the presence of a tunnel can be confirmed if otherwise flat underlying reflections become upwardly convex in nature beneath a strong, discrete reflection event. Air-filled tunnels do not appear as circular features in the radargrams because the radarwave velocity in air (*c.* 0.3 m/ns) is much greater than the velocity in the surrounding soil (*c.* 0.11 m/ns) with the result that the velocity field is distorted and the arrival from the tunnel floor is lost in the tail of the preceding tunnel roof reflection. This distortion is termed 'pull-up' and results in the representation of tunnels as discrete, strong reflection events.

The transmitted radar pulse undergoes a degree of lateral spreading during propagation and so tunnels crossed by orthogonal sweeps will be represented by parabolic reflections (Fig. 7a). Here, true depth to the top of the tunnel is given by the minimum arrival time corresponding to the closest point of the tunnel to the antenna. In marked contrast, tunnels crossed at oblique angles produce broader and more complex anomalies (Fig. 7b).

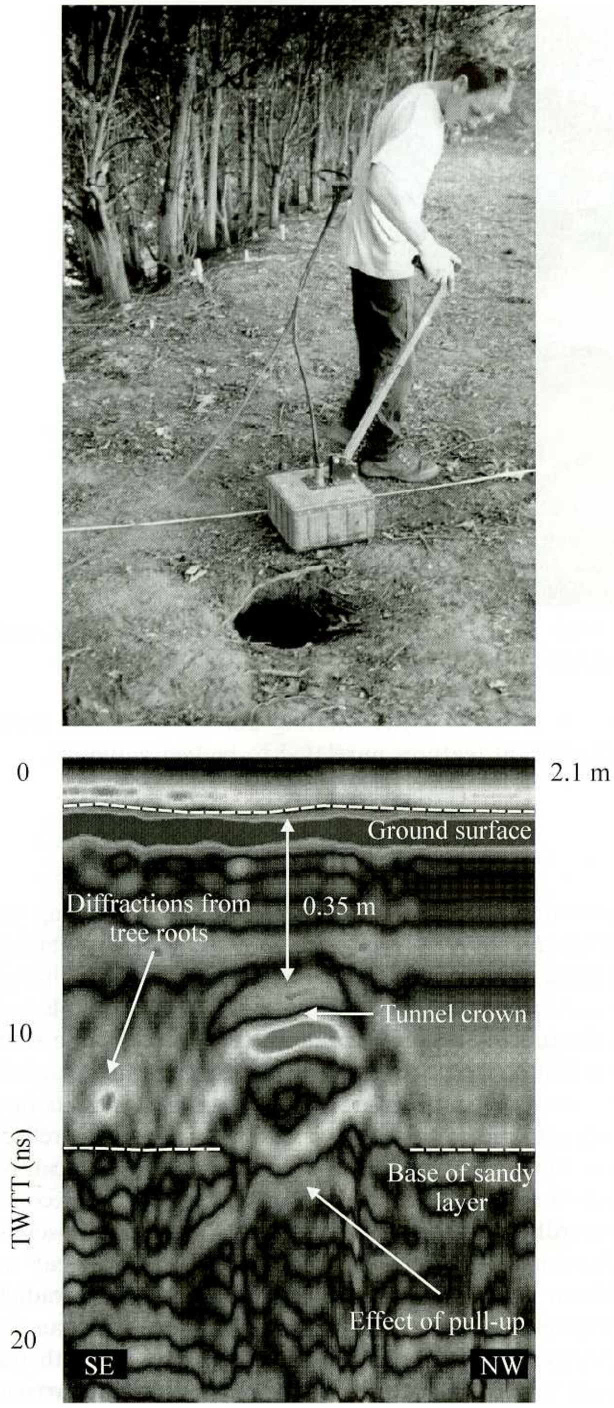

Fig. 6. (a) Calibration of 400 MHz GPR line above a tunnel of measured depth. (b).Interpreted radargram showing the calibrated section.

Initial tests established that the 400 MHz antenna provided superior imaging of buried tunnel structures, providing a nominal radarwave penetration in excess of 1.5 m. The majority of the significant targets identified were encountered within this depth range. At 200 MHz, the system failed to adequately discriminate between adjacent shallow tunnels due to the lower horizontal resolution of the 200 MHz footprint. Accordingly, interpretation was focused on data from the 400 MHz antenna, whilst 200 MHz data were used primarily as a check for features at greater depths.

As a result of arboreal landscaping, numerous tree roots were observed both at the surface and protruding through tunnel walls near the sett entrances. It was also observed that the badgers commonly utilize roots as natural lintels supporting their tunnel entrances. During interpretation, it was important to distinguish roots from the tunnel system. It was observed that the geophysical signature of tree roots differs significantly from that of air voids associated with tunnels; in the data examined, reflections from tree roots tended to be shallower, smaller in size, lower in amplitude and lacking in phase shift. Unexpected deviations observed when mapping some of the deeper tunnels might be explained by the presence of roots that were undetected by the GPR survey.

Significant features encountered on radargrams include tunnel intersections (Fig. 8) and larger voids interpreted as living or nursery chambers (Fig. 9). The sharpest and strongest radar anomalies exist throughout the central region of the surveyed area where surface evidence for badger activity was greatest. Elsewhere on the slope, several entrances were partially filled with sand, leaves and twigs indicating disuse. Reflections in profiles crossing these disused tunnels appeared less pronounced (Fig. 8), possibly due to a reduction in the air gap as a result of roof collapse.

Interpretational model

The interpretational model was constructed by treating the sett as a lattice of tunnels connected to primary nodes representing the entrances, whose positions were recorded during the EDM survey. The adjacent sections of GPR profiles enclosing a primary node (tunnel entrance) were treated as representing the perimeter of an interpretational cell. Anomalies were then identified on the cell perimeter, creating a group of secondary nodes. Where possible, field records indicating the known trend of tunnels leading from the primary nodes were used to support the model. Anomalies on the perimeters of cells adjacent to the primary nodes were then identified and their reflection characteristics and depths compared with those of the secondary nodes. This correlation was used to assess which nodes should be joined together to represent tunnels. Where no difference could be determined or tunnel branching was required (e.g. 3 or 5 nodes identified on a secondary cell perimeter) the simplest geometry was adopted. Interestingly, during fieldwork it was observed that tunnels near the entrances often exhibited steep shafts (> 45°) and switchbacks, so the validity of this approach remains open to question. As the network broadened, the certainty of these picks reduced with increasing distance from the entrance holes, but where networks from neighbouring primary nodes merged, there was generally a good fit among the

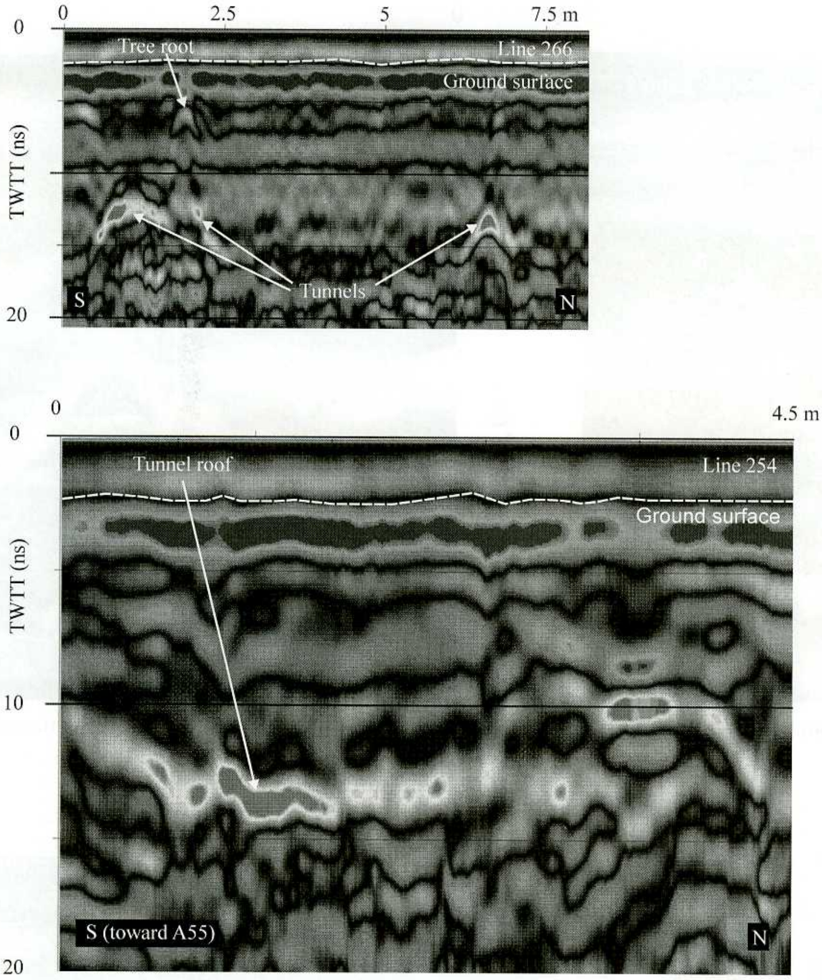

Fig. 7. Example of 400 MHz radargrams acquired perpendicular (a) and sub-parallel (b) to the badger tunnels.

interpreted tunnel trends. Experience gained during the interpretation procedure was cumulative, so that subsequent passes through the data between primary nodes progressively refined the interpretational model.

The final interpretational model is presented in Figure 10. This diagram depicts the entire tunnel network together with the major surface features. The total length of tunnels identified in the model is 324 m.

Interpretation of the general sett structure

Beneath the cutting slope the tunnels rarely descend to depths greater than 1 m and below the flat platform area they typically range between 1 m and 2 m deep. Significantly, no tunnels were detected deeper than 2 m and a change in the background radargram characteristics around this level appears to correspond to the base of the sandy soil stratum. The badger tunnels typically measure 0.25 m high and vary between 0.30 m and 0.35 m wide. Three areas exhibiting broad reflections were identified beneath the cutting slope (labelled Areas A, B and C in Fig. 10) and interpreted as representing larger chambers. The chambers range up to 0.3 m high by 1.0 m wide and appear to be formed by widening of existing tunnels. A typical badger sett comprises a main nursery chamber occupied by the primary breeding pair, with a possible secondary associated chamber occupied by a secondary pair. It is not uncommon for parts of the sett to be taken over by opportunist species such as foxes; when this occurs the badgers may simply extend the sett away from the intruders and excavate new chambers and tunnels. Thus the sett evolves through time and abandoned structures are to be expected.

In Area A, broad high-energy anomalies were recognized, but interpretation proved somewhat uncertain due to poor depth control. Here, the spoil heaps are relatively small and the few entrances that exist appear disused. The physical significance of these broad radar anomalies remains unclear, but they possibly represent an abandoned chamber complex of an annexe or outlier sett.

Area B, in the central part of the site, straddles two large spoil mounds that appeared recently modified. Fresh dung piles and discarded bedding materials were observed nearby. These were scattered around two separate entrances and indicate that a litter had been raised in a nursery chamber close by, probably situated between the entrances. The geophysical data identified a

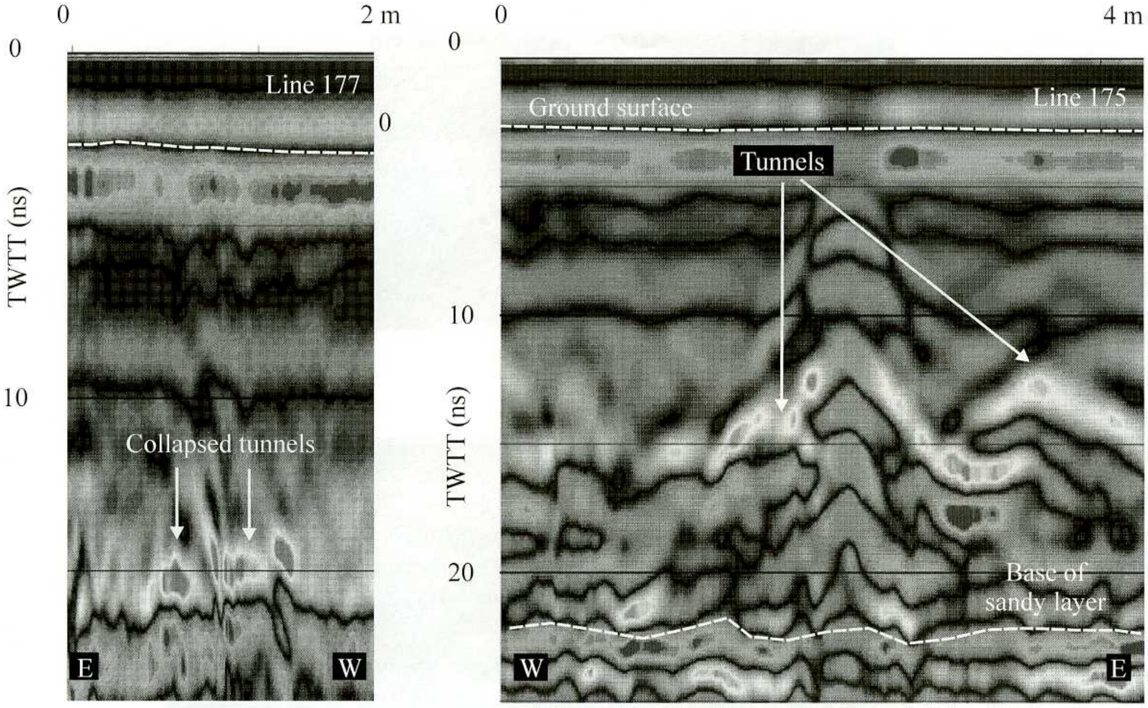

Fig. 8. 400 MHz anomalies interpreted as representing (a) collapsed tunnels and (b) divergent tunnels close to a sett entrance.

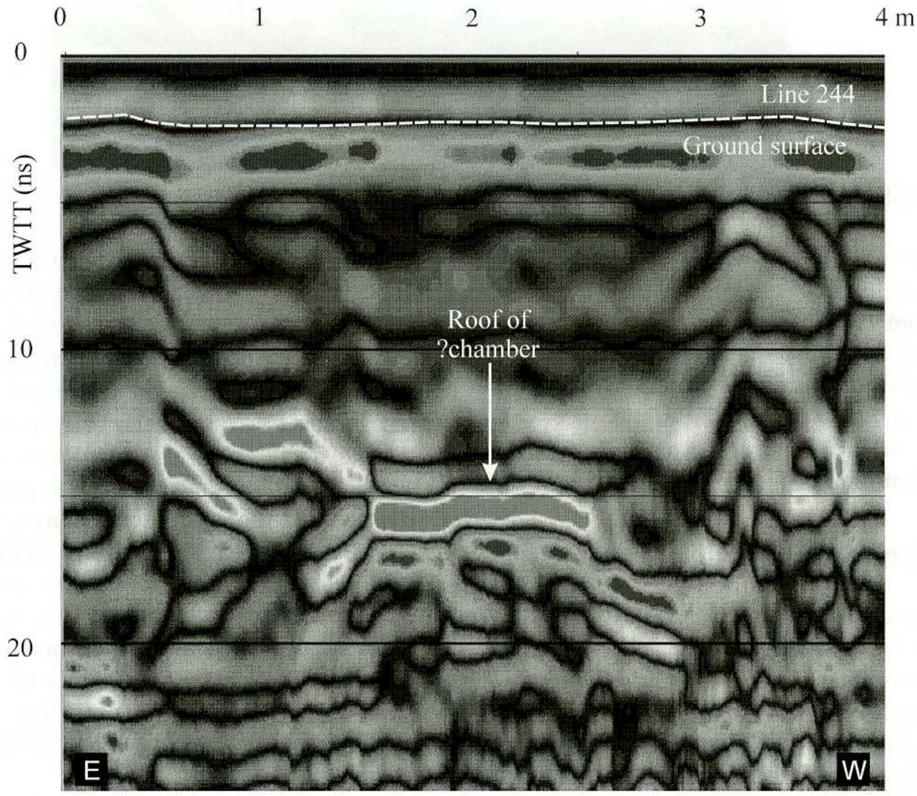

Fig. 9. Strong elongate 400 MHz anomaly interpreted as representing a chamber (Area C).

large chamber at the confluence of numerous tunnels beneath this area. The combined evidence suggests that this is likely to represent the principal living chamber.

Around Area C, most of the entrances appear disused although badger tracks and recently visited latrine sites were observed nearby. Interestingly, the geophysical data indicated that here, a chamber excavation lies

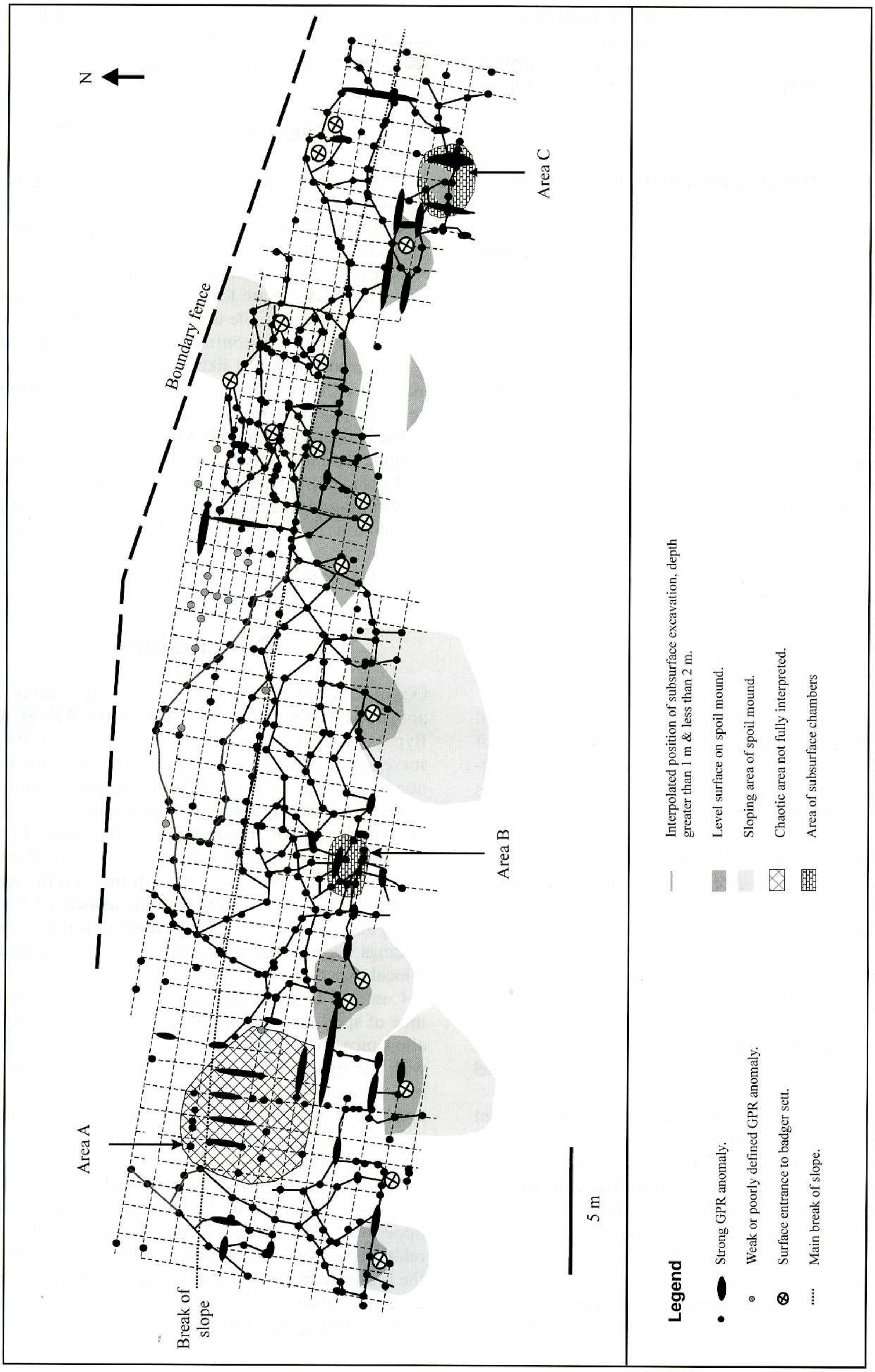

Fig. 10. Final interpretational model of the St Asaph Bypass GPR survey data, showing the position of subsurface excavated features.

immediately beneath the largest of the spoil mounds. This may represent an abandoned group of chambers, but the presence of fresh droppings in the latrines supports the alternative interpretation of an annexe nursery used by a second breeding pair.

Spoil and excavation volumes

A general indication of the accuracy of the GPR survey is provided by comparison of the excavated spoil mound volume with the volume of underground air spaces calculated from the final interpretative model. Data from the topographic EDM survey were used to calculate the approximate volume of spoil material in each mound, based upon the assumption that the slope surface beneath the mounds and over the excavated hollows was originally planar in nature. To correct for expansion of the excavated material, a bulking factor of 0.8 was applied. As the EDM survey point density was rather coarse and the calculation made assuming an initial planar surface, an arbitrary error estimate of $\pm 20\%$ was considered reasonable for the calculated spoil mound volume. No provision was made for bulk losses due to rainwater erosion because of the sheltered nature of the site. Also, no allowance was made for volume exaggeration caused by tunnelling within the large spoil mound in Area C. The calculation for total pre-excavation volume of spoil material yielded a value of $46 \pm 9\ m^3$.

Mapping of the subsurface tunnel network established a total identified tunnel length of 324 m. Dimensions of underground tunnels are likely to vary, but for calculation purposes, typical values of 0.25 m high by 0.35 m wide were adopted. No provision was made for the uncertain anomalies in Area A. However, an upward adjustment was made to account for living and nursery chambers in each of Areas A, B and C, assuming chamber dimensions of 2 m long by 0.3 m high and 0.6 m wide. Another possible source of error in the volume calculations accrues from the subsurface model due to the assumption that tunnels trend in straight lines between nodes. To take account of the influence of variations in tunnel dimensions and straightness, an arbitrary error allowance of 20% was applied, yielding a total excavation volume of $31 \pm 6\ m^3$ for the tunnel network.

The estimated volume of excavated material present on the site was $46 \pm 9\ m^3$, whereas the total tunnel volume was estimated to be $31 \pm 6\ m^3$. Although these values are of the same order of magnitude, the discrepancy remains significant and is difficult to explain. Possibly, the tunnel network associated with Area B extends beyond the survey site and under the open pasture to the north. Alternatively, tunnel diameters may have been consistently underestimated during the volume calculation. It seems unlikely that additional tunnels remain undetected at greater depths, as no evidence was found for any shallow tunnels connecting such deeper diggings to the surface.

Geotechnical aspects

The open cracks along the crest of the cutting provide surface evidence for incipient ground movements. Inspection of radargrams acquired above the cracks failed to identify any relationship between the pattern of cracking and the network of badger tunnels. Conceivably, the cracks relate to older collapsed workings that are no longer detectable using GPR techniques by virtue of a lack of physical contrast. However, in this instance it is considered more likely that the cracks may be ascribed either to soil creep or ground disruption and heaving caused by tree roots.

The badger spoil mounds pose a relatively minor threat to slope stability. Nonetheless, the radar survey has identified disused areas where removal of spoil material from certain mounds may be carried out to alleviate the problem without disturbing the sett. It has also identified that the undermined spoil heap in Area C should not be disturbed, as this might impact upon the badgers.

Conclusions

Occupied badger setts on the highway cutting slope above the eastbound carriageway of the A55 St Asaph Bypass have been successfully mapped using GPR. The survey demonstrated this technique to be viable for the non-invasive detection of animal diggings in sandy soil.

The radar survey delineated the extent of the diggings and the layout of the animal-tunnel system. In total, 324 m of tunnels have been identified from GPR profiles and tied to the positions of sett entrances on the surface. The positions of larger excavations associated with the living and nursery chambers were also identified and the findings were in agreement with an assessment made by a local expert in badger habitats.

Contrary to expectations, estimates of the total volume of spoil material in the badger mounds show, after allowance for bulking, a slight surplus in comparison with the estimated volume of the tunnel system. This may be ascribed to the possible extension of the tunnel network in Area B northwards beyond the survey site, or to the actual dimensions of tunnels exceeding the estimated values.

The radar survey also demonstrated that the animal diggings are limited to the sandy soil stratum in the uppermost 2 m of the cutting slope. In addition, no relationship was apparent between surface cracking and the tunnel network patterns. These findings resolved the geotechnical concerns relating to the structural integrity of the cutting slope. Engineering responses to safeguard the slope proved unnecessary although removal of spoil material from mounds in areas identified as being abandoned could be carried out safely without undue disruption to the badger population.

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