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# Investigating the relationship between trenching practice and road deterioration

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The functioning of modern societies relies on the successful performance of their infrastructure. In the UK, much of the buried infrastructure is located below the road surface, and routine maintenance of these requires networks to be accessed, commonly by open-cut methods. The open-cut operation in roads is likely to change the performance of the pavement structure and potentially how loads are transmitted, thereby affecting the buried infrastructure. The main objective of this paper is to investigate the impact of open-cut construction on the road, ground and buried infrastructure with the aim of improving the current associated guidelines. A fully instrumented site trial was undertaken where two pipes were installed using trenching in a road, with one reinstated according to the higher end of the UK specification and the other on the lower end of the specification. The trench reinstated according to the lower end of the specification experienced serviceability failure, where large settlements (approximately 70 mm) and deflections (up to 2000  $\mu\text{m}$ ) were observed. The other trench also experienced distress, although to a much reduced level. This demonstrates that trenching, even when reinstated according to the higher end of the specification, still weakens the existing road locally.

## Introduction

Modern, developed societies are fundamentally dependent on the successful performance of their infrastructure (i.e. roads, buried utilities and, equally important, but often overlooked, the surrounding ground). Any disruption to their function and serviceability can lead to costly consequences (Matthews and Allouche, 2010; Matthews *et al.*, 2015). These infrastructure systems, which might be many decades old, require maintenance and possible upgrading to cope with the demands placed on them, while various public and private organisations are tasked with overseeing them (depending on the country). In this complex system, an organisation might overlook the needs of the surrounding infrastructure when attempting to manage their own system. This is unfortunate, as it is recognised that individual infrastructures form interconnected systems with others in local proximity, where interventions on one can have unintended, and potentially negative, implications on the relative performance of others.

For instance, deteriorated roads have been shown to accelerate the deterioration of buried utilities (Clarke *et al.*, 2017). Furthermore, the vast majority of installation, maintenance and replacement of

buried utilities are currently conducted through open-cut street works (OCS) (i.e. trenching) with significant negative impacts on the lifespan of roads (Alinizzi *et al.*, 2018). OCS is estimated to be responsible for around a 30% reduction in the structural life of roads (Steele *et al.*, 2003). The increasing number of OCS in England and Wales, around 2.5 million in 2015–2016 (a 13% increase compared with that in 2014) costs the local authorities, on average, 13% of their maintenance budget in relation to repetitive road maintenance (AIA, 2016). Previous research indicates that OCS significantly increases water ingress into the pavement structure (normally through the joints between the trench and the existing road structure), and this can lead to significant surface deformations over time (McHale, 2013; Schaefer *et al.*, 2005; Stevens *et al.*, 2010).

Water entering into the road structure potentially permeates into the ground beneath and interacts with the foundation soil, unless there is sufficient drainage in place (Stevens *et al.*, 2010). This can result in softening of the soil, which not only changes the bearing capacity of the ground, potentially impacting on the performance of the pavement above, but also changes the loading conditions on the buried infrastructure (Clair and Sinha, 2014;

Gould *et al.*, 2009; Rajeev and Kodikara, 2011). Inappropriate reinstatement processes can also result in weakened ground conditions that impact on both the surface and buried infrastructure. In both situations, the changes in ground condition are often overlooked (the ground is often considered inert, but this is often not the case), yet its response is fundamental to the performance of those infrastructures sitting on or buried within it. The authors therefore suggest that the ground should be deemed an equally important infrastructure and the linchpin that interconnects the surface and buried infrastructure.

In an attempt to investigate the impact of OCS construction, including excavation and reinstatement, on the interconnectivity of the surface, ground and buried infrastructures, a field trial was undertaken on a 'controlled', yet real, site. The impacts of three components of the OCS construction were investigated – namely, the backfill material and its compaction and the joint seals. These parameters were selected to showcase the impact of inappropriate OCS practice, which may happen in reality, and to show the need for enforcing the use of quality control measures. The aim of the research was to provide important independent evidential data for practitioners and policymakers to help improve the current guidelines on OCS practice and buried infrastructure management, by emphasising the need to adopt robust quality control measures. The paper initially presents a review of previous research into OCS practice, followed by a detailed description of the trial site construction and instrumentation. Key results from the research are then presented and discussed.

### A summary of previous research into the impacts of OCS

The negative impacts of trenching on road service life and its functionality have been reported in many previous studies (e.g. Burtwell and Spong, 1999; Carder and Taylor, 1983; Chow and Troyan, 1999; Fleming and Cooper, 1995; Jensen *et al.*, 2005; Lee and Lauter, 1999; McHale, 2013; Nichols-Vallerga & Associates, 2000; Schaefer *et al.*, 2005; Steele *et al.*, 2003; Stevens *et al.*, 2010). For instance, Fleming and Cooper (1995) conducted an extensive trenching-monitoring programme, collecting settlement data from over 100 trenches over a 3-year period. The measured data showed that approximately 36% of the monitored trenches were settling 1 year after the reinstatements, at an average rate of 1 mm/month. Schaefer *et al.* (2005) identified two main processes responsible for settlement – namely

(a) poor compaction of the backfill materials, caused, for example, by

- (i) low energy input (e.g. limited number of passes)
- (ii) inappropriate selection of layer thickness prior to compaction
- (iii) use of material with a water content significantly different from the optimum (e.g. if the material has been left exposed to wet or freezing conditions)

(b) the use of inappropriate backfill materials.

Backfill materials (e.g. granular, manufactured and recycled) and compaction procedure (e.g. applied energy) and their correlation with road deterioration have also been examined in the past and found to be of critical importance (e.g. Macy, 2002; Schaefer *et al.*, 2005; Stevens *et al.*, 2010).

Settlement can lead to preferential pathways for surface water, inducing water accumulation and increased infiltration, potentially accelerating the deterioration of the road. However, ground movements are not limited to the vertical plane nor to the boundaries of the trench, and this can be overlooked when considering the suitability of a reinstatement. For example, previous research indicates that disturbance to the road structure adjacent to the excavated area occurs (Jensen *et al.*, 2005; Lee and Lauter, 1999; Steele *et al.*, 2003). This weakened zone, sometimes termed the 'the zone of influence', has been reported to extend around 0.5–1.0 m beyond the trench boundary and is caused by stress relaxation leading to lateral soil movement during construction, which cannot be restored to the required specifications during reinstatement (Stevens *et al.*, 2010).

The negative impacts of varying water content in the backfill material during and after construction have also been studied. For example, the collapse potential of granular backfills under a low degree of saturation have been investigated in a number of studies (Jensen *et al.*, 2005; Schaefer *et al.*, 2005; Stevens *et al.*, 2010). The findings showed that the highest collapse potential for the tested granular material was achieved when the water content was in the range 4–8%. While this range would not necessarily apply to all soils, the water contents were lower than the optimum values for the soils. Hence, the negative pore water pressures developed during compaction improved the stiffness and strength of the backfill. However, with seepage of water into the backfill, these negative pore water pressures (partially) dissipated, resulting in a reduction in strength and stiffness and self-weight compression. These backfills were fundamentally metastable in nature. Water content values closer to the optimum increase the achievable density and decrease the potential for collapse. This demonstrates the importance of controlling water content during the road construction and trench reinstatement. It also demonstrates that measuring stiffness or strength alone would not necessarily provide a guarantee of conformity, as these measurements alone do not provide an indication of the potential metastability of the backfill.

### Problem statement

The current UK specification for street works (DfT, 1991) has the potential for wide interpretation when it comes to trenching and reinstatement operations. There is also only a requirement for those conducting these operations to be responsible for a period of 2 years after the OCS – that is, to provide a 2-year guarantee. As a result, the current practice for conducting street works could tend towards the lower end of the specification rather than the higher end.

Despite previous studies investigating the negative impacts of trenching and the individual factors related to trenching practice and road conditions, none of these studies has provided a direct experimental comparison between OCS practices on higher and lower ends of the specification, where both the practices comply with the current specification (i.e. in the code of practice by the UK Department of Transport (DfT, 1991)).

The research hypothesis is that even when the UK specification for street works involving OCS are followed, those reinstatements at the lower end of the specification can have a much greater negative impact on road condition compared with those reinstatements conducted at the higher end of the specification. This information would be extremely valuable to both practitioners and regulators and would provide evidence that could be used to improve the current guidelines and field practices related to trench construction and reinstatement. Hence, this is the focus of this paper.

Furthermore, the correlation between rainfall and water ingress through unsealed reinstatement joints has not been studied previously, a shortfall that is also addressed in this paper.

## Methodology

A test site was developed at the University of Birmingham (UK) campus and comprised an existing road, with restricted access, being used during the study period by lorries and other heavy vehicles involved with the demolition of a nearby building. Due to the location of the site, only limited access was granted to the research team.

The OCS undertaken on the test site involved the excavation of two trenches, the installation of an instrumented (air-filled) plastic pipe in the base of each trench and backfilling (including pipe bedding, capping layer and road sub-base) before the road was resealed. One trench, trench 1, was reinstated according to the

lower end of the specification, and trench 2 was constructed following the higher end of the specification (both following the reinstatement guidelines stated in the code of practice by the DfT (1991)).

- Trench 1 used suboptimal materials, reduced layer thickness and poor compaction.
- Trench 2 followed the current best practice with high-quality materials, a thicker surface layer and good compaction.

Table 1 provides further details of the two reinstated trenches.

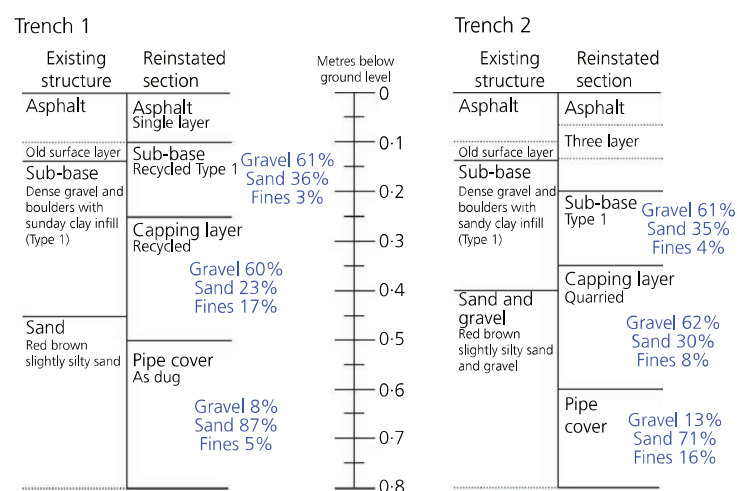
Figure 1 shows the layout and the measured particle size distribution of the existing and reinstated ground layers.

Figure 2 shows the reinstated trenches, excavated in a V-shape in plan so that a single control station could be used and to minimise the length of cabling. The dimensions of each trench were 8 m long, 0.9 m wide and 0.8 m deep. High-density polyethylene plastic pipes, 100 mm dia., equipped with acoustic sensors were

**Table 1.** Characteristics of the two trenches constructed for the field trial

Trench 1		Trench 2	
Material	Thickness: mm	Material	Thickness: mm
Sand (as dug)	300	Sand	200
Recycled capping (granular)	250	Quarried capping layer	250
Recycled type 1 <sup>a</sup>	150	Type 1 <sup>a</sup>	150
Hot-rolled asphalt	100 (one layer)	Hot-rolled asphalt	200 (three layers)
Compaction after recycled type 1		Compaction on all layers	

<sup>a</sup> As defined by the DfT (2012)



**Figure 1.** Layout of the existing and reinstated road structure (including the particle size distribution of the reinstatement materials)





Figure 2. (a) The two reinstated trenches; (b) construction of the poor joints

located in each of the trenches so that the condition of the pipe could be checked for the duration of the trial. Unfortunately, these sensors were damaged during construction and therefore were not used.

The joints between the constructed trench 1 and the existing road were not sealed (Figure 2(b)), while these joints for trench 2 were sealed using overbanding tapes and painting the trench walls with bitumen. Additional poor joints were created on the constructed trench 1 by laying a middle section with vertical edges, rather than the recommended stepped overlapping joints, again without using any overbanding tape.

The rationale was to monitor surface movements, subsurface changes and changes in pipe properties (i.e. acoustic) in an effort to tie these trends to both the traffic loads and the weather conditions. The data collection period lasted approximately 10 months, starting in February 2017.

Unfortunately, the sensors within the two buried pipes ceased communicating with the data collection facilities early on and attempts to re-establish communication at the sensor hub (a waterproofed shed) were to no avail.

Historical data on the road construction were unavailable, although it is believed to have been originally constructed approximately 50 years ago. However, data on the road structure as well as the subgrade were gathered during the trenching operations.

Sensing techniques

Sensors were installed in the sub-base and subgrade layers under the asphalt, and a weather station was installed next to the excavated area to monitor the ambient conditions throughout the trial period (see Figures 3 and 4 and Table 2 for more details on the sensors).

Additional sensors were installed in trench 1. For example, displacement transducers and pressure cells were installed only in trench 1 to monitor the potential inward soil lateral movement and lateral pressure during construction of the nearby trench 2. Soil water content sensors (i.e. GS3 sensors; see Table 2) were also installed in trench 1 to complement the time-domain reflectometer (TDR) soil water content sensors. TDR and temperature sensors were installed in both trenches at different depths to measure the water content and temperature gradients with depth in the sub-base and subgrade layers, respectively. Strain gauges were also installed vertically just beneath the asphalt layer to measure the microstrain caused by passing vehicles. In addition, the traffic

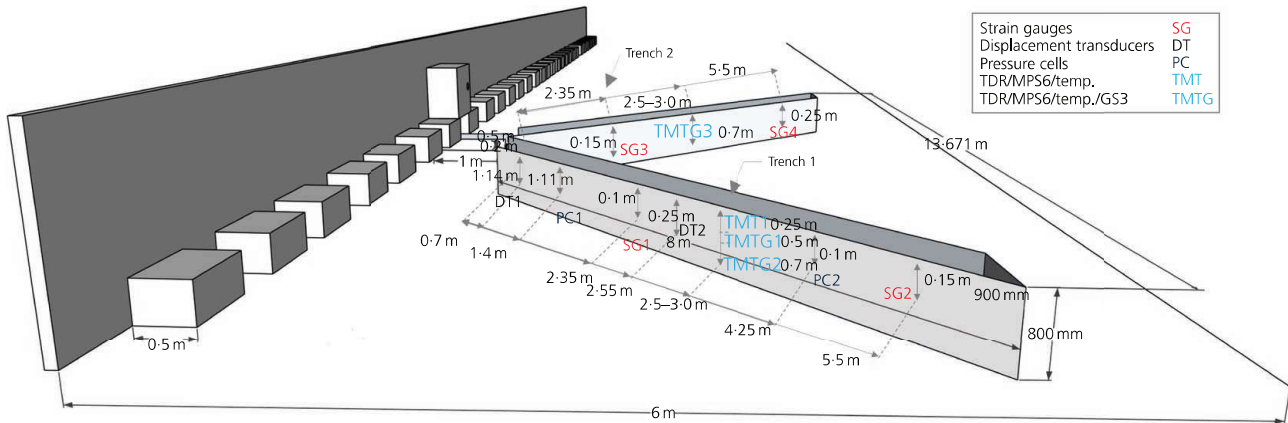


Figure 3. Location of the installed sensors





**Figure 4.** Sensors utilised in the trial: (a) pressure cell; (b) displacement transducer; (c) strain gauge

**Table 2.** List of sensors used in the field trial and their main characteristics

Sensor	Trench/number of sensors	Measured parameter	Measurement interval	Supplier/model
Displacement transducers	Trench 1/two	Lateral soil displacement from the trench walls	2 h	Geokon Inc/4435 2–300 mm
Pressure cells	Trench 1/two	Lateral pressure on the trench walls	2 h	Geokon Inc/model 4800-1
Strain gauges	Both trenches/four (two for each trench)	Vertical strain (microstrain)	0.5 s	Geokon Inc/model 3900
Soil water content sensors (TDR)	Both trenches/six (three for each trench)	Soil water content	4 h	Campbell Scientific/model CS635 with SDMX50 multiplexers and TDR100 unit
Soil water content sensors	Both trenches/four (two for each trench)	Soil water content	4 h	Meter Group (previously Decagon Devices)/model GS3
Temperature sensors	Both trenches/six (three for each trench)	Temperature	4 h	Campbell Scientific/model 107
Weather sensors	N/A	Ambient weather parameters	1 h (summary of higher sampling frequency)	Meter Group/model Atmos 41
Traffic counter sensors	Trench 1	Traffic passes, vehicle type	Recorded continuously	MetroCount

was monitored (at least partially; see the section headed ‘Results’) using a traffic counter system (MetroCount) and a closed-circuit television (CCTV) camera that was capable of motion detection (the camera was also installed for security purposes).

In addition to the permanently installed sensors described earlier, a number of surveys were conducted to assess the functional condition of the road and complement the in situ tests (Table 3).

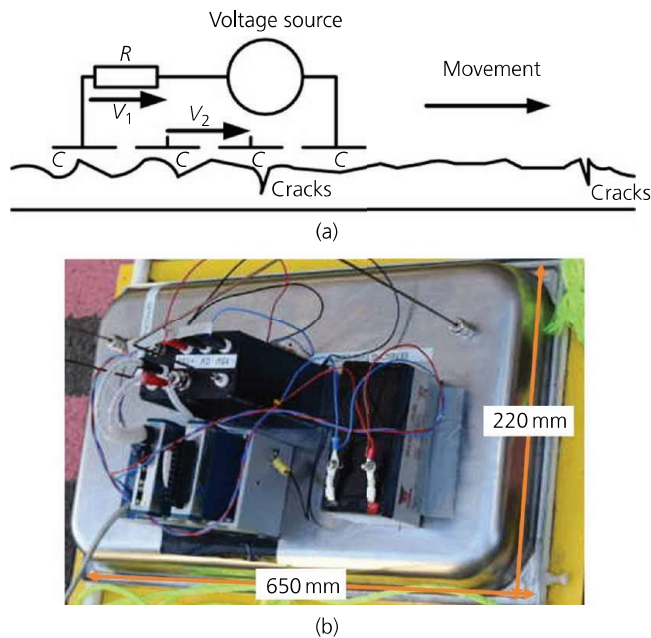
**Table 3.** Utilised test/monitoring techniques

Test/monitoring technique	Supplier
FWD test	Dynatest (2018)
Panda (a DCP) test as an in situ method	Corehard (2013)
In-house levelling surveys with a semi-automatic total station (Leica, model TS15)	University of Birmingham
In-house-developed non-contact electrical resistivity test	University of Birmingham

All the methods listed in Table 3 are commercially available except for the non-contact electrical resistivity test, which was developed in-house and is not conventionally used for road assessment. Therefore, some details of this technique are provided here.

Asphalt is a highly resistive material, but the presence of water in asphalt can result in lower resistivity. Degraded and/or poorly compacted asphalt has more voids and hence can retain more water. Using the resistivity technique, it is possible to examine the quality of the asphalt and the presence of any cracks or voids in the asphalt. However, conventional resistivity techniques are mainly invasive and time-consuming, as they require electrodes to be inserted into the ground (Metje *et al.*, 2007; Reynolds, 2011).

The non-contact resistivity sensor utilised in this study used a set-up similar to the Wenner array by injecting a known current into the ground and measuring the induced voltage at a known distance. The current was induced in the ground using rectangular capacitive



**Figure 5.** Non-contact resistivity sensor: (a) schematic diagram of the measurement unit; (b) the actual unit. The active sensing area is 640 mm × 110 mm

plates. The current source was replaced with a voltage source, and the voltage drop across a precision known resistor was used to measure the injected current. This set-up is shown in Figure 5.

The measurement unit was mounted on a robotic unit (a moving cart) and was controlled automatically with a Leica Total Station to survey the area on a 10 cm by 10 cm grid, typically sensing features within 10 cm of the electrodes. The raw data were conditioned and smoothed using a spatial low-pass filter with a circular impulse response of 25 cm diameter.

## Results

### Water ingress monitoring

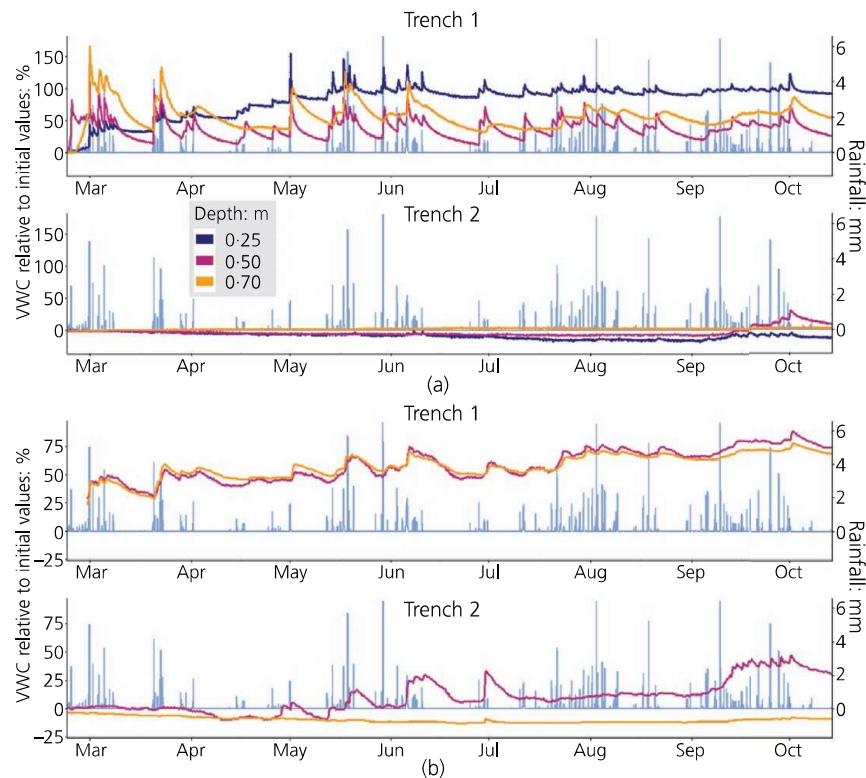
The main environmental factors linked to road deterioration in the UK are the amount of rainfall leading to water infiltration, freeze/thaw processes and general temperature variations potentially contributing to the physical deterioration of the road structure (note that chemical processes were not considered in this study) (Cawsey and Massey, 1988; Dunn and Hudec, 1972). Poor road joints, as well as cracks and defects, can provide routes for water ingress into the road structure. As water content was monitored at different layers throughout the trial, it was possible to say which one of these was responsible for water ingress (i.e. cracks developed towards the end of the trial).

During the monitoring period, no snow precipitation occurred, but a number of rainfall events were recorded with a maximum daily precipitation of between 6 and 7 mm on three occasions (Figure 6). The volumetric water content (VWC) measured by the TDR and

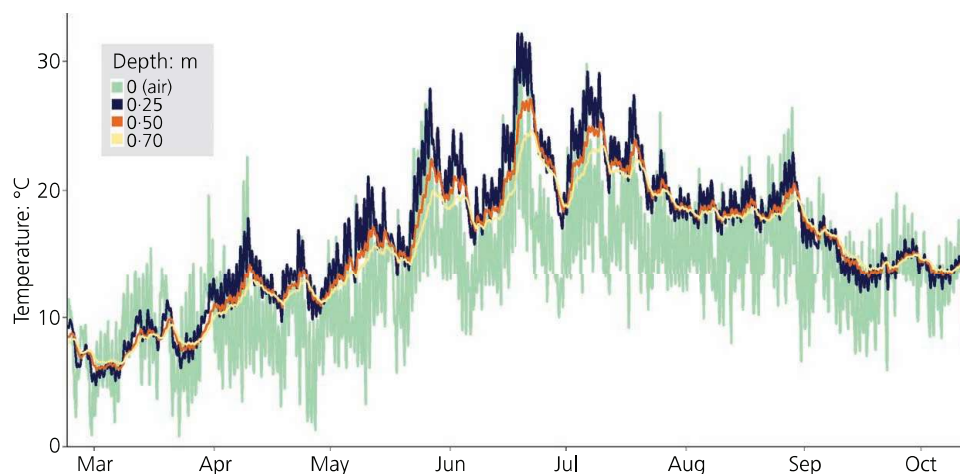
GS3 sensors are shown in Figures 6(a) and 6(b), respectively, at different depths relative to the initial values measured soon after installation. Clearly, these results show a significant difference in the infiltration rates, with smaller water content variations in trench 2 (typically well below 50% relative change) and significant changes corresponding to rainfall events in trench 1 (sometimes of over 100% relative change and regularly affected by rainfall events). The difference in water content between the two trenches, which can be seen from the start of the trial, is an indicator of the significant negative impact of unsealed joints.

The use of relative values was preferred, as this provides a better indication of the variation. However, the measured VWC by the two sensor types did not always match due to the different operating principles and the heterogeneous nature of the soil. With respect to the relative measurements presented, it is interesting to note that the TDR measured sharper spikes corresponding to rainfall events in trench 1 and approximately constant values in trench 2 except in October, when some water reached the probe at 0.50 m depth (Figure 6(a)). The GS3 sensors buried at 0.50 m depth in trench 2 measured clear variations in VWC throughout the monitoring period, although the magnitude of the changes was typically smaller than the changes recorded in trench 1 (Figure 6(b)). It is possible that water reached the location of this sensor through a preferential water path (possibly laterally). An alternative hypothesis is that the road above the sensor started to degrade due to traffic loading and associated cracks and small defects were responsible for that water change (some surface damage was indeed observed visually during site inspections in May). As discussed later, vehicles started moving regularly across the site from 18 April and the larger variations measured by this sensor were subsequent to this date (Figure 6(b)).

Figure 7 shows the air temperature and the temperature measured at different depths in trench 1 (the results from the other trench were very similar and hence are not shown). Sub-zero temperatures were not measured, and maximum temperatures of approximately 30°C were rarely reached and only then for a limited time, suggesting that temperature did not play a major role in deteriorating the road during the trial period. The seasonal and diurnal variation encountered on-site, and the gradient with depth can also be observed in Figure 7. The temperature was consistent in both trenches with only small variations measured (typically well below 1°C) between the two trenches. These differences were slightly more pronounced at a shallow depth of 0.25 m with trench 1 exhibiting a slightly higher temperature than trench 2, probably due to the higher air content and interconnected voids caused by small cracks and poor joints. However, the differences were small and uniform throughout the monitoring period and could also be caused by the different position of the sensors (e.g. if the sensors were installed at slightly different depths) or by slightly different systematic errors. These results suggest that the heat transfer was not significantly affected by the construction method of the trenched sections, which is an interesting finding in itself.



**Figure 6.** VWC change relative to the initial values measured soon after trench reinstatement obtained from (a) TDR sensors and (b) GS3 sensors installed at different depths (note that the embedded bar chart indicates the rainfall events)



**Figure 7.** Air and soil temperature variation at different depths during the trial period

### Backfill material and compaction

Road deterioration can be caused by various triggers, including excessive water and inappropriate backfill material and compaction, although these are not always mutually exclusive. As such, it is not always possible to differentiate road defects based on their exact trigger. However, the following sections report the results of observations and measurements, and where possible, the

potential trigger and interactions have been highlighted. Water ingress in this study was measured independently and therefore was reported separately.

### Response to traffic loading

In addition to the environmental factors described previously, the other major driver of road deterioration is cyclic loading from



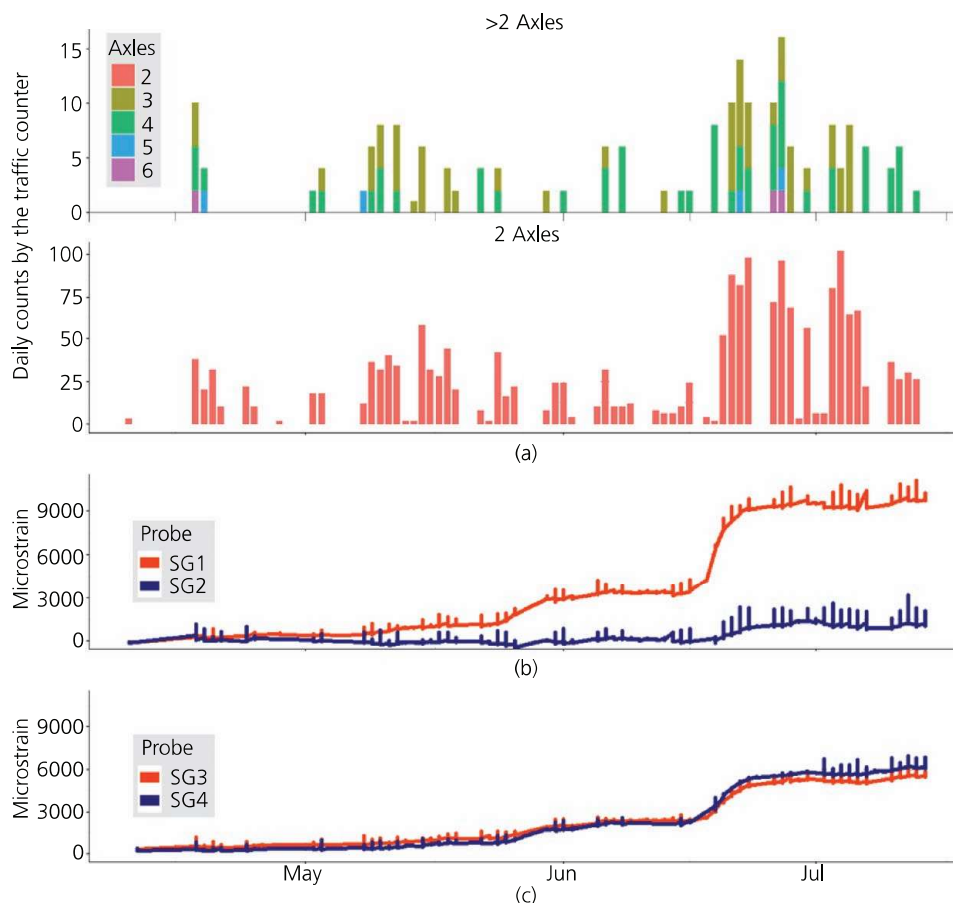
traffic, particularly from multi-axle heavy vehicles such as lorries (Krechowiecki-Shaw *et al.*, 2016). Traffic counters were used to monitor the number and type of vehicles passing over the two trenches.

Figure 8 shows the daily vehicle counts measured by the traffic counters and classified according to the number of axles. The majority of vehicles during this period had two axles, and generally, the number of counts of vehicles with greater than two axles followed the same pattern as the two-axle vehicles. Higher traffic numbers were recorded from the middle of June onwards. The strain gauge sensors buried just beneath the asphalt layer measured increasing microstrain over time (Figures 8(b) and 8(c)). The largest measured increase corresponded to the increase in traffic in the second half of June. Increasing microstrain is caused by movement of the road structure, which was significantly higher in trench 1, up to 50% (Figures 8(b) and 8(c)), as a result of inadequate compaction. A small settlement is expected when a new road section is subjected to traffic loading, due to further compaction (Frost, 2000). One of the sensors in trench 1 (SG1 in Figure 8(b)) measured significantly higher microstrain compared with both the sensors in trench 2, which measured very consistent

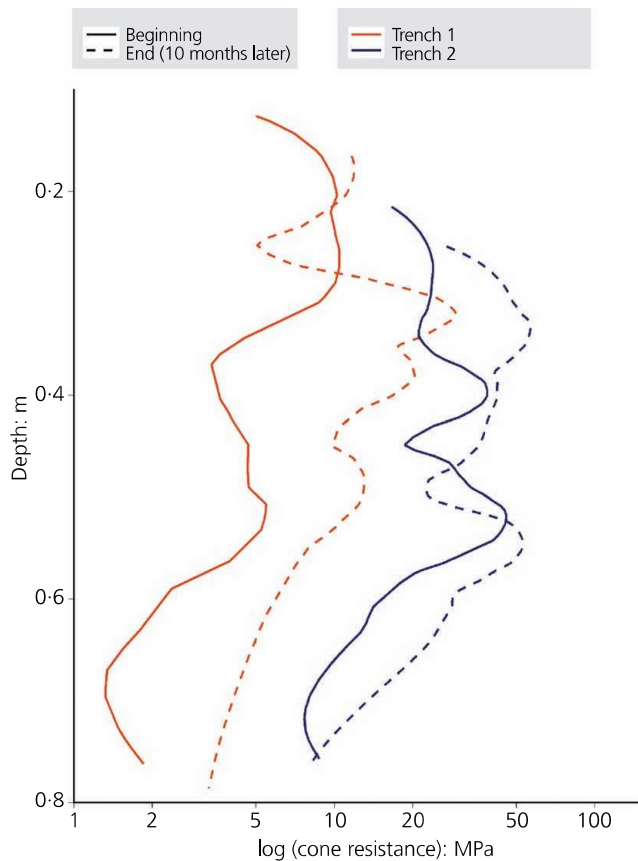
values, although they still reached 6000 microstrain (i.e. up to two-thirds of trench 1 values; Figure 8(c)). The second sensor in trench 1 (SG2 in Figure 8(b)) did not measure equivalent long-term trends. This is thought to be caused by the significant settlement (on the order of centimetres; see the section headed 'Road condition assessment' for more details) occurring near this sensor. The strain gauges were installed vertically, and they measured the microstrain based on the ratio between the displacement of the moving part of the sensor over its length. It is believed that the whole SG2 sensor (Figure 8(b)) was pushed downwards, and therefore, a long-term increase in microstrain was not measured. The regular spikes measured by all the strain gauges were related to the passage of vehicles, confirming the cyclic behaviour of microstrain under regular traffic loading.

#### Road condition assessment

In order to complement the in situ sensors, the condition of the reinstated trenches was also assessed with a number of techniques, most of which can be used as quality control measures for OCS operations as described later on. Figure 9 shows the results of the Panda dynamic cone penetrometer (DCP) surveys conducted at the beginning (immediately after trench reinstatement) and at the end of



**Figure 8.** (a) Volume of traffic measured by traffic counters; microstrain measured by strain gauges located immediately beneath the asphalt layer in (b) trench 1 and (c) trench 2



**Figure 9.** Cone resistance measured in both trenches by the Panda DCP test immediately after reinstatement (beginning of trial period) and at the end of the experiment (after 10 months)

the experiment (10 months later). For each visit, two measurements of the cone resistance were taken in each trench, and the results were averaged and smoothed to facilitate interpretation. Only the depth up to 0.8 m corresponding to the road structure was investigated. The results provide a clear indication of the impact of the trench reinstatement methods on the quality of the material in the two trenches, with significantly lower resistance exhibited by trench 1 compared with trench 2 immediately after reinstatement (Figure 9).

The Panda DCP can be used to estimate the elastic modulus ( $E$ ) of granular material (Lamas-Lopez *et al.*, 2016) using Equation 1 developed by Chua (1988)

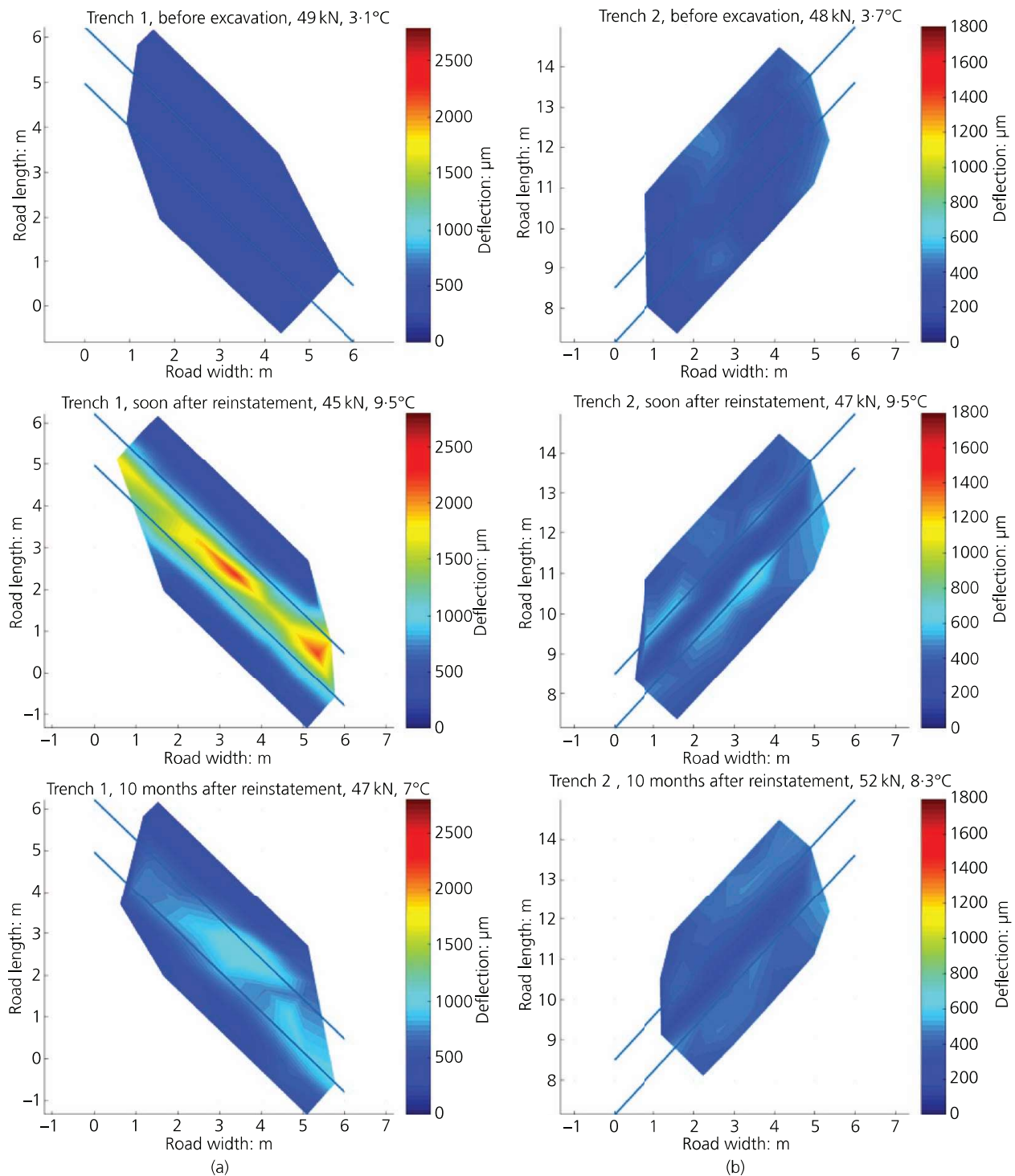
$$1. \quad E = 23 \cdot 2 \times \log(\text{cone resistance}) + 12 \cdot 5$$

The Highways Agency (HA, 2006) requires a minimum 50 MPa elastic modulus for Foundation Class 1 (capping-layer-only design for less than 20 million standard axles) and 100 MPa for Foundation Class 2 (capping and/or sub-base layer design, for less than 80 million standard axles). Using Equation 1, these limits correspond to 1.6 and 3.8 MPa, expressed as log(cone resistance).

After a period of 10 months and as a result of the heavy traffic loading, the cone resistance consistently increased in both trenches with only a couple of exceptions. Although the tests were conducted within 1 m from the location of the first survey, the decrease at certain depths is likely to be due to local conditions of the trench material. The mean increases in cone resistance were 5.9 and 10.8 MPa for trench 1 and trench 2, respectively, with maximum increases of 18.4 and 35.0 MPa, respectively (note that Figure 9 shows the cone resistance on a logarithmic scale, while these values are absolute). This indicates that although both trenches became stiffer over time, trench 2 became relatively stiffer and its resistance remained significantly larger compared with that of trench 1. This implies that the section of road associated with trench 1 would exhibit reduced performance over time.

This method can be used after backfilling and prior to resurfacing to assess the quality of backfill material and compaction by estimating the elastic modulus and comparing it with the design code as described earlier. As for an entire road network, collecting data on a regular basis can help the asset owner make a more informed judgement on the likely performance of trench reinstatements based on historical data that go beyond the broad specifications made in the guidance notes. For example, it would be possible to present evidence that based on the historical data, the lower limit of the specification for trench reinstatements creates unexpected risk to the road performance (as demonstrated in the trial results presented in this paper).

Falling-weight deflectometer (FWD) tests were conducted three times during the study (Figure 10). The first test was conducted on the original road before the trench excavations took place. The second test was completed a few days after reinstatement and before traffic occurred on-site. The FWD test was also repeated at the end of the project, 10 months after reinstatement. Figure 10 compares the surface deflection measured for both trenches after applying a similar amount of energy (approximately 50 kN). The data were interpolated using a triangulation-based linear interpolation method (Watson, 1994). The results clearly show the impact of the construction and reinstatement methods. Trench 1 exhibited significantly higher deflection after the first FWD test, indicating suboptimal characteristics (Figure 10(a) top and middle plots). Therefore, this section of road is expected to have reduced performance. The deflection was smaller during the third visit (bottom plot in Figure 10(a)), suggesting increased stiffness over time. This is expected, as the road settled and compacted over time, particularly after the passage of heavy traffic. However, the values remained around 1000  $\mu\text{m}$ . In contrast, trench 2 (Figure 10(b)) exhibited smaller variations in deflection over time. Interestingly, it is possible to see an area of increased deflection adjacent to the excavated section after the first FWD test (middle plots of Figures 10(a) and 10(b)). Although these results are an interpolation derived from discrete point measurements across the site, they suggest that this zone of influence potentially extends approximately 0.5 m from the edge of the excavated section. This is in line with the findings from other studies (Jensen *et al.*, 2005;



**Figure 10.** Deflection measured at different times for (a) trench 1 and (b) trench 2 using an FWD test with similar energy input

Steele *et al.*, 2003; Stevens *et al.*, 2010). These results are important because they confirm that even the trenches constructed according to the current best practice and specification have an impact on the existing adjacent road structure. The deflection on trench 2 reduced over time after traffic loading (bottom plot in

Figure 10(b)). It should be noted that the colour scales in Figures 10(a) and 10(b) are different for the two trenches (Figure 10(b) is around 700  $\mu\text{m}$ , or 40%, less than Figure 10(a)) to allow the corresponding changes to be clearly visible and that the values for trench 1 remained significantly higher over the entire period.



The FWD is a well-established method for road condition assessment and monitoring in the UK and elsewhere in the world. However, it is not currently used as a quality control measure for OCS. The results of this trial have shown the potential of the FWD for this purpose.

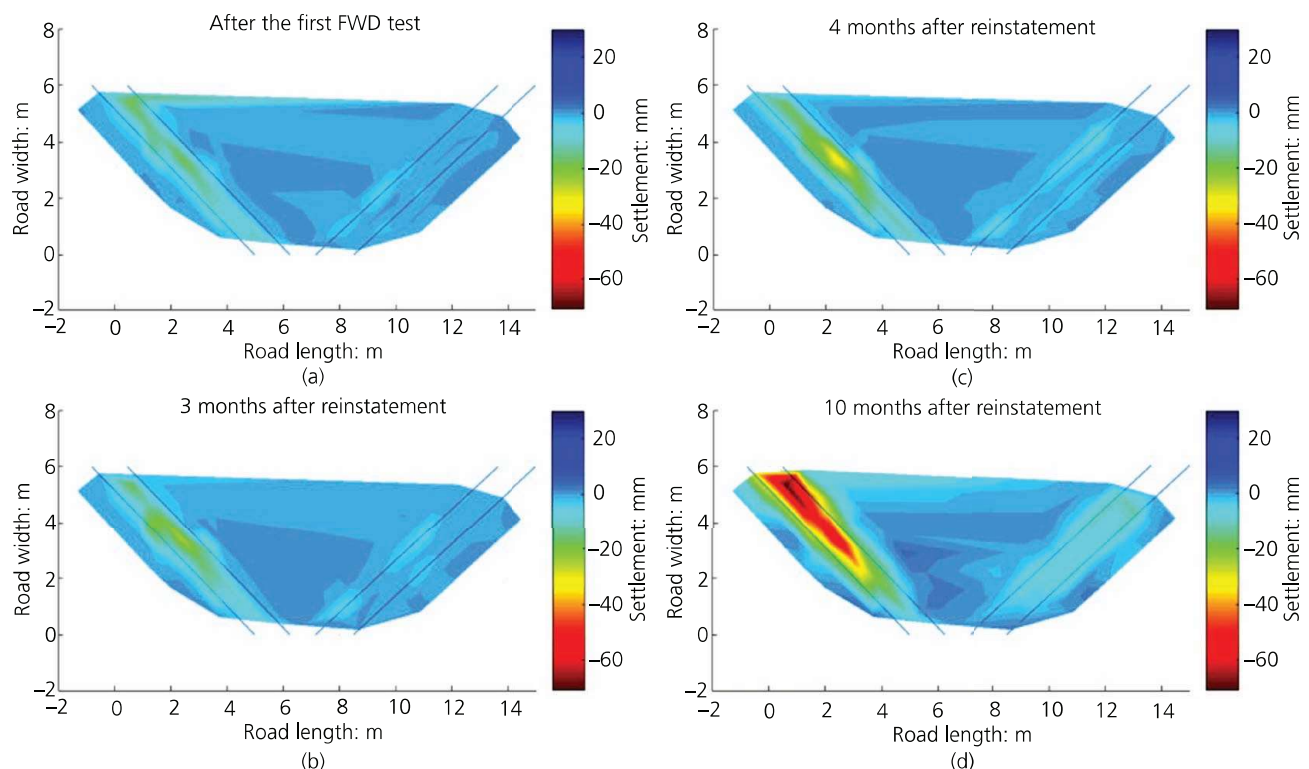
Over a period of 10 months, significant settlement occurred over trench 1, with peaks of 70 mm towards one end of the trench (Figure 11). Smaller settlement was observed over trench 2 with values remaining typically below 10 mm over 10 months. Although quantification of the traffic loading for the whole period was not possible due to the failure of the traffic counters, it is known from the CCTV images, strain gauge data and site visits that regular heavy loading occurred on-site for a period of 2 months between late August and early October 2017. As mentioned earlier, tracked vehicles were often used on-site and so were heavy lorries loaded with demolition waste. Although the trial lasted only a few months, the loading intensity was substantial, and hence, the results (e.g. settlement) can be used to show long-term effects. These results provide additional confirmation of the significantly reduced performance of the trench 1 section of the road compared with the trench 2 section. The majority of the settlement (up to approximately 20 mm) occurred immediately following the second FWD test (the first test after reinstatement; Figure 11(a)), when significant load was applied at specific point locations across the investigated area. Total station measurements taken 3 and 4 months after

reinstatement (Figures 11(b) and 11(c)) demonstrate that settlement increased quickly following initial traffic loading, starting on 18 April (around 2 months after reinstatement), although the vast majority of vehicles recorded during this period had less than four axles, indicating relatively low levels of loading (Figure 8).

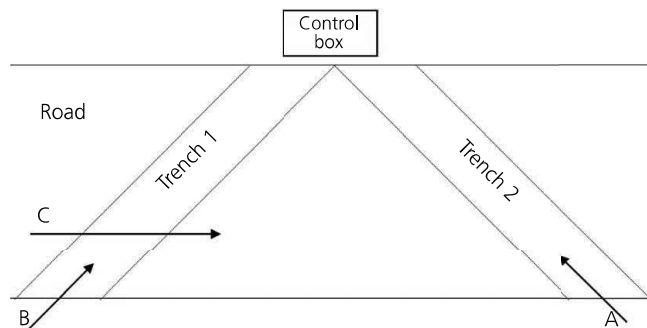
The condition of the road and trenches was also assessed soon after the reinstatement using the in-house non-contact electrical resistivity test (see the section headed ‘Sensing techniques’). The results are presented as resistivity profiles calculated in the direction of the arrows shown in Figure 12.

The survey was conducted during winter corresponding to a wet and rainy period. Although during the actual measurements the surface was reasonably dry, it had been exposed to considerable rainfall beforehand. Figure 13 shows that the existing asphalt had relatively low resistivity compared with the newly reinstated trenches due to the higher water content caused by the deterioration of the asphalt layer over time. The measured profile for trench 2 showed a very high resistivity, which indicates dry conditions in the surface layer. However, trench 1 showed a lower value of resistance, indicating a higher water content.

The three sections of trench 1 are also visible in Figure 13 with the middle section having slightly higher resistivity than the adjacent



**Figure 11.** Change in settlement relative to the measurement immediately after the reinstatement: (a) after the first FWD test and (b) 3, (c) 4 and (d) 10 months after reinstatement

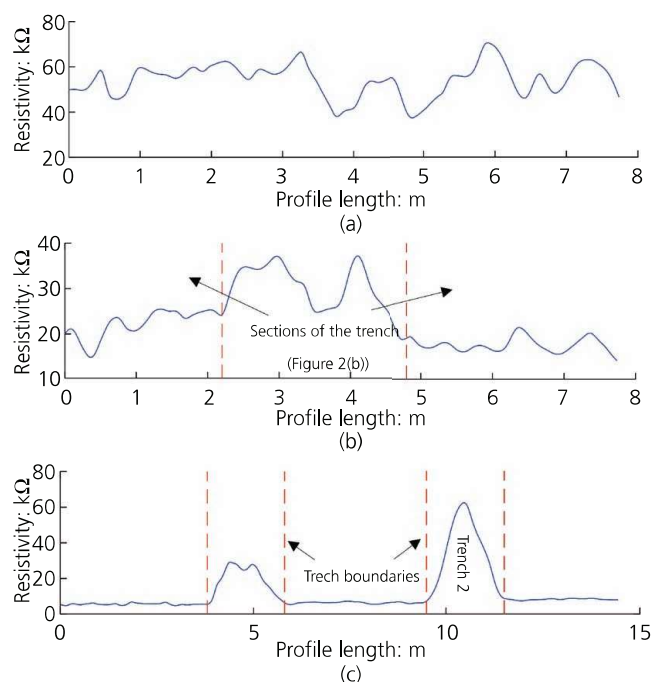


**Figure 12.** Schematic diagram of the measured area in plan; the arrows show the direction of each of the non-contact electrical resistivity measurement (corresponding to the results presented in Figure 13)

sections of the same trench. This difference may be caused by the middle section containing less water than the other two sections, as it was laid later than the others and had been exposed to less rainfall by the time that the measurements were taken.

### Trench wall monitoring

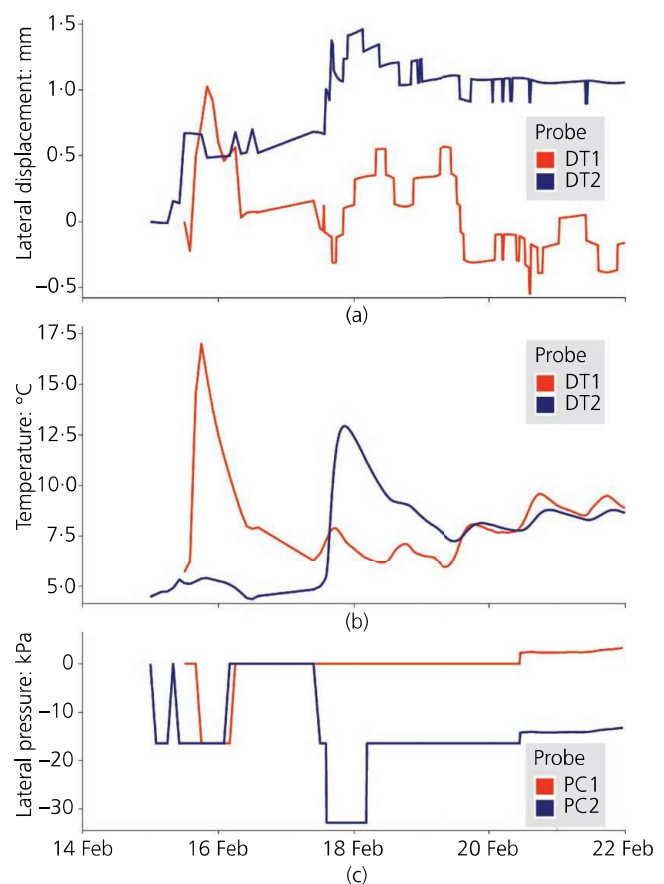
Displacement transducers and vertical pressure cells installed against the trench wall in trench 1 were designed to provide information on the potential movement occurring at the edge of the excavated area during the construction of the nearby trench (i.e. trench 2). This was an attempt to investigate the impact of a nearby OCS on a trench. Horizontal displacement transducers and vertical



**Figure 13.** Measured resistivity (directions are shown in Figure 12) along (a) trench 2, (b) trench 1 and (c) the road

pressure cells (DT1 and DT2 and PC1 and PC2 in Figure 3, respectively) were buried at a shallow depth immediately below the asphalt layer between 0.10 and 0.25 m from the surface (see the section headed ‘Sensing techniques’). The measured data of the lateral displacement (DT sensors) and lateral pressure (PC sensors) were quite erratic, as shown in Figures 14(a) and 14(c), respectively. At least part of the measured variability was associated with temperature variations. This is obvious in Figure 14(b), where two temperature spikes were recorded by the same sensors (Figure 14(b) only shows the temperature measured by the DT sensors, but the values were consistent with the measurements by the PC sensors) corresponding to the times when the asphalt was laid for trench 1 (large spike in Figure 14(b)) and for trench 2 (large blue spike in Figure 14(b)). Both the displacement transducers (Figure 14(a)) and the pressure cells (Figure 14(c)) were affected by these more extreme changes in temperature.

Despite the uncertainty, these results confirm that no significant lateral displacement or change in lateral pressure was measured during the construction phase of the nearby trench. This could be due to the difficulty of measuring these parameters in the field.



**Figure 14.** Monitoring of the trench 1 wall during the construction of the nearby trench: (a) lateral displacement (mm) and (b) temperature (°C) measured by the DTs and (c) lateral pressure (kPa) measured by the PCs

These sensors require good contact with the surrounding medium, but this is not easy to achieve in coarse materials and was particularly true for the pressure cells that were installed in a vertical configuration. It is also possible that despite the two trenches being excavated in a V configuration (see Figure 3), they were still too far apart for the trenching operations on one trench to affect the instrumented area in the adjacent trench.

The distances between sensors and the other trench wall were 1.4, 3.3, 2.1 and 5.0 m for DT1, DT2, PC1 and PC2, respectively. Assuming that these results are reliable, they indicate that the zone of influence of trenching operations is relatively small and that no significant disruption occurs at a greater distance during the construction phase. These findings are in line with previous studies that suggested a range between 0.5 and 1.0 m for the zone of influence around the trench (Jensen *et al.*, 2005; Lee and Lauter, 1999; Steele *et al.*, 2003; Stevens *et al.*, 2010). It is important, however, to note that these results relate to the specific conditions found at this site (including the trenching operations) and that the zone of influence could be larger in other situations. The FWD (Figure 10(b)) and total station surveys (Figure 11) indeed suggest the presence of a weaker zone that extends potentially up to 0.5 m from the excavated section. However, this weakened zone did not cause detectable lateral movement or any noticeable changes in lateral pressure in the nearby trench (note that Figure 14(c) shows drops in pressure down to -30 kPa, but these are linked to the large temperature increase during the asphalt-placing operations (Figure 14 (b)) and are unlikely to indicate an actual change in pressure). The long-term data from the displacement transducers and pressure cells contained significant noise and did not show clear trends over time.

## Discussion

The surface infrastructure (the road) and buried infrastructure (pipes and services) are interconnected by way of the ground (often ignored, but in this context also an important infrastructure). Therefore, when considering an intervention on one, the potential impact on the others should be considered. For example, a trench excavation to fix a buried pipe has an impact on the road structure and the surrounding ground. This interaction means that the condition of one infrastructure has an impact on the health of the others.

Furthermore, a deteriorated road can transfer excessive traffic loading to a buried water pipe, ultimately cracking the pipe, leading to leakage that can soften the surrounding ground and causing further damage to the road. Therefore, any required intervention should consider the interaction between the various infrastructures to minimise the negative impact. Considering the interconnected infrastructure systems and appreciating the aforementioned negative impact, it would seem sensible to consider joint road occupation when conducting OCS by different buried utility and road maintenance teams, to help reduce the associated impacts (Carey and Lueke, 2013; Moran *et al.*, 2017; Nafi and Kleiner, 2009). As demonstrated in the presented field trial, the OCS to install the buried pipes had an impact on the road structure as evidenced from the FWD, Panda and other survey results. In particular, the trial

identified that even when OCS are conducted within the current specifications, there is a considerable range at the lower end of this specification where the results are extremely poor in terms of longevity of the road above the trench itself and also the adjacent road structure. Features such as the quality of compaction, appropriate sealing of the joints and choice of the material all played an important role in the performance of the reinstated road. It is even evident that the trench constructed to the best possible specification still created some issues with the potential long-term performance of the road structure. This shows the need to consider alternative methods of accessing the buried utilities – for example, trenchless technologies, which despite having their own drawbacks, is still a less harmful method (Knight *et al.*, 2004).

In addition, the valuable data collected from this trial from both the in situ instruments and the surface surveys can be used to investigate best practice and potential assessment methods. For example, the Panda DCP results demonstrated it could determine the quality and hence likely performance of the trench reinstatement. The FWD, which is not normally associated with such assessments, also provided valuable information and demonstrates its potential, particularly if smaller, lower-cost versions can be developed in the future. In addition, an innovative and experimental non-intrusive resistivity technique deployed at the site provided information on the asphalt conditions and was capable of detecting dry/wet areas. These quality control measures can be used to minimise the costs of road and buried utilities repairs and therefore save costs by extending the life of assets, potentially beyond the 2 years' guarantee for reinstatements in the UK. Developing a historical database of survey information from OCS using such equipment would create a valuable resource for developing future specifications.

Strain gauge measurements just beneath the asphalt layer indicated deformation and hence load transfer below the road surface, which could have an impact on shallow buried services. In addition, the infiltrated water from poorly sealed joints, combined with the poor compaction, resulted in greater deformation in trench 1 (which could also soften the ground surrounding the pipe), as the infiltrated water reached a depth of 0.7 m, therefore affecting the entire road structure (Clair and Sinha, 2014; Gould *et al.*, 2009; Rajeev and Kodikara, 2011). It should be noted that joint sealing process might be identified as a source of reducing skid resistance and therefore a hazard for road users, including cyclists (BSI, 2015: section 6.8.2; HA, 1994, section 3.1).

Although the present trial contributed to the understanding of the interaction occurring when conducting OCS, particularly in relation to road structure and ground interaction, this is a complex system consisting of the road, the ground and the buried utilities, and there still remains a research gap that needs addressing in future studies. It is suggested that future research should investigate the impact of one controlled element (e.g. compaction energy) at a time, utilising sensor data from controlled trials combined with numerical modelling to predict the actual rates of deterioration. The authors believe that a change in perspective and approach is needed that considers the



shallow subsurface in urban areas as an interconnected system. In particular, road structures and buried utilities should not be treated in isolation. The ground ultimately is the link between the surface and buried infrastructures and should also be considered when making assessments and interventions.

## Conclusions

This study investigated the impact of OCS construction, including compaction procedure, choice of material and joint sealing, on an interconnected infrastructure system. This was done experimentally by excavating and reinstating two trenches where one was constructed to the highest standards and the other to the minimum acceptable standard within the specification – that is, with minimum compaction using as dug material and without sealing the trench joints. The key findings of this paper are as follows.

- Water ingress through the unsealed joints reached a depth of 0.7 m, showing the need to ensure appropriate joint sealing material and procedure.
- Poor compaction of recycled material without any quality control measures resulted in significant road structure deterioration and failure due to major settlements and the development of cracks and deflected areas, as was evidenced from a number of surveys – that is, total station, FWD, Panda and resistivity.
- Panda surveys showed a lower increase in mean cone resistance for trench 1 over time (5.9 MPa compared with 10.8 MPa for trench 2).
- The total station survey results over a period of 10 months showed that significant settlement had occurred over trench 1, up to 70 mm at one point.
- FWD results for trench 1 revealed large deflections (up to 2000  $\mu\text{m}$ ), while results on trench 2 also confirmed that even trenches constructed according to the current best practice and specification have a negative impact on the adjacent existing road structure.
- In situ strain gauges measured significantly higher microstrain results for trench 1, up to 50%, during the heavy traffic period, caused by movement of the road structure, as a result of inadequate compaction.
- An attempt was made to investigate the impact of a nearby OCS on a trench, using in situ horizontal displacement transducers and vertical pressure cells, which did not find any significant impact, probably because the minimum 1.4 m distance between the two trench walls was not small enough to show any significant changes.
- Cracks developed in trench 1 provide route for water ingress through the road structure, increasing the water content (as confirmed by TDR measurements) and softening the ground and further deteriorating the road structure.
- The developed innovative and experimental non-intrusive resistivity technique provided information on the asphalt conditions and was capable of detecting dry/wet areas.

This paper has demonstrated the importance of understanding the compaction quality (relative density) in OCS operations

throughout the trench depth. As for compaction procedure, the focus of current specification in the UK (DfT, 1991) is on controlling performance – for example, minimum passes and lift thickness based on the compaction plant, its weight and the backfill material, rather than controlling the end product. The trial showed that the quality control for compaction can be conducted with some simple methods, such as the Panda DCP test. This simple but highly effective method can be used for checking reinstatement quality immediately after backfilling and prior to placing the surface layer. Such a device could be used as a spot check on selected trenches to ensure quality. Alternatively, FWD or road non-contact electrical resistivity measurement can be used over an entire road network and avoids invasive measurements, which were both successfully tested in the trial.

The performance of the two trenches showed a huge difference between two adopted OCS methods, where trench 2 performed much better than trench 1, which was reinstated according to the lower end of the UK specification. This shows the importance of adopting quality control measures to bring the current practice for OCS closer to the highest standard and ensure less effect on the lifespan of the road.

This paper has presented important independent evidential data for practitioners and policymakers to help improve the current guidelines on OCS practice and buried infrastructure management, by emphasising the need to adopt robust quality control measures.

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