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Monitoring the Response of Roads and Railways to Seasonal Soil Movement with Persistent Scatterers Interferometry over Six UK Sites

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Abstract: Road and rail networks provide critical support for society, yet they can be degraded by seasonal soil movements. Currently, few transport network operators monitor small-scale soil movement, but understanding the conditions contributing to infrastructure failure can improve network resilience. Persistent Scatterers Interferometry (PSI) is a remote sensing technique offering the potential for near real-time ground movement monitoring over wide areas. This study tests the use of PSI for monitoring the response of major roads, minor roads, and railways to ground movement across six study sites in England, using Sentinel 1 data in VV polarisation in ascending orbit. Some soils are more stable than others—a national soil map was used to quantify the relationships between infrastructure movement and major soil groups. Vertical movement of transport infrastructure is a function of engineering design, soil properties, and traffic loading. Roads and railways built on soil groups prone to seasonal water-logging (Ground-water Gley soils, Surface-water Gley soils, Pelosols, and Brown soils) demonstrated seasonal subsidence and heave, associated with an increased risk of infrastructure degradation. Roads and railways over Podzolic soils demonstrated relative stability. Railways on Peat soils exhibited the most extreme continual subsidence of up to 7.5 mm year^{-1}. Limitations of this study include the short observation period (~13 months, due to satellite data availability) and the regional scale of the soil map—mapping units contain multiple soil types with different ground movement potentials. Future use of a higher resolution soil map over a longer period will advance this research. Nevertheless, this study demonstrates the viability of PSI as a technique for measuring both seasonal soil-related ground movement and the associated impacts on road and rail infrastructure.

Keywords: Persistent Scatterers Interferometry; Sentinel 1; synthetic aperture radar; infrastructure monitoring; soil movement; soil compression; shrink swell; environmental risk; road; railway

1. Introduction

Ground movement is the soil-related geohazard most damaging to infrastructure in the UK [1]. As such, the ability to measure the impact of soil movement on infrastructure networks in a cost-effective manner offers great value to utilities, insurance companies, and governments. Infrastructure resilience can be compromised by infrastructure pressures (ageing assets, embrittlement, thinning, increasing demand and loading), environmental pressures (changing climate, soil movement), and financial pressures. However, a fully functioning and fault-resistant system of infrastructure is important for the critical operation of healthcare, transport, trade, and commerce. The UK government is set to invest £100 billion in infrastructure by 2021 to ensure that the UK's infrastructure needs are met for future generations [2]. Monitoring the structural condition of infrastructure networks is essential to ensure its long-term resilience. Developing suitable methods to monitor infrastructure networks at the regional to national scale is also a key challenge [2].

Several in situ techniques are available for the local monitoring of infrastructure assets, including manual visual inspection, levelling, total station surveying, and GPS technologies [3]. These approaches provide highly accurate measurements of deformation at a single point, yet they require significant investment of human resources and equipment to obtain a high density of measurements suitable for wide-scale infrastructure monitoring. On this premise, satellite remote sensing—particularly with the onset of new generation high resolution Synthetic Aperture Radar (SAR) sensors—can measure deformation over areas several tens of kilometres wide while retaining high precision and accuracy. This allows the cost-effective monitoring of surface deformation [4].

Advanced Differential Interferometry (D-InSAR) techniques, such as Persistent Scatterers Interferometry (PSI), offer promise for the monitoring of large scale soil movement and long-term deformation of infrastructure networks. PSI requires at least 20 SAR images to measure surface deformation over months or years, removing the effects of atmosphere, topography, and signal noise [5,6]. Several applications of PSI have previously been investigated. Some examples include monitoring either natural or anthropogenic urban subsidence [3,7,8], measuring the inter-annual variability of soil related ground movement [3,9,10], the detection of natural hazards such as landslides [11,12], as well as observing the structural condition of infrastructure [13,14].

This technique is of great potential value to utility companies wishing to monitor assets in near real-time, and could ultimately lead to observations of an entire infrastructure network with a high spatial and temporal resolution. In a recent study of Mexico City, a density of 575 PS targets per km^2 was achieved using the European Space Agency's Sentinel 1 data [15]. With the advent of very high resolution SAR data, such as TerraSAR-X, a PS density of up to 5201 targets per km^2 have been recorded [16]. Lower resolution datasets such as the ERS, and the ENVISAT satellite constellations have an archive of data extending back to 1992, enabling historical evaluations of surface deformation if required [17]. However, new satellite missions such as the Sentinel 1 offer an increased spatial resolution with a quicker revisit period of 6 days drawing on a combination of Sentinel 1a and 1b, making it a promising new tool for environmental monitoring. On this basis, PSI applied to Sentinel 1 data could provide high density measurements of ground movement on a regional scale and over a range of different land cover types [3]. Furthermore, PSI outputs can be integrated into a Geographical Information System (GIS) which allows for a greater understanding of the relationships between surface deformation and the natural environment [18,19]. Additional data such as soil maps, geological maps, and climate and meteorological data, can all provide information to further explain observed deformation phenomena [18]. Therefore, remote infrastructure observation with PSI has the potential to prompt proactive asset maintenance, increase network resilience and reduce the need for expensive in situ monitoring.

One example of a PSI investigation is Aldiss et al.'s study [18], in which a large time series of 60 ERS and ENVISAT images in descending orbit were collected between March 1997 and December 2005, with ground movement being quantified over a 95 $\times$ 55 km scene over London, UK. The study found that PSI targets in large parts of the Thames estuary subsided between 0.9 and 1.5 mm $year^{-1}$ with the fastest soil subsidence rate being, on average 2.1 mm $year^{-1}$. By combining PSI outputs with geological data in a GIS, the authors noted that regional patterns of uplift and subsidence are controlled by both deep geological features, such as the relative mass of underlying geology, and shallow geological features such as fault lines. Boyle et al.'s study [20] noted that the shrink swell behavior of the London clays can give rise to 50 mm $year^{-1}$ of vertical movement (cumulative shrink and swell) over wide areas. This rate of movement was attributed largely to dry summers and wet winters. Both studies [18,20] noted the importance of external factors such as extreme meteorological conditions, local topography, urban fabric, vegetation, and anthropogenically-induced subsidence such as tunneling and water abstraction.

National soil maps, such as the one used in this study [21], often estimate ground movements based on the laboratory assessment of clay soils' volumetric change potential. Such categorical maps are widely used by utilities, with classes such as "high" and "low" ground movement potential [22]. Quantification of the vertical movement of soils is difficult due to numerous external factors (vegetation, agriculture, erosion etc.). Therefore, applying PSI over engineered surfaces that maintain high coherence can act as one possible method to quantify soil movement.

Previous studies have investigated the effects of engineering design on the rates of observed surface movement [3,16]. The importance of foundation depth is consistently noted as a predominant control over surface deformation of structures. This paper seeks to measure directly how road and rail networks respond to the movement of different soils. By investigating the use of PSI over 6 different UK urban areas (Bristol, Bath, Bournemouth, Kings Lynn, Peterborough and Grantham), a wide range of environmental conditions, soil types and asset responses can be included in the analysis. This work will improve the current knowledge of how different types of infrastructure respond to soil movement—particularly in the UK—and will help determine the suitability of the PSI technique to monitor critical infrastructure networks nationally.

2. Materials and Methods

This study uses Sentinel 1a C-band SAR data to produce a time-series of interferograms used in the PSI process. Sentinel-1 Single Look Complex (SLC) data has a swath width of 250 km in Interferometric Wide (IW) mode, with a spatial resolution (pixel size) of 3 m $\times$ 20 m in range and azimuth, respectively. The tandem satellites (Sentinel 1a and 1b) cycle over 175 different orbits and have a full-global repeat cycle of 6 days. Many areas—such as the UK—receive more frequent data acquisition.

Sentinel 1 images were selected based on the same orbit number to ensure full spatial coverage of the study areas. Precision orbit ephemerides files were downloaded for each SAR image to ensure that no errors occurred in the co-registration of the data. This process, known as de-bursting, ensures phase continuity over the burst limits. If no precise orbit files are applied, then linear features can appear in some interferograms [15]. Images were also selected as per the minimum separation between two orbits for each pair (perpendicular baseline) at an interval of at least 12 days, so limiting the temporal and spatial decorrelation of the interferometric pairs. Data were collected in two separate areas (see Figure 1) so comparison between infrastructure responses over a large area could be undertaken. For the Western study area (Bristol, Bath and Bournemouth), data were downloaded between the 8 September 2015 to the 31 December 2016, with a polarization of VV (Vertical transmit and Vertical receive) in ascending orbit. In total, 23 images were downloaded for processing, including one master image which was selected as the 16 July 2016. For the Eastern study area (Grantham, Peterborough and Kings Lynn), 23 images were collected from the 13 January 2016 to the 8 March 2017, also collected in VV polarisation in ascending orbit. The master image for all Eastern England sites was selected as the 16 August 2016. See Table 1 for a description of the image dates, perpendicular and temporal baselines of the Sentinel 1a images used in this study.

All PSI processing was conducted using Harris Corporation's (Melbourne, FL, USA) ENVI SARscape software v5.3. After the SAR images were connected (spatially and temporally), a series of interferometric pairs were created. These image pairs were then consequently co-registered to the master images' slant geometry. Each of the slave images were then co-registered to the master to calculate the phase difference between each image pair. A Doppler filter was applied to reduce the temporal decorrelation of the image pairs. In this step, a SRTM 3 Digital Elevation Model (DEM) was downloaded with a spatial resolution of 90 m to correct errors related to phase and atmospheric effects between the interferometric pairs. For each study site Ground Control Point (GCP) files were created to correct the images geometrically, after which a Goldstein filter was applied to decrease the signal-to-noise ratio by filtering the differential phase [23]. Values of 5 in range and 1 in azimuth were used in the multi-looking phase to obtain square pixels for the image pairs. This step is used to avoid the effects of over and under sampling on geocoded images.

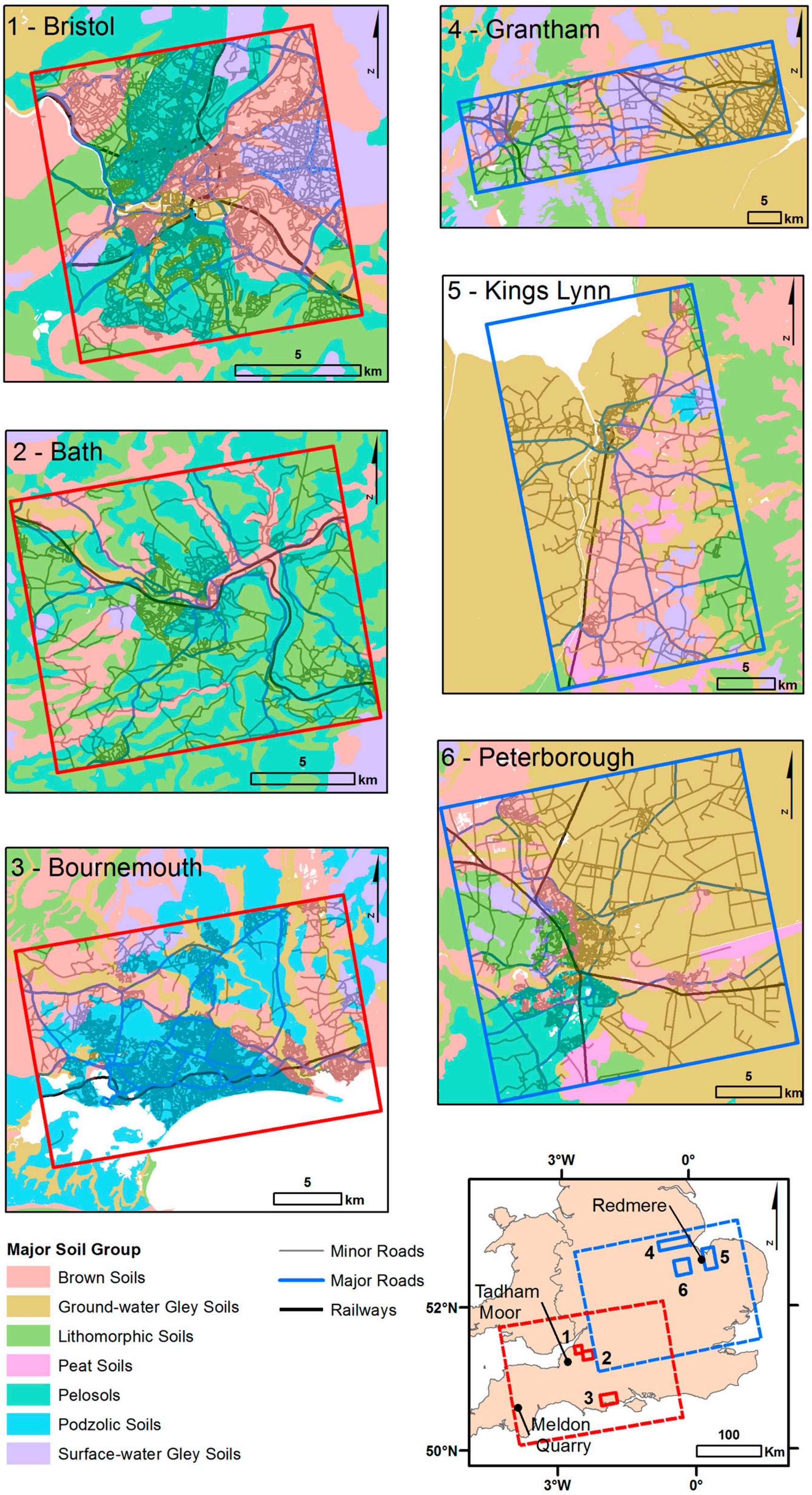

Figure 1. Study area extents shown with major soil group and infrastructure extent. Western sites—shown in red—include: (1) Bristol; (2) Bath; (3) Bournemouth. Eastern sites—shown in blue—include: (4) Grantham; (5) Kings Lynn; (6) Peterborough. The insert map locates the sites within the UK. Dashed red and blue outlines represent the area extent of the Sentinel 1 data frames (Western England—relative orbit number 30, Eastern England—relative orbit number 132). The locations of Meldon Quarry validation test site, Tadham Moor, and Redmere meteorological stations, have been shown in the insert map.

Table 1. Dates of Sentinel 1 images and their perpendicular (*Bperp*) and temporal (*Btemp*) baselines for Bristol, Bath, Bournemouth, Grantham, Kings Lynn and Peterborough.

	Bristol		Bath		Bournemouth	
Date	***Bperp***	***Btemp***	***Bperp***	***Btemp***	***Bperp***	***Btemp***
19 November 2015	−51.04 m	−240	−49.76 m	−240	−48.22 m	−240
1 December 2015	−26.69 m	−228	−25.62 m	−228	−23.93 m	−228
13 December 2015	36.48 m	−216	37.01 m	−216	36.28 m	−216
6 January 2016	79.81 m	−193	80.28 m	−193	80.69 m	−193
18 January 2016	−13.55 m	−180	−12.22 m	−180	−10.56 m	−180
30 January 2016	−13.55 m	−168	34.51 m	−168	36.29 m	−168
11 February 2016	61.99 m	−156	62.75 m	−156	63.24 m	−156
30 March 2016	−78.46 m	−108	−77.46 m	−108	−75.60 m	−108
23 April 2016	29.07 m	−84	28.88 m	−84	28.15 m	−84
10 June 2016	−51.98 m	−36	−51.34 m	−36	−50.14 m	−36
4 July 2016	31.98 m	−12	31.74 m	−12	30.64 m	−12
16 July 2016 *	0.00 m	0	0.00 m	0	0.00 m	0
28 July 2016	−17.18 m	12	−16.62 m	12	−18.17 m	12
9 August 2016	−41.68 m	24	−41.10 m	24	−39.72 m	24
21 August 2016	−23.03 m	36	−22.90 m	36	−23.06 m	36
2 September 2016	118.61 m	48	117.87 m	48	116.71 m	48
14 September 2016	32.81 m	60	32.81 m	60	32.63 m	60
26 September 2016	−24.01 m	72	−23.57 m	72	−23.30 m	72
1 November 2016	69.37 m	108	69.65 m	108	69.59 m	108
13 November 2016	74.92 m	120	75.22 m	120	74.93 m	120
25 November 2016	32.35 m	132	33.09 m	132	34.33 m	132
19 December 2016	−37.74 m	156	−36.24 m	156	−34.43 m	156
31 December 2016	35.72 m	168	36.40 m	168	36.39 m	168
	Grantham		**Kings Lynn**		**Peterborough**	
Date	***Bperp***	***Btemp***	***Bperp***	***Btemp***	***Bperp***	***Btemp***
13 January 2016	29.43 m	−216	33.8966 m	−216	31.4909 m	−216
6 February 2016	72.79 m	−192	73.777 m	−192	72.6985 m	−192
1 March 2016	−89.76 m	−168	−84.46 m	−168	−88.76 m	−168
18 April 2016	−19.41 m	−120	−18.63 m	−120	−19.28 m	−120
12-May-2016	−105.47 m	−96	−101.63 m	−96	−104.62 m	−96
5 June 2016	31.86 m	−72	31.38 m	−72	30.18 m	−72
29 June 2016	−62.16 m	−48	−60.12 m	−48	−61.79 m	−48
23 July 2016	8.829 m	−24	9.02 m	−24	9.028 m	−24
4 August 2016	12.73 m	−12	12.8 m	−12	12.63 m	−12
16 August 2016 *	0.00 m	0	0.00 m	0	0.00 m	0
9 September 2016	−72.56 m	24	−69.2 m	24	−71.73 m	24
21 September 2016	−79.30 m	36	−75.10 m	36	−77.98 m	36
3 October 2016	46.36 m	48	46.49 m	48	46.15 m	48
15 October 2016	71.74 m	60	72.11 m	60	71.76 m	60
27 October 2016	21.81 m	72	22.85 m	72	20.59 m	72
8 November 2016	−42.22 m	84	−36.16 m	84	−41.21 m	84
26 December 2016	75.52 m	132	76.92 m	132	75.13 m	132
7 January 2017	26.39 m	144	26.50 m	144	23.90 m	144
19 January 2017	−21.13 m	156	−24.98 m	156	−19.71 m	156
31 January 2017	−27.96 m	168	−22.01 m	168	−26.86 m	168
12 February 2017	53.10 m	180	55.20 m	180	53.38 m	180
24 February 2017	58.00 m	192	60.06 m	192	58.65 m	192
8 March 2017	37.62 m	204	38.51 m	204	38.01 m	204

* Indicates master image.

The interferometric pairs were then processed by the first and second inversion steps in the ENVI PSI workflow to locate the potential Persistent Scatterers (PS). The first inversion step estimates the residual height and displacement velocity of the study area, and is applied to flatten the interferograms. Reference points are used in this step (one or more) and are automatically selected (based on high coherence and minimal deformation) for the removal of the offset phase from all interferograms. For the processing of large areas, the scene is split into sub-areas where individual processing is undertaken. A mosaicking operation is then conducted to merge all smaller subset areas to produce the final velocity map, and in this instance several reference points are selected. The second inversion step removes the atmospheric phase effects from the interferograms using the low and high pass filters, which correct the spatial and temporal distributions of atmospheric effects. The low pass filter accounts for the spatial distribution of atmospheric variations. The high pass filter accounts for the temporal distribution of atmospheric variations. The second model inversion creates the date-by-date displacements, which is then used to create the geocoded output, which is displacement along the Line of Sight (LOS). The interferometric workflow is based on Ferretti et al.'s methodology, for a mathematical account of the algorithms used see Ferretti [11,12].

Transport infrastructure data was freely sourced from the UK Ordnance Survey Meridian 2 dataset, which provides a frequently updated and accurate network of principle infrastructure types across Great Britain. The data provides information on the location and extent of motorways, A-roads, B-roads, Unclassified roads and Railways at the nominal viewing scale of 1:50,000. Data is provided in a GIS ready format, with road classification provided as attributes. Road types were categorised into minor roads (Unclassified and B-roads) and major roads (A-roads and Motorways), to simplify the analysis. From these categorisations, a buffer distance of 2 m from the center line of infrastructure was created for minor roads, 3 m for major roads and railways, and 4 m for motorways. This buffer zone was then used to subset the PSI output. This ensured that only PSI points which are in close proximity to the infrastructure were analysed, which reduces the number of PS points returned from pavements (sidewalks), surrounding buildings and vegetation and adjacent unconsolidated ground.

By analysing the PSI output in a GIS environment, each PS point was attributed with information pertaining to the major soil group, which permitted contrasting the information about ground deformation with major soil groups. This study uses Cranfield University's National Soil Map [21]. The 1:250,000 scale soil map contains information related to soil properties including ground movement potential (based on the laboratory assessment of volume change potential of soils, categorized from "low" to "high"), texture, drainage, fertility, land cover, and habitats. The major soil groups included in this study were Brown soils, Ground-water Gley soils, Lithomorphic soils, Pelosols, Podozolic soils, Surface-water Gley soils, and Peat soils—see Table 2 below for their descriptions.

Table 2. Short descriptions of the major soil groups discussed in this study along with their associated classification in the World Reference Base (WRB).

Major Soil Group Type	Description	Soil Movement Potential	WRB Classification
Brown soils	Widespread soils with predominantly brownish or reddish sub surface. They have no gleying above 40 cm depth and are mainly associated with agriculture land use.	Moderate-High	Arenosols Cambisols Luvisols Regosols
Ground-water Gley soils	Soils normally developed over permeable materials which appear uniformly gleyed. These soils are subject to periodic waterlogging by fluctuating groundwater-tables.	High	Gleysols
Lithomorphic soils	Often shallow soils which have been formed over bedrock, or soft unconsolidated material at 30 cm depth.	Moderate-Low	Arenosols Histosols Leptosols Phaeozems
Pelosols	Slowly permeable clay soils with no gleyed subsurface horizon above 40 cm depth. These soils can show significant desiccation in dry seasons.	Moderate-High	Cambisols Luvisols
Podzolic soils	Soils usually formed as a result of acid weathering conditions, and have an unincorporated acid layer at their surface.	Moderate-Low	Podzols Umbrisols
Surface-water Gley soils	Seasonally waterlogged, and slowly permeable soils, which appear predominantly mottled above 40 cm depth.	High	Planosols Stagnosols
Peat soils	Organic soils derived from partially decomposed plant remains that accumulated under waterlogged conditions.	High	Histosols

Validation of the PSI outputs was undertaken over the closed Meldon quarry site (50.716084N, −4.026326W—see Figure 1. Meldon Quarry has been disused since 2007 [24], and comprises a mixture of metamorphic and igneous rocks. To this extent, the geology is highly stable and so presents itself as an area of high coherence, excepting natural erosion and deposition. The PSI processing over Meldon Quarry was undertaken with an identical model set up as for the 6 other test sites, so direct comparison upon the reliability of the results could be determined.

In total, six sites were selected for this study, separated into two distinct study areas, see Figure 1 and Table 3. The prevailing climate across all sites is classified as temperate oceanic, with all areas receiving regular precipitation events throughout the year. Sites situated in the West of England receive on average 195 mm more precipitation annually than sites in Eastern England. Of the six sites, Bournemouth receives the highest annual precipitation of 835 mm, whilst Grantham receives the least (608 mm). Temperature ranges exhibit very little variation between all six sites, with typical maximum average summer temperatures of ~21 °C and minimum average winter temperatures of ~1 °C. Bournemouth receives the highest range in monthly total precipitation from 47.8 mm in July to 100.7 mm in December. Grantham receives its highest monthly precipitation in October—59.3 mm—and its lowest—36.8 mm—in February. Bristol and Bath show similar precipitation trends to Bournemouth, whilst Kings Lynn and Peterborough show similar trends to Grantham. Due to the seasonal changes in temperature and precipitation all study sites have annual profiles of soil moisture which gives rise to the conditions required for the shrinking and swelling of clay soils. Moreover, soils which are prone to seasonal waterlogging (i.e., Ground-water Gley soils, Brown soils, Pelosols and Surface-water Gley soils) may also show shrink and swell cycles in accordance to available soil moisture. In situ soil moisture data was obtained from two representative meteorological stations (data provided by the Centre for Ecology and Hydrology). The data provided in Figure 2 shows the daily averaged (from 30-minute measurements) soil Volumetric Water Content (VWC), taken at a depth of 10 cm using a Time-domain Transmission probe. As expected, the Eastern site (Redmere) held the lowest VWC value 14.8% (2 September 2016) with a range of 26.6%, whilst the Western site (Tadham Moor) had a significantly larger VWC—49.5% (1 August 2016)—and a range of 33.9%, Figure 2. Therefore, some degree of surface deformation was expected in all study sites where clay soils, or soils which have significant volume change potential, are present.

The Bristol and Bath study sites both have had an extensive history of coal mining dating back to 1223 [17], as well as mineral mining which can be dated back further to 2000 years. Due to high likelihood of surface deformation, a previous PSI investigation using ERS and ENVISAT data has been undertaken over Bristol and Bath [17] and despite the historic mining activity, compressible alluvium, and shrink swell soils being present, no surface deformation was observed using PSI in this study. This present study measures recent surface deformations over Bristol and Bath using Sentinel 1 data. However, our results can be compared with previous DinSAR investigations in the area, offering continuity of surface deformation data between previous and current satellite missions.

Table 3. Study area characteristics and infrastructure lengths for the study sites.

Study Site (Western or Eastern Area)	Area (km^2)	Length of Minor Roads (km)	Length of Major Roads (km)	Length of Railways (km)	Historic Mining Present?	Urban Coverage Density
Bristol (W)	118	817	108	34	Yes	Mostly Urban
Bath (W)	165	265	76	31	Yes	Urban/Rural
Bournemouth (W)	284	1207	126	22	No	Mostly Urban
Grantham (E)	688	837	149	71	No	Semi-Rural
Peterborough (E)	539	907	144	55	No	Urban/Rural
Kings Lynn (E)	585	1261	190	130	No	Semi-Rural

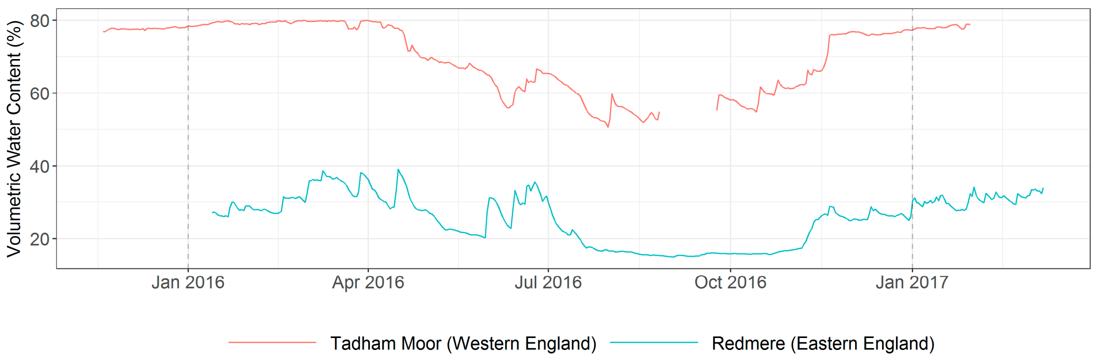

Figure 2. Daily Volumetric Water Content (VWC %) for the corresponding periods of PSI investigation for Western and Eastern England. VWC is measured at 10 cm depth from two in situ meteorological stations: Tadham Moor (Western England, 51.207099, −2.828639) is shown in red and Redmere (Eastern England, 52.443551, 0.433083) in blue.

The other sites were selected based on the high potential for infrastructure responses to shrink swell cycles of soil. Sites selected in Eastern England have the highest shrink-swell potential of soils in England, based on the largest annual Soil Moisture Deficit (SMD) [25]. Pritchard, O.G. et al. [25] notes that Eastern England has the highest SMD rates in the country, calculated from the daily precipitation, evapotranspiration and drainage of the soil, and describes the amount of water needed for the soil to return to field capacity (in mm). Furthermore, we include the response of railways to peat soils deformation in the Peterborough area, which is of importance given the significant peat wastage rates described in [26]. The predominant land use in Eastern England sites is agriculture. Bournemouth has been selected as a control site, with freely and quickly draining bedrock lithology (of chalk and gravels) and Podzolic soils which are not prone to soil deformation. To our knowledge, Bournemouth, Kings Lynn, Peterborough and Grantham have not been included in any previous PSI investigations. The sites selected all have different urban densities, which help in understanding the effectiveness of PSI for monitoring infrastructure across a range of landscapes. The study areas of Bristol and Bournemouth have the most-dense urban fabric, whilst Bath and Peterborough contain a mix of rural and urban areas. Grantham and Kings Lynn are mostly a rural (agricultural) landscape, with pockets of dense settlements allowing for the PSI process to be undertaken. A description of the lengths of infrastructure, study area extent, and a description of urban coverage is provided in Table 3.

3. Results

3.1. Minor Road, Major Road and Railways Infrastructure Movement

A total of 70,406 PS points were analysed for minor roads, major roads, and railways across the six study areas. Western sites returned higher PS densities than Eastern sites in all infrastructure classes analysed, due to the study areas focusing predominantly on urban centers. Returned PS densities were highest for railways in all six study sites, with an average density of 18.23 PS targets returned per km of track, suggesting suitability of this infrastructure class for PSI analysis. Due to their relative widths, major roads—motorways buffered at 4 m, A-roads buffered at 3 m—returned a higher PS density than minor roads—B-roads and Minor-roads buffered at 2 m—returning 15.34 PS targets compared to 9.28 PS, respectively, per km of infrastructure. The resulting PSI velocity maps are shown in Figure 3. Overall PS densities highly varied across the six study sites. Urban areas such as Bristol and Bournemouth achieved a very high density of 3799 PS km^2 and 2058 PS km^2 respectively. Bath and Peterborough, which are an urban/rural mix attained only 795 and 730 PS km^2, respectively. As expected, the semi-rural study areas of Grantham and Kings Lynn achieved significantly less at 414 PS km^2 and 343 PS km^2, respectively.

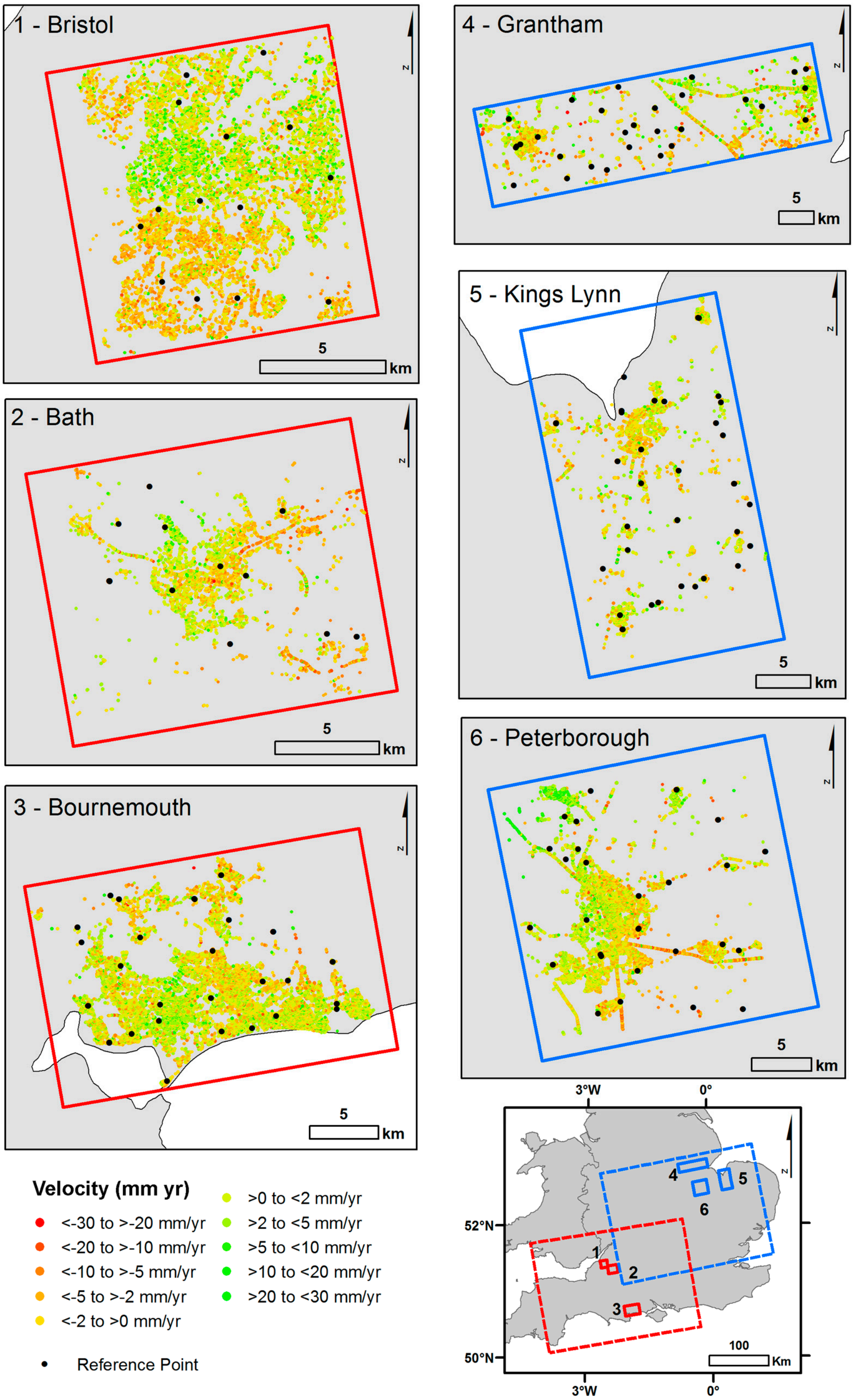

Figure 3. Surface deformation map showing PSI values expressed as millimeters per year for the Six study areas. Dark red indicates subsidence of up to 30 mm year^{-1} whilst Bright green indicates uplift of up to 30 mm year^{-1}. Insert map shows the location of the sites in the UK.

Railways exhibited the largest range of movement for all infrastructure types investigated, as depicted in Table 4. This is particularly so for Bath, where the average change in railway track level was −2.59 mm year^{-1} (standard deviation 5.38 mm year^{-1}) with Brown soils and Pelosols showing the highest rates of deformation. On average, railway tracks subside −0.88 mm year^{-1}. However, cyclical patterns of infrastructure movement of greater velocities that 0.88 mm year^{-1} were observed for Brown soils, Pelosols, Ground-water Gley soils and Surface-water Gley soils in Bristol, Grantham, Kings Lynn and Peterborough. Railways heave up to 2.5 mm for these major soil groups during winter months (December to April), and subside up to 5 mm during the summer months (April to September). Railways over Peat soils in Peterborough, exhibited the highest subsidence rate observed in this study, −7.5 mm year^{-1}. As Table 5 highlights, a very small sample size of 113 PS points were analysed for railway tracks over Peat soils, so further investigation of this would be necessary to comment on these findings with confidence. Deformation of railways in Bath and Bournemouth present a linear pattern of deformation. Railway infrastructure in Bath is observed to subside when over Brown soils and Pelosols, whilst Bournemouth shows no deformation over Podzolic soils, as presented in Figure 4. No subsidence was detected for railways over Lithomorphic soils in Bath and Peterborough.

Table 4. Summary description of PS targets analysed in Bristol, Bath and Bournemouth.

Type	Study Area	Average PS Deformation Rate mm year^{-1}	Standard Deviation	Maximum Uplift Value mm year^{-1}	Minimum Subsidence Value mm year^{-1}	Number of PS Points	Density of PS (PS km)
Minor road (West)	Bristol	−0.24	3.18	25.05	−21.35	16557	13.16
	Bath	−0.60	3.00	11.90	−23.52	4005	7.71
	Bournemouth	0.26	3.09	23.16	−25.34	16986	13.11
	Mean	*−0.19*	*3.09*	*20.03*	*−23.40*	*12516*	*11.32*
Major road (West)	Bristol	0.04	2.83	16.13	−21.91	2920	25.54
	Bath	−0.83	2.91	17.29	−18.28	1211	14.08
	Bournemouth	0.30	2.87	15.44	−22.78	1554	10.64
	Mean	*−0.16*	*2.87*	*16.28*	*−20.99*	*1891*	*16.75*
Railway (West)	Bristol	−0.84	4.30	21.99	−18.92	688	22.93
	Bath	−2.59	5.38	14.85	−24.45	484	15.61
	Bournemouth	0.14	4.07	19.22	−15.28	487	18.03
	Mean	*−1.09*	*4.58*	*18.68*	*−19.55*	*553*	*18.85*
Minor road (East)	Grantham	−0.02	3.69	22.62	−25.06	5005	5.46
	Peterborough	0.38	3.32	24.96	−20.36	9504	10.39
	Kings Lynn	−0.25	2.91	23.47	−18.39	3882	5.89
	Mean	*0.03*	*3.30*	*23.68*	*−21.27*	*6130*	*7.24*
Major road (East)	Grantham	0.03	3.87	20.76	−24.89	1048	6.55
	Peterborough	0.24	3.08	25.56	−14.38	2328	16.16
	Kings Lynn	−0.20	3.03	13.16	−13.45	736	19.08
	Mean	*0.02*	*3.32*	*19.82*	*−17.57*	*1370*	*13.93*
Railway (East)	Grantham	−0.01	4.27	18.05	−19.14	1220	15.64
	Peterborough	−1.59	5.57	23.40	−20.67	1607	29.21
	Kings Lynn	−0.38	4.97	20.64	−16.00	184	8.00
	Mean	*−0.66*	*4.93*	*20.69*	*−18.60*	*1003*	*17.61*

Table 5. Sample size of PS points analysed for minor roads, major roads and railways by major soil group. Grey shading represents very low sample sizes (<100) which have been consequently removed from analysis.

		Brown Soils	Ground-Water Gley Soils	Lithomorphic Soils	Pelosols	Pozolic Soils	Surface-Water Gley Soils	Peat Soils
West	Minor roads	9276	1134	3925	7409	13490	2210	0
	Major roads	1990	440	768	882	1165	385	0
	Railways	457	204	108	469	333	10	0
East	Minor roads	5028	7885	1549	2426	16	1428	0
	Major roads	887	1717	386	838	0	279	0
	Railways	524	1284	291	354	0	445	113

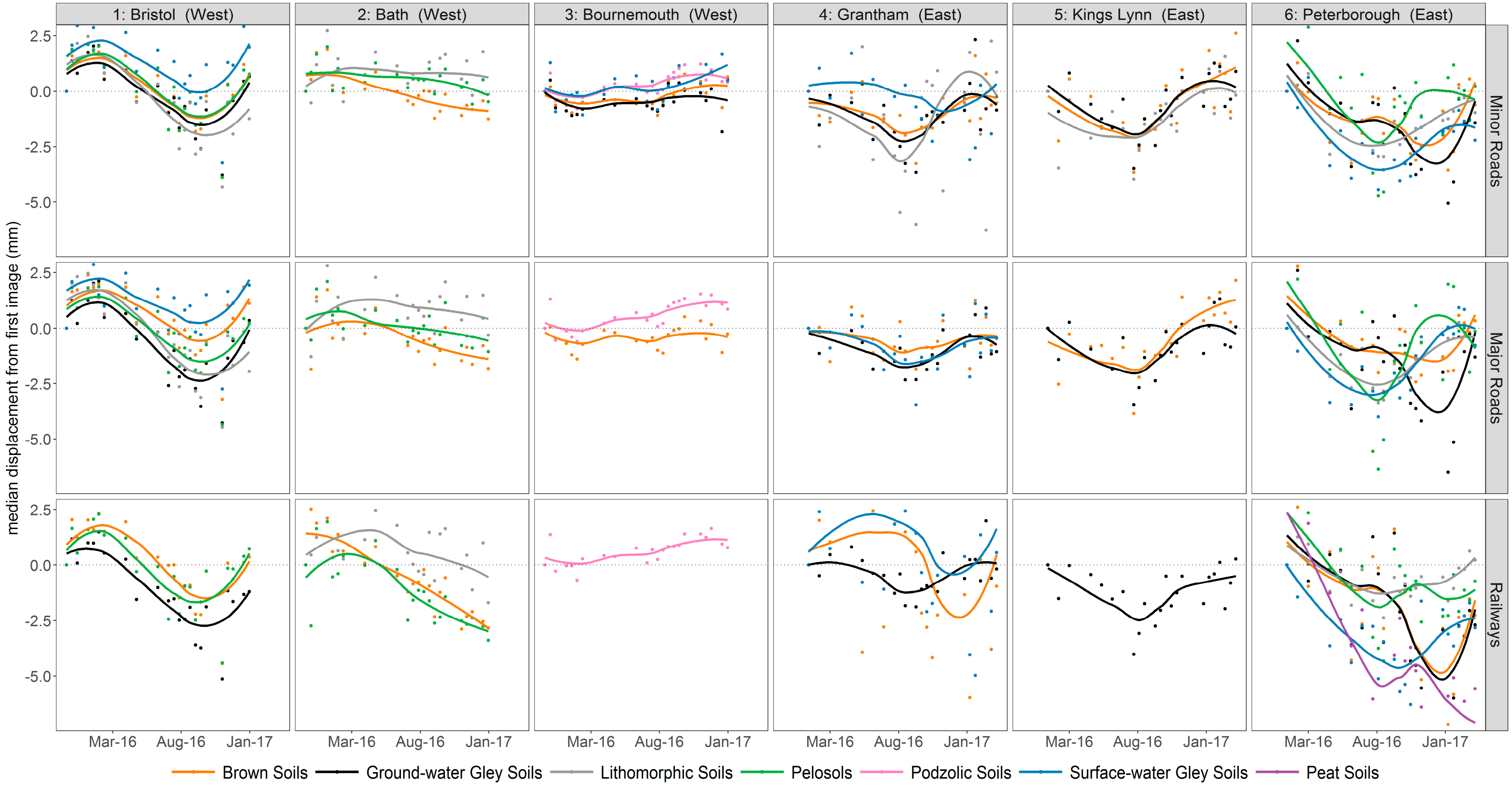

Figure 4. Trends in vertical movement (mm) by major soil group and infrastructure type. Points show median value for all PSI points on an infrastructure type and major soil group. Solid line show a loess-smoothed trend through the plotted medians. Dashed lines identify 1st January. To ensure validity, classes with less than 100 PSI points have been removed from this plot (Table 5).

Due to the extensive coverage of major and minor roads, more major soil groups have been analysed in the Western and Eastern study areas. Patterns and deformation trends remain mostly similar between minor roads, major roads, and railways, with minimal differences between them, as shown in Table 4. Cyclical patterns of deformation are observed in Bristol, Grantham, Kings Lynn and Peterborough, with Brown soils, Surface-water Gley soils, Lithomorphic soils, Pelosols, and Ground-water Gley soils all showing subsidence in summer months and corresponding heave during winter months. Bristol presents the most uniform deformation profile of shrink and swell, with subsidence during the drying period (spring into summer), and heave during the wetting period (autumn into winter). The Eastern study sites show a larger variation of surface deformation between the major soil groups, with each major soil group showing different surface deformation characteristics. Ground-water Gley and Brown soils in Peterborough show a lagged response to the general shrink swell sequence in all infrastructure classes, with the maximum subsidence observed during December 2016. This lag corresponds to the Eastern study areas soil moisture profile (Figure 2), where low soil moisture content was recorded until late November 2016.

3.2. Validation Test Site

Using identical parameterisation as per the analysis described, a PSI investigation over the disused Meldon quarry (Figure 1) was undertaken to assess the general performance of the technique over a known area of no deformation. The results suggest that there was a deformation with a range of 2.24 mm between the minimum and maximum median PSI values within the quarry. Generally, there is 1 to 1.5 mm of error attributed each month to the median of all data values, represented by grey shading in Figure 5. The annual profile of surface deformation demonstrates a smooth, stable annual trend, with fluctuations of ±1.5 mm during March and April. Surface deformation has been calculated by the median of 1579 PS points which have been returned from bare rock surfaces within the quarry itself. It is expected that there is minimal movement in this quarry, apart from the natural weathering processes affecting the quarry's exposed outcrops. Therefore, it can be assumed that an error of approximately ±1.5 mm can be attributed to the PSI measurements obtained in this study. The full area of observation contained 186,749 PS points, with an average range of 11.64 mm. This further confirms the stability of the PSI points over an area of known stability (i.e., Meldon Quarry) and gives confidence in the accuracy of the outputs in the six study areas included in this study.

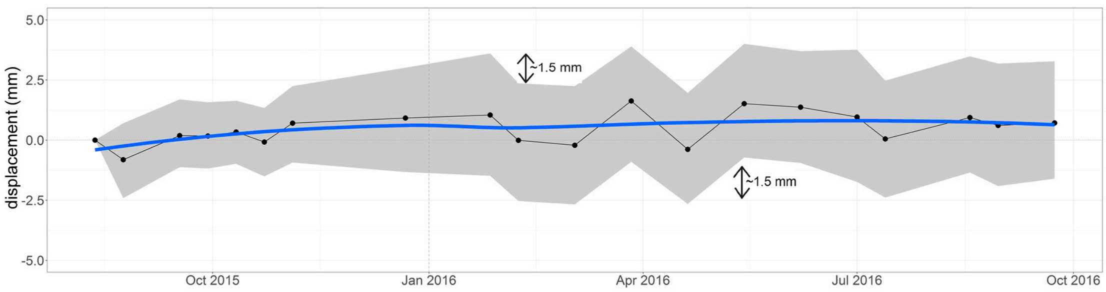

Figure 5. Median ground deformation (mm) for 1579 PSI points over Meldon Quarry, Dartmoor National Park (50.716084, −4.026326). The Solid line represents loess-smoothed trend through the plotted median PSI values. Grey ribbon indicates the inter-quartile range of Median values.

4. Discussion

Sentinel 1 is highly effective to monitor infrastructures over the selected study sites. The response to seasonal soil moisture changes has been detected in the three of the infrastructures investigated. Observed surface deformation has been discussed as a function of both major soil group type, soil moisture change and the infrastructure's engineered design. Observed deformation across all sites reveal unique spatial and temporal patterns of measured movement, which have been discussed as functions of the regional water use and the shrink swell potential of the different soil types studied. Sentinel 1 has proved itself to be effective at capturing these patterns across relatively wide study areas. This holds operational promise for the long-term monitoring of infrastructure using Sentinel 1 with PSI.

It is evident that different soil types have an influence on observed infrastructure movement. This is particularly so for soils which are seasonally waterlogged and exhibit cycles of drying and wetting. Surface deformation of infrastructure has been observed to deform (along LOS) in all infrastructure classes analysed, mostly coinciding with the expected periods of soil shrink (summer months), and soil heave (autumn and winter months). The main soil groups included in this study which are prone to seasonal volume change are Ground-water Gley soils, Brown soils, Pelosols, and Surface-water Gley soils. All these major soil groups condition the heave and shrink of infrastructure, see Figure 4. Several surface deformation trends do not appear to follow seasonal pattern of shrink and swell. These unexpected results may be attributed to regional factors associated to the regional water regime such as intense agriculture, water abstraction, irrigation, and the presence of rivers and lakes. Direct analysis of these factors is out of the scope of this paper, yet for the Eastern study sites it should be noted that this region is under highly intensive agricultural land use, with significant drainage and irrigation, so it may not follow the expected seasonal response to soil moisture change. In such areas, variations from the expected deformation patterns are particularly evident for Brown soils (common agricultural soils) and Ground-water Gley soils in Peterborough, where a lag in infrastructure shrink is present, demonstrating a maximum subsidence in December 2016. This lag might be the result of active water management, such as irrigation and drainage from agricultural practices, which stabilises water content during summer and drains land during winter. These effects are particularly prevalent in the Fenlands (Eastern study sites) where the artificial pumping of water manages peat drainage [26]. Moreover, upon analysis of the soil moisture content for Redmere (Figure 2), a low soil moisture was recorded until November that year, which further explains the lagged result seen in surface deformation over soils directly affected by the often anthropogenically controlled soil moisture content of this area. Remotely sensed soil moisture measurements would enhance the understanding of the relationships between surface soil moisture change, and observed ground movement using PSI, however this was also out of scope for this paper.

In comparison, Bournemouth shows relative stability (Figure 4) in infrastructures. The main soil groups are Podzolic soils, Brown soils, Ground-water Gley soils, and Surface-water Gley soils. The observed stability can be attributed to the freely draining soils over permeable bedrock in Bournemouth, consisting predominantly of chalk, limestone, sands, and gravels.

Variations in deformation rates are evident for Lithomorphic soils in Bath, Bristol, Grantham, Kings Lynn and Peterborough. For example, Bath, Kings Lynn, and Peterborough show minimal deformation over Lithomorphic soils whilst Grantham and Bristol show significant deformation profiles. As a major soil group, these soils are mostly very shallow and consist of seven sub-groups [27]. Therefore, analysis of the major soil group in this case may not fully represent the area's soil characteristics and thus the resultant infrastructure movement being observed. Further analysis of more detailed soil classes is required to fully characterise the interactions between Lithomorphic Soil types and infrastructure movement.

Despite its low sample size of just 113 PS points, infrastructure underlain by Peat soils showed subsidence rate of -7.5 mm year^{-1}. Peterborough is the only site to have included analysis of Peat soils, but the findings of this remain important due to the high potential impact subsidence can have on the railway network operation and safety. Rates of deformation observed in this study are slightly less than that found by the assessment in [26] of the East Anglia Fenland wastage, in which it is noted that mean average wastage (over open fenland) can vary between 19 mm yearr^{-1} and 127 mm year^{-1} for thin and thick deposits of Peat soils respectively [26]. However, Holman, I. et al. [26,28] makes no direct mention of the impact of infrastructure on peat wastage. The railway observed within this study is situated on a raised, highly-engineered embankment just to the west of the Holme fen nature reserve. The impact of the railway embankment compressing the peat may lead to compaction of the Peat soil, which is suggestive as to the cause of rates of subsidence observed within this study.

A validation of the PSI output was undertaken over the disused Meldon Quarry in Dartmoor National Park [24] (Figure 5). This test site was selected for its highly stable bedrock and coherence. No vertical movement was expected during this observation period, apart from some deposition from the weathering of the quarry walls. Figure 5 shows minimal movement from the 1579 PS points on the quarry. However, in between March and May 2016 uplift and subsidence of approximately $\pm$1.5 mm is observed. As this movement is consistent across the inter-quartile range of the points, and more sudden and extreme than expected, it is suggested that this movement is due to issues of the data, data cleansing, or PSI technique. This level of uncertainty must be taken into consideration when reporting these results. Given the scale of the movements considered in this study and their seasonal patterns, observations of the trend—rather than individual movement—are suggested as being appropriate. Obtaining levelling or GPS data during this study's observation period for a number of locations in all study sites would improve the validation of the results.

The rates of deformation in this study are aligned to previous investigations which have used PSI to monitor earth surface movement in the UK [18]. Apart from [20,25], there is limited work reporting investigation of the relationships between major soil group type and infrastructure movement using PSI, particularly in the UK, so limited direct comparisons can be made. Several papers have investigated infrastructure deformation using the PSI technique [3,8,14], but these studies use PSI to assess the structural condition of infrastructure assets in areas of known continual ground deformation. These studies note the importance of regional deformation phenomena, such as ground-water abstraction, legacy mining works or seismic activities as key considerations to make when investigating infrastructure deformation at a network level. The rates of deformation from these studies [3,8,14] are highly variable, but often much higher than those reported in this study (up to -73.3 mm year^{-1}) in the case of [3].

Peduto et al. [29] used PSInSAR to monitor the impacts of soil movement upon building damage in Rotterdam, Netherlands. Observed deformations of >10 mm year^{-1} were attributed to high risk soil types such as clay and peat. Despite the observed surface deformation velocities being higher than in this current study, the high risk soils identified correlate to this present study thus increasing confidence in the findings presented. Spatial correlations of deformation were analysed, and PS observations categorized into moving/non-moving, using a 2 mm year^{-1} threshold. The approach of categorizing buildings into moving/non-moving classes would help better identify at-risk areas in linear infrastructure assets which might help to prompt pro-active management by utility operators.

Previous PSI investigations of Bristol and Bath have revealed no evidence that the history of mining in this area has induced any long-term subsidence [17]. This paper found no notable trends in mining-induced subsidence when analysing the PSI output with historic mining extents. This is aligned to the results in [17], however the limited observation period of this study should be taken into consideration. The Terrafirma study [17] also noted that differential compaction was evident across both Bristol and Bath, which is confirmed by this current study, which reflects the diverse range of soil types found across the Bristol and Bath basin. To our knowledge, this is the first study of its kind investigating Bournemouth, Peterborough, Kings Lynn, and Grantham using PSI, so no direct comparison of results can be made.

5. Conclusions

This study has applied a surface deformation investigation using PSI in six UK study sites to determine the impact that different soils have on the LOS deformation of roads and railways. Sentinel 1 has been shown to be effective at measuring surface deformation of these thin, linear infrastructure assets across a range of environmental settings, thus demonstrating PSI with Sentinel 1's potential for wide scale infrastructure monitoring. By combining PSI outputs with the 1:250,000 scale National Soil Map, this study has identified, in these areas, four major soil groups which pose a ground movement risk to infrastructure networks (Brown soils, Ground-water Gley soils, Pelosols, and Surface-water Gley soils). These soils are characterised by seasonal waterlogging. The change in soil moisture is associated with volume change in clay soils. Minor and major roads showed a similar response to soil movement, whilst railways appeared to act independently, particularly when over Peat soils. Podozolic soils remained stable in this stud—for all infrastructure classes investigated—due to the permeable nature of these soils over freely draining bedrock. Further investigations are required to determine the response of Lithomorphic soils, as the results were inconclusive due to the broad taxonomic nature of this group. Major soil groups in this study can contain numerous soil series, with many different soil textures and properties. This can lead to differential ground movement even within a classified major soil group. The use of higher resolution soils data will help better explain observed deformation trends. Re-running the PSI analysis with a higher resolution soil map would allow better characterization of the observed movements to individual soil series. Furthermore, inclusion of a higher resolution DEM (such as Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global) would also help achieve better correction in the geocoding stage. The inclusion of new Sentinel 1 data to increase the length of time series would also be highly beneficial to reveal long term trends soil-related infrastructure deformation.

Furthermore, a comparison between PSInSAR and other techniques such as the Small BAseline Subset (SBAS) [30] and Intermittent SBAS (SBAS) [31] would help to further establish the suitability of these techniques for wide scale monitoring of infrastructure deformation. SBAS and ISBAS generate near continuous coverage of ground deformation measurements, even over vegetated areas. This could help to better identify surface deformation phenomena occurring adjacent to linear infrastructure assets, which have the potential to cause a long-term risk or embankment failure.

In the absence of In-Situ levelling data, a validation site was established within a disused quarry in Dartmoor National Park, England. The results from this exercise returned the expected result of an associated error of ± 1.5 mm, which suggests a good performance of the Persistent Scatterers Interferometry technique investigating soil impacts on infrastructure.

This work contributes to an increased understanding of the risks posed by soil movement to infrastructure networks in the UK. It has helped to quantify relationships between infrastructure movement and major soil groups. This is critical for the planning and monitoring of large-scale infrastructure projects such as the UK's planned High Speed Rail 2, for which an understanding of the soil-related risk is key to the success of the project. This paper has demonstrated the potential of PSI and Sentinel 1 to be used as a tool for remotely monitoring environmental risks to transport infrastructure networks.

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References

1. Wescott, A. *The State of the Nation Infrastructure 2014*; Institute of Civil Engineers: London, UK, 2014; pp. 1–28.
2. HM Government. *National Infrastructure Delivery Plan 2016–2021*; National Infrastructure Plan; HM Government: London, UK, 2016; p. 113.
3. Lan, H.; Li, L.; Liu, H.; Yang, Z. Complex Urban Infrastructure Deformation Monitoring Using High Resolution PSI. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2012**, *5*, 643–651. [CrossRef]

4. Crosetto, M.; Monserrat, O. Persistent scatterer interferometry: Potentials and limits. In Proceedings of the ISPRS Hannover Workshop 2009: High-Resolution Earth Imaging for Geospatial Information, Hannover, Germany, 2–5 June 2009.
5. Ferretti, A.; Prati, C.; Rocca, F. Nonlinear Subsidence Rate Estimation Using Permanent Scatterers in Differential SAR Interferometry. *IEEE Geosci. Remote Sens.* **2000**, *38*, 2202–2212. [CrossRef]
6. Ferretti, A.; Prati, C.; Rocca, F. Permanent Scatterers in SAR Interferometry. *IEEE Geosci. Remote Sens.* **2001**, *39*, 8–20. [CrossRef]
7. Stramondo, S.; Bozzano, F.; Marra, F.; Wegmuller, U.; Cinti, F.R.; Moro, M.; Saroli, M. Subsidence induced by urbanisation in the city of Rome detected by advanced InSAR technique and geotechnical investigations. *Remote Sens. Environ.* **2008**, *112*, 3160–3172. [CrossRef]
8. Zhao, Q.; Lin, H.; Jiang, L.; Chen, F.; Cheng, S. A study of ground deformation in the guangzhou urban area with persistent scatterer interferometry. *Sensors* **2009**, *9*, 503–518. [CrossRef] [PubMed]
9. Culshaw, M.; Tragheim, D.; Donnelly, L.B. Measurement of ground movements in Stoke-on-Trent (UK) using radar interferometry. In Proceedings of the 10th Congress of the International Association for Engineering Geology and the Environment (IEAG 2006), Geological Society, London, UK, 6–10 September 2006; pp. 1–10.
10. Huang, Y.; Lee, C. Detecting Ground Surface Movements with Differential Insar Techniques. In Proceedings of the ASPRS Annual Conference, Reno, Nevada, 1–5 May 2006.
11. Lauknes, T.R.; Piyush Shanker, A.; Dehls, J.F.; Zebker, H.A.; Henderson, I.H.C.; Larsen, Y. Detailed rockslide mapping in northern Norway with small baseline and persistent scatterer interferometric SAR time series methods. *Remote Sens. Environ.* **2010**, *114*, 2097–2109. [CrossRef]
12. Tofani, V.; Raspini, F.; Catani, F.; Casagli, N. Persistent Scatterer Interferometry (PSI) Technique for Landslide Characterization and Monitoring. *Remote Sens.* **2013**, *5*, 1045–1065. [CrossRef]
13. Ventisette, C.D.; Intrieri, E.; Luzi, G.; Casagli, N.; Fanti, R.; Leva, D. Using ground based radar interferometry during emergency: The case of the A3 motorway (Calabria Region, Italy) threatened by a landslide. *Nat. Hazards Earth Syst.* **2011**, *11*, 2483–2495. [CrossRef]
14. Chen, F.; Lin, H.; Li, Z.; Chen, Q.; Zhou, J. Interaction between permafrost and infrastructure along the Qinghai-Tibet Railway detected via jointly analysis of C- and L-band small baseline SAR interferometry. *Remote Sens. Environ.* **2012**, *123*, 532–540. [CrossRef]
15. Crosetto, M.; Devanthéry, N.; Monserrat, O.; Crippa, B. Exploitation of the full potential of PSI data for subsidence monitoring. *Proc. IAHS* **2015**, *372*, 311–314. [CrossRef]
16. Yu, B.; Liu, G.; Zhang, R. Monitoring subsidence rates along road network by persistent scatterer SAR interferometry with high-resolution TerraSAR-X imagery. *J. Mod. Transp.* **2013**, *21*, 236–246. [CrossRef]
17. Capes, R.; Marsh, S. The Terrafirma Atlas—The Terrain Motion Information Sevice for Europe, GMES-ESA. 2009. Available online: http://esamultimedia.esa.int/multimedia/publications/TerrafirmaAtlas/pageflip.html (accessed on 6 August 2017).
18. Aldiss, D.; Burke, H.; Chacksfield, B.; Bingley, R.; Teferle, N.; Williams, S.; Blackman, D.; Burren, R.; Press, N. Proceedings of the Geologists' Association Geological interpretation of current subsidence and uplift in the London area, UK, as shown by high precision satellite-based surveying. *Proc. Geol. Assoc.* **2014**, *125*, 1–13. [CrossRef]
19. Meisina, C.; Zucca, F. PS InSAR Integrated with Geotechnical GIS: Some Examples from Southern Lombardia. *Geod. Deform. Monit. Geohphys. Eng. Roles* **2006**, *131*, 65–72.
20. Boyle, J.; Stow, R.; Wright, P. *In-SAR Imaging of London Surface Movement for Structural Damage Management and Water Resource Conservation*; Report for BNSC Link Programme, Project 4; National Remote Sensing Centre: Farnborough, UK, 2000; p. 7.
21. Keay, C.A.; Hallett, S.H.; Farewell, T.S.; Rayner, A.P.; Jones, R.J.A. Moving the National Soil Database for England and Wales (LandIS) towards INSPIRE Compliance. *Int. J. Spat. Data Infrastruct. Res.* **2009**, *4*, 134–155.
22. Pritchard, O.G.; Hallett, S.H.; Farewell, T.S. Soil impacts on UK infrastructure: Current and future climate. *Proc. Inst. Civ. Eng. Eng. Sustain.* **2014**, *167*, 170–184. [CrossRef]
23. Goldstein, R.M.; Werner, L. Radar interferogram filtering for geophysical applications. *Geophys. Res. Lett.* **1998**, *25*, 4035–4038. [CrossRef]
24. Meldon Aplite Quarry—Educational Register of Geological Sites. Available online: http://www.devon.gov.uk/geo-meldon-aplite-quarry.pdf (accessed on 6 August 2017).

25. Pritchard, O.G.; Hallet, S.H.; Farewell, T.S. Soil geohazard mapping for improved asset management of UK local roads. *Nat. Hazards Earth Syst.* **2015**, *15*, 2079–2090. [CrossRef]
26. Holman, I.; Kechavarzi, C. *A Revised Estimate of Peat Reserves and Loss in the East Anglian Fens, Commissioned by the RSPB*; Department of Natural Resources, Cranfield University: Cranfield, UK, 2011; p. 31.
27. Clayden, B.; Hollis, J.M. *Criteria for Differentiating Soil Series*; Soil Series Technical Monograph No. 17; Rothamsted Experimental Station: Harpenden, UK, 1984.
28. Thomson, A.M.; Mobbs, D.C.; Milne, R.; Skiba, U.; Levy, P.E.; Jones, S.K.; Billett, M.F.; Van Oijen, M.; Ostle, N.; Foereid, B.; et al. *Inventory and Projections of UK Emissions by Sources and Removals by Sinks Due to Land Use, Land Use Change and Forestry*; Annual Report 2007; Department for the Environment, Food and Rural Affairs Climate, Energy, Science and Analysis Division: Edinburgh, UK, 2007.
29. Peduto, D.; Nicodemo, G.; Maccabiani, J.; Ferlisi, S. Multi-scale analysis of settlement-induced building damage using damage surveys and DInSAR data: A case study in The Netherlands. *Eng. Geol.* **2017**, *218*, 117–133. [CrossRef]
30. Berardino, P.; Fornarno, G.; Lanari, R.; Sansosti, E. A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. *IEEE Geosci. Remote Sens.* **2002**, *40*, 2375–2383. [CrossRef]
31. Sowter, A.; Bateson, L.; Strange, P.; Ambrose, K.; Fifik, M. DInSAR estimation of land motion using intermittent coherence with application to the South Derbyshire and Leicestershire coalfields. *Remote Sens. Lett.* **2013**, *4*, 979–987. [CrossRef]