Case study

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Increasing road network resilience to the impacts of ground movement due to climate change: a case study from Lincolnshire, UK

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Abstract: The UK road network is deteriorating due to ageing infrastructure, climate change and increasing traffic. Due to community and economic reliance on a functioning road system, there is an urgent requirement to build resilience. The roads of south Lincolnshire have high susceptibility to ground movement due to the underlying geology. Deposits such as peat, tidal flat deposits and alluvium have a high susceptibility to compress, particularly when loaded or through loss of water content driven by climate change or lowering of water in drainage channels. The shallow foundations of Lincolnshire's rural evolved roads, originating from old mud tracks, are poorly constructed, increasing their vulnerability to movement. Types of damage include longitudinal cracking, edge failure and uneven long-section profiles. Through knowledge exchange, data sharing and collaboration between the British Geological Survey and Lincolnshire County Council, a direct relationship between road condition and geohazard susceptibility has been demonstrated; showing compressible ground has a greater correlation with road damage than originally considered. This suggests improved understanding of the relationships between the geological, climatic and anthropogenic driving forces on ground movement and road damage enables more informed repair prioritization, decision support and improved bespoke road repair practices, increasing future resilience of road networks.

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The national road network's resilience to degradation is a major challenge due to its age, a changing climate and ever-increasing traffic density, particularly from loading by heavy vehicles. UK motor vehicle traffic increased by 1134% from 1949 to 2019 (Department for Transport 2021). In the county of Lincolnshire, UK, annual road traffic rose from 2.8 billion vehicle miles (bvm) in 1993 to 4.3 bvm in 2019 (Department for Transport 2023*a*). Even post-COVID in 2021, it remained high in the county at 3.9 bvm. Post-COVID, there has been an increase in ordinary goods vehicles (OGVs) and heavy goods vehicles (HGVs) on the roads (Department of Transport 2023*b*), partly fuelled by the rise of online deliveries. The UK is gradually falling down the international ranks for road quality (World Economic Forum 2021), ranking 14th globally in 2006 but dropping to 37th by 2019. However, the importance of resilient existing infrastructure to a country's sustainable development has been highlighted within the United Nations Sustainable Development Goals (Bricker *et al.* 2021; Lagesse *et al.* 2022; United Nations 2022). Berg *et al.* (2015) concur, highlighting that 'roads are the arteries through which the economy pulses; linking producers to markets, workers to jobs, students to school, and the sick to hospitals, roads are vital to any development agenda'. The Fenlands, which stretch into the south of Lincolnshire, are known as the breadbasket of England (Natural England 2023). The clay-, silt- and peat-rich soils are a major resource of national importance for agriculture, leading to the roads being vital for the transfer of agricultural products to the rest of the UK, and internationally.

In 2021, the United Nations Climate Change Conference (COP26) acknowledged that communities will continue to feel the inevitable impacts of a changing climate, and stated its aims to limit the rise in global temperatures and drive action globally on mitigation, adaptation, finance and collaboration (COP26 2021).

In 2022, the Climate Change Committee published its third Independent Assessment of UK Climate Risk (Climate Change Committee 2022). The importance of the road network was emphasized, stating 'transport is fundamental to day-to-day life, but regularly faces climate challenges from flooding, heat, erosion, subsidence, and extreme weather. As the climate continues to change, the severity of these risks is projected to increase'. Committee members go on to declare that 'in the absence of additional adaptation, the impacts of climate change … will lead to costly disruption or loss of service' (UK Climate Risk 2022, p. 3). They also underline the long lifespan of transport infrastructure, and therefore the importance that climate risks are considered for all existing, retrofitted and new assets, and gaps are identified in planning by many of the country's critical infrastructure providers.

Nationally, Great Britain's minor, or non-strategic roads, are maintained by local authorities and represent 87% of the country's overall road network (Department for Transport 2022). These are all A, B, C and unclassified (U) roads. Within Lincolnshire, 87% of roads are minor (7866 km), aligning with the national average, but the percentage of rural C and U roads is higher at 66% (5969 km) compared to 45% nationally. These roads, generally, have little or no foundations (Pritchard *et al.* 2015) and are therefore vulnerable to natural shallow processes that cause ground movement.

Over the last decade, Lincolnshire has experienced significant increases in road damage, including undulations, ridges, cracking and subsequent weaknesses in the road surface that are attributable to the conflation of natural and anthropogenic processes (Pritchard *et al.* 2014). These have contributed to major traffic disruptions such as road closures and road traffic incidents. There are several well-identified geohazards in the county, driven by near-surface soil water content changes, which cause ground movement, including clay shrink–swell and compression. The main lithologies affected are the fine-grained deposits, such as tidal flat deposits and organic soils (i.e. peats).

The road network of Lincolnshire is adapted to its drainage system, which has developed since Roman times, draining low-lying areas to make them suitable for cultivation. There are deep dykes and ditches, often running parallel only 1–2 m from the road. The drainage channels have influenced where roads have been built, and controlled the height of the water table, road construction methods and consequently ongoing road conditions. Despite the county providing approximately 70% of the UK's food produce processed in the country, its limited road network is mostly single lane. The increasingly high volume of heavy haulage traffic transporting agricultural products leads to loading that the roads were not designed for and, therefore, increased potential for carriageway deterioration. 'Other Goods Vehicles 2' (OGV 2s), have the biggest impact on Lincolnshire's network in terms of damage and wear. The volume of 'Heavy Goods Vehicles' (HGVs), which includes OGV2s, has increased recently on the main A roads in the county. An increase of 23 and 35% was recorded on the A17 and A15, respectively, between 2011 and 2021 (Department for Transport 2023*a*).

Future projections, made by the British Geological Survey (BGS) and based on United Kingdom Climate Projections (UKCP) climate scenarios, indicate that large areas of Lincolnshire could experience greater road degradation during the twenty-first century (Harrison *et al.* 2020) due to increased susceptibility of the geology to shrink–swell and compression due to more extreme changes in water content. Through knowledge exchange and data sharing between the BGS and Lincolnshire County Council's Highways department, another increasingly important hazard in the county has been recognized as impacting the local road network, volume reduction of deposits classified as highly compressible. Consolidation, due to compression from static and dynamic loading from infrastructure and heavy traffic, and shrinkage, caused by decreasing water content, is affecting road condition in the county. In addition, once cracks in the surface course occur, ingress of water leads to freeze–thaw processes that cause further damage. Not only are the roads exposed to ground movement due to their shallow construction but previous conventional short-term repair methods, such as adding overlay, can increase loading and result in further consolidation of the ground below.

The County Council, as the local highway authority, recognizes the need for improved understanding of future vulnerability and risk to the road system. This requires relevant information to support the decision-making process to mitigate and adapt to the projected changes in both road traffic and climate change. Initially, the highway authority's priority was susceptibility to ground movement from clay shrink–swell but the increased thickness of subgrade material on compressible deposits poses additional, previously unforeseen, challenges.

The BGS has developed six national GeoSure datasets to provide geological information about potential ground movement due to shrink–swell, compression, collapsible soils, landslides, running sand and soluble rocks (Lee and Diaz Doce 2018). The BGS GeoClimate clay shrink–swell dataset utilizes GeoSure shrink–swell and UKCP09 and UKCP18 climate projection data. GeoClimate provides datasets that can be used as part of a decision support tool to address changes in susceptibility to shrink–swell due to climate change in the UK (Harrison *et al.* 2019, 2020). Lincolnshire County Council now includes BGS GeoClimate Open data, as well as their existing road network data, in their decision-making process for highway maintenance to establish which specific treatments highway engineers can use to improve damaged road sections, especially in areas where major failures have occurred.

This paper introduces four case study sites that demonstrate the most common problems experienced in the local road network of Lincolnshire. It then presents county-level temporal road-damage data, and identifies the relationships between road condition and remaining life, and the underlying geological units. Finally, it proposes more appropriate, and cost-effective, mitigating road construction and maintenance strategies. The findings are also relevant to global areas with similar land use and geological properties, particularly reclaimed land and large river flood plains.

Geological and geomorphology setting

The administrative county of Lincolnshire is situated in mid-eastern England, spanning from the Humber Estuary in the north to The Wash in the south (Fig. 1). The county's relief is predominately low lying (0–50 m above sea level) and covered by Quaternary deposits, except for the Lincolnshire Wolds in the central-northern area of the county where the Chalk Group crops out, and the Lincolnshire Limestone Formation escarpment, running north–south, in the western part of Lincolnshire on which lies the historical part of Lincoln. These hills range from 50 to 200 m above sea level. Much of the southern part of the county is low lying, has fertile soil and the land use is predominantly high-intensity agriculture.

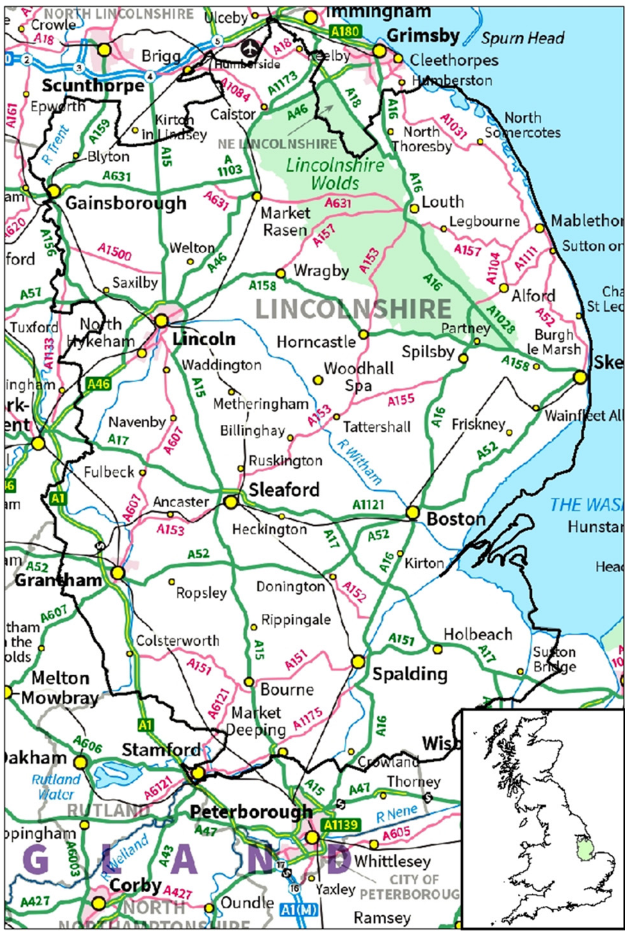


Fig. 1. Map of Lincolnshire County Council area. Insert: map of the UK showing the location of Lincolnshire County Council in green. Contains Ordnance Survey data © Crown copyright and database right [2022].

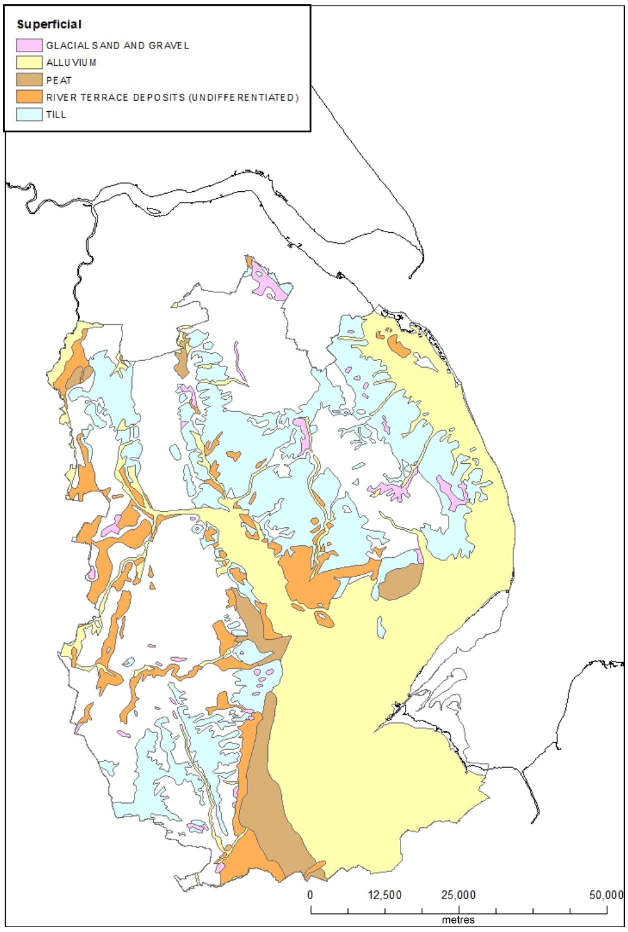


Fig. 2. Superficial geology of Lincolnshire (BGS Geology 625 k Scale). Contains Ordnance Survey data © Crown copyright and database right [2022].

Historical land use

It is likely that prehistoric farming of the rich soils for agriculture and, in particular, horticulture was limited due to regular inundation by the sea, resulting in saline ground conditions. The first attempts to drain the Fens were made by the Romans, who were also the first to construct roads in the county. Notably, they built the Fen Causeway, which avoids much of the soft, compressible soils of the Fens where possible and, in places, raises it above the marshland using a gravel base. There is also limited evidence of drainage during the Middle Ages. During the seventeenth century, after King James I considered the land to be a 'waste and unprofitable', large-scale drainage works constructed major drainage channels including the Old and New Basford rivers in the central Fens to the SW of Lincolnshire. However, drainage resulted in lowering of the land surface and so flood protection was also required. Eventually, in the 1820s, large-scale drainage and flood protection of the Fenlands was successfully undertaken, utilizing pumping stations. This has led to the geomorphology that can be seen today, that of a lower surface with rivers and dykes draining the area, often situated alongside the road network, and rigid roads remaining relatively higher than the surrounding farmland.

Quaternary deposits

Quaternary deposits overlie much of the county's bedrock geology (Fig. 2; Table 1), dominating the north as sheets of till and the southeastern areas as unconsolidated Holocene sediments. The Quaternary period began 2.6 myr ago (Head 2019), and consists of cycles of cold 'glacial' periods interspersed by warmer 'interglacial' periods. Ice sheets advanced over parts of Lincolnshire at least three times during these glacial periods. The Anglian glaciation occurred *c.* 450 kyr ago. It was by far the largest glaciation and ice covered most of the country, reaching as far south as the River Thames. Anglian till deposits would have covered much of Lincolnshire. These have since been eroded by Devensian glacial activity, when ice lobes advanced at least twice into the north of the area and along the east coast, once around 40 kyr ago and again during the Last Glacial Maximum, *c.* 20 kyr ago (Straw 2008). Tills are identified by their fine-grained matrix with suspended mixed rock fragments up to boulder size.

In contrast, SE Lincolnshire is dominated by The Fenlands. These span inland from The Wash, with the northern tip reaching into Lincolnshire. The Fens are a low-lying marshy plain, underlain by thick sequences of interbedded peats, silts and clays with coarser-grained old river channels – evidence of the variations in sea level over the last 18 kyr. The cycle of marine inundation and retreat supported the development of mineral- and organic-rich soils. The Fenlands can be clearly identified by the large swathe of alluvium deposits in the 625 k scale generalized geological map (Fig. 2), with alluvium and tidal flat deposits classified as Alluvium at this scale.

Roddons are the deposits of old rivers and tidal creek systems that meandered through the Fenland landscape during the mid–late Holocene (Smith *et al.* 2010), and can be found throughout this part of the county. They comprise silt, clay and sand, sometimes gravel, but little organic matter, having a lower water content locally in comparison to the surrounding tidal flat deposits and peat. After deposition, the component sediments underwent much less consolidation due to water loss than other deposits, meaning that the roddons now form a slightly raised dendritic network of positive topographical features within the landscape.

Bedrock geology

The bedrock of Lincolnshire comprises an easterly-dipping succession of Triassic and Jurassic mudstones and clays to the west, with younger Cretaceous chalks to the far east, with a NNW–SSE sub-crop (Fig. 3). The bedrock is largely concealed beneath a thick cover of Quaternary deposits, which control the ground movement susceptibility within the area, with the underlying bedrock having little or no direct impact.

Contributing factors to ground movement

Lincolnshire's road network is more at risk than other counties due to a greater exposure to more susceptible geology and a greater

Table 1. *Characteristics of the superficial deposits of Lincolnshire*

Geological unit	Main lithologies	Depositional environment	Engineering unit
Peat	Peat	Organic low-energy fluvial deposits	Organic
Glaciolacustrine deposits	Laminated clay, silt and fine sand	Glacial lake environment	Soft/loose
Alluvium	Silt and clay with lenses of sand and gravel	Floodplain deposits	Soft to firm/loose to dense
Tidal flat deposits	Silty clay with layers of sand, gravel and peat	Tidal deposits	Soft/very soft
Glacial tills	Sandy, gravelly clay with cobbles and boulders	Glaciogenic deposits	Stiff/dense

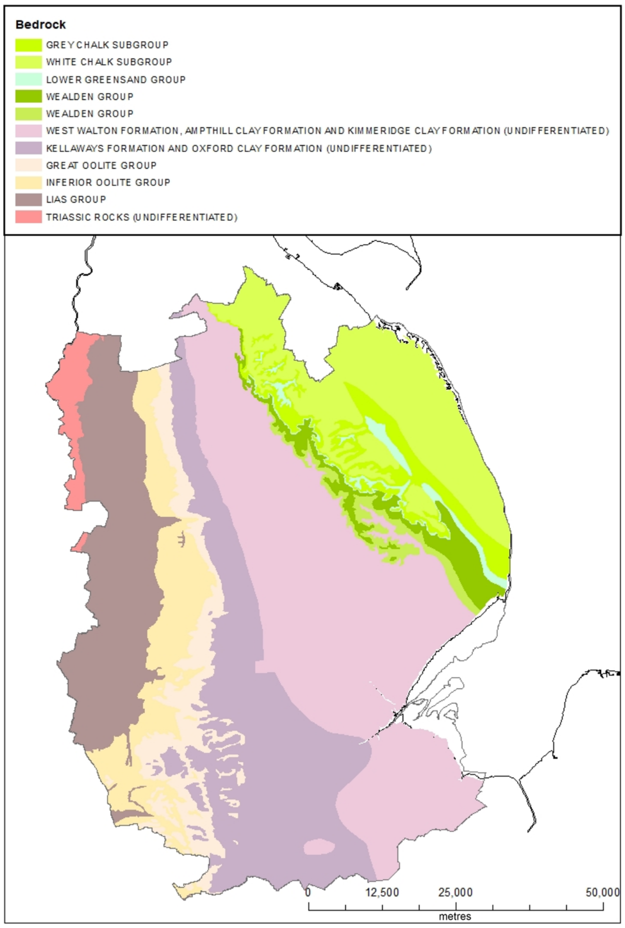


Fig. 3. Bedrock geology of the Lincolnshire County Council area (BGS Geology 625 k scale). Contains Ordnance Survey data © Crown copyright and database right [2022].

vulnerability due the shallow foundations of the evolved road network, which originates from old mud tracks. Figure 4 demonstrates common road structure and thickness in the county. At Chalk Lane, Withern (543327, 382202), the thin surface course of 25 mm has no underlying foundations; as seen in Church Road, Friskney (546188, 355195), if repair work is required these courses have been overlaid and the thickness gradually built up, reaching a depth of 200 mm.

Geological susceptibility to ground movement

The main geological controlling factors of susceptibility to subsidence in the county are the presence, thickness and heterogeneity of shrinkable and compressible deposits. In Lincolnshire, these are primarily tidal flat deposits and peats, which were deposited with a high water content. As they are relatively recent deposits – and have not been loaded by more recent deposits that would facilitate natural consolidation – they have maintained their high water content. This high water content, and their low density, is more likely as these deposits generally have some organic content, which tends to retain water.

If subsidence susceptibility exists at a site, local factors contribute to the increase in likelihood of ground deformation. These include: road construction type; vegetation such as trees and large shrubs in the vicinity; proximity of dykes and other excavations; agri-industry practices such as water management, including water pumping from the dykes and irrigation; and type of road traffic and use of HGVs. The potential amount of volume change is dependent on the water content of a material.

Climate change

The county currently has a mild temperate climate and a relatively low mean annual rainfall of around 619 mm a^{-1} (Met Office 2022*a*). Looking to the future, the UK Climate Projections 2018 scenarios (UKCP18) project a greater chance of hotter, drier summers, as well as warmer, wetter winters (Murphy *et al.* 2018). This, coupled with the county's underlying geology, will continue to result in some of the highest soil moisture deficits (SMDs) in the UK. Abnormal summers like 2003, one of the hottest on record, when the county experienced much higher than average damage to many of its roads could occur regularly by the year 2050 because of climate change (Met Office 2022*b*). Agricultural practices also play a part and need to be considered; during dry weather the farmland is irrigated using water from the drainage channels, further lowering groundwater levels and reducing near-surface water content.

Flooding resulting in embankment and ditch slope failures has increased in occurrence recently due to more frequent high-intensity rainfall events. For example, a bank failure occurred in November 2019 at Fodderdyke Bank, following a high-intensity rainfall event, causing the bank to become quickly saturated. This caused the adjacent highway to become unstable as the minimal subgrade to the carriageway slipped away as part of the bank failure (Fig. 5).

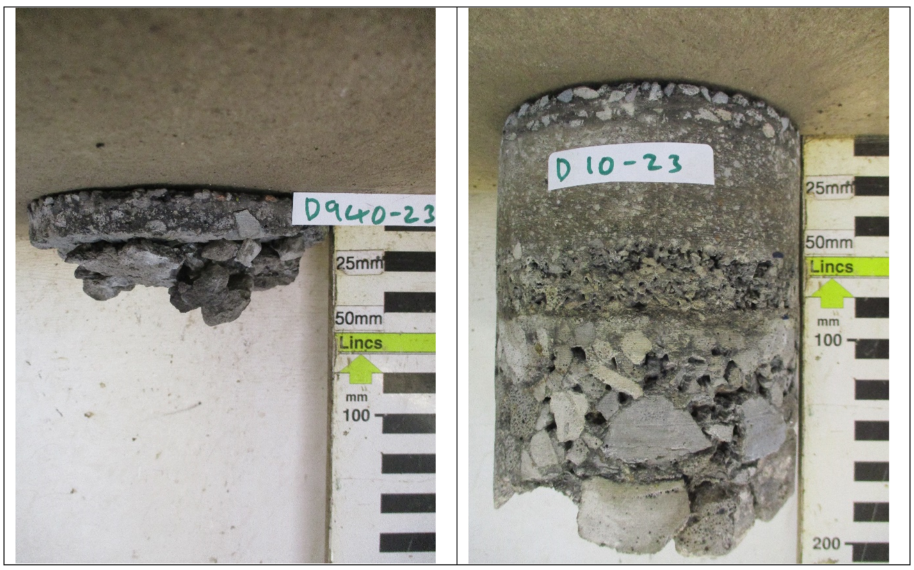


Fig. 4. Typical depths of 'evolved' road foundations in the county. (Left) Chalk Lane, Withern has a depth of 2.5–5 cm and (right) Church Lane in Friskney has a depth of 20 cm. At least four surface courses can be seen to have been added at Friskney.

Fig. 5. Landslide in a large ditch adjacent to road, causing road subsidence and closure for repairs in autumn 2019. Fodderdyke Bank, Midville. © Mark Heaton, Lincolnshire County Council.

Irrigation practices

Lincolnshire's drainage system is often closely aligned with the adopted road network, with deep ditches running parallel to roads that are often only a few metres away. Thus, they have a strong influence on the water levels below the road network.

The Internal Drainage Board (IDB) manages water levels in the county's dykes. During the last decade, it has seen increased irrigation in the summer months due to the warmer, drier summers. This has led to the IDB meeting levels at the lower end of their range during the summer months due to the larger volumes of water required for irrigation. This is in comparison to the rainier winter months when levels are kept even lower. This is to meet increasing field drainage requirements due to generally wetter winters, assisting in keeping the fields dry to ensure early planting of crops.

In addition, climate change is leading to higher sea levels, which is affecting tidal rivers in the area. This leads to a greater hydraulic gradient between the managed drainage regime and the surrounding tidal rivers, thus increasing the pressure on the IDB to irrigate and retain the required water levels.

Road maintenance practices

Road condition and underlying geology are not considered within the central government funding distribution, which is informed by condition assessment, asset management and carriageway length. Therefore, Lincolnshire County Council must plan and prioritize repair and maintenance work in the county as there is a higher percentage of vulnerable roads requiring attention compared to many other counties. In the past, the local highway authority would repair road surfaces as and when the damage occurred. However, although a short-term fix, this patching work adds further load and compounds the compression of susceptible geological units, leading to the need for further repair work in coming years.

Increased traffic

As the county provides a high percentage of the country's food production, a high number of HGVs travel on the 'evolved roads', with no 'main' road alternative. There are no other options such as major railway routes in the county. This has led to an increasing load from heavy vehicles such as farming machinery and those transporting agricultural products to the rest of the country.

Vegetation

It is also noted in all case study sites that there is a relationship with the proximity of vegetation (trees and large shrubs) to the carriageway edge and accelerated deformation/subsidence. Trees and large shrubs adjacent to the carriageway remove water from the ground locally through evapotranspiration, leading to a variation in water content across the carriageway and, therefore, differential ground movement, causing road damage. The depth and extent of the removal of ground water is dependent on the species and size of the plant. However, vegetation also provides shelter, reducing the risk of frost in winter and preventing road surface bleeding in summer, and provides wind breaks, along with other environmental benefits such as supporting animal habitats. Removal of vegetation can also have detrimental effects as the root systems can assist stabilization of banks. If the trees are removed, then there may be swelling of the unsaturated soil layers, and roots may rot and cause further settlement as they change volume.

Case study sites

Four case study sites have been selected to demonstrate the geological, climatic and anthropogenic controls that affect vulnerability to road damage in Lincolnshire, and the impacts observed on the road network (Table 2; Fig. 6).

Table 2. *Summary of the Lincolnshire case study sites*

Case Study Site	Location and other details	Vulnerability	Superficial geology	Associated geohazards
1. Fodderdyke	537955, 356956 (*X*, *Y*) HGVs causing increased loading. Road is flanked by steep-sided drainage ditches and has been raised due to consolidation and peat shrinkage in the surrounding area. Increased soil moisture deficit due to irrigation practices	Adopted road with no foundations	Peat with roddons	Variable compressibility. Geological heterogeneity leading to variability in susceptibility. Potential for differential ground movement
2. Brandy Wharf	501820, 397087 (*X*, *Y*) Road passes over the pre-canalized River Ancholme deposits	Adopted road with no foundations	Thin peat/ glaciolacustrine deposits	Compression Geological heterogeneity leading to variability in geohazard susceptibility. Potential for differential ground movement
3. Witham Bank	518837, 359977 (*X*, *Y*) Overgrown vegetation along the west side, River Witham to the east. Increased traffic	Adopted road with no foundations	Alluvium/tidal flat deposits	Compression
4. Amber Hill	522349, 347593 (*X*, *Y*) Drainage ditches on both sides, adjacent to the road, experiencing lower levels of water than usual	Adopted road with no foundations	Alluvium/tidal flat deposits	Compression

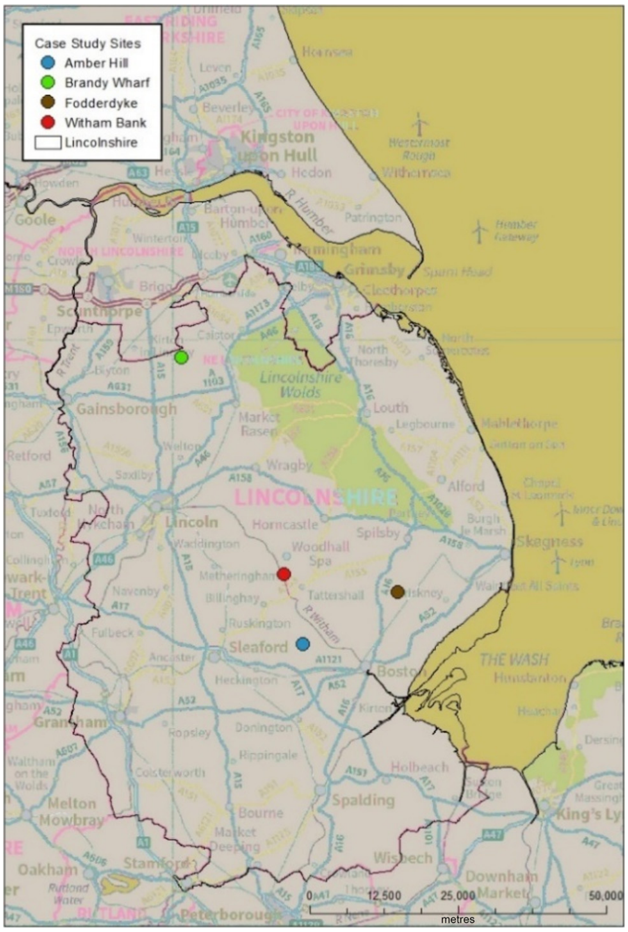


Fig. 6. Map of Lincolnshire showing the location of the case study sites (OS MiniScale data © Crown copyright and database right 2022).

Site 1: Fodderdyke Bank – increased loading due to HGV use

Fodderdyke (537955, 356956) is a 5 km stretch of road near Midville, north of Boston, and is a cut-through road from the A16 to the A52. It is flanked by steep-sided drainage dykes and is raised relative to its surroundings. It is a 'C' class part of the network and has relatively modest traffic flows but includes large agricultural vehicles and HGVs.

Movement history

During the last decade, splitting along the longitudinal section (Fig. 7), undulations, deformation including localized shears, slope movement and other subsequent highway failures have developed. Due to the worsening state of the road, it became relatively unsafe for travelling on at speed. In 2015 a road traffic incident took place; tragically, this resulted in a fatality, and a lower speed limit was enforced until repair work could be completed. Mitigation work was successfully completed by the local authority during 2018. Although overlays had been the typical repair method, a different approach was used to increase the life of the road and reduce future maintenance requirements. This entailed recycling of the existing road surface; therefore, not introducing additional load. Due to the length of this road this is a rolling programme with works being undertaken each year. It is still ongoing, giving the highway authority the opportunity to review, monitor and make fine adjustments to the design, whilst continuing its research.

Geological background

A depth of 5–10 m of peat underlies the western stretch of the highway, and tidal flat deposits lie beneath the road to the east.

Potential causes of movement at the site and future climate change impacts

The Environment Agency (EA) LiDAR scan data (Fig. 7) show the lower ground to the north of Fodderdyke, which coincides with the highly compressible peat deposits. These are topographically similar to the tidal flat deposits to the south, which are also susceptible to consolidation due to loading and shrinkage due to a reduction in water, although this movement is less than found in the peat as they have a lower natural water content and show less ground movement. The roddons cross the area from north and south, raising the ground surface, appearing as 'inverted channels'. North of the road, compression of the peat deposits has led to the land surface lowering, and therefore a lowering of the overlying roddons. Due to less movement in the tidal flat deposits to the south of the road, the roddons have a comparably slightly higher elevation to the south compared to the north. However, in all locations, roddons provide a positive topographical feature. The presence of deposits with different lithology and characteristics along the road leads to large variation in the amount of movement seen.

Considering the increasing SMDs projected for the area, and the higher subsidence susceptibility of the peat deposits, the difference in elevation is expected to increase, causing further road damage where peat deposits meet the road and differential movement occurs. The

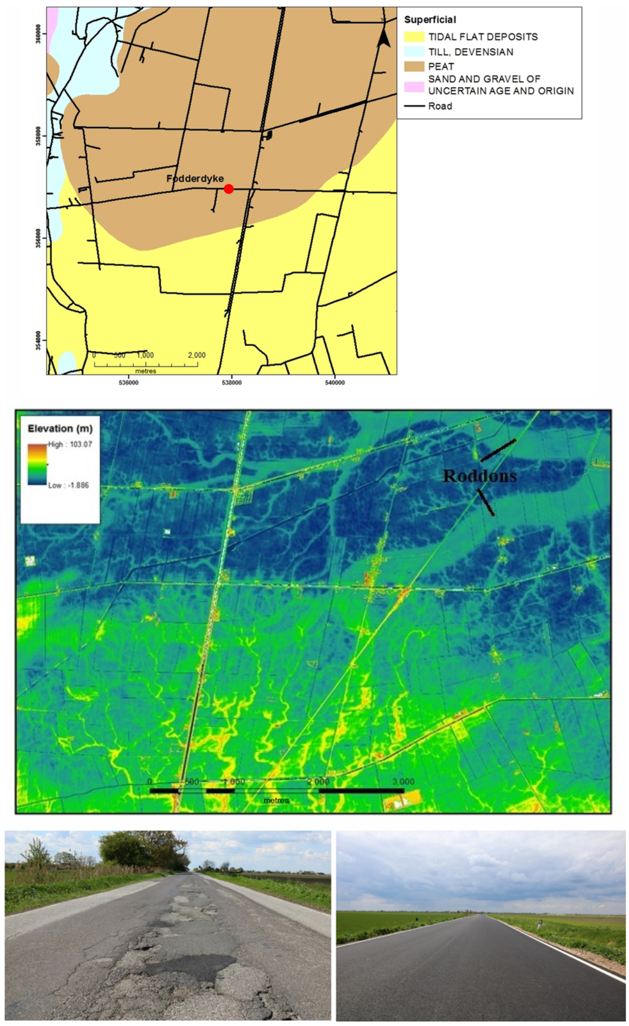


Fig. 7. (Top) Superficial geological map. (Middle) LiDAR image. © Environment Agency copyright and/or database right 2022. All rights reserved. (Bottom left) Previous road damage and patching work at Fodderdyke western stretch (May 2018). BGS © UKRI 2018. (Bottom right) Present-day post road repair Fodderdyke eastern stretch (May 2018). BGS © UKRI 2018.

presence of roddons leads to further heterogeneity in the underlying ground conditions and increased undulations along the road.

The road surface is impermeable and restricts ingress of water directly beneath it. The presence of ditches either side of the road means that a larger surface area is exposed, driving enhanced changes in water content. As the adjacent ground experiences annual fluctuations in water content, and resulting volume changes, the soil water content beneath the road remains relatively constant, sealed off from external variations. This leads to a soil water content gradient from the edge to the centre of the road, and a gradual drying out of the outer edges of the road over time. This drying causes a decrease in soil water content and pressure, leading to volume reduction and longitudinal deformation parallel to the edge of the road, as can be seen in Figure 7. This process is further exacerbated by heavy loading from vehicles travelling along the road, and the carriageway being informally widened over time, so load is being applied nearer to the break in slope. Once deformation has occurred, these weak zones are broken up by deformation cracks that allow water ingress, causing further damage through localized changes in water content and freeze–thaw processes. Acting locally, within a few metres, the presence of vegetation, such as trees and large bushes, exacerbates these processes due to evapotranspiration.

Site 2: Brandy Wharf – peat compression

The site is a 400 m section of the B1205, situated 3 km east of Waddingham village (501820, 397087), in the hamlet of Brandy Wharf Spa. The road is relatively low lying with a shallow drainage ditch running along the northern edge.

Movement history

The road has developed large undulations in the surface, as well as edge cracking.

Geological background

The site is in an area of peat, underlain by glaciolacustrine deposits (silts and sands). The New River Ancholme is at the western edge of the site. In the seventeenth century, the River Ancholme was canalized from Bishopbridge to Ferriby, passing through Brandy Wharf, with this work taking more than 200 years to complete. This New River Ancholme now carries most of the water but the old course still meanders, reduced nearly entirely to a ditch. The Environment Agency (EA) LiDAR data (Fig. 8) show the meandering trace of the old river channel running north–south in the centre of the LiDAR map, in darker blue, and marks the eastern edge of the site. The damaged part of the road is along the short stretch that passes over the peat.

In September 2020, Lincolnshire County Council undertook windowless sample holes, drilling to a maximum depth of 4.5 m, at four points along the stretch of road (Fig. 8). The road surface had a consistent 40 cm of asphalt, underlain by *c.* 60 cm of fill and sub-base. The depth of peat in the boreholes beneath the road ranges from 1 to 3 m, showing large variability between each of the sites; with WS4 recording much shallower peat that WS1–WS3 (Figs 9–12). The deposits underlying the peat at all four sample holes are clayey peats and clays with rare organics, considered to be glaciolacustrine deposits. These are much thicker in WS4 than at the other three locations. Sand with flint gravel is at depth in all four holes, located at around 2 m depth at WS1–WS3 and at almost 4 m at WS4. The LiDAR image (Fig. 8) indicates the presence of a roddon at WS1 and the old River Ancholme passing through WS4.

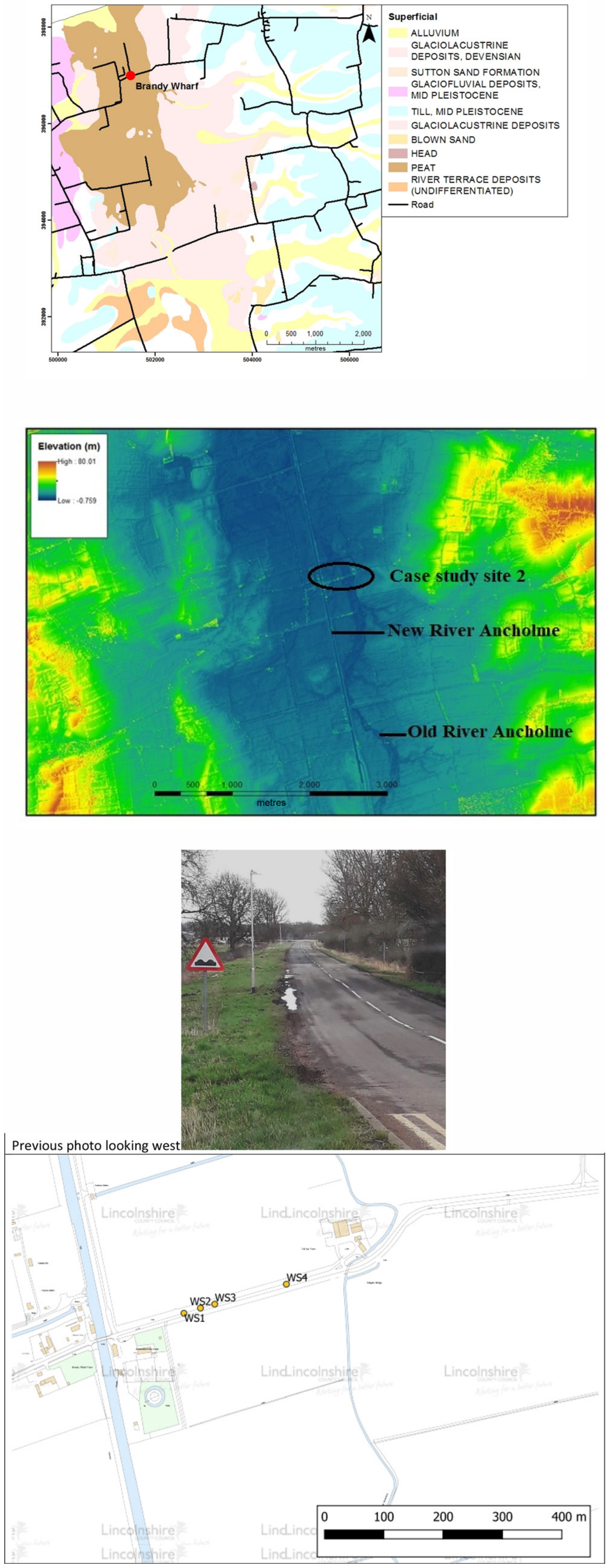


Fig. 8. Brandy Wharf. (Top) Superficial geological map. (Middle) LiDAR data. © Environment Agency copyright and/or database right (2022). All rights reserved. (Second to bottom) Photograph of case study site, looking west, showing the undulating road surface (September 2020) © Mark Heaton, Lincolnshire County Council. (Bottom) Sample hole locations. ©Lincolnshire County Council.

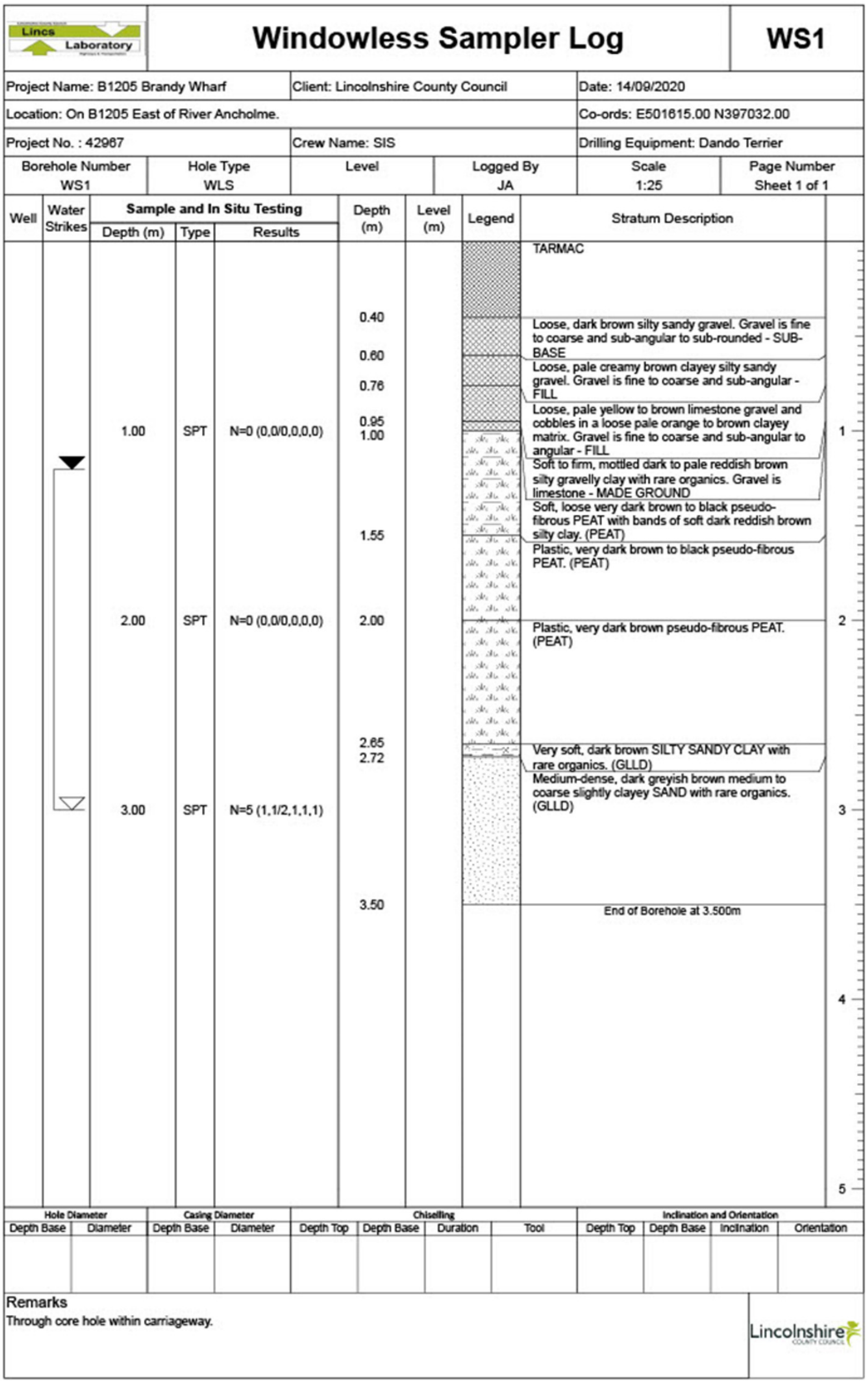


Fig. 9. Brandy Wharf Lincs Laboratory Windowless sampler log WS1. © Lincs Laboratory.

However, disturbance due to the construction of the new river channel, and the road construction, could have disturbed deposits laid down by shallow river channels (roddons) in the location of borehole WS1.

Potential causes of movement at the site and future climate change

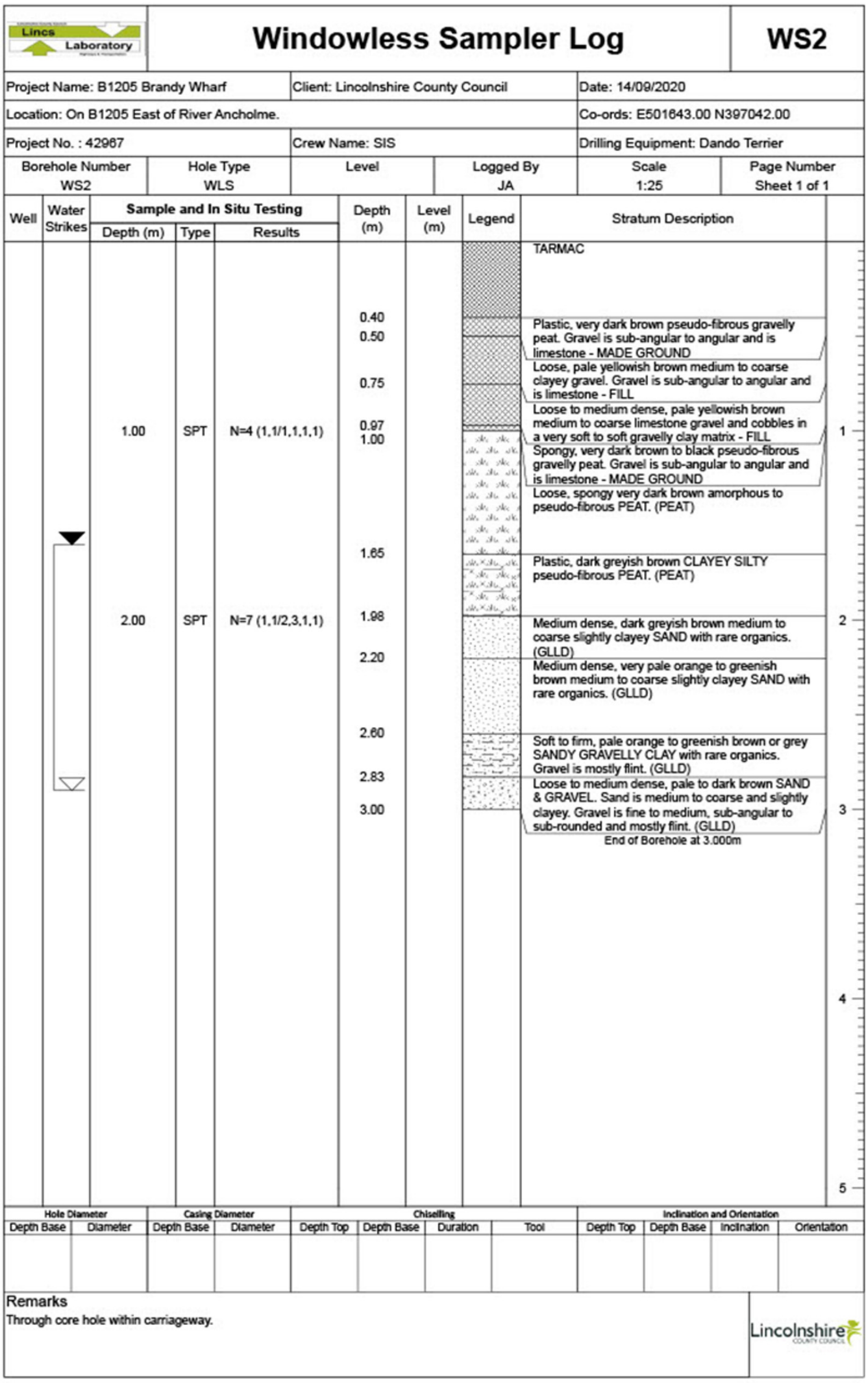
At sites WS1–WS3, the peat is deeper, and the road has experienced more subsidence and damage than at WS4, due to the high compressibility of the peat. In addition, the underlying glaciolacustrine deposits, with a varying organic content, increase in depth towards the east (WS4), leading to further variations in compressibility along the short stretch of road. With the presence of roddons and the old river course passing over the site, the variable and complex history of the site leads to large differences in susceptibility along the short section of road.

Site 3: Witham Bank – alluvium with vegetation

Witham Bank (518837, 359977) is an evolved road with no foundations, running parallel to the River Witham.

Movement history

Lateral variation in water content across the carriageway has led to subsidence and the generation of a longitudinal crack in the road surface (Fig. 13), commonly up to 20 cm wide. A likely cause of this variation is the increase in vegetation along the western edge during the last decade, as seen in Figure 13 (May 2018), which



Lincs Laboratory

Windowless Sampler Log — **WS2**

Project Name: B1205 Brandy Wharf	Client: Lincolnshire County Council	Date: 14/09/2020
Location: On B1205 East of River Ancholme.		Co-ords: E501643.00 N397042.00
Project No. : 42967	Crew Name: SIS	Drilling Equipment: Dando Terrier

Borehole Number	Hole Type	Level	Logged By	Scale	Page Number
WS2	WLS		JA	1:25	Sheet 1 of 1

Sample Depth (m)	Type	Results	Depth (m)	Stratum Description
				TARMAC
			0.40	Plastic, very dark brown pseudo-fibrous gravelly peat. Gravel is sub-angular to angular and is limestone - MADE GROUND
			0.50	Loose, pale yellowish brown medium to coarse clayey gravel. Gravel is sub-angular to angular and is limestone - FILL
			0.75	Loose to medium dense, pale yellowish brown medium to coarse limestone gravel and cobbles in a very soft to soft gravelly clay matrix - FILL
1.00	SPT	N=4 (1,1/1,1,1,1)	0.97	Spongy, very dark brown to black pseudo-fibrous gravelly peat. Gravel is sub-angular to angular and is limestone - MADE GROUND
			1.00	Loose, spongy very dark brown amorphous to pseudo-fibrous PEAT. (PEAT)
			1.65	Plastic, dark greyish brown CLAYEY SILTY pseudo-fibrous PEAT. (PEAT)
2.00	SPT	N=7 (1,1/2,3,1,1)	1.98	Medium dense, dark greyish brown medium to coarse slightly clayey SAND with rare organics. (GLLD)
			2.20	Medium dense, very pale orange to greenish brown medium to coarse slightly clayey SAND with rare organics. (GLLD)
			2.60	Soft to firm, pale orange to greenish brown or grey SANDY GRAVELLY CLAY with rare organics. Gravel is mostly flint. (GLLD)
			2.83	Loose to medium dense, pale to dark brown SAND & GRAVEL. Sand is medium to coarse and slightly clayey. Gravel is fine to medium, sub-angular to sub-rounded and mostly flint. (GLLD)
			3.00	End of Borehole at 3.000m

Hole Diameter: Depth Base, Diameter; Casing Diameter: Depth Base, Diameter; Chiselling: Depth Top, Depth Base, Duration, Tool; Inclination and Orientation: Depth Top, Depth Base, Inclination, Orientation

Remarks
Through core hole within carriageway.

Lincolnshire County Council

Fig. 10. Brandy Wharf Lincs Laboratory Windowless sampler log WS2. © Lincs Laboratory.

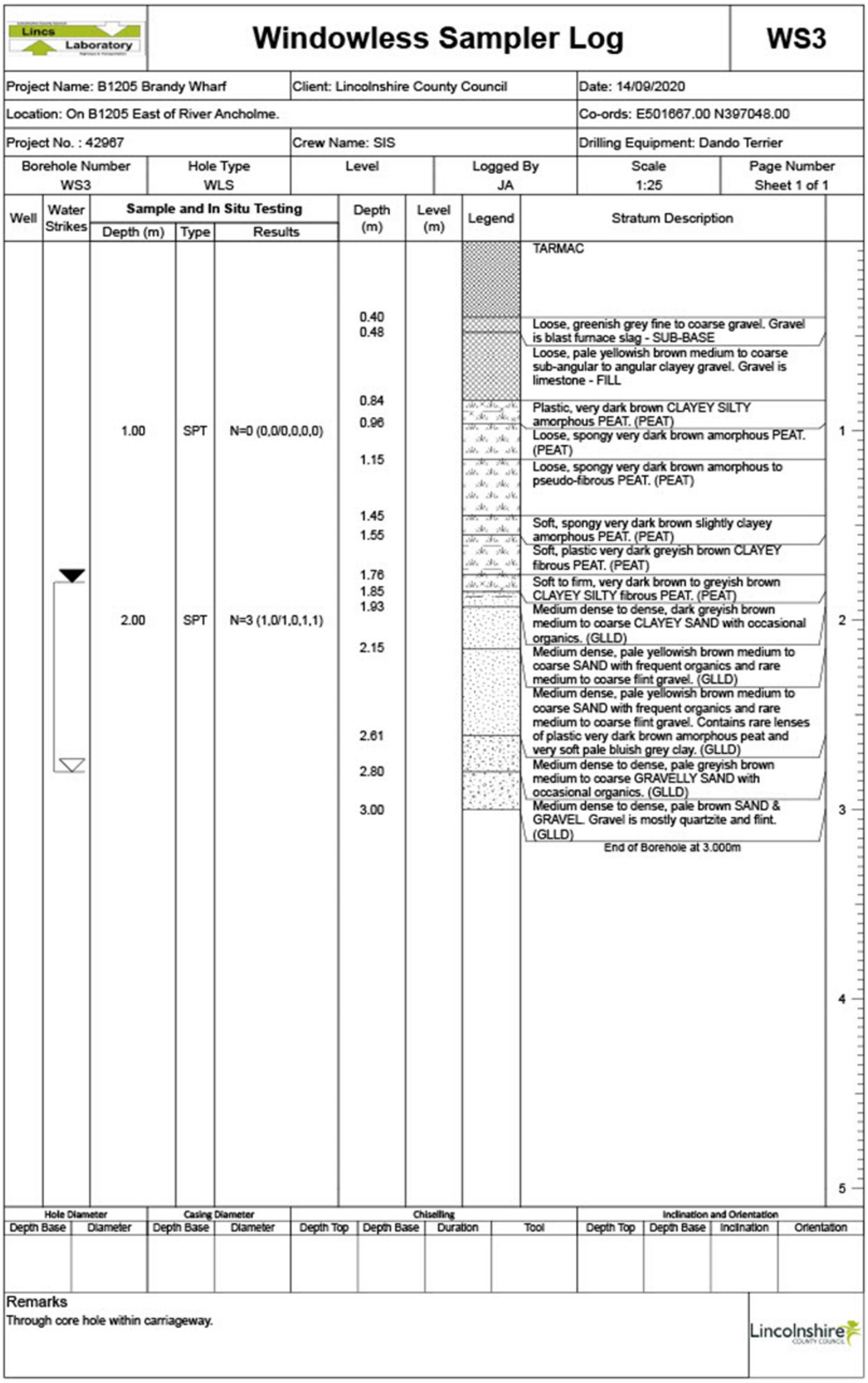
withdraws water from the ground on the western side. Other potential processes could be compounding changes in water content at the site. These include: the western bank potentially being steeper than the eastern bank; the road having been historically widened on the west rather than the east; the parallel ditch having been recently overdug; or the water table dropping due to pumping to the west.

Geological background

The road is underlain by highly compressible alluvium. In 2020, the authority undertook a small ground investigation to 6 m below the carriageway on Witham Bank. Below 3 m of made ground, fibrous peat or peaty clay was found. The peat was continuous to 6 m depth. The material was laminated and denser than typical spongy fibrous peat deposits. It is considered that the increased density was due to compression of the peat from the loading of the embankment and possibly the lowering of the groundwater level.

Potential causes of movement at the site and future climate change

Recently, there has been an increase in dynamic loading caused by an increase in traffic, as well as increased static loading due to repair work with the addition of overlays. These add to the load, leading to compression and thus exacerbating the cracking.



Windowless Sampler Log — **WS3**

Lincs Laboratory

Project Name: B1205 Brandy Wharf	Client: Lincolnshire County Council	Date: 14/09/2020
Location: On B1205 East of River Ancholme.		Co-ords: E501667.00 N397048.00
Project No. : 42967	Crew Name: SIS	Drilling Equipment: Dando Terrier

Borehole Number	Hole Type	Level	Logged By	Scale	Page Number
WS3	WLS		JA	1:25	Sheet 1 of 1

Sample Depth (m)	Type	Results	Depth (m)	Stratum Description
				TARMAC
			0.40	Loose, greenish grey fine to coarse gravel. Gravel is blast furnace slag - SUB-BASE
			0.48	Loose, pale yellowish brown medium to coarse sub-angular to angular clayey gravel. Gravel is limestone - FILL
			0.84	Plastic, very dark brown CLAYEY SILTY amorphous PEAT. (PEAT)
1.00	SPT	N=0 (0,0/0,0,0,0)	0.96	Loose, spongy very dark brown amorphous PEAT. (PEAT)
			1.15	Loose, spongy very dark brown amorphous to pseudo-fibrous PEAT. (PEAT)
			1.45	Soft, spongy very dark brown slightly clayey amorphous PEAT. (PEAT)
			1.55	Soft, plastic very dark greyish brown CLAYEY fibrous PEAT. (PEAT)
			1.76	Soft to firm, very dark brown to greyish brown CLAYEY SILTY fibrous PEAT. (PEAT)
			1.85	Medium dense to dense, dark greyish brown medium to coarse CLAYEY SAND with occasional organics. (GLLD)
2.00	SPT	N=3 (1,0/1,0,1,1)	1.93	Medium dense, pale yellowish brown medium to coarse SAND with frequent organics and rare medium to coarse flint gravel. (GLLD)
			2.15	Medium dense, pale yellowish brown medium to coarse SAND with frequent organics and rare medium to coarse flint gravel. Contains rare lenses of plastic very dark brown amorphous peat and very soft pale bluish grey clay. (GLLD)
			2.61	Medium dense to dense, pale greyish brown medium to coarse GRAVELLY SAND with occasional organics. (GLLD)
			2.80	Medium dense to dense, pale brown SAND & GRAVEL. Gravel is mostly quartzite and flint. (GLLD)
			3.00	End of Borehole at 3.000m

Remarks
Through core hole within carriageway.

Lincolnshire County Council

Fig. 11. Brandy Wharf Lincs Laboratory Windowless sampler log WS3. © Lincs Laboratory.

It is anticipated that projected changes in climate will further intensify the cracking due to lower water levels and drying out.

Site 4: Amber Hill – tidal flat deposits with deep drainage ditch

North of Amber Hill village, Sutterton Drove (522349, 347593) is an evolved road that runs parallel to a large drainage ditch.

Movement history

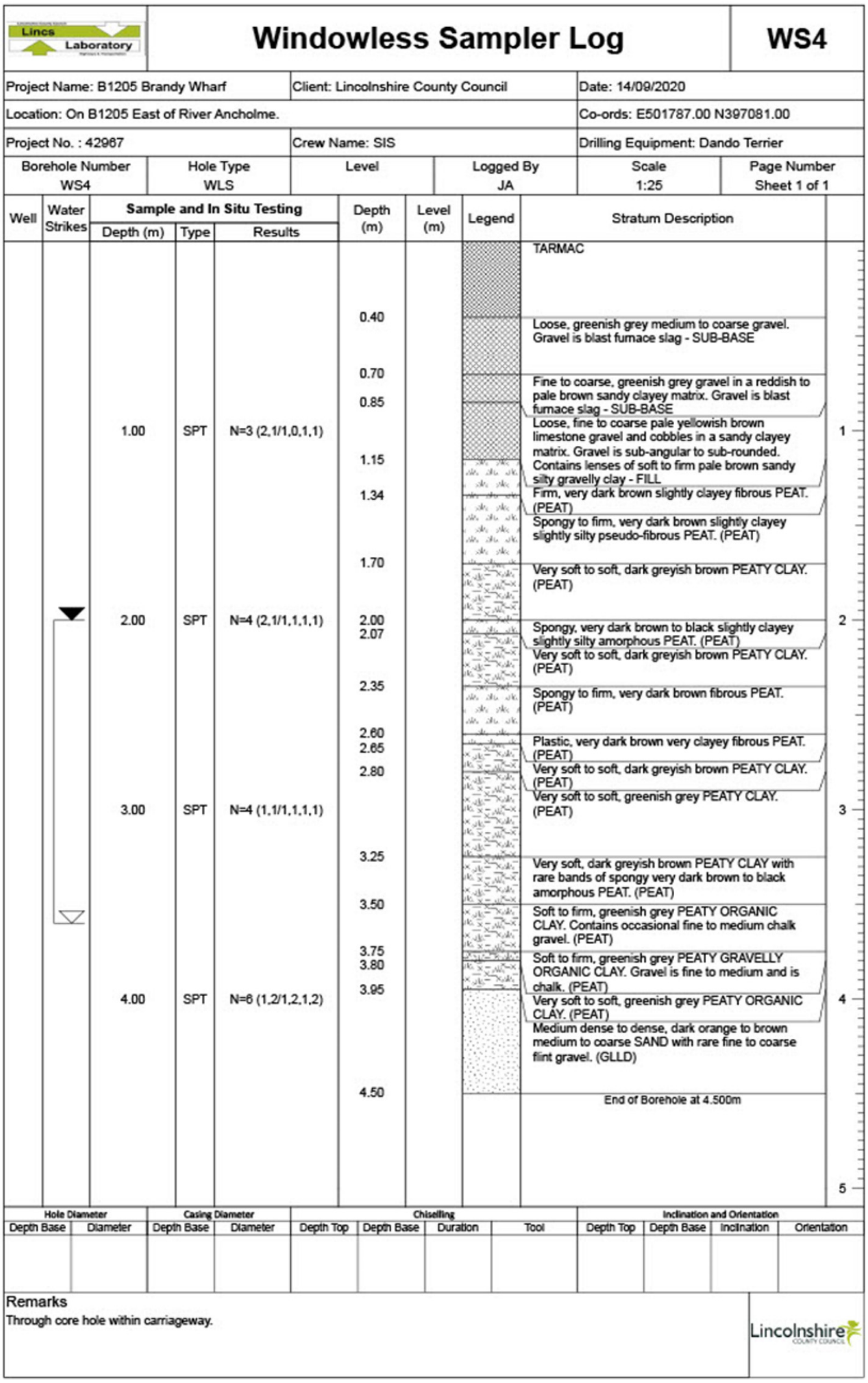
Longitudinal cracking has occurred down the centre of the carriage way, as can be seen in Figure 14.

Geological background

Geological maps and borehole logs indicate tidal flat deposits with a thickness of *c.* 5 m, underlain by thick gravels.

Potential causes of movement at the site and future climate change

Changes in water management, causing fluctuations in pump volumes in the winter due to changes in precipitation and changes in agricultural practice, including field irrigation during dry winters, has led to lower water levels in ditches and drying out of the embankment, much more so than in the recent past. As seen in Figure 14, trees are established adjacent to the drainage ditch. As water



Lincs Laboratory

Windowless Sampler Log WS4

Project Name: B1205 Brandy Wharf	Client: Lincolnshire County Council	Date: 14/09/2020
Location: On B1205 East of River Ancholme.		Co-ords: E501787.00 N397081.00
Project No. : 42967	Crew Name: SIS	Drilling Equipment: Dando Terrier

Borehole Number	Hole Type	Level	Logged By	Scale	Page Number
WS4	WLS		JA	1:25	Sheet 1 of 1

Sample Depth (m)	Type	Results
1.00	SPT	N=3 (2,1/1,0,1,1)
2.00	SPT	N=4 (2,1/1,1,1,1)
3.00	SPT	N=4 (1,1/1,1,1,1)
4.00	SPT	N=6 (1,2/1,2,1,2)

Depth (m)	Stratum Description
0.40	TARMAC
0.70	Loose, greenish grey medium to coarse gravel. Gravel is blast furnace slag - SUB-BASE
0.85	Fine to coarse, greenish grey gravel in a reddish to pale brown sandy clayey matrix. Gravel is blast furnace slag - SUB-BASE
1.15	Loose, fine to coarse pale yellowish brown limestone gravel and cobbles in a sandy clayey matrix. Gravel is sub-angular to sub-rounded. Contains lenses of soft to firm pale brown sandy silty gravelly clay - FILL
1.34	Firm, very dark brown slightly clayey fibrous PEAT. (PEAT)
1.70	Spongy to firm, very dark brown slightly clayey slightly silty pseudo-fibrous PEAT. (PEAT)
2.00	Very soft to soft, dark greyish brown PEATY CLAY. (PEAT)
2.07	Spongy, very dark brown to black slightly clayey slightly silty amorphous PEAT. (PEAT)
2.35	Very soft to soft, dark greyish brown PEATY CLAY. (PEAT)
2.60	Spongy to firm, very dark brown fibrous PEAT. (PEAT)
2.65	Plastic, very dark brown very clayey fibrous PEAT. (PEAT)
2.80	Very soft to soft, dark greyish brown PEATY CLAY. (PEAT)
3.25	Very soft to soft, greenish grey PEATY CLAY. (PEAT)
3.50	Very soft, dark greyish brown PEATY CLAY with rare bands of spongy very dark brown to black amorphous PEAT. (PEAT)
3.75	Soft to firm, greenish grey PEATY ORGANIC CLAY. Contains occasional fine to medium chalk gravel. (PEAT)
3.80	Soft to firm, greenish grey PEATY GRAVELLY ORGANIC CLAY. Gravel is fine to medium and is chalk. (PEAT)
3.95	Very soft to soft, greenish grey PEATY ORGANIC CLAY. (PEAT)
4.50	Medium dense to dense, dark orange to brown medium to coarse SAND with rare fine to coarse flint gravel. (GLLD)

End of Borehole at 4.500m

Remarks
Through core hole within carriageway.

Lincolnshire County Council

Fig. 12. Brandy Wharf Lincs Laboratory Windowless sampler log WS4. © Lincs Laboratory.

levels decrease in the ditch, the trees could be taking additional water from the road side of the embankment. Longitudinal cracking has occurred down the centre of the carriage way due to the high soil water gradient between the embankment and beneath the road surface.

Regional-scale datasets

Lincolnshire County Council and the BGS started exchanging knowledge and data after meeting in 2015 at a stakeholder event that contributed to the design and development of the GeoClimate shrink–swell UKCP09 data product (Harrison *et al.* 2020). This collaboration has continued and developed to sharing lessons learnt with national infrastructure managers through conferences and meetings (e.g. Harrison 2018; LCRIG 2022).

BGS GeoSure and Lincolnshire County Council residual life dataset

Lincolnshire County Council monitor the road network using several methods to enable them to prioritize the maintenance work and utilize funds efficiently. Deflectogram surveys (Highways England 2020) provide an estimate of residual road life (RL) for the principle and strategic road network in the county. The RL is calculated from the maximum deflection of the road surface, when a vehicle of a known weight and speed passes over it, at a spacing of *c.* 4 m intervals. The estimated RL is the number of years remaining before the onset of 'investigatory' conditions, meaning that more intensive monitoring is required of the road's structural condition. Deflectogram surveys are completed regularly, providing annual data for many roads within the county.

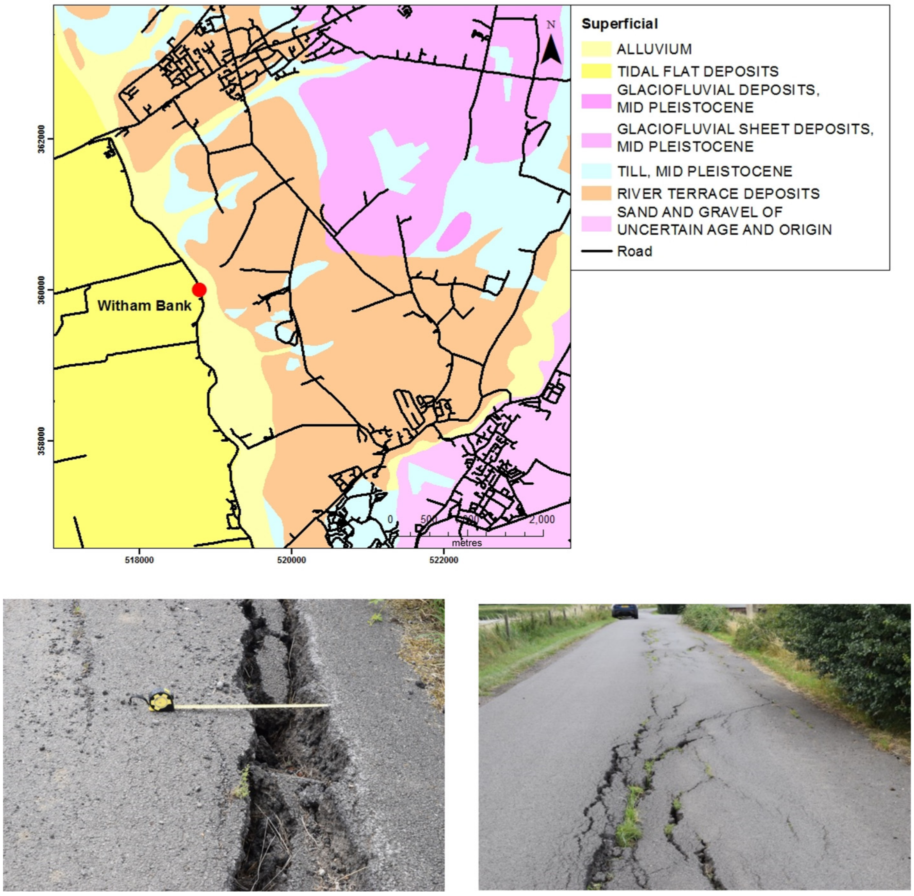


Fig. 13. Longitudinal cracking at Witham Bank. (Top) Superficial geological map. (Bottom left) Present-day photograph (June 2020). © Mark Heaton, Lincolnshire County Council. (Bottom right) Road surface damage, looking south (May 2018). BGS © UKRI 2018.

Fig. 14. Amber Hill. (Top) Superficial geological map. (Bottom) Photograph taken in May 2018 showing longitudinal cracking along the centre of the road. BGS © UKRI 2018.

Deflectogram data for 3 years, which includes a period of drought conditions (2010–2012), were analysed against BGS datasets. The data do not correspond with the case study sites due to the deflectogram surveys being limited to the county's principal and strategic road network. The decrease in RL value was calculated to provide a measure of road deterioration. BGS GeoSure compressibility and clay shrink–swell datasets were used to compare susceptibility to ground movement of the underlying geology with road deterioration (GeoSure compressibility is shown in Fig. 15) to assess whether it is related to the underlying geological units and/or transitions between units with different lithological characteristics.

Table 3 provides an explanation of the GeoSure compressibility and clay shrink–swell values. Table 4 compares the relationship of average annual deterioration with the shrink–swell and compressibility GeoSure ratings of the underlying geological units. This comparison demonstrates a strong inverse relationship between RL and the GeoSure compressibility rating (Fig. 16). Roads within areas where the compressibility of the underlying strata is classed as high or very high (D and E) experience much more rapid deterioration rate in RL than those with lower compression susceptibility. Roads within areas where the compressibility of the underlying strata is classed as high or very high (D and E) experience much more rapid deterioration, and therefore decrease in RL, than those in areas with lower compression susceptibility.

In contrast, there is a weak relationship with GeoSure clay shrink–swell values, with the average deterioration rate remaining relatively static for all clay shrink–swell values, with the average RL deterioration rate for A and D being very similar (1.10 and 1.15 years per year). This suggests that clay shrink–swell is not the primary driving factor for carriageway deterioration on principle roads in Lincolnshire, and other intersecting processes are more influential.

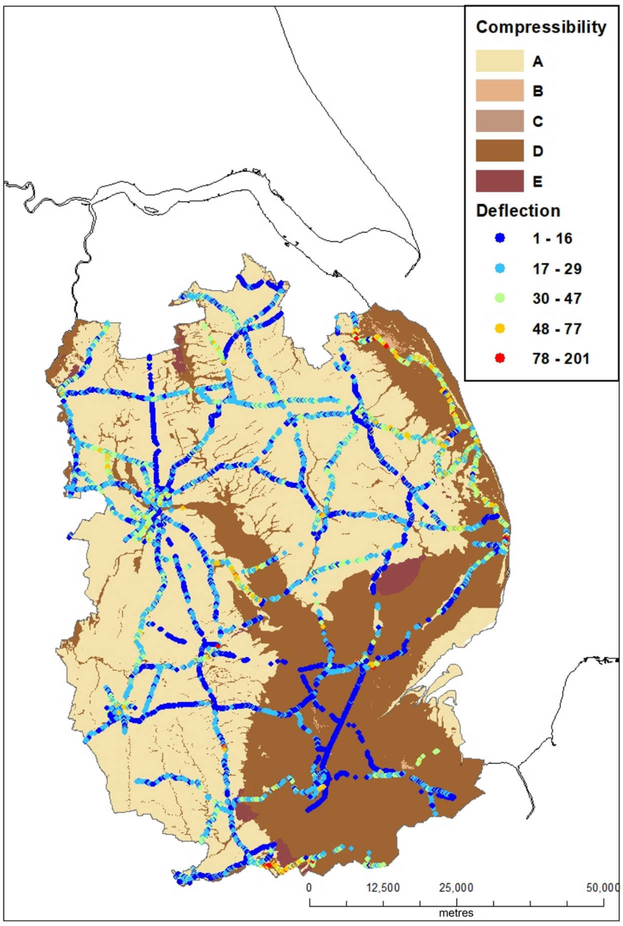


Fig. 15. Lincolnshire County Council deflectogram survey residual life (RL) data for 2010–2013 and the BGS GeoSure compressibility susceptibility map. © Lincolnshire County Council. Contains Ordnance Survey data © Crown copyright and database right [2022].

When analysing these datasets further and removing all A roads, a much faster road deterioration, and therefore decrease in RL, is shown on roads underlain by geology with a very significant compressibility GeoSure rating (E), increasing from a deterioration rate of just 3 years to 17 years annually. Areas with compressibility GeoSure rating D, also see a large increase in deterioration; from 1.1 years per year including A roads to 3.2 years per years without. Similarly, removing the A roads in the analysis of areas with higher clay shrink–swell susceptibility also leads to an increase in deterioration of the roads. This demonstrates that when A roads are removed, the rate of road deterioration increases in areas of high susceptibility to ground movement, indicating that engineered A roads, with deeper foundations, are more robust and less influenced by natural ground conditions.

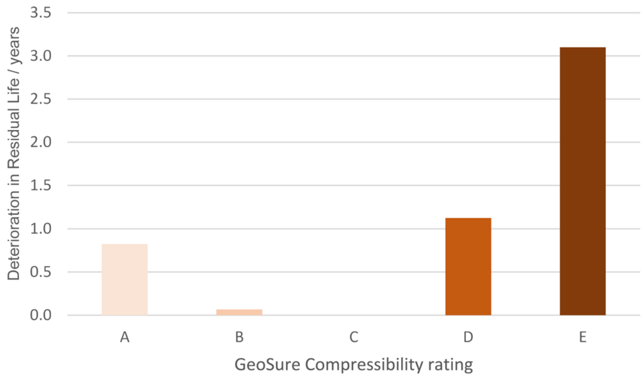


Fig. 16. GeoSure compression values against the residual life (RL) deterioration rates (all roads).

BGS GeoSure and Coarse Visualization Inspections

Lincolnshire County Council also carry out Coarse Visualization Inspections (CVIs) of their unclassified road network; generally, the roads that have much shallower foundations. The CVI is carried out on a slow-moving vehicle, or by foot, by a trained surveyor, who records cracking, rutting and defects in the road surface. This provides information on the structural condition of the road, in the form of the Structural Condition Index (CI), which is expressed as a value between 0 and 93, with 0 being very good condition and 93 being very poor condition. Table 5 and Figure 17 show a direct relationship between higher CI values (worse structural condition) and the compressibility of the underlying geology. Although there are no data for roads on geology with a GeoSure compressibility

Table 3. *GeoSure compressibility and clay shrink–swell hazard ratings*

Hazard rating value	Compressibility hazard rating text	Clay shrink–swell hazard rating text
A	No indicators for compressible deposits identified	Ground conditions predominantly non-plastic
B	Very slight potential for compressible deposits to be present	Ground conditions predominantly low plasticity
C	Slight possibility of compressibility problems	Ground conditions predominantly medium plasticity
D	Significant potential for compressibility problems	Ground conditions predominantly high plasticity
E	Very significant potential for compressibility problems	Ground conditions predominantly very high plasticity

Table 4. *Annual deterioration in the residual life (RL) of all Lincolnshire roads*

		GeoSure compressibility rating					
		A	B	C	D	E	Average deterioration
GeoSure shrink–swell rating	A	0.8	0.2		0.3	3.1	1.10
	B	1.1	0		0.6		0.57
	C	0.9	0		1.8		0.90
	D	0.5			1.8		1.15
	E						
	Average deterioration	0.83	0.07		1.13	3.10	

Grey shading indicates that there is no road network on this geohazard rating in Lincolnshire.

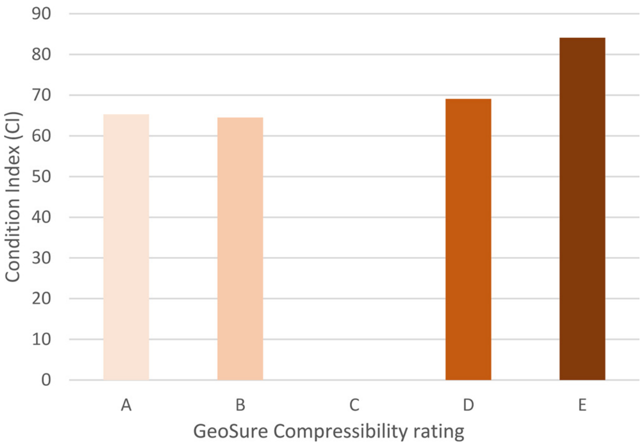


Fig. 17. Average Condition Index (CI) between 2010 and 2013 of all surveyed Lincolnshire roads in areas with a GeoSure compressibility rating of A–E.

value of C, the higher CI values with worse structural condition are in areas with very high susceptibility to ground movement due to compression.

BGS GeoSure and Lincolnshire County Council drought-damage data

In 2003, when the UK experienced one of its hottest summers on record, Lincolnshire reported a greater deterioration in the condition of its highways than in previous, non-drought, years. Since 2003, all 10 years recording the highest annual temperature since 1884, when records began, have occurred (Met Office 2022*c*). In 2011, the dry period led to Lincolnshire making a bid to central government for road repairs related to what was assumed to be drought-related subsidence. The roads affected, mostly unclassified and C roads, are shown in red in Figures 18 and 19. Most of the damaged roads are underlain by superficial deposits, primarily high water content, compressible tidal flat deposits (represented by alluvium in the 625 k scale geological map) and peat. The four case study site locations are highlighted for context.

A comparison of Lincolnshire County Council drought-damage data and BGS GeoSure clay shrink–swell compression datasets (Fig. 19) showed that clay shrink–swell was not the county's only likely cause of road damage, and that compressible ground had a greater correlation with road damage than was originally considered (Pritchard *et al.* 2015).

BGS GeoClimate and road-damage projections

The GeoClimate datasets are national datasets showing potential changes in clay shrink–swell subsidence susceptibility due to changes in climate (Harrison *et al.* 2019, 2020). They have been developed by considering climate projections and the associated changes in SMD, alongside hydrogeological modelling and the

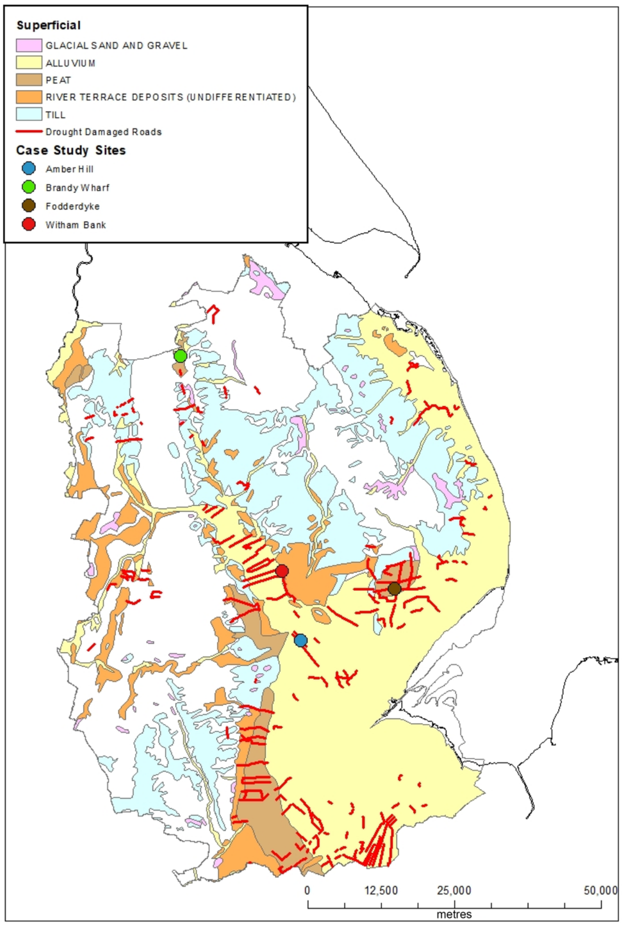


Fig. 18. Drought-related subsidence claims in Lincolnshire 2011 and the BGS 625 k scale superficial geological map. © Lincolnshire County Council. The four case study sites are highlighted by the coloured dots. NB The 625 k scale generalized superficial geological map compiles alluvium and tidal flat deposits as alluvium. Contains Ordnance Survey data © Crown copyright and database right [2022].

geotechnical properties of the ground (Tables 6 and 7) to provide long-term, modelled analysis for resilience assessments. They provide information on the potential for clay shrink–swell to occur at a given location during a given future time period. GeoClimate projections for clay shrink–swell susceptibility for Lincolnshire for the coming century are shown in Figure 20.

The GeoClimate projections shown in Figure 20 (Harrison *et al.* 2019) are partially driven by the Met Office UKCP09 climate projections (Murphy *et al.* 2009). The SMD increases that are projected for the county are reflected in the values calculated for each case study site (Table 8). These are based on the UKCP18 Met Office climate projections (Murphy *et al.* 2018) modelled using the UK national-scale recharge model (Mansour *et al.* 2018). The SMDs at each site increase from modelled historical values (1979–

Table 5. *Structural CI and GeoSure compressibility values*

	2010		2011		2012		2013		All years
GeoSure compression	No. of roads	Average CI	No. of roads	Average CI	No. of roads	Average CI	No. of roads	Average CI	Overall average
A	9216	60.4	9479	63.2	9717	68.7	9212	68.9	65.3
B	36	66.3	324	64.4	53	63.5	14	64.7	64.5
C									
D	6860	61.6	11 199	66.4	9920	74.8	8062	72	69.1
E	261	79			1102	85.4			84.1

Grey shading: no data available as no roads on applicable GeoSure compression values surveyed during that year.

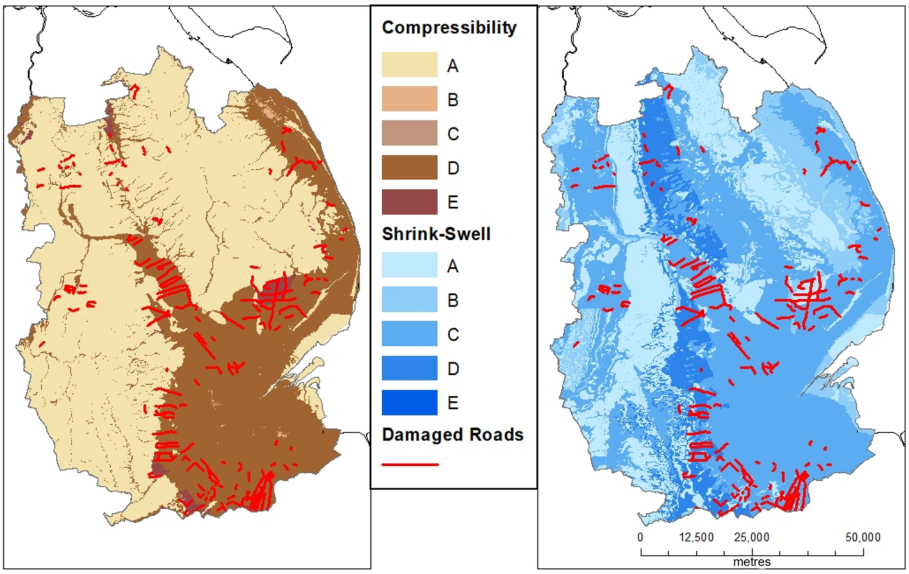


Fig. 19. GeoSure compression and clay shrink–swell with sites recorded (red lines) by Lincolnshire County Council as requiring remedial work due to drought damage during 2011–2012. © Lincolnshire County Council. Contains Ordnance Survey data © Crown copyright and database right [2022].

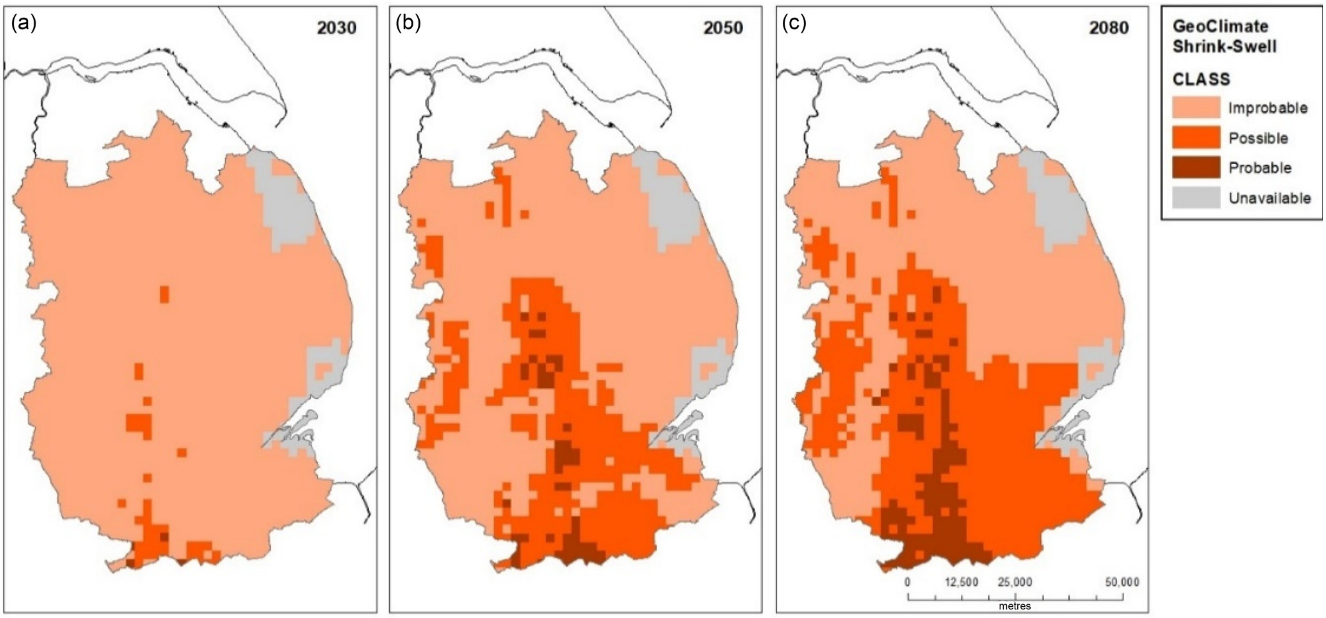


Fig. 20. GeoClimate09 Open for Lincolnshire: (**a**) 2030s (**b**) 2050s and (**c**) 3080s. Contains Ordnance Survey data © Crown copyright and database right [2022].

Table 6. *GeoClimate Open colours, classes and susceptibility text*

Class	Associated susceptibility text (legend text)
Improbable	It is ‘improbable’ that climate change will affect clay shrink–swell susceptibility and change the likelihood of ground movement, which causes subsidence
Possible	It is ‘possible’ that climate change will affect clay shrink–swell susceptibility and change the likelihood of ground movement, which causes subsidence
Probable	It is ‘probable’ that climate change will affect clay shrink–swell susceptibility and change the likelihood of ground movement, which causes subsidence

2000) and are projected for 2060–2080. These indicate an increased likelihood of drier ground conditions at the case study sites and in Lincolnshire in the coming century. The natural change in water content, due to changes in climate over the coming century, will impact shrinkable and compressible deposits across the country, and cause changes in volume over the short, medium and long term. Compressible ground will also be affected due to loading and anthropogenic practices such as surface water management.

Amendments in road repair and maintenance practices

Based on an increased knowledge of variability in geological hazard susceptibility across the county, Lincolnshire County Council has developed new road repair and maintenance practices, founded on recycling and reinforcement techniques. The new regime is not only more cost-effective but the authority has found that it also further extends the road’s life in comparison to

Table 7. *GeoClimate Open susceptibility matrix highlighting dependence on days in drought and GeoSure classification*

	Score	GeoSure class value				
		A	B	C	D	E
Days in drought	1	Change in susceptibility improbable	Change in susceptibility improbable	Change in susceptibility improbable	Change in susceptibility improbable	Change in susceptibility improbable
	2	Change in susceptibility improbable	Change in susceptibility improbable	Change in susceptibility improbable	Change in susceptibility improbable	Change in susceptibility improbable
	3	Change in susceptibility improbable	Change in susceptibility improbable	Change in susceptibility improbable	Change in susceptibility possible	Change in susceptibility possible
	4	Change in susceptibility improbable	Change in susceptibility improbable	Change in susceptibility possible	Change in susceptibility probable	Change in susceptibility probable
	5	Change in susceptibility improbable	Change in susceptibility possible	Change in susceptibility possible	Change in susceptibility probable	Change in susceptibility probable

Days in drought is calculated based on the number of days projected above a soil moisture deficit (SMD) threshold, where 1 is the lowest number (wetter) and 5 is the highest (drier). The colours represent the likelihood that vulnerable foundation types will be affected by increased clay-induced subsidence due to climate change where: light orange denotes improbable, mid-orange denotes possible and brown denotes probable.

Table 8. *Average projected soil moisture deficit (SMD) for each case study site (from data in Mansour et al. 2018)*

	Average projected SMD values (mm/day)			
Time period	Fodderdyke	Brandy Wharf	Witham Bank	Amber Hill
1979–2000	121	26	103	143
2020–2040	142	27	112	119
2060–2080	162	30	120	175

previous practices and reduces the carbon footprint of the work. The practices included '*in situ* (re-tread)', recycling the existing road top surface, and reinforcement of the road surface with wire mesh, dependent on the road conditions and underlying geology. Lincolnshire County Council is increasingly focusing on lower carbon solutions. This research has driven how maintenance techniques are now being considered, taking into account carbon reduction.

Following extensive investigation and review of previous trials undertaken by Lincolnshire County Council, the recommendation for repair work at Fodderdyke (Case Study Site 1) was:

(a) to pulverize the existing road to a depth of *c*. 250 mm;
(b) shape and compact the pulverized material to make a new and increased thickness sub-base;
(c) lay 60 mm of AC20 binder course material (asphaltic concrete with a maximum aggregate size of 20 mm),
(d) lay and pin a steel reinforcing grid over the whole width, including overlaps at the joints;
(e) lay 60 mm of AC20 binder course material; ans
(f) lay 40 mm of 40 mm surface course.

Remedial work at Fodderdyke was carried out during 2018 (Figs 21–23), reflecting the knowledge of the underlying road conditions, their geotechnical properties and the impact of projected climate scenarios on susceptibility to movement in the future. Recognizing the addition of added weight would cause more compression, the existing road surface was recycled. A mesh was included, covering the width of the road, enabling it to move as a single entity and thus experience less differential movement, resulting in less surface cracking. Although this initial repair work was costlier and took longer than the traditional patching, this informed decision-making was targeted and defendable. It alleviates the requirement of abundant future repair work and associated road closures with their resultant economic costs, demonstrating improvements both financially for the authority

Fig. 21. Shaping and compaction of the pulverized existing road surface at Fodderdyke Bank (March 2018). © Mark Heaton, Lincolnshire County Council.

Fig. 22. Station Road (western end of Fodderdyke), Eastville, underlain by tidal flat deposits (May 2018). BGS © UKRI 2018.

and for the local community. The authority has shared an online overview of the work carried out at Fodderdyke (LincolnshireCC 2018).

Benefits of this type of construction have been the non-removal of tar-bound material off site, which can be classed as a hazardous material with high disposal costs, and the associated carbon savings. Keeping this material onsite has helped to regulate and reshape these deformed roads. The use of the steel mesh ensures that the road ‘holds together’, preventing failures beneath the road surface potentially causing major collapse overnight.

Reshaping keeps material onsite and has been efficient in terms of reconstruction speed, and, hence, opening roads quicker, which is especially important in rural fenland areas where diversion routes can be many miles. Although the technique has proven successful, it is expensive and can prove problematic when future resurfacing is required or if a utility company wishes to undertake works on this road network.

Looking to the future, work and research is being undertaken on this type of treatment and how the authority can continue to maintain its highway network. In terms of new techniques, the authority is developing and working with industry and academia, examining climate change and carbon calculations for the designs of schemes. Where possible, the authority is using thinner materials, with similar strength characteristics and flexibility. New proposals and trials are being constantly considered to overcome the cost and carbon issues that the industry is seeing, whilst simultaneously ensuring they are informed and prepared for any future changes in legislation.

Fig. 23. Fodderdyke (eastern end of Fodderdyke) following resurfacing using the new recycling method (May 2018). BGS © UKRI 2018.

Conclusions

Lincolnshire roads in the south of the county have a high susceptibility to ground movement due to the underlying geology, accentuated by additional causal factors, to varying degrees, including the presence of vegetation, road maintenance regimes and drainage practices. The superficial peat, tidal flat deposits and alluvium all have a high susceptibility to compression when loaded or due to loss of water content because of drought or ground water lowering through managed drainage and irrigation. The shallow foundations of the county’s evolved road network increases its vulnerability to these fluctuations, meaning that ground movement often causes road damage. This includes longitudinal cracking and edge failure, and uneven long-section profiles due to localized failures. Knowledge exchange and data sharing between Lincolnshire County Council and the BGS has enabled the direct relationship between unclassified/evolved road residual life (RL) and structural condition, as well as the compressibility of the underlying geological formations, to be demonstrated.

Historically, repair work by the authority has included sprays and overlays, adding a new road surface on top of the existing one, adding weight and compounding the issue, and causing further damage in future years. Additional anthropogenic pressures on the network include increased road traffic (Lincs Laboratory pers. comm. 16 March 2023), including heavier farm vehicles and lorries transporting goods, and decreases in water levels in the dykes managed by the Internal Drainage Board (IDB). The modifications in water management are necessitated by irrigation of crops due to changes in climate. Hotter drier summers, and warmer wetter winters, lead to naturally higher annual SMDs than the road network has experienced. These are projected to increase into the future, leading to the need to either prevent or mitigate against the consequences. This will involve collaboration between geotechnical asset managers and engineering geologists to make informed decisions about maintenance and repair based on an understanding of geological properties and processes, and how these may change in future.

This paper has presented examples of changes in maintenance and repair work instigated by Lincolnshire County Council as an example of the successful application of this new regime. It has also assisted the local highway authority in starting to reduce its carbon footprint with the utilization of recycling techniques (reduction of materials to landfill) and the limited usage of virgin materials, together with thinner layers of materials.

The limited budgets for highway maintenance are well documented by local authorities, and the entire spectrum of uncertainties of new Parliamentary Acts and the consequences of implementing such Acts have not been fully researched. This collaborative research undertaken by the BGS and Lincolnshire County Council demonstrates that further work on climate change and highway construction needs to continue to ensure the longevity of this vital UK asset. Future monitoring, such as remote sensing and regular condition surveys, would demonstrate the precise efficacy of new repair techniques, and the resilience of the network to climate change.

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Data availability The data that support the findings of this study are available from British Geological Survey and Lincolnshire County Council but restrictions apply to the availability of these data, which were used under licence for the current study and so are not publicly available. Data are, however, available from the authors upon reasonable request and with permission of British Geological Survey and Lincolnshire County Council.

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