



**Soil geohazard
mapping for
improved asset
management of UK
local roads**

O. G. Pritchard et al.

This discussion paper is/has been under review for the journal Natural Hazards and Earth System Sciences (NHESS). Please refer to the corresponding final paper in NHESS if available.

Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard, S. H. Hallett, and T. S. Farewell

School of Energy, Environment and Agrifood, Cranfield University, Cranfield, UK

Received: 2 April 2015 – Accepted: 13 April 2015 – Published: 8 May 2015

Correspondence to: S. H. Hallett (s.hallett@cranfield.ac.uk)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

Unclassified roads comprise 60 % of the road network in the United Kingdom (UK). The resilience of this locally important network is declining. It is considered by the Institution of Civil Engineers to be “at risk” and is ranked 26th in the world. Many factors contribute to the degradation and ultimate failure of particular road sections. However, several UK local authorities have identified that in drought conditions, road sections founded upon shrink/swell susceptible clay soils undergo significant deterioration compared with sections on non-susceptible soils. This arises from the local road network having little, if any structural foundations. Consequently, droughts in East Anglia have resulted in millions of pounds of damage, leading authorities to seek emergency governmental funding.

This paper assesses the use of soil-related geohazard assessments in providing soil-informed maintenance strategies for the asset management of the locally important road network of the UK. A case study draws upon the UK administrative county of Lincolnshire, where road assessment data have been analysed against mapped clay-subsidence risk. This reveals a statistically significant relationship between road condition and susceptible clay soils. Furthermore, incorporation of UKCP09 future climate projections within the geohazard models has highlighted roads likely to be at future risk of clay-related subsidence.

1 Introduction

UK minor, or non-strategic, roads which are owned and managed by local authorities represent 98 % of the overall network (Defra, 2013). As a subclass, the unclassified road network represents 60 % of this minor network (DfT, 2011) supporting local communities, society and the wider economy.

The Institution of Civil Engineers (ICE, 2014) regards one-third of the UK’s road network as being in urgent need of maintenance, stating that immediate action

NHESSD

3, 3151–3180, 2015

Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Soil geohazard
mapping for
improved asset
management of UK
local roads**

O. G. Pritchard et al.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	

required to improve road conditions is its top priority. A number of factors can lead to road deterioration, including (but not restricted to): traffic volume, road works, poor construction or reinstatement after repair of buried infrastructure, cold weather, tarmacadam oxidation and underlying ground conditions. Several authorities have argued that during drought conditions, changing moisture contents in underlying soils, in particular those clay soils prone to volumetric shrinking and swelling, have resulted in considerable structural damage to their highway networks (Table 1). Highways assets themselves exacerbate developing drought conditions by prohibiting the permeation of water into the underlying soils (Harrison et al., 2012).

A number of drivers of soil-related ground movement impact on UK highway networks, including: clay shrinkage and swelling; sand-washout; compression of soft soils; and peat shrinkage (Pritchard et al., 2014). The county of Lincolnshire reported the largest impact of drought conditions on its highways in 2003 (Table 1), indicating that it is particularly prone to ground movement due to the county’s abundance of shrink-swell susceptible clays soils. As clay-related shrink-swell is the dominant form of ground movement in the UK, this paper examines the impact of clay-related shrink-swell on road infrastructure.

Soil surveys, which classify the uppermost layer (0 to ca. 1.2 m) of the earth’s surface, provide an understanding of soil properties and their spatial distribution. However, despite the intimate link between the soil and the infrastructure it supports, the application of soil surveys in highways asset management has seldom been undertaken within the UK. Elsewhere, this is not the case, examples including: USA (Bauer, 1973; Santi and Martens, 2003; Allemeier, 1974; Lee and Griffiths, 1987; Beatty and Bouma, 1973), Netherlands (Westerveld and Van Den Hurk, 1973) and Australia (Murtha and Reid, 1976; Biggs and Mahony, 2004). Whereas it is recognised that soil surveys have an established role (Hartnup and Jarvis, 1979), the UK still tends to look only to deeper geological maps for indications of surface movements.

Highways engineers and asset managers often have a civil engineering background, and many possess only general knowledge of earth sciences, geology and geotechnics.



Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Clear spatial information which describes the risk of hazardous ground conditions, without the need for geological interpretation, is therefore potentially of great benefit to practicing engineers (Royse, 2011). Thematic soil-related geohazard maps, derived through reinterpretation of traditional soil maps and fusion with meteorological data, can provide decision makers with a clear view of the potential hazards affecting their assets.

This paper aims to demonstrate how soil-related geohazard assessments can serve within a decision support tool in the asset management of local highways. Many tangible associations have been posited with regard to the impact of geology/soils on road condition (Willway et al., 2008), especially in light of climatic change. However, quantitative analyses are currently lacking, providing this study with its novel approach.

To achieve this aim, empirical road condition data provided by Lincolnshire County Council (LCC) has been intersected spatially with an existing soil-related geohazard model to understand the statistical and spatial relationship between the two datasets. Furthermore, we investigate the use of UKCP09 climate projections to understand future clay-related subsidence risk in Lincolnshire. Subsequently, suggestions and recommendations resulting from the use of this approach for planned operational maintenance in Lincolnshire is described. Finally, we consider how this can form a framework for other local authorities to follow, both in the UK and internationally.

2 Lincolnshire study area

2.1 Climatic, topographical and geological 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 of the county (Fig. 1). As a result of its flat, fertile lands, a large area of the county is devoted to high intensity agriculture. The county's relief is predominantly low-lying (0–50 m a.s.l.) excepting the Lincolnshire Wolds in the central-northern area of the county; a chalk outcrop, where heights range between 50 and 200 m a.s.l.

Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	

This area of Eastern England has a relatively mild, temperate climate. Annual rainfall is relatively low, for example in Lincoln it is 577 mm. Consequently, it is one of the driest areas in the country (Hough and Jones, 1997). This low rainfall, coupled with high evapotranspiration rates, contribute to some of the highest soil moisture deficits (driest soils) in the UK in an average year (Hodge et al., 1984; Robson, 1990).

The superficial geology and subsequently the soil parent material of Lincolnshire is predominantly derived from Pleistocene and more recent deposits (Hodge et al., 1984). The influence of previous glaciations and regressions and transgressions of the North Sea around the Wash have led to extensive deposits of silts, clays and the formation of peat material (Chatwin, 1961). Marine and riverine alluvium, and glacial till represent a large proportion of the deposits, with glaciofluvial deposits dominating the Lincolnshire Wolds. As a result, Lincolnshire contains a broad range of soil types, encompassing 73 soil associations (Cranfield University, 2015). Further details of soil types and their distribution in Lincolnshire can be found in Hodge et al. (1984).

Industrial drainage in the fenlands of Lincolnshire since the 1600's have caused such extensive peat wastage that previously underlying clays and silts are now exposed at the ground surface. Substantial thicknesses of peat are therefore now confined to the edge of the fens or to areas remaining undrained (Hodge et al., 1984). In 1985 it was recorded that only 16 % (240 km²) of the pre-drained peatland remained (Burton and Hodgson, 1987). The presence of large areas of predominantly clay soils and their susceptibility to volumetric shrinkage, combined with high soil moisture deficits, means that Lincolnshire is particularly affected by clay-related subsidence.

2.2 Unclassified road distribution

This paper considers the unclassified road network of Lincolnshire (Fig. 1), representing 66 % of the county's highways (Table 2). 85 % of Lincolnshire's unclassified roads being in rural areas. Unclassified roads are defined by the Department for Transport (DfT) as *local roads intended for local traffic* (DfT, 2012).



The majority of unclassified highways in Lincolnshire, as with many other UK counties, are deemed to be *evolved*. Evolved roads have not been designed to modern engineering standards and have instead evolved from historic or even ancient roads, even dating in some specific instances to the Roman and Bronze Age eras (Astbury, 1958).

A Coarse Visual Inspection (CVI) is a nationally defined standard of assessing road defects and is principally used on the UK's minor road networks. Further technical information regarding this survey can be found in Wallis (2009). CVI surveys revealed that Lincolnshire's unclassified road network has been subjected to severe drought-related subsidence, particularly during 2003 (Table 1) (M. Coates, personal communication, 2015). Moreover, during the 2010–2011 period, approximately 154 road sections were highlighted by the CVI survey as having been damaged as a direct result of drought conditions realising the shrinkage potential of clay rich soils (Fig. 2). These two event years led Lincolnshire County Council (LCC) to place a bid to central government for additional emergency road funding.

LCC highlight several safety hazards arising from soil-related drought damaged roads, which are often unclassified, and have speed limits of up to 60 mph (miles per hour). Specific risks include:

- increased deterioration of the longitudinal profile of roads, requiring drivers to reduce speeds below those that would normally be appropriate for the width and alignment of the road;
- severe localised transverse depressions, which require drivers to slow to speeds below 20 mph;
- longitudinal differential settlement and cracking, requiring supplementary road signs to warn drivers and allow roads to remain open;
- defects which are not easily seen at night or in adverse weather conditions, increasing risk to motorists.

Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3 Data

3.1 Natural Perils Directory (NPD)

The Natural Perils Directory™ (NPD) geohazards thematic dataset, developed and maintained by staff at Cranfield University, provides a detailed and comprehensive assessment of the environmental vulnerabilities to building structures and infrastructure posed by soil-related geohazards (Jones et al., 1995; Hallett et al., 1994). NPD represents a thematic reinterpretation of the national soil map (NATMAP) which shows the spatial distribution of all ~ 700 soil series in England and Wales (Cranfield University, 2015). This soil data, alongside climatic data and expert knowledge are encompassed within a “Land Information System” (LandIS) (Keay et al., 2009). LandIS is regarded as the principle source of soil information for England and Wales by Defra (Department for Environment, Food and Rural Affairs).

A core component of the NPD is the clay-related subsidence model, or the underground foundation stability (UFS) model. Based upon a pedo-climatic approach, UFS assesses the likelihood of a soil to undergo shrink-swell and subsequently, whether a potential soil moisture deficit (PSMD) is present for shrink-swell potential to be realised. Once classified, a 9 point vulnerability class, ranging from *Extremely High* to *Extremely Low* is assigned. The NPD model output is expressed in GIS (Geographical Information System) format on a vector polygon basis across England, Wales and Scotland (Scottish soils data provided by the James Hutton Institute). This makes it suitable for easy integration with other geospatial data (e.g. infrastructure networks). It is predominantly used by the insurance, reinsurance and water sector. However, its use in highways asset management has not been explored until now.

3.2 Highway condition data

CVI assessment data for ~ 4400 km (75%) of unclassified roads, collected between 2007 and 2014, was supplied in a GIS vector-polygon format by Lincolnshire County

NHESSD

3, 3151–3180, 2015

Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Council’s highways department (M. Coates, personal communication, 2015). Data were supplied for 4 survey periods, 2007–2011, 2011–2012, 2012–2013 and 2013–2014. CVI is expressed as a series of indices, including assessments for wearing course, edge effects and structural condition. Following discussion with LCC, it was identified that the “structural condition index” provided the most suitable index in understanding the effects of soil on the network, also incorporating edge defects. Conversely, wearing course degradation is a factor of traffic use, direct climatic effects and road surfacing techniques and so therefore soils do not exert a direct effect.

Each structural condition index GIS vector polygon represented a 50 m rolling average survey area, where increasingly higher values indicated a worsening structural condition of the highway (P. Shevill, personal communication, 2015); values ranged between 0 and 93. Generally, a value of < 40 represents a road in a good state of repair, whereas values > 40 require further investigation and likely treatment options.

3.3 UKCP09 future climate projections

UKCP09 climate projections (Jenkins et al., 2009) indicate that the UK is likely to experience hotter, drier summers and warmer wetter winters, especially in the south-east and east Anglian region of England, for the forthcoming century. Such weather patterns will exacerbate clay-related subsidence.

The long lifespan of road infrastructure in the UK leads to particular susceptibility to hazards under future climates (Willway et al., 2008). Research undertaken by the authors as part of the Infrastructure Transitions Research Consortium (www.itrc.org.uk) project has involved the modelling of probabilistic potential soil moisture deficit (PSMD) for the future scenarios of 2030 (2020–2049) and 2050 (2040–2069). Model parameters, daily rainfall and potential evapotranspiration (Eq. 1) were derived from a spatially coherent, 5 km² resolution gridded output from the UKCP09 weather generator (Burton et al., 2013; Jenkins et al., 2014).

$$\text{PSMD} = \sum (\text{rainfall} - \text{potential evapotranspiration}) \quad (1)$$

5 Results

5.1 Current risk

Our results suggest that a spatial and statistical relationship exists between clay-related subsidence risk and CVI (structural index) value. The boxplots in Fig. 5 present the relationship between CVI over the survey periods of 2007–2011, 2011–2012, 2012–2013 and 2013–2014. Due to the extensive unclassified road network in Lincolnshire, a 4 year rolling CVI assessment program is used by the Council. Therefore, each survey year often represents different road sections to those assessed in the previous year.

Ideally analysis would have considered many years/decades. However, the use of GIS in Lincolnshire's highways asset management remains a relatively emergent technology. Prior to GIS techniques, CVI data recording was predominantly paper-based and is therefore difficult to investigate alongside other environmental data.

Overall, the CVI structural index for Lincolnshire's unclassified network shows significant deterioration between the years 2007 and 2014. This is especially so on soils with an *Extremely High to High* risk of clay-related subsidence, where consistently high CVI values (i.e. > 60) are observed; representing a significant deterioration of the structural road condition on these higher-risk soils: roads identified at current risk are provided in Fig. 7. Moreover, by 2012–2013 the CVI value on these soils has reached a critical point, whereby the roads are deemed to have failed structurally (i.e. CVI > 80), resulting in the enforcement of speed restrictions as a result.

CVI for roads on soils at a *Medium Low* risk for all survey periods showed a consistently high level of subsidence risk. However, this is only representative of a relatively low number of CVI points for each survey period (9, 10, 10 and 10, respectively) (Table 3). These values were therefore excluded from the analysis.

NHESSD

3, 3151–3180, 2015

Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



5.2 Future risk

The entire unclassified road network for Lincolnshire was intersected with future projections of clay subsidence risk for 2030 and 2050 (Fig. 3), using the 50th percentile or *central estimate*. From this, metrics were produced that identify lengths (kilometres) of road sections falling into each particular clay-related subsidence risk class. The resultant graph (Fig. 7) shows clear shifts of road sections into higher vulnerability classes from the baseline (1961–1990) through to 2050 (2040–2069). This is especially so for the *Extremely High* class where between the baseline (1961–1990) and 2050, there is a $\approx 300\%$ increase in the amount of road length on these soils. There is also a $\sim 1200\%$ shift from roads being at a *Medium* risk to those becoming at *Medium High* risk between baseline and 2030 and 2050 scenarios. However, *Medium High* risk soils do not appear to exert such structurally damaging effects on road condition as compared with the higher classes (Fig. 5).

6 Discussion and conclusions

The low traffic volumes on local road networks mean that the large capital investments required to adequately engineer all unclassified roads on highly shrinkable soils are an unaffordable solution in mitigating the impact of soil-related subsidence. Road deterioration is affected by a number of factors, however, this paper has shown quantitatively that clay-subsidence prone soils exert a profound structural impact upon road condition in the Lincolnshire study area. This has resulted in subsequent economic impacts, with calls made by the county for emergency funding from the DfT to clear the maintenance backlog.

ADEPT (2009) argue that climatic change may lead to wide-scale failure of the UK minor highways network. As this work shows, UKCP09 scenarios indicating hotter, drier summers and warmer, wetter winters through to 2080 (Jenkins et al., 2009) are likely to exacerbate clay-related subsidence risk (Harrison et al., 2012; Blenkinsop

Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



et al., 2010). Williams et al. (2012) argue that decisions around risk made by local authorities are predominantly a consequence of regulatory obligations. As a result, many studies have discussed the acute problem of flooding impact on highways, which causes widespread and economically significant damages (e.g. Bollinger et al., 2014).

5 However, little attention has been brought to the impact of more chronic, systemic and less visible geohazards such as clay-related subsidence to highway infrastructure. An analysis of the impacts of current and future geohazards to road infrastructures nationally will lead to a greater awareness amongst local authorities and policy-makers. It will also lead to a better understanding of the viable adaptation and mitigation options
10 which can be implemented to tackle the issue at hand (Williams et al., 2012) as well as informing the debate on infrastructure investment planning.

The construction of entirely new roads in the UK is rare. More commonly, existing networks are upgraded (Brown, 2013). Rawlins et al. (2013) state that with new developments, an awareness of the potential hazards and the influence of climate change should be incorporated into design principles. As a result, the findings of this
15 research can aid planning of new highways.

The All Party Parliamentary Group on Highway Maintenance recently called for the incorporation of highway asset management plans (HAMP) within local authorities highways departments to become mandatory (APPGHM, 2013). Moreover, recommendations exist to make funding streams from the Department for Transport
20 accessible only if HAMP's are in place. Therefore, specific risk information, in this case relating to the spatial distribution of hazardous soils, are vital in supporting these asset management plans. Within LCC, integration of clay-related subsidence assessment within the planning of highway maintenance has provided the basis for a decision-support tool for establishing which specific treatments highways engineers can use
25 to improve drought-damaged road sections. Whereas previously a blanket approach to resurfacing would have been applied to all affected sections, it is now recognised that unclassified road sections on drought susceptible soils are predominantly prone

**Soil geohazard
mapping for
improved asset
management of UK
local roads**

O. G. Pritchard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Soil geohazard
mapping for
improved asset
management of UK
local roads**

O. G. Pritchard et al.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	

or articulated delivery vehicles, can result in shear slippage, slope movement and subsequent highway failure (Hawkins, 2013; Loveridge et al., 2010). As a result of agricultural and drainage practices, much of the highway network in Lincolnshire is flanked by steep-sided drainage dikes, or has been left raised above the surrounding land due to peat shrinkage. Therefore, these steep sided embankments and the presence of shrink-swell soils can lead to specific localised slope failure (e.g. Fig. 8).

This paper has assessed the use of soil-related geohazard mapping in the asset management of minor highway networks within Lincolnshire. The risk-assessment framework (Fig. 4) presented has enabled LCC to prioritise its limited road maintenance capital on road sections at risk from drought-related clay subsidence. It has also acted as the basis for a decision-support tool, making highways engineers more conscious as to where hazardous soils present themselves spatially, highlighting the damaging effect that these can have upon the unclassified road network during drought conditions, as well as guidance as to which treatments prove economically and structurally viable.

The study also highlights the structurally damaging effects that are likely to occur on England’s unclassified road network under the UKCP09 climate projections, and on soils prone to clay-related subsidence, especially in the south-east of England. The incorporation of probabilistic subsidence projections provides a novel approach to evaluate the future risk of soils to highway networks. The standardised CVI method of road condition survey within the UK means that rapid soil-geohazard assessment could be readily applied to other administrative areas affected. Furthermore, with appropriate soils data (e.g. national soil survey maps) and empirically derived shrink/swell assessment, the methodology presented here could be used internationally. Further research is required to consider the potential impacts of other infrastructures (e.g. utility trenches and water mains failures) on the road network, and what impact these have upon the soil structure on which these roads are founded.

Acknowledgements. The research reported in this paper was part of the UK Infrastructure Transitions Research Consortium (ITRC), funded by the Engineering and Physical Sciences Research Council under programme grant EP/I01344X/1. The authors are grateful to Mike



References

- 5 ADEPT (Association of Directors of Environment, Economy, Planning and Transport): Climate change and evolved pavements, available at: http://www.climatesoutheast.org.uk/images/uploads/Climate_Change_and_evolved_pavements.pdf last access: 5 February 2015, 2009.
- Allemeier, K.: Application of pedological surveys to highway engineering in Michigan, in: Non Agricultural Application of Soil Surveys: Developments in Soil Science 4, edited by: Simonson, R., Elsevier, Amsterdam, 87–98, 1974.
- 10 APPGHM (All Parliamentary Group on Highway Maintenance): Managing a valuable asset: improving local road condition, available at: http://www.highwaysmaintenance.org/images/library/files/APPG_Report_-_Managing_a_valuable_asset.pdf, last access: 14 December 2014, 2013.
- Astbury, A. K.: The Black Fens, The Golden Head Press Ltd., Cambridge, 1958.
- 15 Bauer, K. W.: The use of soils data in regional planning, *Geoderma*, 10, 1–26, 1973.
- Beatty, M. T. and Bouma, J.: Application of soil surveys to selection of sites for on-site disposal of liquid household wastes, *Geoderma*, 10, 113–122, 1973.
- Biggs, A. and Mahony, K.: Is soil science relevant to road infrastructure?, in: *Conserving Soil and Water for Society: Sharing Solutions*, Proc. 13th International Soil Conservation Organisation Conference, 4–9th July 2004, Brisbane, edited by: Raine, R. S., Biggs, A. J. W., Menzies, N. W., Freebairn, D. M., and Tolmie, P. E., ASSSI/IECA, Paper 410, 2004.
- 20 Blenkinsop, S., Hallett, S., Truckell, I., and Fowler, H.: The CREW project: Towards a toolkit for the use of probabilistic climate change projections, BHS Third International Symposium, 19–23 July, Newcastle, Role of Hydrology in Managing Consequences of a Changing Global Environment, 2010.
- 25 Bollinger, L. A., Bogmans, C. W. J., Chappin, E. J. L., Dijkema, G. P. J., Huibretgse, J. N., Maas, N., Schenk, T., Snelder, M., van Thienen, P., de Wit, S., Wols, B., and Tavasszy, L. A.: Climate adaptation of interconnected infrastructures: a framework for supporting governance, *Reg. Environ. Change*, 14, 919–931, 2014.

Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Brown, S. F.: An introduction to asphalt pavement design in the UK, *Proc. Inst. Civ. Eng. Transp.*, 166, 1–14, doi:10.1680/tran.11.00076, 2012.
- Burton, A., Glenis, V., Jones, M. R., and Kilsby, C. G.: Models of daily rainfall cross-correlation for the United Kingdom, *Environ. Modell. Softw.*, 49, 22–33, doi:10.1016/j.envsoft.2013.06.001, 2013
- Burton, R. and Hodgson, J.: *Lowland Peat in England and Wales*, Soil Survey of England and Wales, Harpenden, 1987.
- Cranfield University: National Digital Soil Map 1 : 250 000 scale (NATMAP), NATMAPvector, available at: <http://www.landis.org.uk/data/natmap.cfm> (last access: 3 March 2015), 2015.
- Defra (Department for the Environment, Food and Rural Affairs): The National Adaptation Programme: Making the country resilient to a changing climate, The Stationery Office, London, available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/209866/pb13942-nap-20130701.pdf, last access: 23 November 2014, 2013.
- DfT (Department for Transport): Road Network Policy Consultation, London, available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/2439/roadnetworkconsultation.pdf, last access: 7 December 2014, 2011.
- DfT (Department for Transport): Guidance on Road Classification and the Primary Route Network, London, available at: <http://www.thensg.org.uk/documents/GuidanceonRoadClassificationandPrimaryRouteNetwork.pdf>, last access: 7 December 2014, 2012.
- Fedeski, M. and Gwilliam, J.: Urban sustainability in the presence of flood and geological hazards: the development of a GIS-based vulnerability and risk assessment methodology, *Landscape Urban Plan*, 83, 50–61, doi:10.1016/j.landurbplan.2007.05.012, 2007.
- Hallett, S. H., Keay, C., Jarvis, M., and Jones, R. J. A.: INSURE: subsidence risk assessment from soil and climate data, in: Proceedings of the Association for Geographic Information (AGI) National Conference: Markets for Geographic Information, 15–17 November, Birmingham, Association for Geographic Information, 16.2.1–16.2.7, 1994.
- Harrison, A. M., Plim, J. F. M., Harrison, M., Jones, L. D., and Culshaw, M. G.: The relationship between shrink–swell occurrence and climate in south-east England, *Proc. Geol. Assoc.*, 123, 556–575, doi:10.1016/j.pgeola.2012.05.002, 2012.
- Hartnup, R. and Jarvis, M.: Soils in civil engineering and planning, in: *Soil Survey Applications*, edited by: Jarvis, M. and Mackney, D., Soil Survey: Technical Monograph No. 13, Harpenden, 110–134, 1979.

Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Hawkins, A.: Some engineering geological effects of drought: examples from the UK, *Bull. Eng. Geol. Environ.*, 72, 37–59, doi:10.1007/s10064-013-0458-7, 2013.
- Heaton, M.: Case Studies: Carriageway Retread in Lincolnshire 2013–14, *Asphalt Professional*, available at: <http://www.instituteofasphalt.org/index.php?id=asprooverview> (last access: 31 November 2014), 2014.
- Hodge, C. A. H., Burton, R. G. O., Corbett, W. M., Evans, R., and Seale, R. S.: Soils and Their Use in Eastern England, *Soil Survey of England and Wales*, Harpenden, 1984.
- Hough, M. N. and Jones, R. J. A.: The United Kingdom Meteorological Office rainfall and evaporation calculation system: MORECS version 2.0-an overview, *Hydrol. Earth Syst. Sci.*, 1, 227–239, doi:10.5194/hess-1-227-1997, 1997.
- ICE (Institution of Civil Engineers): The State of the Nation: Infrastructure 2014, London, available at: <http://www.ice.org.uk/Information-resources/Document-Library/State-of-the-Nation--Infrastructure-2014>, last access: 29 April 2015, 2014.
- Jenkins, G., Murphy, J., Sexton, D., Lowe, J., Jones, P., and Kilsby, C.: UK Climate Projections: Briefing Report, Met Office, Exeter, available at: <http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87867&filetype=pdf>, last access: 29 April 2015, 2009.
- Jenkins, K., Hall, J., Glenis, V., Kilsby, C., McCarthy, M., Goodess, C., Smith, D., Malleson, N., and Birkin, M.: Probabilistic spatial risk assessment of heat impacts and adaptations for London, *Clim. Change*, 124, 105–117, doi:10.1007/s10584-014-1105-4, 2014.
- Jones, R. J. A., Hallett, S., Gibbons, J., and Jarvis, M. G.: Subsidence risk – using a complex dataset to identify areas most at risk, in: *Proceedings of the Association for Geographic Information (AGI) National Conference: Insurance*, 21–23 November, Birmingham, Association for Geographic Information, 2.4.1–2.4.7, 1995.
- Keay, C. A., Hallett, S. H., Farewell, T. S., Rayner, A. P., and Jones, R. J. A.: Moving the National Soil Database for England and Wales (LandIS) towards INSPIRE Compliance, *International Journal of Spatial Data Infrastructures Research*, 4, 134–155, doi:10.2902/1725-0463.2009.04.art8, 2009.
- Lee, E. and Griffiths, J.: The importance of pedological soil survey in land use planning, resource assessment and site investigation, in: *Planning and Engineering Geology*, M. Culshaw, M., Bell, F. G., Cripps, J. C., and O'Hara, M., Geological Society of London, London, 453–465, 1987.

Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Loveridge, F. A., Spink, T. W., O'Brien, A. S., Briggs, K. M., and Butcher, D.: The impact of climate and climate change on infrastructure slopes, with particular reference to southern England, *Q. J. Eng. Geol. Hydrogeol.*, 43, 461–472, doi:10.1144/1470-9236/09-050, 2010.
- 5 Murtha, G. and Reid, R.: Soils of the Townsville area in relation to urban development, CSIRO Australia, Division of soils, Divisional report No. 11, available at: <https://publications.csiro.au/rpr/pub?list=BROandpid=procite:6a36119d-65e2-4786-a73e-3985057ea5a9>, last access: 24 January 2015, 1976.
- Page, R.: Reducing the cost of subsidence damage despite global warming, *Struct. Surv.*, 16, 67–75, 1998.
- 10 Pritchard, O. G., Hallett, S. H., and Farewell, T. S.: Soil impacts on UK infrastructure: current and future climate. *Proc. Inst. Civ. Eng. Eng. Sus.*, 167, 170–184, doi:10.1680/ensu.13.00035, 2014.
- Pritchard, O. G., Hallett, S. H., and Farewell, T. S.: UKCP09-derived probabilistic soil moisture for assessment of UK clay-related subsidence vulnerability, in preparation, 2015.
- 15 Rawlins, B. G., Harris, J., Price, S., and Bartlett, M.: A review of climate change impacts on urban soil functions with examples and policy insights from England, UK, *Soil Use Manage.*, doi:10.1111/sum.12079, online first, 2013.
- R Core Team: R: A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, Austria, available at: <http://www.R-project.org/>, last access: 18 March 2015, 2014.
- 20 Robson, J.: Soils of Boston and the Spalding District, Soil Survey and Land Research Centre, Silsoe, UK, 1990.
- Royse, K. R.: The handling of hazard data on a national scale?: a case study from the British Geological Survey, *Surv. Geophys.*, 32, 753–776, 2011.
- 25 Santi, P. M. and Martens, J. L.: Engineering soils maps, *Environ. Eng. Geosci.*, 9, 179–183, 2003.
- Wallis, J.: The UKPMS User Manual. Volume 2: Visual data collection for UKPM S, Chapter 7: Coarse Visual Inspection (CVI), available at: http://www.pcis.org.uk/iimni/UserFiles/Applications/Documents/Downloads/UKPMSManualsandGuides/Manual/UKPMSManual_02_09v05.pdf, last access: 29 April 2015, 2009.
- 30 Westerveld, G. J. W. and Van Den Hurk, J. A.: Application of soil and interpretive maps to non-agricultural land use in the Netherlands, *Geoderma*, 10, 47–65, 1973.

Williams, K., Joynt, J. L. R., Payne, C., Hopkins, D., and Smith, I.: The conditions for, and challenges of, adapting England's suburbs for climate change, *Build. Environ.*, 55, 131–140, 2012.

5 Willway, T., Reeves, S., and Baldachin, L.: Maintaining pavements in a changing climate, Department for Transport/Transport Research Laboratory, London, available at: <http://www.ukroadsliaisongroup.org/download.cfm/docid/77CBE77B-93A4-4D1D-B9782B47987990C1>, last access: 10 December 2014, 2008.

NHESSD

3, 3151–3180, 2015

Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Table 1. Drought damage to roads in 2003 (data sourced from: Wilway et al., 2008).

Authority	Reported drought damage (GPB 000)
Lincolnshire	7397
Essex	5614
East Sussex	5568
Kent	4167
Cambridgeshire	3522
Hampshire	3030
Peterborough	2400
West Sussex	2221
Isle of Wight	1500
Wiltshire	1302
Buckinghamshire	1200
Surrey	1000
Suffolk	750
Norfolk	650
Bedfordshire	300
Total	40 621

Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

Table 2. Road classification in terms of length and percentage of network in Lincolnshire.

LCC hierarchy	Road class (DfT)	Length (km)	Percentage
1	A (principal)	888	10
2	A, (some) B	560	6
3	B, (some) C	1458	16
4 and 5	C, all unclassified	5808	66

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

Table 3. CVI points assessed for each survey period per subsidence risk class.

	Extremely high	Very high	High	Medium high	Medium	Medium low	Low	Very low	Extremely low
2007–2011	3065	4976	1348	1544	4615	9	0	1249	11 794
2011–2012	3311	5237	1359	1577	4779	10	0	1340	12 373
2012–2013	3340	5483	1398	1588	4904	10	0	1360	12 181
2013–2014	3418	5367	1336	1541	4775	10	0	1323	11 801

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

NHESSD

3, 3151–3180, 2015

Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

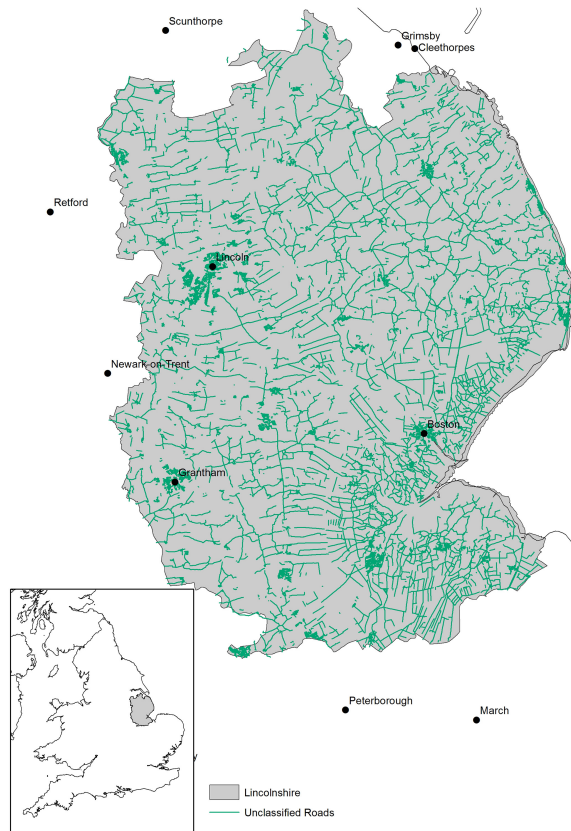


Figure 1. Lincolnshire location map and the distribution of unclassified roads.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

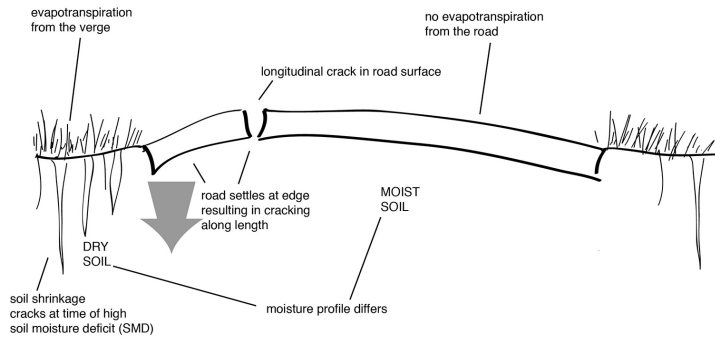


Figure 2. Soil processes leading to longitudinal cracking of road surface with photo example from Fodderdyke, Lincolnshire (photograph: Lincolnshire County Council, reproduced with permission).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

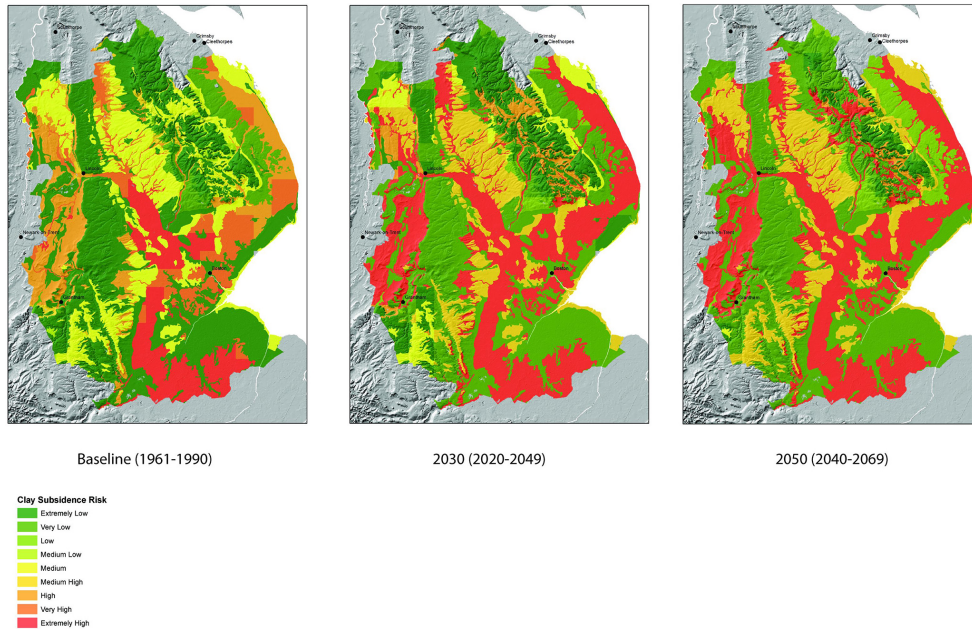


Figure 3. Modelled clay-subsidence risk, at the Central Estimate (50th percentile) for baseline (1961–1990), 2030 (2020–2049) and 2050 (2040–2069) UKCP09 scenarios for the administrative county of Lincolnshire (soils data ©Cranfield University and for the controller of HMSO 2015).

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

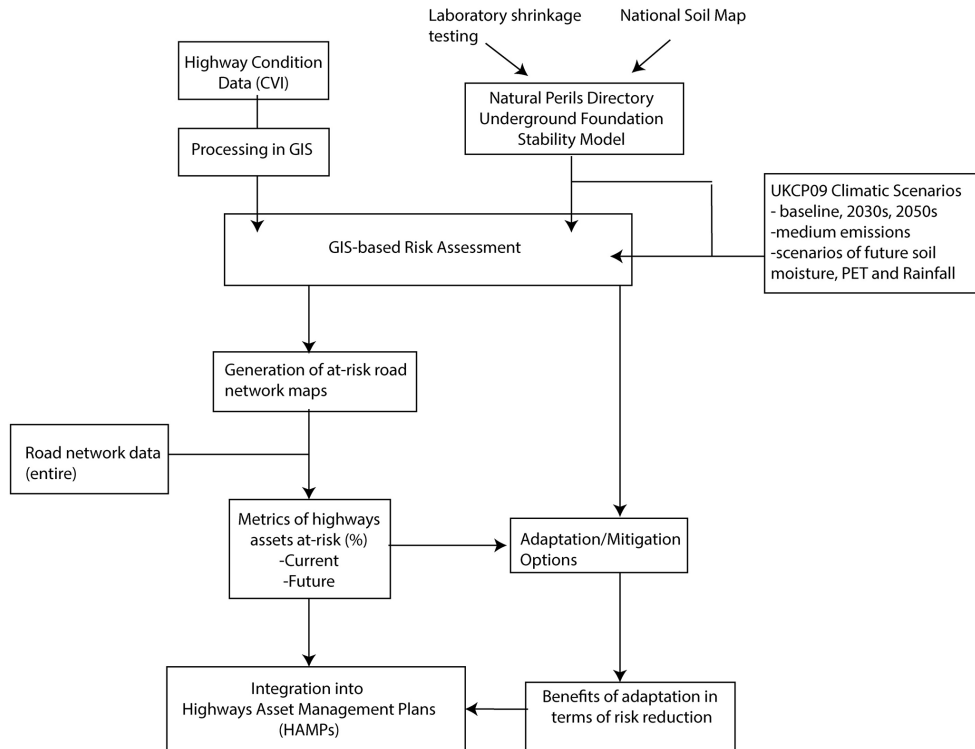


Figure 4. Conceptual risk-assessment framework for spatial clay subsidence risk impacts upon Lincolnshire road network.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

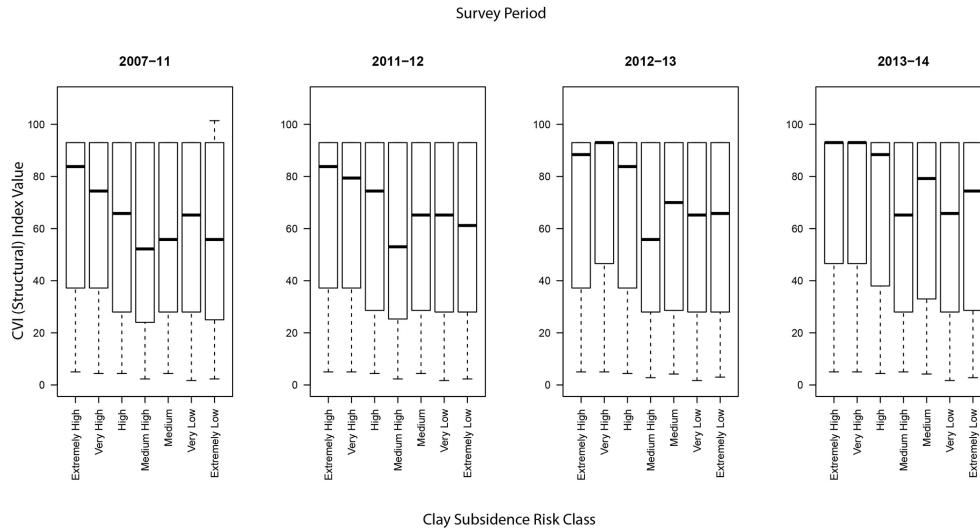


Figure 5. Clay subsidence risk against structural CVI (coarse visual inspection).

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	

Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

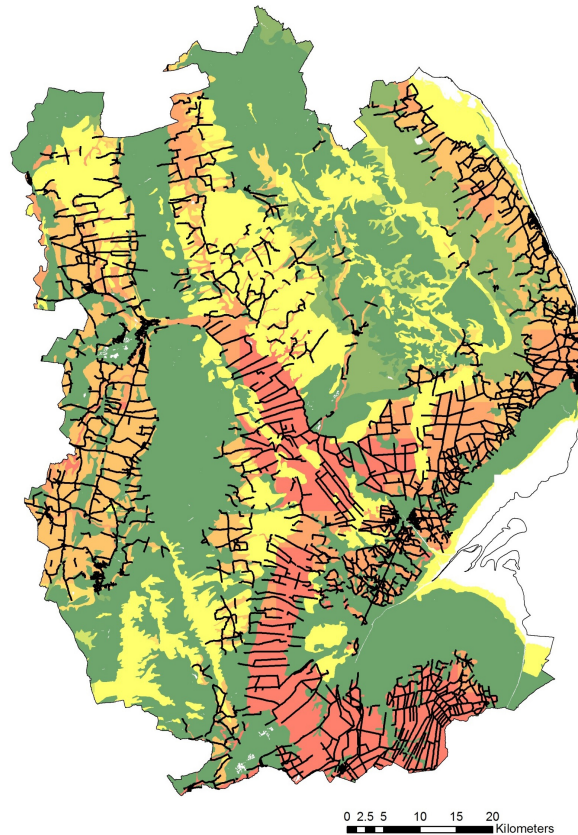


Figure 6. Road sections identified “At Risk” of clay related subsidence at present (soils data ©Cranfield University and for the controller of HMSO 2015).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

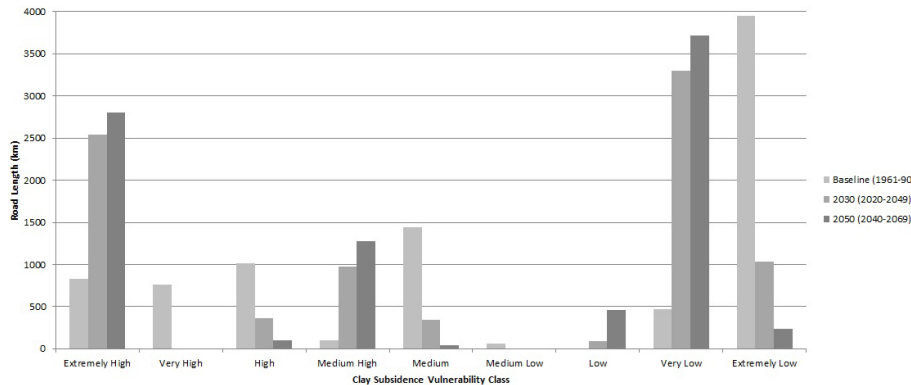


Figure 7. Road length kilometres per clay subsidence vulnerability class for Baseline, 2030 and 2050 scenarios.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





Figure 8. Road embankment instability, B1165 Ravens Bank, Lincolnshire (photo: O. Pritchard).

Soil geohazard mapping for improved asset management of UK local roads

O. G. Pritchard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion