Infrastructure Transitions Research Consortium

Working paper series

Road subsidence in Lincolnshire: Soils and road condition

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2013

National Soil Resources Institute

Road subsidence in Lincolnshire: Soils and road condition

A report for Lincolnshire County Council

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Document v1

Cranfield UNIVERSITY

Contents

Table of Figures

Table of Tables

Table of Equations

Executive Summary

It was recognised by Lincolnshire County Council that an increasing number of roads on their network have been subject to apparent drought-related subsidence during the last several years. UK Government has highlighted extreme climatic events as a high risk to highway infrastructure assets.

There are many types of soil related ground movement that could have exerted an impact on the highway infrastructure of Lincolnshire, all of which are influenced by climatic processes, including: 1) clay shrinkage and swelling; 2) sand-washout; 3) frost heave; 4) compression of soft soils; and 5) peat shrinkage.

Making use of a range of road condition survey data provided by Lincolnshire County Council and Cranfield University National Soil Resources Institute's Natural Perils Directory (NPD) geohazard thematic dataset, the relationship between soil type and road degradation has been investigated and further understood. A Geographical Information System (GIS) was used to capture, present and analyse the data; the ESRI GIS ArcMap v.10.1 was used for this study.

This rapid assessment has revealed that, although road deterioration is affected by a number of recognised factors such as traffic use, infrastructure service trenches, cold weather, poor construction of roadway etc., the soil type also appears to have had an important impact upon the condition of the highway network. Clay and silt soils have the most contributory effect to road degradation. Subsequently, the low deflection rates observed in 'at risk' silt soils possibly indicate that 'frost heave' may be responsible for the worsening road conditions in certain areas of the Lincolnshire road network, contrary to the drought related issues initially identified. It was not possible to determine the fully representative effect of peat soils due to the short length of surveyed road network.

Further work would consider individual soil series and the effect of future climate change scenarios, also the economic impact of specific soil types could be established. However the rapid use of soil mapping as a proxy of road condition has been established.

From this research in particular several key questions have been raised;

- Due to the lack of roads surveyed on peat soils, further data needs to be considered, if available, to understand if peat soils are in fact having a damaging effect on the highway network of Lincolnshire.
- Silt-related subsidence appears to a major contributing factor to road degradation in Lincolnshire, therefore what mechanisms are responsible, is drought (shrinkage) the major issue or is frost (heave) of silty soils causing roads to degrade?

Together, this and the further studies identified will allow for a more effective asset management approach for the Lincolnshire road network in an area that is very susceptible to small climatic change and resultant soil processes.

Glossary

CVI – Coarse Visual Inspection
GIS – Geographical Information Systems
ITRC – UK Infrastructure Transitions Research Consortium
LandIS – Land Information System
MSA – Million Standard Axles
NPD – Natural Perils Directory
NSRI – National Soil Resources Institute
UK – United Kingdom

Citation. This report may be cited as follows:
Pritchard, O.G., Hallett, S.H. and Farewell, T.S. (2013) Road subsidence in Lincolnshire: Soils and road condition). 35pp. NSRI, Cranfield University, UK.

Report cover, shows a section of archetypal Lincolnshire fenland road on Walcott Fen, undulating as a result of subsidence. (Richard Croft, 2011, Geograph).

This document is submitted as part of Cranfield University's involvement in the UK Infrastructure Transitions Research Consortium (ITRC) project, Work Stream Two under contract to Oxford University.

1. Introduction

It was drawn to our attention that the highways infrastructure within the county of Lincolnshire had been subjected to drought related subsidence (Mike Coates, *Pers. Comm*.). This had led to Lincolnshire County Council (LCC) placing a bid to central government for additional road funding that had ultimately been unsuccessful. The scale of the problem was reported in the local media, with the Peterborough Telegraph stating "'Drought' cracking up roads in Peterborough: multi million pound bid for cash for repairs" (Peterborough Telegraph, 2011).

Disruption in the highway network within this largely rural community has the potential to result in significant knock-on effects regarding the everyday running of society and business. In this current age of austerity the economic consequences of road deterioration can be great, Lincolnshire County Council's adaptation report showed that in the extremely dry summer of 2003 that £7 million worth of damage was caused to over 200 roads in Lincolnshire as a result of the extreme weather.

Defra (2011) have highlighted that 'extreme' weather events present a significant challenge to UK infrastructure, being likely to exert a substantial impact both now and in the future. With average UK summer temperatures set to rise by approximately 3-4^{o}C by the 2080's (Jenkins *et al*. 2009), the likelihood of drought(s) conditions could become more frequent causing significant effects on the highway network if not properly understood. The Royal Academy of Engineering (2011) state that the renewal cycle (in terms of Highway Agency assets) for major routes is approximately 30 years with a third of the network resurfaced on average every 10 years, suggesting how future climate regarding actions taken at present will be an important factor for future resilience of the highway network of the UK. Approximately 70% of weather events highlighted in the Lincolnshire area directly affected the highways network (Nicholls, Undated).

There are many types of soil related ground movement that could have an impact on the highway infrastructure of Lincolnshire, Farewell *et al*. (2012) highlight several of these, namely: 1) clay shrinkage and swelling; 2) sand-washout; 3) frost heave; 4) compression of soft soils; and 5) peat shrinkage.

It has been identified by several highways authorities (Lincolnshire, Suffolk, Norfolk and Cambridgeshire) that the shrinkage of peat and subsequent subsidence of their highway network appears to be an ever-increasing issue, especially in times of drought.

The peatlands of the UK are extensive with fenlands alone covering an area of 439,000 Ha (Carey *et al*. 2008), showing that they are likely to intersect with the linear highway networks of Lincolnshire. The fenlands of East Anglia in particular are also considered an important agricultural resource (Dawson *et al*. 2010).

Peat wastage as a result of drainage measures has had a great impact on both infrastructure and residential dwellings. The addition of overburden pressure, in the form of roads, greatly increases the risk of settlement and subsidence of the peat (Kechavarzi *et al*. 2010). An applied load of overburden 'strongly influences the relationship between the shrinkage geometry factor and moisture value', resulting in a greater magnitude of subsidence (Oleszczuk *et al*. 2003). Lightweight fill has been utilized in some countries in order to construct road embankments using 'polystyrene blocks, sawdust, brushwood, and peat bales' upon soft soils (Waltham, 2002).

The majority of the relatively minor (unclassified) roads in the fenlands can be deemed to be *evolved*, whereby they have not been subject to modern engineering development and instead have 'evolved' from older roads, dating back, in some cases, even to Roman occupation and possibly previous. Astbury (1958) suggests that 'Fen' roads were among the first roads to be built in England, in the Bronze Age era.

This report aims to assess which, if any, soil types are having an effect on the road condition/quality in the County of Lincolnshire. This has been undertaken through data acquisition of road condition data supplied by Lincolnshire County Council and its subsequent interaction with the soil data collection of England, held at Cranfield University's National Soil Resources Institute (NSRI) (www.landis.org.uk).
The methodology and results are discussed below followed by a short discussion on soil type and road condition status.

1.1 NSRI and the Natural Perils Directory

Within the National Soil Resources Institute (NSRI), Cranfield University (Appendix 1) is held the national soil map data for England and Wales. This is held in a computerised 'Land Information System' (LandIS), the largest database of its kind in Europe and recognised by UK Government as the definitive source of national soils information (Keay *et al.*, 2009).

NSRI have obtained from LCC data covering the County of Lincolnshire which have utilised a range of survey techniques assessing the surface and structural condition of the Lincolnshire highway network ranging from 'A' through to 'unclassified' road networks. Together with the NPD data, these two vast datasets have been 'fused' in seeking to understand whether there is a correlation between soil type and highway network degradation in the County of Lincolnshire. This work was informed by earlier communication between Lincolnshire County Council and Cranfield University regarding the impact of drought on their highway network.

1.1.1 Derivation of the NPD dataset

NSRI's Natural Perils Directory (NPD) geohazards thematic dataset comprises a detailed and comprehensive assessment of the environmental vulnerabilities to building structures and infrastructure posed by soil-related subsidence, flood extent and wind exposure (Hallett *et al*., 1994; Jones *et al*. 1995). The dataset is expressed in GIS format on a vector polygon basis across England, Wales and Scotland. This unique data provided exclusively by NSRI represents the most detailed available information for any kind of soil-related vulnerability assessment in the environmental sector. The subsidence peril includes a range of soil-related models together with associated climatic scenarios, the relevant ones of which are displayed within this report.

Subsidence damage is the result of ground movement at and around foundation depth. The kinds of soil effects directly associated with ground movement include:

- Clays – shrinkage and swelling of clays, known as *clay related subsidence*;
- Sands – sandy soils susceptible to sub-surface erosion, causing *sand-related subsidence*
- Silts – silty soils associated with heave under frosty conditions causing *silt related subsidence*;
- Soft soils – soft (alluvial and peat) soils being compressible and susceptible to *soft-soil related subsidence*;
- Peats – peat, which shrinks considerably on drying causing *peat-related subsidence*

Other natural mechanisms are known to cause ground movement and foundation subsidence, including mining subsidence, landslip, solifluction and the formation of swallow holes. At present the NPD database does not attempt to model these latter causes, concentrating instead on the soil related subsidence types noted above. Of these, it is universally accepted that clay-related movement caused from shrink-swell is by far the most extensive cause of soil related subsidence in the UK and together with the other soil related hazards represents approximately 70-80% of soil subsidence cases. NPD provides a detailed and informed assessment of the location of clays prone to shrinkage across the UK.

The exact amount of shrinking and cracking depends upon clay content and type, density and previous weather conditions. The potential of a soil to 'shrink-swell' has been determined from direct laboratory measurements on a large number of samples from the UK. Shrink-swell potential is normally assessed at a depth of 1 metre and is calculated via laboratory measurement of volumetric shrinkage. This is defined as the change in volume between field capacity [winter wetness state equating with 0.05 bar (5kPa) suction], and permanent wilting point [very dry summer conditions equating with 15 bar (1500kPa) suction], and is expressed as a percentage of the volume at field capacity. Shrink swell classes range from very low (<3% volumetric shrinkage) and low, through moderate, to high and very high (>15% volumetric shrinkage).

In predicting subsidence vulnerability it is important to understand the cycle of wetting and drying in soil profiles at different locations. Using rainfall and evaporation data, the cycle of wetting and drying can be expressed in terms of the overall Potential Soil Moisture Deficit (PSMD). Average values of maximum PSMD have been derived from 30 years of weather data collected at more than 1,000 field meteorological stations representing the full range of conditions in England, Scotland and Wales.

The Underground Foundation Stability (UFS) model within the NPD system combines the average maximum value of PSMD and shrink-swell data, incorporating expert knowledge of soil behaviour to derive 9 vulnerability classes (as used in this assessment), ranging from *extremely low* with very low shrink swell potential and a PSMD of <100mm to *extremely high* with very high shrink-swell potential and a PSMD of >200mm.

Because of the natural fine-scale local variation of soils, multiple soil series are present within the delineated polygons of the NPD data. Therefore the NPD features the inclusion of the 'subdominant' soil types in the assessment of the geohazard(s). Each of the soil series that are included within the national soil map have been considered for the individual geohazards and the distribution of the risk classes, within each geohazard classification, have been calculated on the basis of this area.

The standard *clay related subsidence* model uses the mean maximum PSMD value calculated from the PSMD dataset. This can be considered as representing the 'average' conditions. The NPD dataset models a range of extremes regarding PSMD values by increasing the mean maximum PSMD value by the addition of the standard deviation, or fraction, or multiples thereof. The higher the standard deviation the more extreme an event is likely to be. For example with the addition of 2.5 SD to the mean maximum PSMD probably represents a reasonable estimate of the driest year in 150, the 1 in 150 year event has been included within this study.

1.2 Soils of Lincolnshire

Soils are defined by soil scientists as 'the layer of the earth's surface containing living matter and capable of supporting plants' and within the UK these soils penetrate to a depth of approximately 1.5 m below ground level (Busby *et al*. 2012). They are the result of a number of 'complex, interacting processes, which are most intense near the surface' (Hodge *et al*. 1984).

The relief of Lincolnshire is generally low lying (0-50 metres above sea level) except for the central northern part of the county identified as the Lincolnshire Wolds where heights range between 50-200 metres above sea level.

A large proportion of the superficial geology and subsequently the soil parent material of the Lincolnshire county consists of alluvium with glacial till and glaciofluvial deposits dominating the Lincolnshire Wolds (Hodge *et al*. 1984).

Lincolnshire contains a broad range of soil types (Figure 1) and further reference should be made to the literature identified in Appendix 2 for more detailed information. Peat is extensive around the Southern Fenland area along with interbedded marine clays and silts that have been deposited under changing conditions since the end of the last ice age (Chatwin, 1961). However since the introduction of drainage measures since 1630 the peat in many areas has wasted to an extent that the previous underlying clays and silts have been exposed at the surface. Substantial thickness of peat therefore are now confined to the edge of the fens or in areas that have remained undrained (Hodge *et al*. 1984). As of 1985 it was recorded that only 240 km^2 of peatland remained, some 16% of that pre draining activities (Burton and Hodgson, 1987). The fenland area is within 'a broad clay vale surrounded by limestone and chalk' (Burton and Hodgson, 1987).

Cranfield have derived thematic geohazard maps from the soil maps and produced the 'Natural Perils Directory' dataset, which shows the differential vulnerability of locations to soil-related geohazard threats (Figure 2).

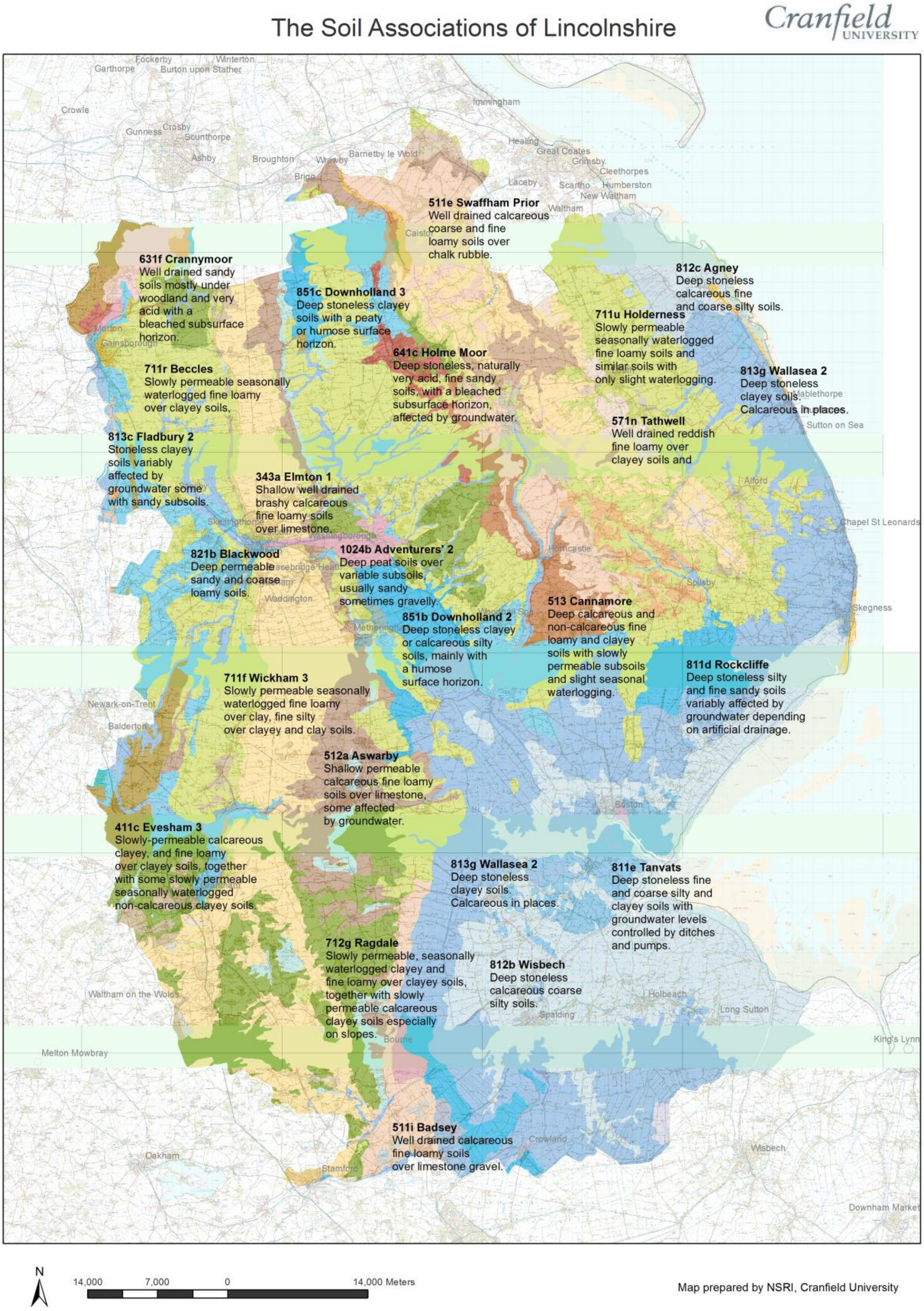

Figure 1: Principle Soil Associations of Lincolnshire.

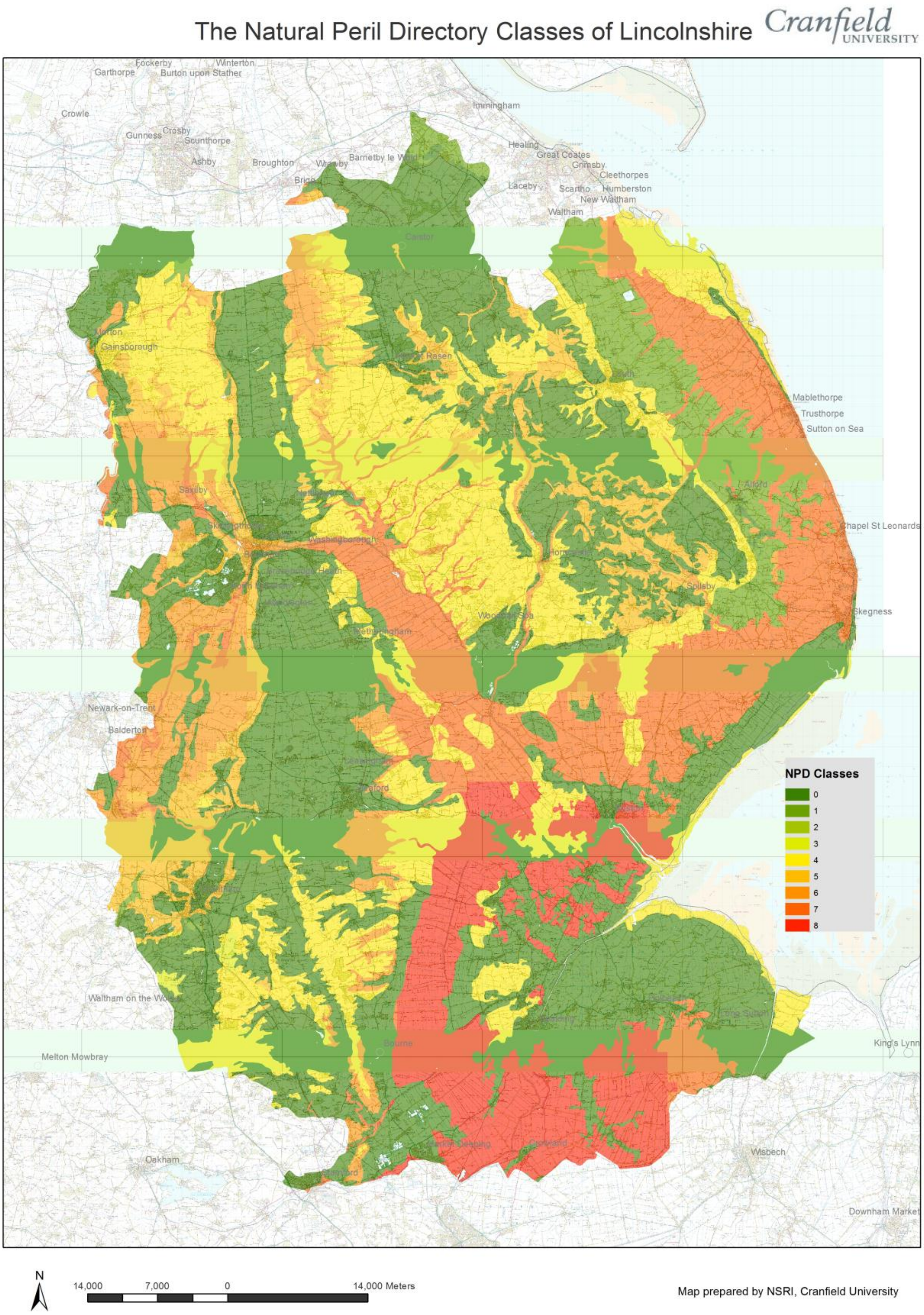

Figure 2: The Natural Peril Directory classes for Lincolnshire.

2. Coarse Visual Inspection and soil type (Unclassified Roads)

2.1 Methodology

For unclassified road networks, inspections are carried out by Lincolnshire County Council as a 'Coarse Visual Inspection' (CVI) and then expressed as a number of indexes, however in the respect of soil type the value of 'structural condition index' (UC_Struc_CI) is most appropriate in relating soils to road condition, within this index is the 'survey_obs_value' that provides a condition index value (50m average) for structural condition index is expressed as a range of values between 0-93, where the higher value, the worse the structural condition of the road (Phil Shevill, *Pers. Comm*.). Example structural index data is presented in Table 1.

A Geographical Information System (GIS) was used to capture, present and analyse the data; the ESRI GIS ArcMap v.10.1 was used. Using the calculated 'survey_obs_value' data, intersection with the NPD dataset using the GIS software was undertaken. Subsequently the CVI index was calculated by dividing the sum of 'survey_obs_value' by the road length (metres) that intersected with each subsidence class for the differing soil types (Equation 1). As the CVI survey is presented in GIS format as a line, road length can be readily calculated and is expressed in kilometres on the graphical outputs (Figure 3).

$$\boldsymbol{CVI\ Index} = \frac{Sum(sov)}{RLm}$$

Where:
sov – 'survey_obs_value'
RLm – Road Length (metres)

Equation 1. Calculation of Coarse Visual Inspection (CVI) Index.

Table 1. Example of structural index data table for individual line and description of data.

File: UC_Struc_CI	Structural Condition Index for Unclassified road network. SCI derived from UKPMS Coarse Visiual Inspection (CVI) surveys and calculated using RP10.01. Survey_obs_value gives 50m average value.	
Field	**Data example**	**DESCRIPTION**
Object ID *	1	
Shape *	Polyline	
central_asset_id	LCC/8700020689	Unique ID for section in Confirm (Asset Management System)
survey_obs_start	50	Start chainage within road section
survey_obs_end	100	End chainage within road section
xsp_lane_offset	0	Offset from centre line for plotting results
xsp_name	Carriageway	XSP=Cross Sectional Position - Describes position of data
observe_type_name	Condition Index - Structural	Description of Index
survey_obs_value	47.2	Condition Inedx Value - 50m average
obs_parm_opt_name	Valued	N/A
site_code	12605684	USRN from National Street Gazeteer
plot_number	10000001	N/A
asset_id_code		N/A
site_name	FISHTOFT DROVE	Street Name
feature_location	FISHTOFT DROVE FROM PEACOCKS ROAD TO END	Description of road section
feature_key	191266	N/A
survey_number	249	Record ID of Data Analysis in Confirm
survey_feat_end	27/08/2008 23:59	N/A
data_set_key	2	N/A
feature_id	PMS:96U500/10	Road section reference
calc_location	C, 50 to 100	Description of location
node_key_start	0	N/A
node_key_end	0	N/A
survey_obs_notes	4B	National Hierarchy
feature_group_code	CWBU	Feature group code
feature_group_name	Carriageway Bituminous/Unknown	Feature group name
xsp_code	C	Carriageway XSP
Shape_Length	51.621524	

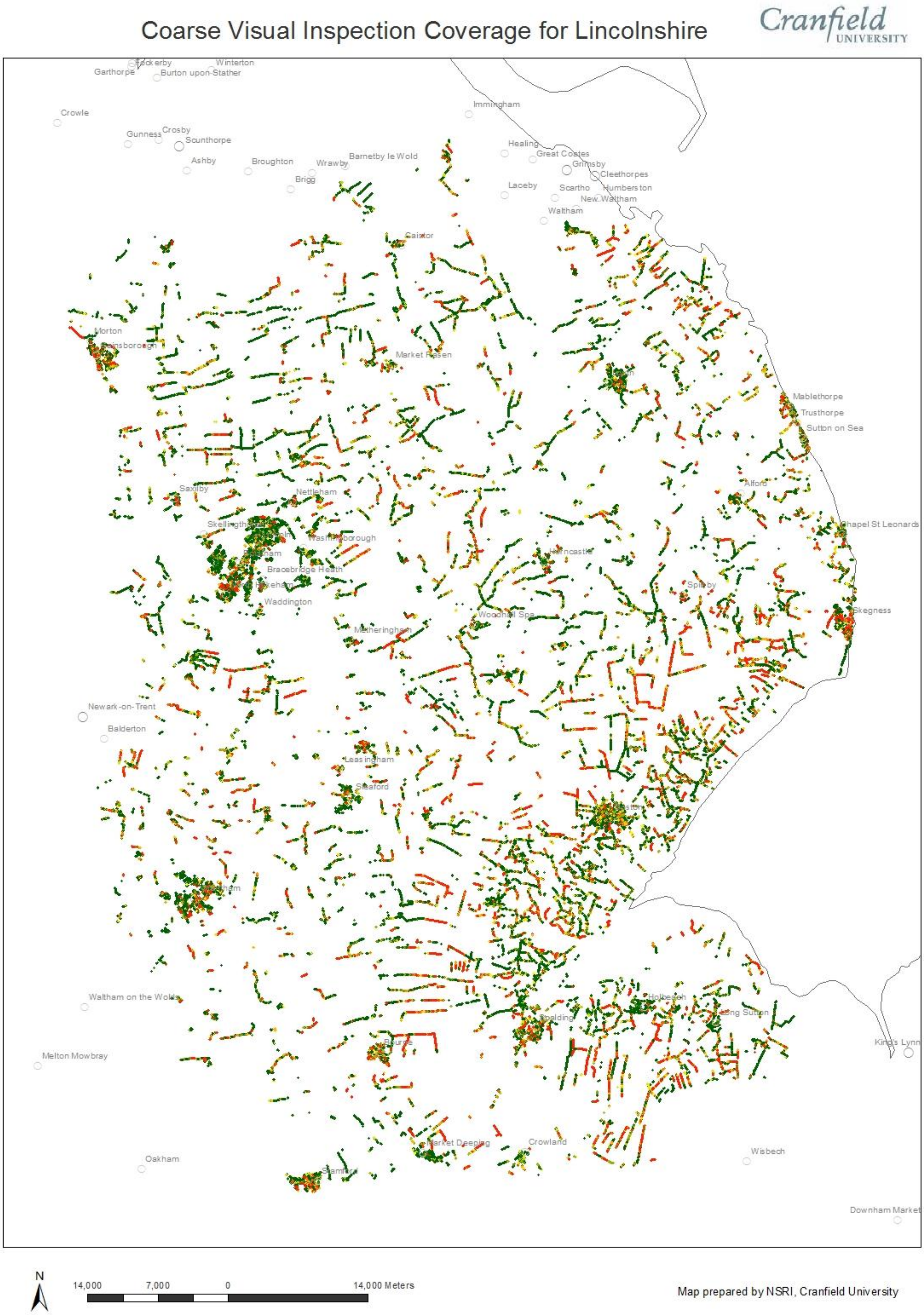

Figure 3: County of Lincolnshire with CVI coverage for unclassified roads shown in colour weight format (Green: Longer road life; Red: Shorter road life).

2.2 Results

Each soil type (clay, sand, silt, peat etc.), and then subsequently each of the differential subsidence classes within the NPD dataset have been assessed alongside the calculated CVI index in order to determine which soils (if any) exert an effect on ‘unclassified’ road condition upon the surveyed roads in Lincolnshire. In interpreting the charts, note that the higher the CVI Index, the more detrimental the road condition is as a result of the ‘coarse visual inspection’.

2.2.1 Clay related subsidence risk – Standard model

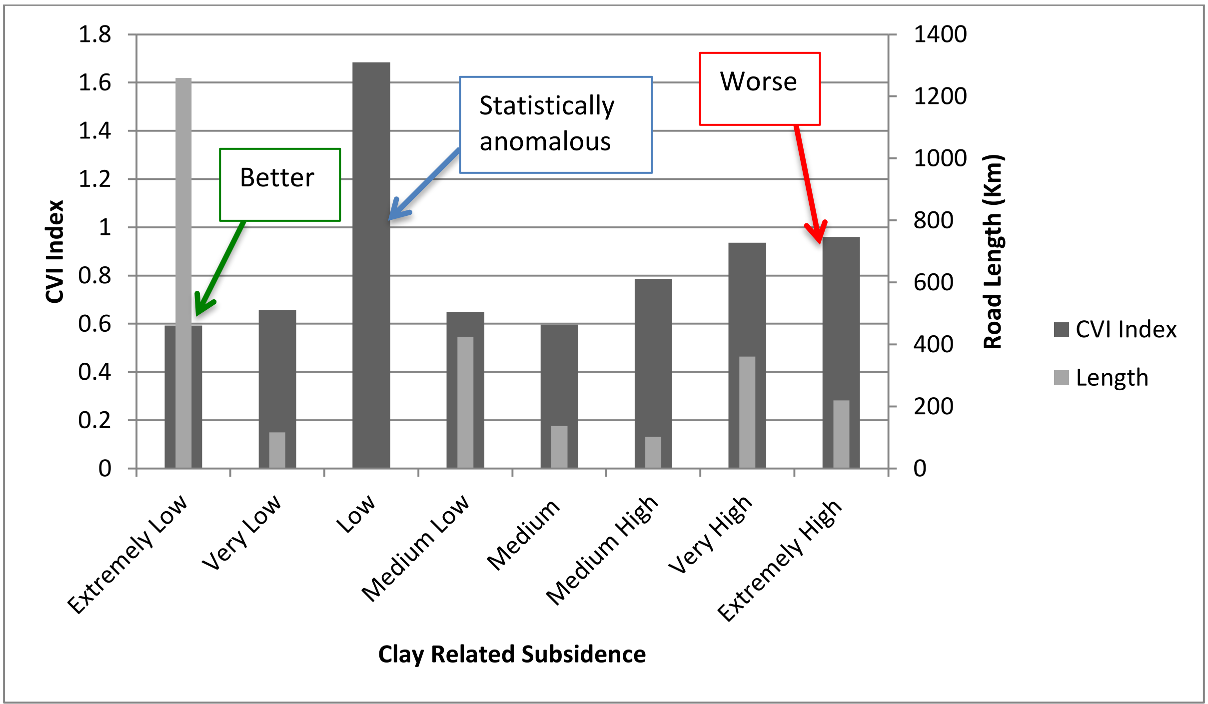

Figure 4: Clay related subsidence and CVI index

Figure 4: Clay related subsidence and CVI inde**4**: Clay related subsidence shows a general trend of increasing CVI index values, associated with areas of higher clay subsidence risk. ‘Low’ subsidence risks shown are interpreted to be statistically insignificant as this CVI index is based upon only 0.5 km of associated roads.

2.2.2 Clay related subsidence risk – 1 in 150 year period model

Figure 5: Clay (1 in 150 year) related subsidence and CVI index

Figure 5: For the 1 in 150 year clay subsidence vulnerability there is an upward trend regarding CVI Index and increasing subsidence risk, similar to Figure 4: Clay related subsidence and CVI inde. The 'low' and 'very high' categories are not included within the 1 in 150 year risk model, hence it not being present in the figure above, therefore redistribution of the data has made harder any direct correlation with the standard clay

2.2.3 Peat related subsidence risk

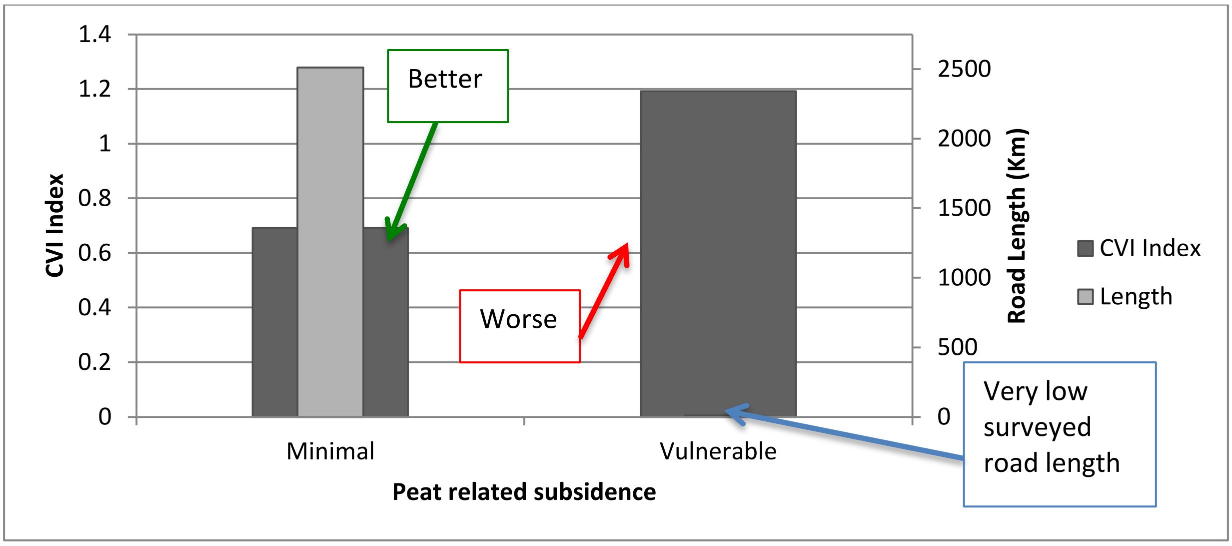

Figure 6: Peat related subsidence and CVI index

Figure 6: Within the NPD data, peat soils are classified in terms of their subsidence risk as minimal and vulnerable, as shown above. The CVI Index shows that vulnerable peats coincide with higher observed road values (worse condition). However the road length data shows that a very small proportion of roads pass through 'vulnerable' areas of peat (9.6 km) compared to that of 'minimal' (2,512 km). Therefore in statistical terms this relationship does not accurately represent the relationship between peat soils and CVI index.

2.2.4 Silt related subsidence risk

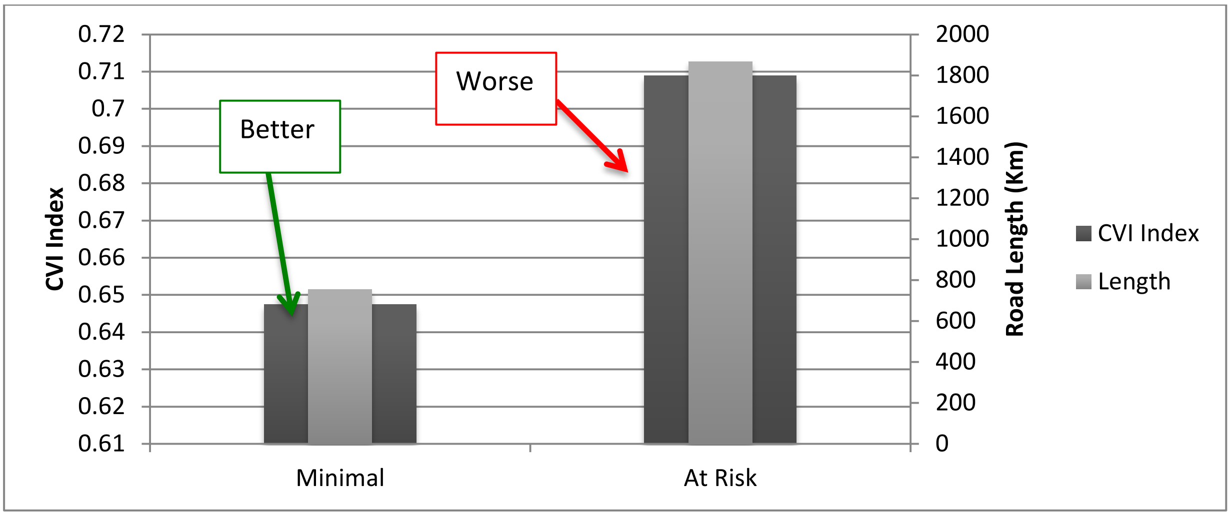

Figure 7: Silt related subsidence and CVI index

Figure 7: Silt subsidence risk within the NPD data is identified by being either 'at risk' or 'minimal'. From the figure above it can be noted that a larger proportion of the road network in Lincolnshire is built upon soils that are 'at risk' of silt related subsidence, which subsequently coincides with the higher CVI Index compared to that of 'minimal' risk.

2.2.5 Sand related subsidence risk

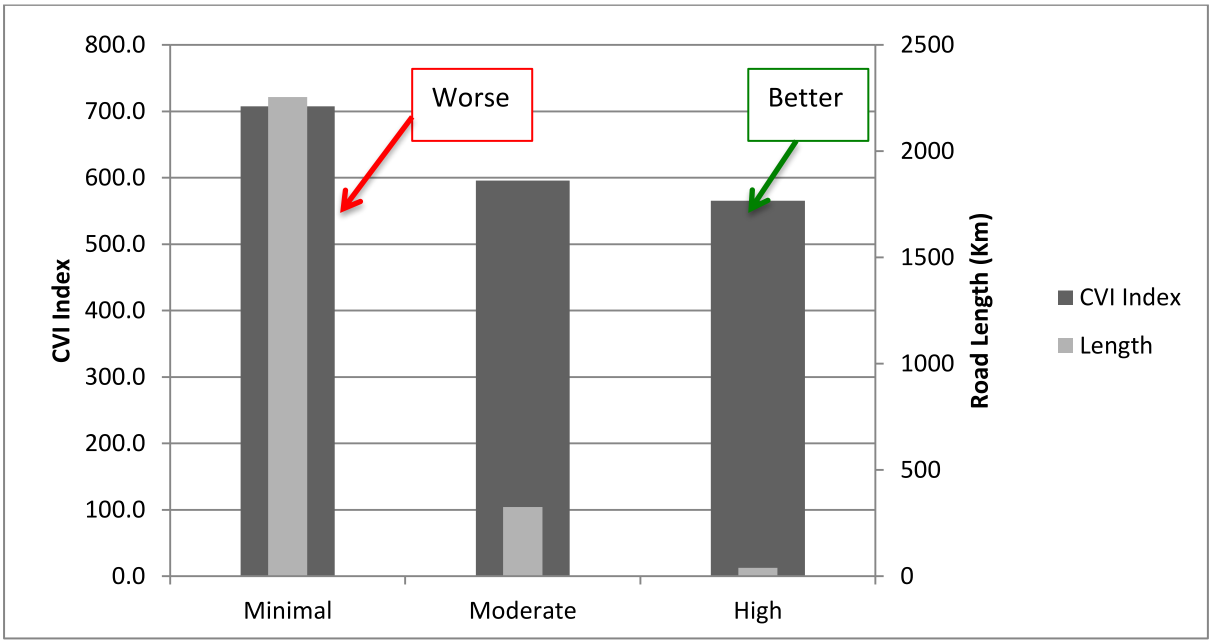

Figure 8: Sand related subsidence and CVI index

Figure 8: Sand subsidence risk within the NPD dataset is defined as being, 'minimal', 'moderate' or 'high', and applies when running water (from burst pipes or leaking drains) forms cavities in loose textured soils. The figure shows that the majority of Lincolnshire roads are built upon soils that have a 'minimal' risk of sand related subsidence. However this minimal subsidence risk also coincides with the highest CVI Index suggesting that sandy soils do not have as much of an impact as other soil types. The high CVI indexes for the other two sand subsidence risk classes may be explained by the relatively short road lengths that are

3. Highway Residual Life and Soil type ('A' and 'B' Roads)

As part of Lincolnshire County Council's monitoring of their highway network, the structural integrity of the road is measured using a 'deflectograph'. Deflectogram surveys are particularly useful as they give reliable estimates of residual road life for both engineered (main) roads and evolved (minor) roads (WDM, 2011). The deflectograph is mounted under a lorry of a known weight (~3175 kg), 'the maximum deflection of the road surface is then measured at approximately 4m intervals simultaneously in each wheel-path while the deflectograph travels at a constant speed of 2.5 km/h'(WDM, 2011).

The deflection of the road surface gives an indication of the road pavement strength and from this value a residual life is calculated, both in years and expressed in million standard axles (MSA), a standard axle being defined as that of a weight of 80 kN (Highways Agency, 2006). Ultimately these values enable the highway authority to prioritise road maintenance and replacement funds to areas of need. The data provided by Lincolnshire is in GIS format as a series of polygons, characterised by the 4m intervals of the deflectograph measurements.

3.1 Methodology

Using calculated residual life data both in years and as a value of MSA, as well as the measurement of deflection (100ths of millimetres) have been intersected with the NPD dataset. A Geographical Information System (GIS) was used to capture, present and analyse the data; the ESRI GIS ArcMap v.10.1.

The residual life index was calculated by dividing the sum of residual life (years and/or MSA) by the road length (metres) that intersected with each subsidence class for differing soil types. As the residual life survey is presented in GIS format as a polygon linked data (Table 2), one cannot ascertain line length, therefore road length was calculated using the approach whereby each polygon represents a 4m long section. The 4m section is held as representative of the test interval used when undertaking the deflectogram survey(s), thereafter the total 'count' of polygons within each subsidence class was calculated and multiplied by 4 to give the total road length surveyed in metres. This was then converted to kilometres and is shown within the graphic outputs. The Deflection Index was calculated (Equation 2) via the same method whereby the sum of the deflection (100^{ths} of millimetres) for each subsidence class was divided by the road length (metres).

$$\boldsymbol{Residual\ Life\ Index\ (Years)} = \frac{Sum(RLIy)}{RLm}$$

$$\boldsymbol{Residual\ Life\ Index\ (MSA)} = \frac{Sum(RLImsa)}{RLm}$$

$$\boldsymbol{Deflection\ Index} = \frac{Sum(DI)}{RLm}$$

Where:
DI – Deflection Index
RLIy – 'Residual_Life_Years'
RLImsa – 'Residual_Life_MSA'
RLm – Road Length (metres)

Equation 2. Calculation of Deflection Index

Table 2. Example of residual life data used in assessment

File: Residual_Life_Summary	Residual Life in years calculated from Deflectograph surveys using ther PANDEF model.	
Field	**Data example**	
Object ID *	1	**DESCRIPTION**
Shape *	Polygon	
Road	21U165	Road Number
Section	PMS:21U165/10	Road network section label
XSP	CL1	XSP=Cross Sectional Position - Describes position of data
Start	0	Start chainage within road section
End	50	End chainage within road section
SurveyDate	26/09/2010	Survey Date
Residual_Life_Years	50	Residual Life in Years
Residual_Life_MSA	399.97	Residual Life in MSA (Million Standard Axles)
Overlay_20_Year	0	Overy required in mm to achieve 20 year life
Deflection	7	Measured deflection in 100ths of mm
SurveyDate_v2	09/05/2004	Survey date of previous survey (version 2)
Residual_Life_Years_v2	50	Res life from previous survey (version 2)
SurveyDate_v3	<Null>	Survey date of previous survey (version 3)
Residual_Life_Years_v3	0	Res life from previous survey (version 3)
Change_In_Life_v2_to_v1_Yrs	0	Change in life from v2 to v1
SummaryDate	01/04/2013	Date life is calculated from
LastUpdate	12/12/2012	Date table was last updated
Shape_Length	170.490721	
Shape_Area	1809.993551	

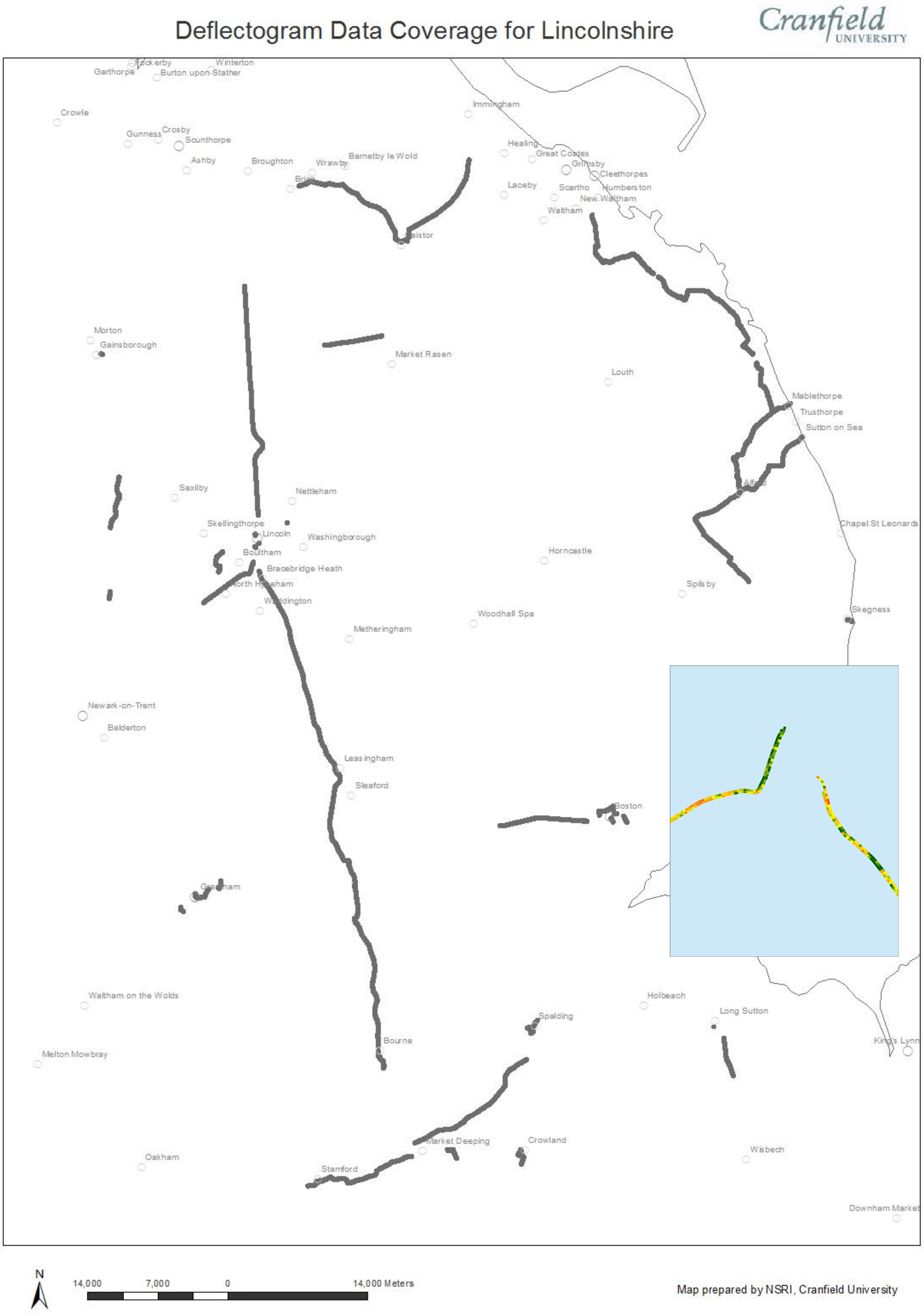

Figure 9: Distribution of deflectograph data available (Inset: Close view of residual life data;Red: Lower residual life; Green: Higher residual life)

3.2 Results

3.2.1 Clay related subsidence

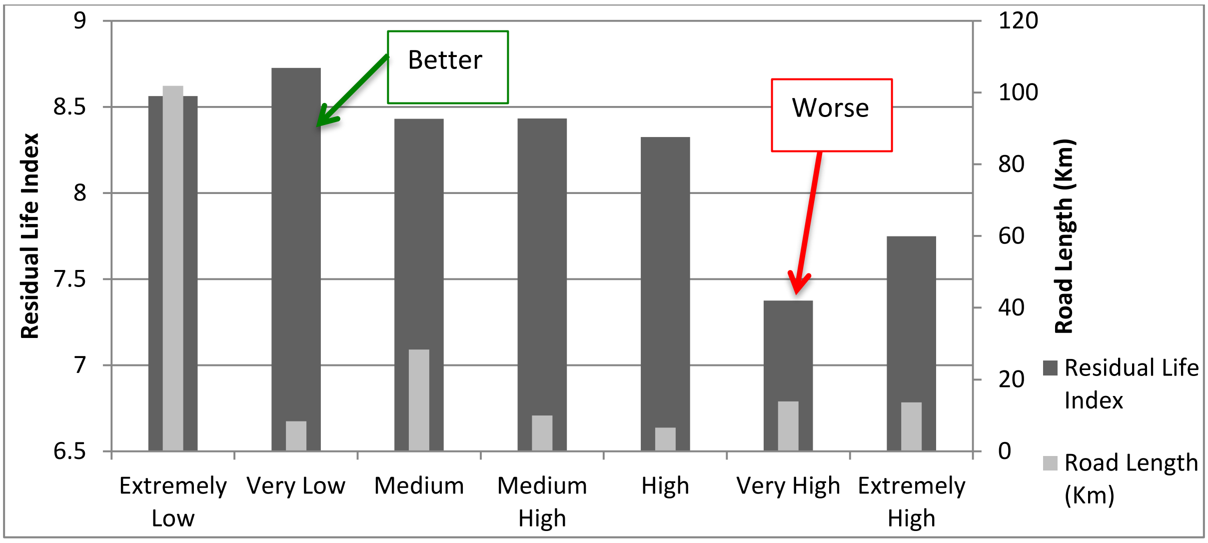

Figure 10: Clay related subsidence and residual life index (years)

Figure 10: Residual life index (years) is shown to have a general negative trend with regards to higher risk subsidence classes. However several indexes may be tentative due to the small length of roads surveyed. The majority of roads within the survey were situated on soils of an 'extremely low' subsidence class. It is also interesting to note that the 'very high' subsidence class has a lower residual life index (years) than that of 'extremely high', both have similar surveyed road lengths.

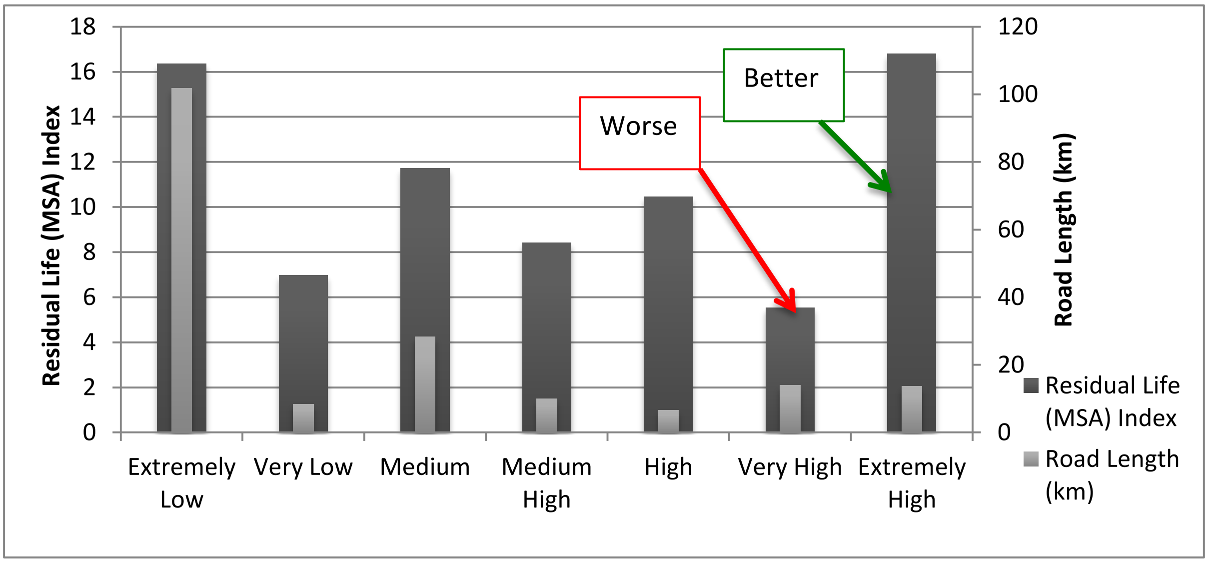

Figure 11: Clay related subsidence and residual life index (Million Standard Axles)

Figure 11: When assessing the residual life index (MSA) there does not appear to be any clear trend in the data, however what is most surprising is that the highest index is recorded for the 'extremely high' subsidence class.

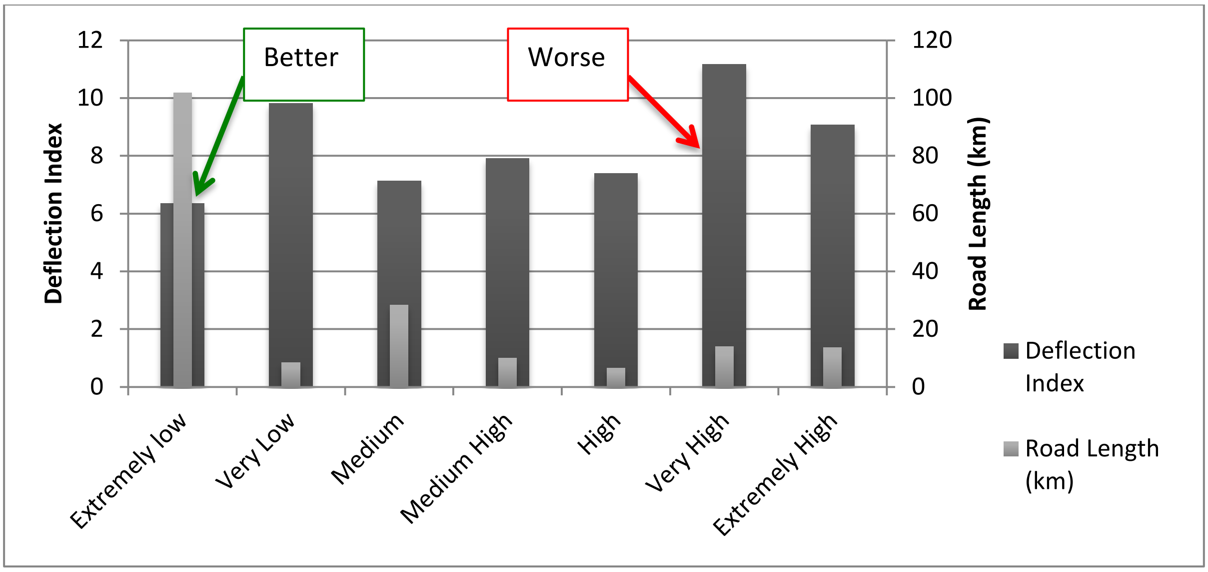

Figure 12: Clay related subsidence and deflection index

Figure 12: The deflection index shows a generally increasing trend with higher clay subsidence class. The 'high' and 'very high' class do not conform to this but this may be as a result of the low and higher road lengths respectively surveyed, similarly 'very low' class could be considered to be statistically insignificant.

3.2.2 Clay (1 in 150 year) related subsidence

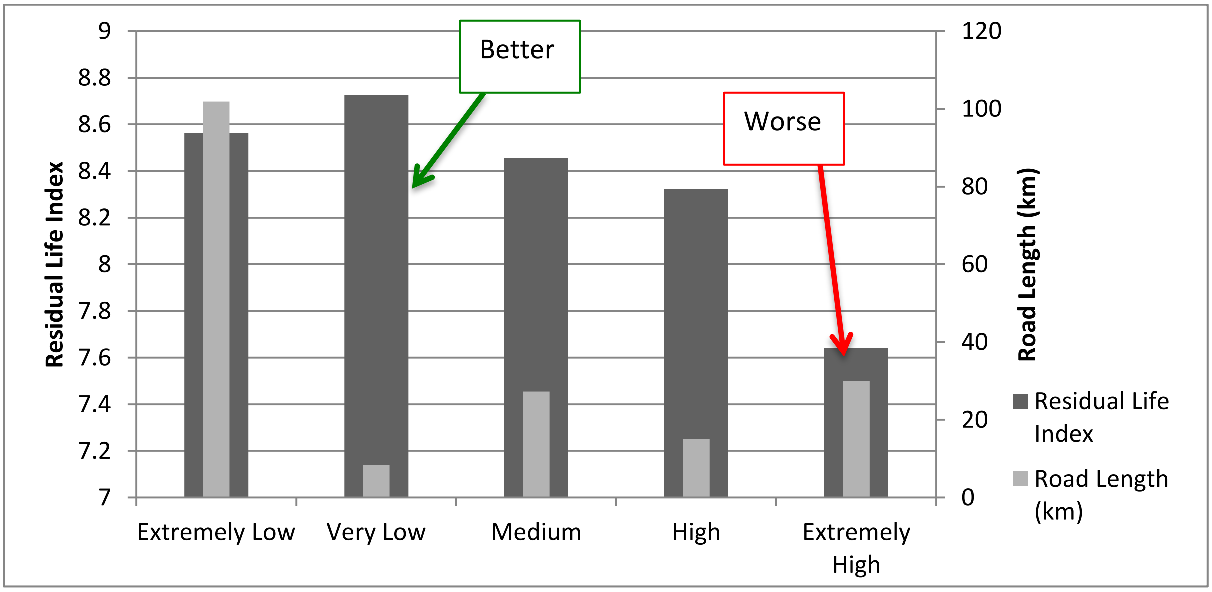

Figure 13: Clay (1 in 150 year) related subsidence and residual life index (years)

Figure 13: The residual life index (years) in the 1 in 150 year clay subsidence scenario is broadly similar to that of clay, however for the high and extremely high subsidence classes the residual life can be seen to be slightly decreased. This possibly indicates that clay soils of a high and extremely high class are likely to have a detrimental effect on residual life in future scenarios.

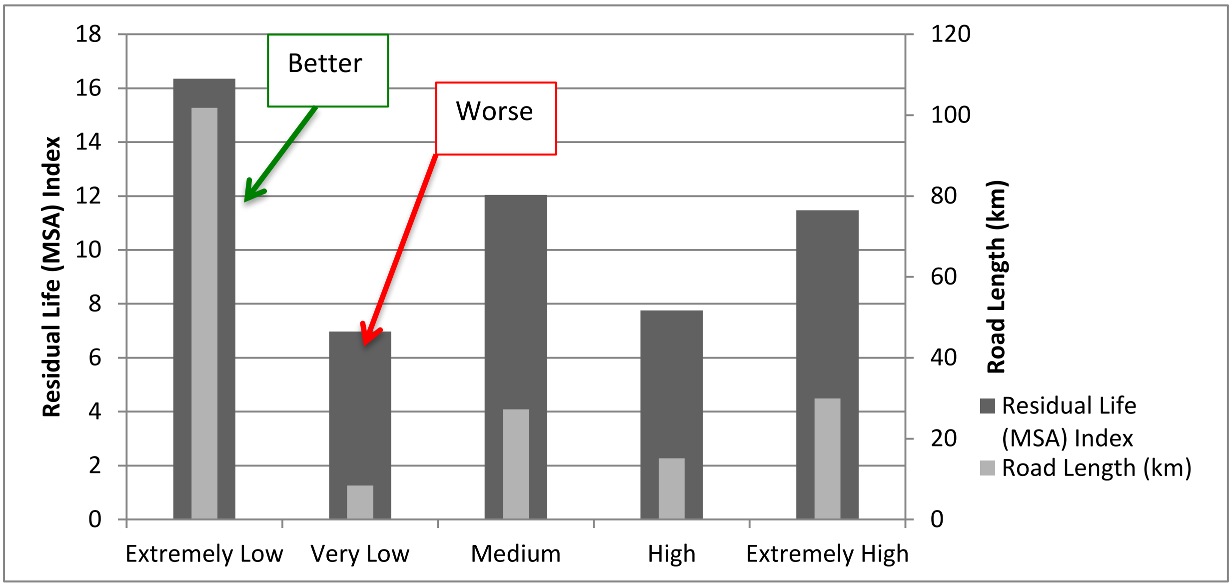

Figure 14: Clay (1 in 150 year) related subsidence and residual life index (Million Standard Axles)

Figure 14: With regards to residual life as a factor of MSA, again there is a similar resemblance to that of the clay identified previously. However, similar to the residual life (years), the high and extremely high subsidence classes show a fall in the residual life (MSA) in the 1 in 150 year scenario. This is especially so in the extremely high subsidence class which has a fall in residual life (MSA) index of ~6. This could be partially explained by the fact that for the 1 in 150 year model only uses 5 classes of subsidence class compared to the 7 used by the dominant clay model which could have redistributed the data giving the resultant changes in the residual life indices.

Figure 15: Clay (1 in 150 year) related subsidence and deflection index

Figure 15: The deflection index shows an increasing trend with higher risk of subsidence in the 1 in 150 year clay subsidence model. The 'very low' subsidence class is based upon a relatively small surveyed road length so could be considered statistically insignificant.

3.2.3 Silt related subsidence

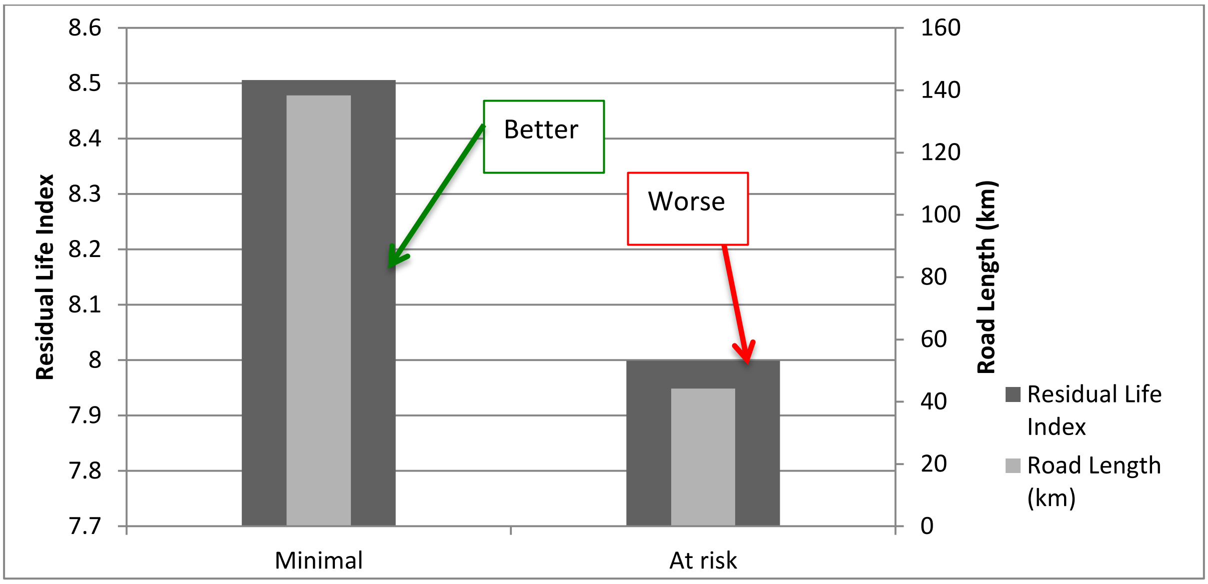

Figure 16: Silt related subsidence and residual life index (years)

Figure 16: The majority of surveyed roads in Lincolnshire are placed upon 'minimal' subsidence soils (138km) compared to 'at risk' soils (44km). The residual life index (years) is greatly decreased on 'at risk' soils, however this may be a factor regarding the distances in the road lengths surveyed.

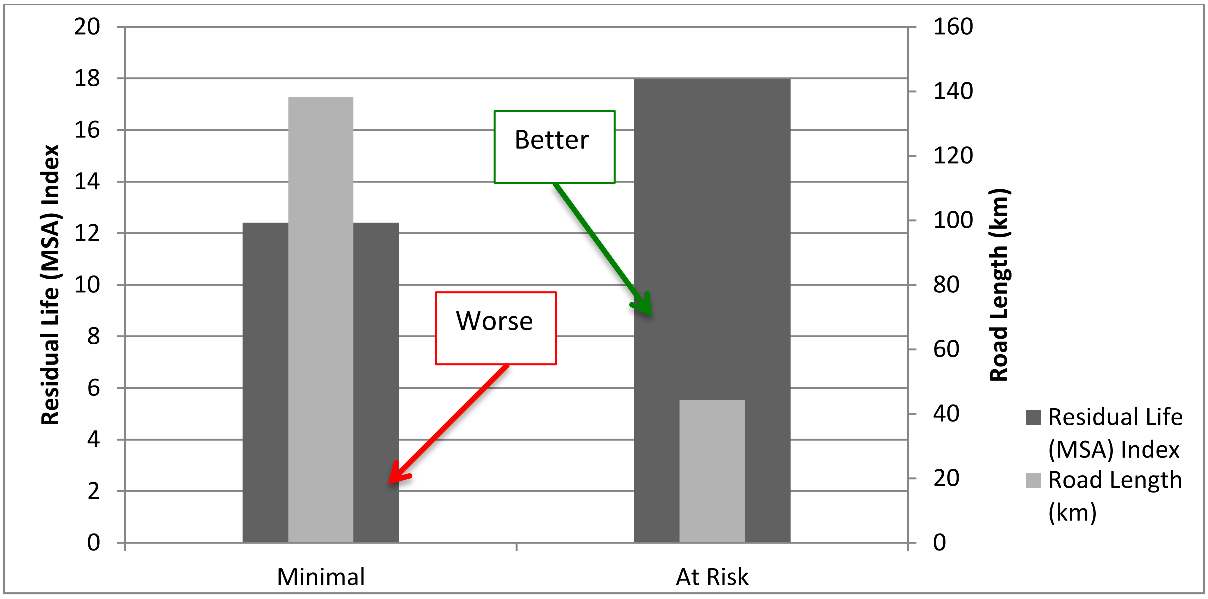

Figure 17: Silt related subsidence and residual life index (Million Standard Axles)

Figure 17: When silt related subsidence soils are compared against residual life as a factor of MSA we see a reverse effect whereby the residual life is increased on 'at risk' soils, at present it is unclear why this reverse effect is occurring between residual life index as a factor of years and as MSA.

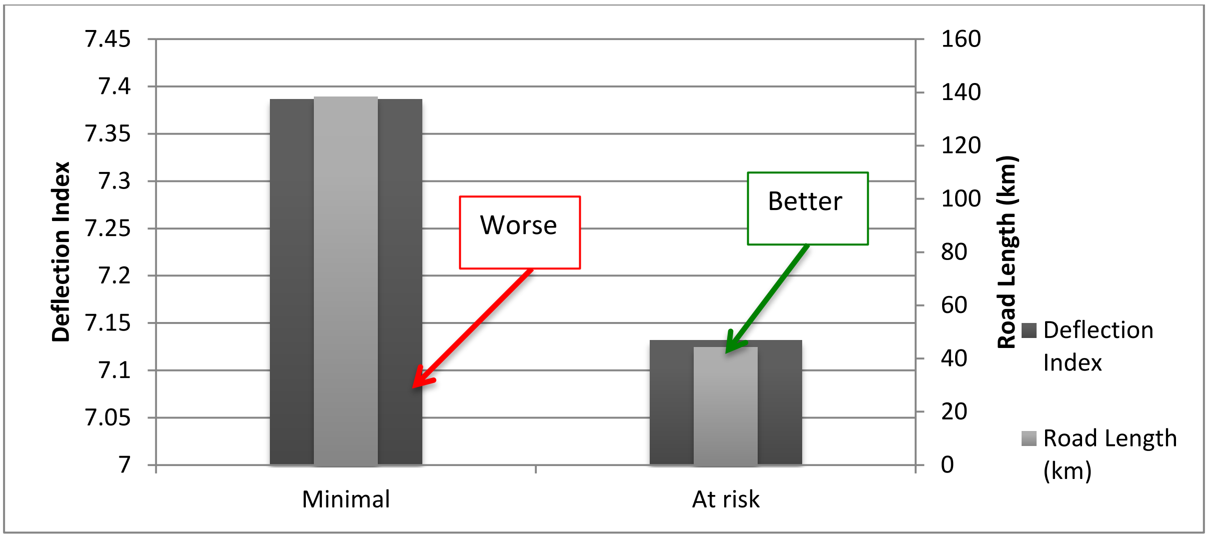

Figure 18: Silt related subsidence and deflection index

Figure 18: The deflection index shows a higher ratio for soils at 'minimal' risk of silt related subsidence. This is interesting as when referring to the residual life index (years) it would be expected to see a higher deflection index on the 'at risk' soils. However this also supports the theory that silty soils are susceptible to 'frost heave' rather than being subject to 'shrink-swell' processes, possibly explaining why the deflection is lower for the 'at risk' soils.

3.2.4 Peat related subsidence

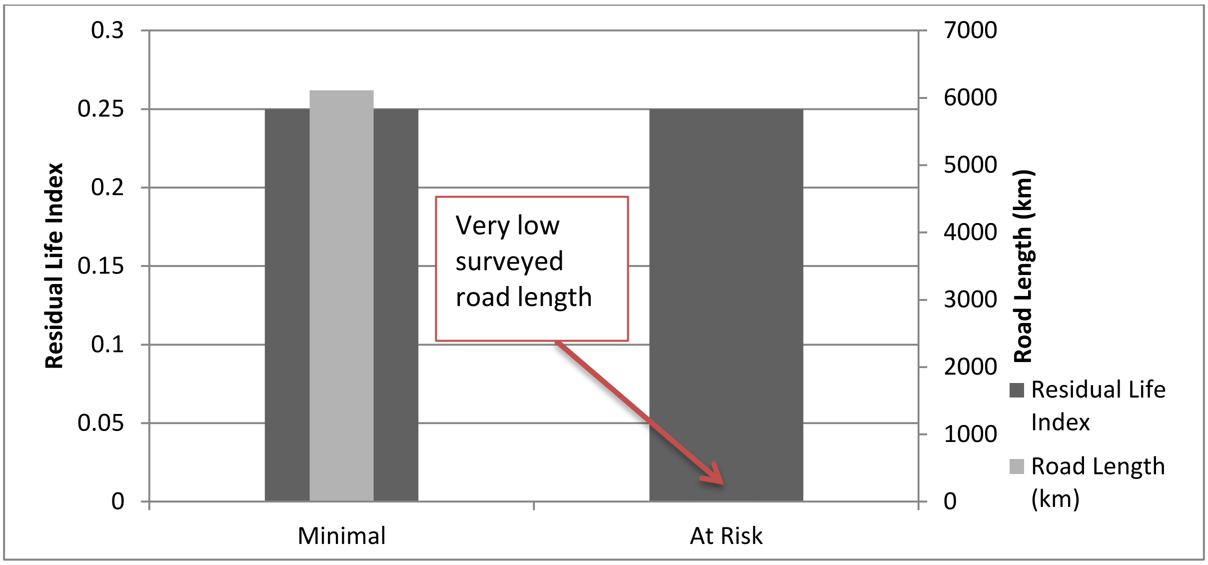

Figure 19: Peat related subsidence and residual life index (years)

Figure 19: It appears from the data that very few major 'A' and 'B' roads are built upon peat containing soils within Lincolnshire. Only 0.2km of surveyed roads using the deflectograph intersect with 'at risk' peat related subsidence compared to that of 182km that are at 'minimal' risk, the statistical significance of this data therefore cannot be relied upon.

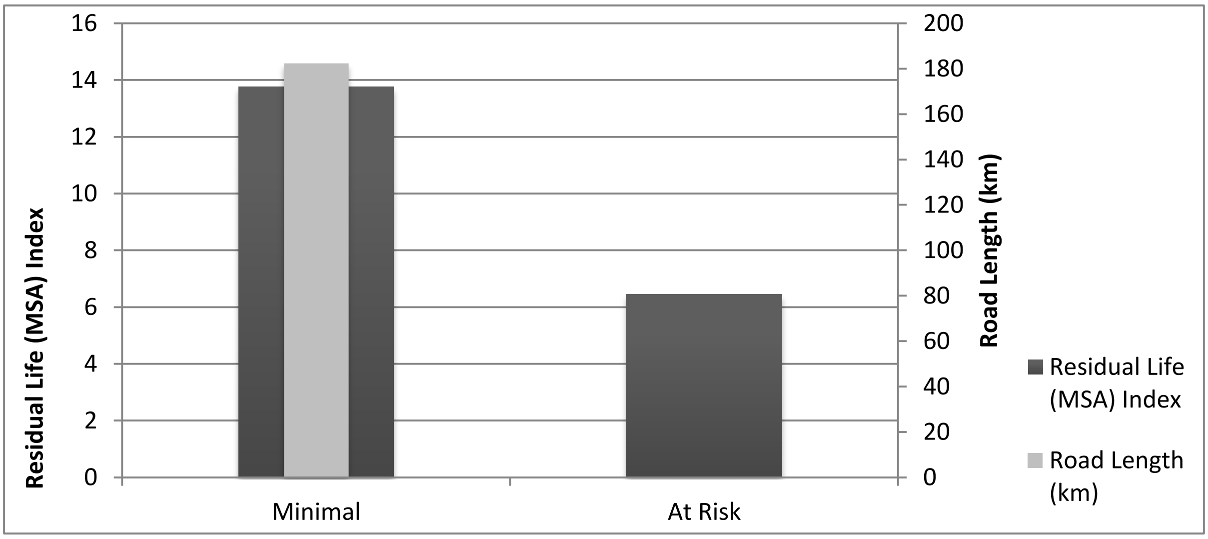

Figure 20: Peat related subsidence and residual life index (Million Standard Axles)

Figure 20: Similarly to Figure 19, the low surveyed road length of roads within 'at risk' peat soils means that this data cannot be relied upon for analysis.

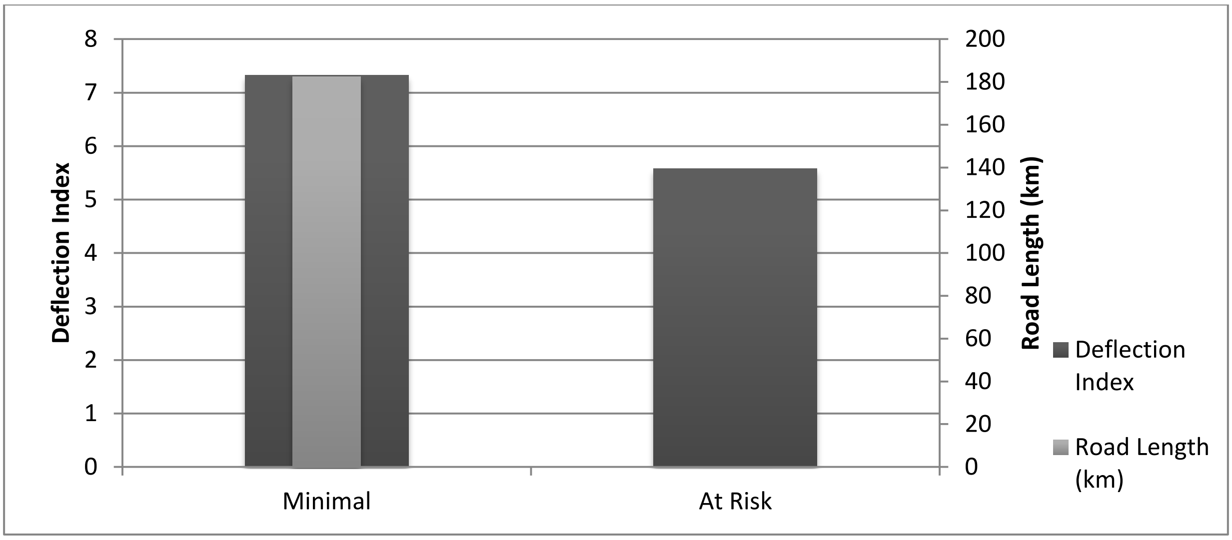

Figure 21: Peat related subsidence and deflection index

Figure 21: Similarly to Figure 19 and 20, the low surveyed road length of roads within 'at risk' peat soils means that this data cannot be relied upon for analysis.

3.2.5 Sand related subsidence

Figure 22: Sand related subsidence and residual life (years)

Figure 22: The majority of surveyed roads in Lincolnshire appear to be placed upon soils that have a 'minimal' sand related subsidence risk (148km) compared to those facing a 'high' risk (5km). Therefore some statistical errors could be resulting in this data.
Residual life (years) shows a clear pattern in regards to sand subsidence, where increasing sand content of the underlying soils has a positive effect on residual life. The relatively small length of road surveyed in the 'high' subsidence class could be resulting in an over exaggeration of residual life. However the figure above initially suggests that sandy soils are not significant in lowering the residual life of the road network.

Figure 23: Sand related subsidence and residual life index (Million Standard Axles).

Figure 23: In the context of residual life as a factor of MSA, sand content appears to have a negative effect on road condition, however it is not currently understood why this should be the case, suggesting that further analysis of data is needed.

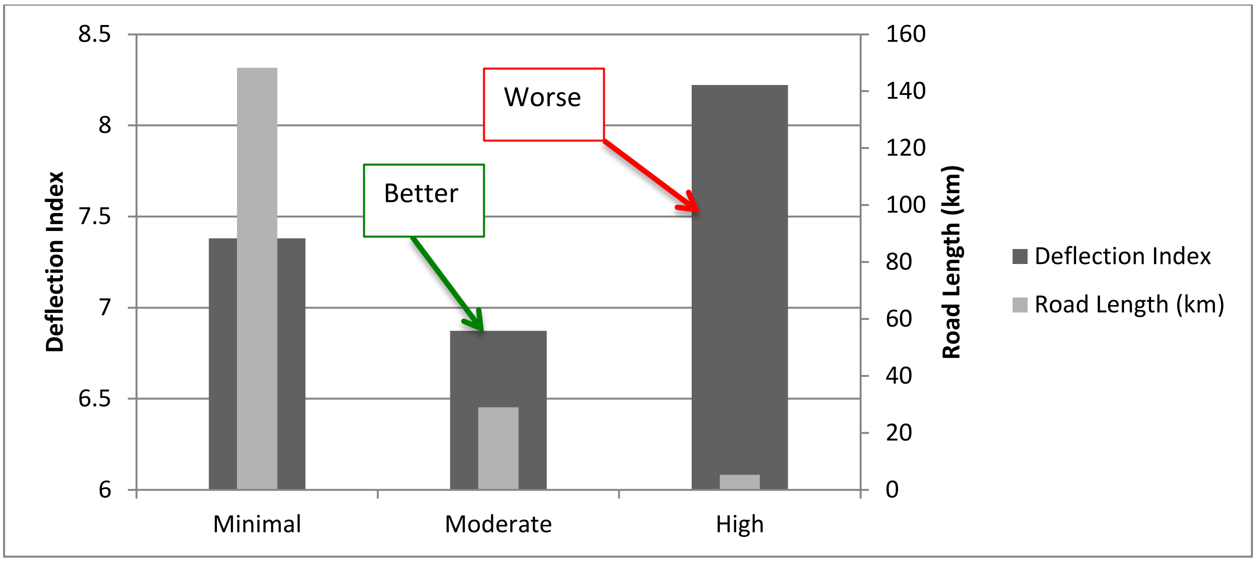

Figure 24: Sand related subsidence and deflection index

Figure 24: The deflection index increases with lesser sand content of soils when considering the ‘minimal’ and ‘moderate’ classes. However the ‘high’ subsidence class shows the largest deflection index, however this could be as a result of the short road length encountered within the survey. It could also suggest that with high sand content that the underlying soils are prone to subsidence, possibly as a result of sand-washout. However this is not the case when related against figure(s) 22 and 23 above.

3.2.6 Soft Ground related subsidence

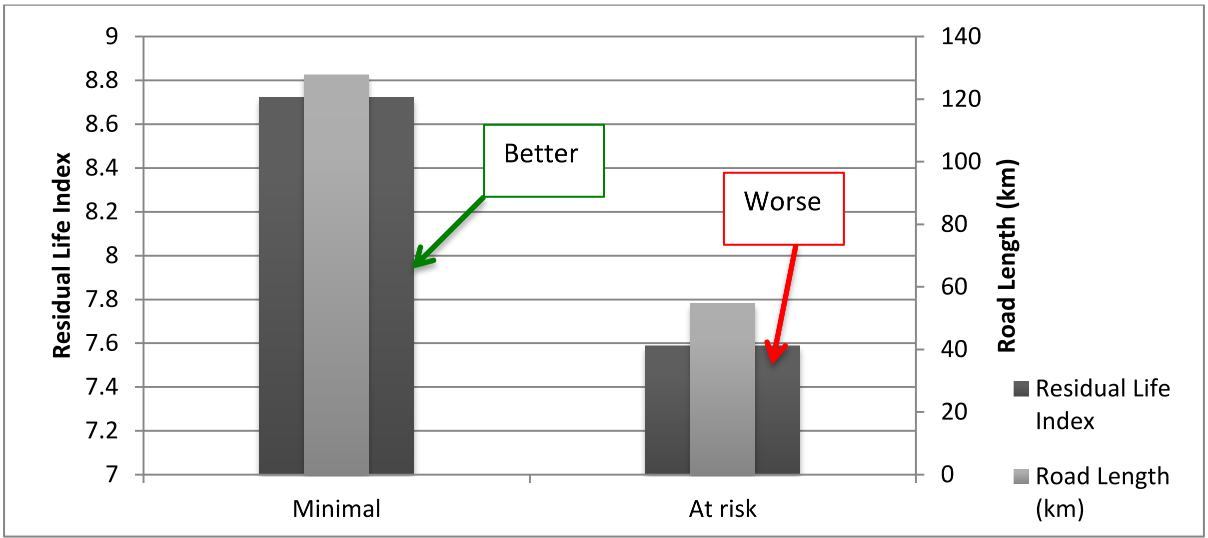

Figure 25: Soft ground related subsidence and residual life index (years)

Figure 25: Residual life index shows a clear trend with regards to subsidence related to soft ground. With lower residual life being associated with 'at risk' soils, also significant surveyed road lengths are associated with the two subsidence classes giving the trend statistical significance.

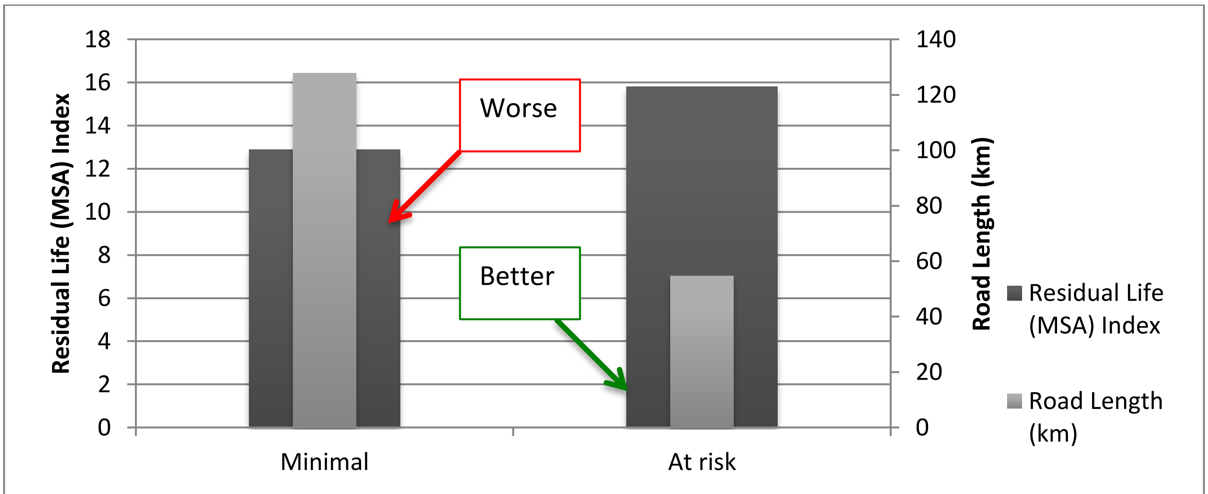

Figure 26: Soft ground related subsidence and residual life index (Million Standard Axles)

Figure 26: When residual life as a factor of MSA is considered it shows an opposite trend to Figure 25, whereby lower residual life is associated with 'minimal' risk soils. The reason for this relationship is currently unexplained and requires further research.

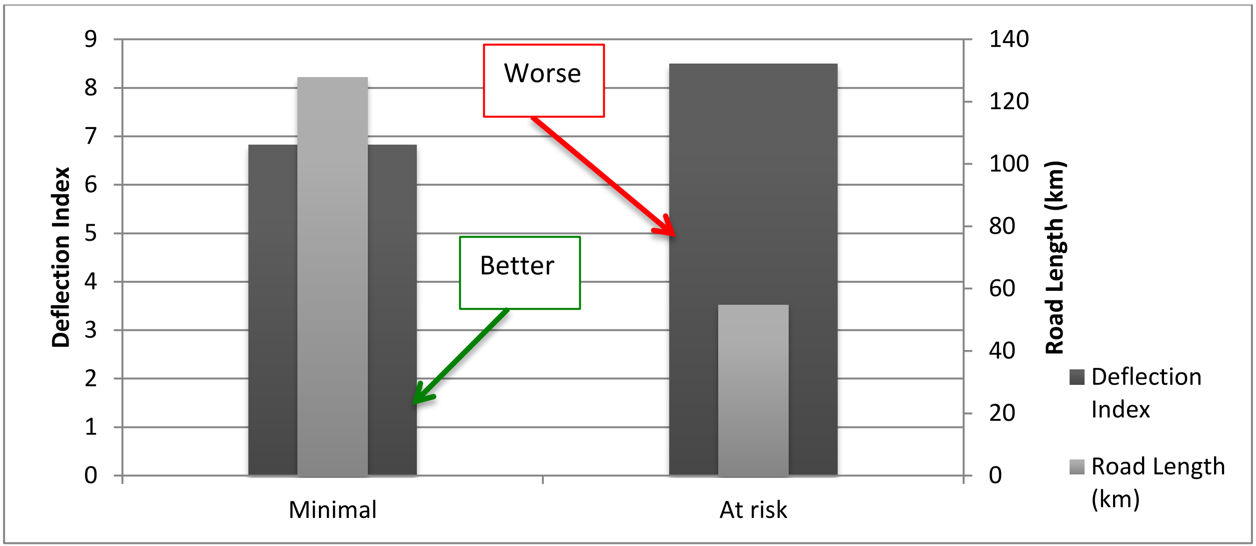

Figure 27: Soft ground related subsidence and deflection index

Figure 27: Deflection index is greatest on 'at risk' soils which is what would have been expected with regards to soft ground conditions.

4. Discussion

Road deterioration is affected by a number of recognised factors such as traffic use, infrastructure service trenches, cold weather, poor construction of roadway etc. These preliminary findings indicate that soil type also appears to have an important impact upon the condition of the highway network in the County of Lincolnshire. Indeed, certain soils have a striking relationship with road condition and from the data expressed within this report, it has become apparent that clay and silt containing soils are most damaging to the highway network in Lincolnshire. Although peat has been regarded as being prone to substantial ground movement the relatively few roads surveyed that are built on peat soils mean that the 'true' risk they have to the road network cannot be established through this short study alone.

The abundance of 'unclassified' surveyed roads on silt dominated soils could be explained by historical road building within the fenlands where roads were often placed upon extinct river channels (rodhams) (Astbury, 1958) which primarily consist of silt sized material, this was undertaken as not to encroach on the soft unsuitable surrounding peat soils of the fenlands (Figure 28). For example differential settlement of housing stock has occurred where house fronts are built upon the silt levee's and the rears encroach upon surrounding peat soils, with greater movement in the peat (Astbury, 1958).

It was interesting to see with regards to the deflection index that greater deflections were encountered on 'minimal' risk silt subsidence risk soils compared to that of 'at risk' class. This possibly suggests that silt soils might be subject to frost heave rather than 'shrink-swell' or 'compressible' processes, therefore not appearing compressible during the deflectogram survey. Road degradation on areas underlain by silt soils therefore could be a factor of colder weather and not necessarily a result of drought conditions. However peat soils that underlie the silt 'rodhams' (Figure 28) in certain areas of Lincolnshire under drought conditions could be subject to shrinkage processes resulting in subsidence of the silt and increased damage to roadways. Therefore further analysis of individual soil series for such areas are needed in order to further understand the issues at play.

The threat from future climate scenarios is not yet fully understood with regards to the impact of soil related processes on the highway network of Lincolnshire, however from this preliminary data it can be seen that certain soil types are having a statistically significant effect on the road condition. Especially if we consider the

1 in 150 year clay subsidence model which suggests that with increasing risk of subsidence class, the higher the road degradation.

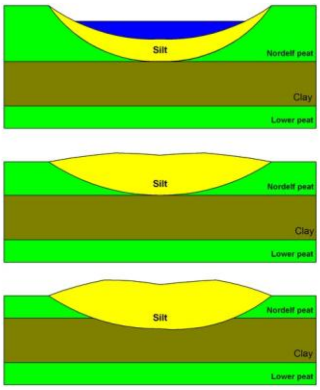

Figure 28: Formation of 'Rodhams' (Adapted from Fowler, 1932)

With a past knowledge of how certain soil types affect the highways network, future climate models could be utilised to gain an understanding of how soil type will affect road networks in the future, allowing more confident asset management for areas that are under threat from hazardous ground conditions (Forster and Culshaw, 2004).

4.1 Future Research Directions

This rapid, preliminary assessment has thus far shown how soil mapping and Natural Perils (NPD) geohazard data can be related to the condition of the roads in the County of Lincolnshire.

This short study is forming part of one of the author's (Oliver Pritchard) doctoral research at Cranfield University in 'Assessing the resilience of UK critical infrastructure to the impacts of soil related geohazards'. The research is being carried out on behalf of the Infrastructure Transitions Research Consortium (ITRC) project on the 'Long-term dynamics of interdependent infrastructure system', Work Stream 2 'Understanding the future risks of Infrastructure failure', considering an analysis of strategies for infrastructure provision in Great Britain (See www.itrc.org.uk for further information).

Encompassed within this research, future work could possibly consider previous year's road condition surveys, especially in times of drought, frost, and other significant climatic events. The economic impact of specific soil types on road condition and subsequent remediation costs could also be considered.

From this research in particular several key questions have been raised;

- Due to the lack of roads surveyed on peat soils, further data needs to be considered, if available, to understand if peat soils are in fact having a damaging effect on the highway network of Lincolnshire.
- Silt-related subsidence appears to a major contributing factor to road degradation in Lincolnshire, therefore what mechanisms are responsible, is drought (shrinkage) the major issue or is frost (heave) of silty soils causing roads to degrade?

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5. Acknowledgements

The authors would like to acknowledge the extensive contribution of infrastructure highways data by Mike Coates and Phil Shevill, Lincolnshire County Council. Thanks also go to Doug Robinson, Lincolnshire County Council for providing extensive information regarding Climate Adaptation in Lincolnshire.

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/!.

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Appendix One: National Soil Resources Institute

The National Soil Resources Institute, NSRI, is a centre within Cranfield University's Department of Environmental Science and Technology and leads Cranfield's research on soil, specifically by:

- Understanding the physical, chemical and biological processes that make up soil systems and that provide capacity for soil-based ecosystem services;
- Creating, maintaining and exploiting inventories and monitoring systems for soil resources;
- Developing digital soil mapping, pedometric methods and data specifications to represent thematic soil characteristics;
- Describing processes that expose or protect soils from threats (e.g. geohazards, impacts of diffuse agrochemicals, organic matter loss, erosion, contamination, compaction, loss of biodiversity and sealing), and developing policy and better technology for soil management and conservation in both rural and urban areas, including for sports surfaces;
- Applying engineering design and evaluation methods to improve the performance of off-road vehicles, construction equipment and land-based machinery.

NSRI holds and has the responsibility for managing national soil resource inventories for England and Wales. NSRI is the UK National Reference Centre for soil and is also a listed member of the European Topic Centre on Soil, a part of the European Environment and Observation Network (EIONET).

Through the work of staff across a number of inter-linked thematic areas covering Soil Conservation and Management, Soil Resources, Soil Systems and Agricultural and Environmental Engineering, as well as with our ownership of national and international soil data sets and other assets, NSRI is widely recognised as the 'national authority on soil resources in England and Wales'. Our profile as a leading European institute specialising in soil management and protection is high due to our membership of the European Soil Bureau Network, and our engagement with a series of key European research projects. The Agricultural and Environmental Engineering area has a strong pedigree of its own.

Scientific footprint
NSRI has traditionally worked within the following broad topic areas.

- Soil resources – characterisation, monitoring, sustainable management and protection;
- Soil as a component of the environment – soil functionality/ecosystem services, soil processes and the atmosphere and water resources, soils and climate change mitigation/adaptation, soil contamination, soil and the management of waste;
- Agriculture and the environment – diffuse pollution of water, interactions between soil and land use and management, integrated soil and water management;
- Land use – land classification and suitability, land use policy, development planning;
- Soils and machines – the machine:soil interface, precision soil/crop management systems, off-road vehicles.

NSRI online
More information regarding NSRI is available online:

Website URL	Description
www.cranfield.ac.uk/sas/nsri	The corporate home page of NSRI within the University
www.landis.org.uk	The home of LandIS, the Land Information System. Here links can be found to the many other resources offered, including:

National Soil Resources Institute (NSRI), Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK

Appendix Two: Soil Literature for Lincolnshire

During Cranfield University's (Dr. Stephen Hallett and Oliver Pritchard) visit to Lincolnshire County Councils 'Lincs Laboratory' on the 18th February 2013 we were pleased to present Mike Coates (Laboratory services manager) with the following literature pertinent to the soils of the County of Lincolnshire;

Books and associated maps:

Hodge CAH, Burton RGO, Corbett WM, Evans R and Seale RS. ***Soils and their use in Eastern England***.
Eastern England: Flat map 1:250,000

George H, Robson JD and Heaven FW. ***Soils in Lincolnshire I (Woodhall Spa)***
1:25,000 outline soil map
1:25,000 outline land use capability map
1:25,000 outline soil drainage map

George H and Robson JD. ***Soils in Lincolnshire II (Sleaford)***
1: 25,000 coloured soil map
1:25,000 coloured land use capability map

Heaven FW. ***Soils in Lincolnshire III (Donington on Bain)***
1:25,000 coloured soil map
1:25,000 coloured land use capability map

Robson JD. ***Soils in Lincolnshire IV (Friskney)***
1:25,000 coloured soil map

George H**.** ***Soils in Lincolnshire V (Covenham)***
1:25,000 outline soil map

Heaven FW. ***Soils in Lincolnshire VI. (Kirton in Lindsey)***
1:25,000 outline soil map

Heaven FW. ***Soils in Lincolnshire VII (Old Bolingbroke)***
1:25,000 outline soil map

Robson JD. ***Soils of the Boston and Spalding district***
1:50,000 coloured soil map

This literature should be consulted if any clarification is needed on the soil types encountered within the Lincolnshire County.