NF93

# Foundation solutions:

## future proofing against climate change

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NHBC FOUNDATION

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## future proofing against climate change

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NHBC Foundation

NHBC House
Davy Avenue
Knowlhill
Milton Keynes
MK5 8FP
Tel: 0344 633 1000
Email: info@nhbcfoundation.org
Web: www.nhbcfoundation.org
Twitter: @nhbcfoundation

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## Disclaimer

This publication provides general information on how climate change effects may influence building foundations. It may not deal with every aspect of how the design, construction or operation should be applied to particular circumstances and should not be treated, or relied on, as a substitute for specific advice relevant to particular circumstances. No responsibility is accepted for any loss that may arise from reliance on the information provided.

**The alternative materials and foundation solutions within this review are for illustrative purposes only and should not be viewed as any endorsement by the NHBC Foundation or as meeting NHBC Technical Requirements.**

All information is current at the time of researching of this document (July 2022) but may vary subsequently as this field is developing rapidly.

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## For further information, please contact:

NHBC Foundation, NHBC House, Davy Avenue, Knowlhill,
Milton Keynes, Buckinghamshire, MK5 8FP

Tel: 0344 633 1000

Email: info@nhbcfoundation.org

Web: www.nhbcfoundation.org

Twitter: @nhbcfoundation

# Executive briefing

What are the known and anticipated impacts of climate change on buildings and what are the implications for the design and construction of their foundations? This report provides an overview of the current state of knowledge in this area.

The report commences with the background to the climate emergency before outlining the predicted climate change impacts for the UK, such as extreme weather patterns (including higher intensity storm events), higher temperatures, increased flooding and sea level rise. The risks these pose to buildings, and those specifically associated with their foundations, are then identified.

Current and emerging policies, regulations and standards relevant to climate change/net zero and building construction and wider development are discussed. The review has been supplemented with data from an industry survey that has provided a 'snapshot' of current views and supporting anecdotal information on issues that have been experienced to date.

The report then homes in on two key risk areas: the effects of changing weather patterns and increased canopy cover (trees) in development, examining in detail the specific risks, likely future trends and current uncertainties and unknowns. The following risks are considered in the context of climate change impacts and associated mitigation options:

- subsidence/heave in shrinkable cohesive soils (shrink-swell)
- washout-induced damage or settlement
- reduction in soil strength associated with increases in porewater pressure
- dissolution and anthropogenic hazards of chalk/limestone, evaporites and other mining areas
- collapse settlements in earthworks and fills
- higher sea levels in coastal areas/corrosion of foundations from salt water.

Alongside the need for climate change adaptation, foundations represent a significant component of carbon emissions relating to construction, and this needs to be reduced to achieve net zero. This includes 'direct' emissions associated with materials, earthworks, transport, plant and waste for the installation of foundations and 'indirect' emissions through the relationship between foundations and carbon embodied in the rest of building structures. The range of currently available low carbon foundation solutions is considered along with the interactions between low carbon design and construction solutions and climate change resilience.

Case studies are used throughout the document to illustrate the issues and solutions covered.

In conclusion, the report recommends that for new build, designers of building foundations and developers should consider the identified climate change risks and associated geohazards and how these may vary over the lifetime of each development. Since it will take some time for further research to justify changes to the NHBC Standards or Building Standards, it is recommended that developers consider increasing their minimum foundation depths now to increase climate resilience rather than waiting for changes in standards to take place. However, this needs to be balanced against net zero considerations and the need to reduce, rather than increase, embodied carbon associated with building construction, so alternative foundation options should also be considered.

Recommendations are also made for further research in this area, including to inform future updates to NHBC Standards.

# 1 Introduction

Climate change is increasingly being seen as an existential risk, with action being taken at international, national and local levels. There is increasing evidence that climate change effects can exacerbate existing known risks, as well as pose additional risks, to buildings and their foundations. At the same time, the need to reduce carbon emissions during construction and over the operational lifetime of buildings is recognised. This also comes at a time of a recognised need for a significant increase in the construction of new homes due to demographic changes. This review focuses on the resultant risks to building foundations for houses and other low-rise buildings, which has received relatively little attention to date.

This review reflects on the most recent revision of planning policy in all UK nations, including the requirement for new developments to take a proactive approach to mitigating and adapting to climate change, considering the long-term implications for flood risk, biodiversity and landscapes, and the risk of overheating from rising temperatures.

The review also builds on the 2007 NHBC Foundation publication Climate change and innovation in house building: designing out risk.[1] This identified a wide range of risks relating to climate change impacts and other issues. With regard to foundations, these include soil dry/shrink or swell/heave changes in water tables, increased risk of damage by subsoil water and increased risks to basements.

A key aim of this review is to consider these and other risks in greater detail, to document current understanding and to identify the implications for foundation design and construction, including, where relevant, current NHBC Standards.

The implications for foundation failure mechanisms due to changes in weather patterns and climate are considered, along with the effects of increased tree/canopy cover on housing developments. The review also identifies recommendations for mitigation of the risks and any further research considered beneficial to address current uncertainties and data gaps.

In addition, the review aims to consider the carbon footprint of foundation systems, how this can be reduced and the interactions between climate change resilience and low carbon design and construction solutions. Case studies are used throughout the document to illustrate the issues and potential solutions are covered.

**The materials and foundation solutions discussed within this document are for illustration only and are not necessarily accepted by the NHBC.**

This review therefore aims to provide relevant information to support housing developers, their advisers and contractors to design and build resilient foundations to protect homes against the effects of climate change and that in themselves have minimal carbon emissions. It is intended to be read by anyone with a professional interest in the design and construction of housing. It will be of value in supporting housebuilders, contractors, consultants, architects, planners and regulators to understand how and why climate change has and will influence foundation choice, materials and design. The focus is on the UK context, but the content may be of wider interest beyond the UK.

# 2 Background to the climate change emergency

## 2.1 Introduction

This section opens with a brief description of the international (COP/UN) position on the climate emergency. It then covers known and predicted changes to the UK climate, climate-related hazards and risks and known costs of climate change events to the UK economy through reference to Environment Agency and Association of British Insurers (ABI) data on insurance claims. This leads on to discussion of climate-related risks specific to buildings and their foundations, focusing on four types of impact: hotter and drier summers; warmer and wetter winters; continued sea-level rise; and increased frequency and intensity of storms with high rainfall events.

The section also considers uncertainties and presents the findings of an online survey with relevant industry contacts completed as part of this review. This gathered anecdotal information on issues relating to design and construction of foundations with regard to potential climate change effects.

## 2.2 The climate emergency

### 2.2.1 Intergovernmental Panel on Climate Change

The Intergovernmental Panel on Climate Change (IPCC) recently released its latest report, Climate Change 2021: The Physical Science Basis,[2] which brings together the most recent advances in climate science to outline the current state of climate change. The opening line of the report's Summary for Policymakers reads: "It is unequivocal that human influence has warmed the atmosphere, ocean and land." The report, which was approved by 195 national governments, shows that rapid human-induced change is occurring in our climate. The concentration of $CO_2$ in the atmosphere is the highest it has been in two million years; sea level rise is at its fastest in 3000 years and arctic sea ice is at its lowest levels in at least 1000 years. Climate change can be a natural process, when temperature, rainfall, wind and other elements vary over decades or more. Over millions of years, the global temperature has been warmer and colder than it is now.

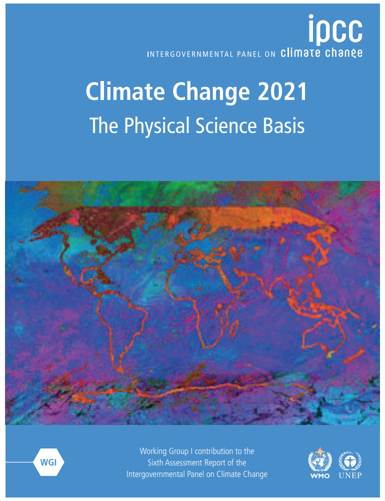


**Image 1** IPCC Climate Change 2021: The Physical Science Basis (Source: IPCC)

However, we are experiencing unprecedented rapid warming associated with human activities, primarily due to burning fossil fuels that generate greenhouse gases (GHG) such as carbon dioxide. The use of fossil fuels, including diesel and petrol to power vehicles and fuel oil and coal for heating, contributes to the release of carbon dioxide. Methane is another GHG which, along with carbon dioxide, is released by industry, landfill and agriculture.

According to the IPCC, GHG concentrations are at their highest levels in two million years and continue to rise. As a result, the Earth is about 1.1°C warmer than it was in the 1800s. The last decade was the warmest on record.

### 2.2.2 The United Nations Framework Convention on Climate Change

The UN 'Earth Summit' held in 1992 produced the United Nations Framework Convention on Climate Change (UNFCC), which was the first step towards addressing the issue of climate change. To date, 197 countries have ratified the convention.[3]

The Kyoto Protocol[4] set binding emission reduction targets for industrialised countries and economies in transition, with a focus on seven greenhouse gases. It had two commitment periods that ended in 2012 and 2020.

At the Conference of the Parties 21 (COP21), held in Paris in December 2015, 195 countries adopted the first-ever universal global climate deal (the Paris Agreement), which came into force in 2020. The agreement set out a global action plan to put the world on track to avoid dangerous climate change by limiting global warming to well below 2°C above pre-industrial levels and pursue efforts towards limiting to 1.5°C.[5]

The Paris Agreement is a legally binding international treaty, sponsored by the UNFCC, addressing crucial areas necessary to combat climate change[6] including:

- to well below 2 degrees Celsius, while pursuing efforts to limit the increase to 1.5 degrees
- establishing a global goal on adaptation: enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change in the context of the temperature goal of the Paris Agreement
- recognising the importance of averting, minimising and addressing loss and damage associated with the adverse effects of climate change, including extreme weather events and slow onset events, and the role of sustainable development in reducing the risk of loss and damage
- climate change education, training, public awareness, public participation and public access to information.

With these aims in mind, the agreement is revisited on a five-yearly basis to allow Parties to the Convention to evaluate and enhance the level of ambition of their climate action plans, known as nationally determined contributions (NDC).

In November 2021, the Conference of the Parties 26 (COP26) was held in Glasgow, involving 197 countries with a principal aim of limiting the rise in global temperature in line with the Paris Agreement. This concluded with all country participants agreeing to the Glasgow Climate Pact ('the Pact'),[7] that aims to accelerate action on climate change with a global focus. The Pact agreed actions across four key areas:

- **Mitigation** – reducing emissions, with more than 90% of world GDP covered by net zero commitments and 153 countries proposing new 2030 emissions targets.
- **Adaptation** – helping those already impacted by climate change, with 80 countries adopting either Adaptation Communications or National Adaptation Plans to increase preparedness for climate risks.
- **Finance** – enabling countries to deliver on their climate goals, with significant progress in delivering the $100 billion climate finance goal by 2023.
- **Collaboration** – working together to deliver even greater action through common reporting of emissions and support via the Enhanced Transparency Framework.[8]


**Image 2** COP 26, Glasgow, 2021 (Source: COP26)

## 2.3 Known and predicted changes to the UK climate

UK government responses to the climate emergency are summarised in **Section 3**.

The UK Climate Change Committee (CCC) published its Independent Assessment of UK Climate Risk (CCRA3)[9] in June 2021. The report looks at the priority climate change risks and opportunities in the UK alongside statutory adaptation advice for the UK government. The observed changes in aspects of UK climate taken from this report are shown in **Figure 1**, with the assessment reporting the following:

- The UK's annual average temperature has risen by around 0.6°C above the average of the 1981–2000 period, consistent with a trend of around nearly 0.3°C per decade since the 1980s. Sea levels have risen by 16 cm since 1900. The level of the seas around the UK has risen by around 6.5 cm since the 1981–2000 period.
- Episodes of extreme heat are becoming more frequent, with the chance of a hot summer now up to 25% per year compared to less than 10% a few decades ago. Cold extremes have also decreased in frequency and intensity.
- Data for heavy rainfall generally show an increase in very wet days across the UK, although there are challenges in distinguishing between human-induced climate change and the large interannual variability in the observational record at a UK-wide scale. There is some evidence that human-induced climate change has increased the likelihood of some observed UK precipitation extremes linked to significant flooding impacts.

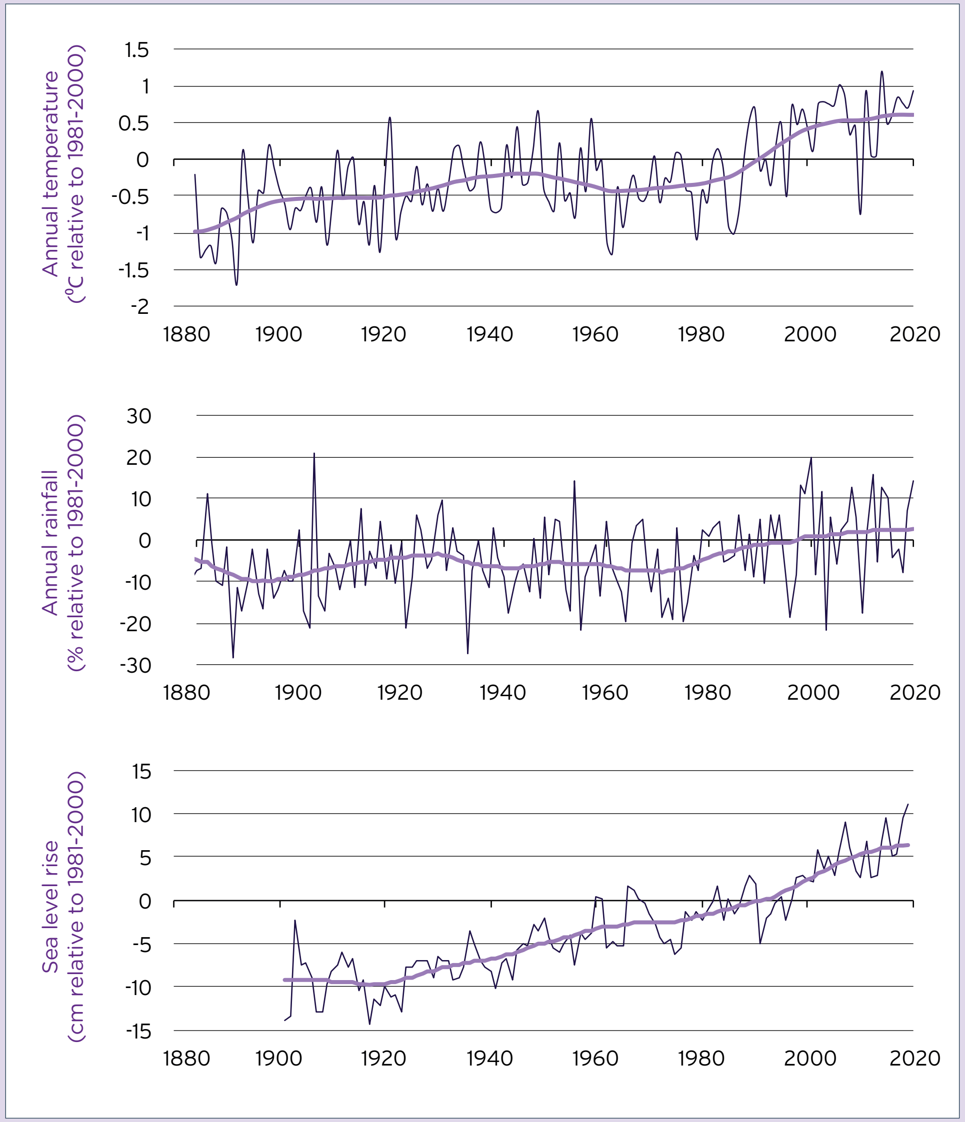


**Figure 1** Observed changes in aspects of UK climate (Source: CCC)

The report states that future changes in UK weather and climate depend on both the amount of future global GHG emissions and on how the climate responds to these emissions. However, expected changes in the UK's climate to 2050 are largely independent of the pathway of global emissions. The expected changes in UK weather and climate are stated to be as follows:

- **Warmer and wetter winters**: By 2050 the UK's average winter could be around 1°C warmer (0.5°C cooler – 2.5°C warmer uncertainty range) than it was on average over 1981–2000 and around 5% wetter (10% drier – 20% wetter uncertainty range). An increase in both the intensity of winter rainfall and the number of wet days is expected.
- **Hotter and drier summers**: By 2050 the UK's average summer could be around 1.5°C warmer (0°C – 3°C uncertainty range) than it was on average over 1981-2000 and around 10% drier (30% drier – 5% wetter uncertainty range). A summer as hot as that in 2018 (the joint hottest summer on record) for the UK as a whole, or indeed that experienced in July 2022, could be normal summer conditions by 2050. The temperature of the hottest days each year are expected to increase more than the average summer temperature increase. The intensity of summer rainfall (when it occurs) is expected to increase.
- **Continued sea-level rise**: The seas around the UK will continue to rise over the next three decades to 2050. By 2050 sea levels could be around 10-30 cm higher than over 1981-2000, depending on the specific location in the UK.

These changes in aspects of the UK's weather and climate over the next three decades will create additional weather and climate risks. For example, wetter winters will drive up the risk of flooding; drier summers increase the risks of water shortages and wildfire risk; hotter summers come with more intense heatwaves that can affect farming, human health and materials; and higher sea levels increase the risk of coastal erosion and coastal flooding from high tides and storm surges. Changes in rainfall and storm patterns will also have impacts.

Beyond 2050, changes in global and UK climate strongly depend on the future trajectory of global greenhouse gas emissions. Levels of global warming of 2°C and 4°C above pre-industrial levels by 2100 are used as indicative of the range of possible long-term changes that could occur for this risk assessment.

**Figure 2** is taken from CCRA3 and summarises observed and projected changes in UK hazards to 2100 due to climate change.

| Observed change | Expected change by mid-century | Global warming of 2°C above preindustrial levels by 2100 | Global warming of 4°C above preindustrial levels by 2100 |
|---|---|---|---|
| **0.6°C** from 1981 - 2000 | **~1.3°C** from 1981 - 2000 | **~1.5°C** from 1981 - 2000 | **~3°C** from 1981 - 2000 |
| **10 – 25%** chance of a '2018 summer',up from <10% a few decades ago | **~50%** chance each year | **~50%** chance each year | **>>50%** chance each year |
| **0** no significant long term trend | **~10%** drier than over 1981 - 2000 | **~15%** drier than over 1981 - 2000 | **~30%** drier than over 1981 - 2000 |
| **0** no significant long term trend | **~5%** wetter than over 1981 - 2000 | **~5%** wetter than over 1981 - 2000 | **~20%** wetter than over 1981 - 2000 |
| **0** some increase, but no significant long-term trend | **~10%** increase | **~20%** increase | **~50%** increase |
| **~6.5cm** above 1981-2000 | **10–30cm** above 1981-2000 | **25–45cm** above 1981-2000 | **55–80cm** above 1981-2000 |

Average annual UK temperatures · 'Hot summer' occurrence · Average summer rainfall · Average winter rainfall · Heavy rainfall · Sea level rise

**Figure 2** Observed and projected changes in UK hazards due to climate change (Source: CCC)

## 2.4 UK climate-related hazards and risks

As weather patterns change towards warmer and wetter winters and hotter and drier summers with high variability, CCRA3 also identifies weather-related hazards in the UK, including:

- increases in average and extreme temperatures in winter and summer; with hotter summers come more intense heatwaves
- changes to rainfall patterns, leading to flooding in some places at some times and water scarcity in others; wetter winters will drive up the risk of flooding while drier summers increase the risks of water shortages
- increased coastal flooding and erosion; higher sea levels increase the risk of coastal erosion and coastal flooding from high tides and storm surges
- increased frequency and intensity of wildfires
- potential changes to other weather variables, including wind strength and direction, sunshine and UV levels, cloudiness and sea conditions such as wave height.

As required by the Climate Change Act 2008, the UK government has undertaken the third five-year assessment of the risks of climate change to the UK, which was published in January 2022.[10] This Technical Report for the third UK Climate Change Risk Assessment presents strong evidence that even under low-warming scenarios, the UK will be subject to a range of significant and costly impacts unless significant further action is taken now. Full details of the risk assessment are contained in a series of reports published by the Climate Change Committee (CCC), which are endorsed by the UK government and the devolved administrations.

The third Technical Report identifies 61 climate risks cutting across multiple sectors of society. It identifies a wide range of potential costly impacts of climate change, including on health and productivity, affecting many households, businesses and public services. Impacts range from a deterioration in soil health and agricultural productivity to impacts on water availability and quality and implications for alternative energy supply. Section 2.6 considers these risks specifically in the context of buildings.

Based on the latest UK climate projections provided by the Met Office (UKCP18), the current data does not indicate the climate stabilising this century and climate change, therefore, should be considered an ongoing phenomenon, rather than be defined as a step change. The challenge faced is consequently one of adaptation, both to ensure that the necessary frameworks, policy and design codes are established, enabling robust, sustainable and future-proof construction in the face of intensifying extremes, but also, initially, to enable a clear understanding of the effects of such extremes on the natural mechanisms and functions in the environment that are driving the requirement for change. This review explores a variety of existing UK geohazards that face amplification under projected changes to our climate and weather systems, which both current and future development will be required to withstand.

Beyond the standard UK climate projections, it is also recognised that there are additional risks ("known unknowns" and "unknown unknowns") relating to climate change impacts, which are considered in **Appendix A**.

## 2.5 Known costs of climate change events to the UK economy

### 2.5.1 Insurance claims

In March 2020, the ABI reported[11] insurance payouts in response to property damage caused by the February 2020 storms Ciara and Dennis in the region of £363 million. Of this amount, £214 million related to flooding, with 350 residential property flood claims totalling an estimated £107 million. The average cost of repairing a flood-damaged home was around £32,000.

More specifically in relation to building foundations, according to the ABI,[12] 2018's extreme summer heatwave led to more than 10,000 households needing to claim for damage caused by subsidence, at a cost of more than £64 million. Further analysis of the data indicates that only 2500 claims (totalling £14 million) were recorded during the previous quarter of 2018. This represents a quarter-on-quarter increase of 350%, the highest seen in the previous 25 years. It is also worth noting that most insurance policies have an excess of around £1000 for a subsidence claim, therefore the figures quoted will be an underestimate of the total cost impacts.

Subsidence-related claims are expected to increase significantly as a result of the hot and dry summer of 2022: "an increased frequency and severity of major weather events means a higher number of more costly claims for insurers to deal with, globally as well as in the UK." [13]

### 2.5.2 Environment Agency flood management

In July 2021, the government published Flood and Coastal Erosion Risk Management: An Investment Plan for 2021 to 2027 [14] based upon £5.2 billion investment over six years, funding around 2000 new defence schemes protecting 336,000 properties.

## 2.6 UK climate-related risks specific to buildings

CCRA3 includes consideration of risks to people, communities and buildings from river and surface flooding, coastal flooding and sea level rise. For example, for a 2°C increase by 2100, annual damage from flooding for non-residential properties across the UK is expected to increase by 27% by 2050 and 40% by 2080. For a 4°C increase, this rises to 44% and 75% respectively over the same timescales.

In addition, "risks to building fabric" are one of twenty risks assessed as requiring "further investigation" at the UK-wide level. This means more evidence is required to fill significant gaps or reduce the uncertainty in the current level of understanding in order to assess the need for additional action. The magnitude of the risks to building fabric are categorised as "High" (defined as £ hundreds of millions per annum) in the 2050s and "Very High" (defined as over £1 billion per annum) in the 2080s.

**Table 1** lists the climate change impacts, risks and implications for the design and construction of building foundations, which is the focus of this review. These specific geohazards are considered further below, with the items in bold covered in detail in Sections 4 and 5. There are other potential considerations for potential impact to buildings, such as high winds accompanying storms, however these are not considered explicitly here as they do not relate direct to building foundations.

| Climate change impacts | Risks* | Discussed in detail in sections | Geohazards that could impact existing buildings and foundation design for new buildings |
|---|---|---|---|
| **Hotter and drier summers** | **Desiccation effects in shrinkable cohesive soils (clays) leading to subsidence/heave and building damage (shrink-swell)** | 4.3.1 | Potential damage to existing buildings constructed in accordance with current standards.<br><br>New buildings may require design and construction of deeper foundations to counter the effects or use of alternatives. |
| | | 5.6 | Interface with increased canopy cover/ trees/vegetation exacerbating effects. |
| | Wildfires spreading from vegetated areas causing fire damage to buildings | 2.6.1 | - |
| **Warmer and wetter winters** | Lack of ground freezing and higher water tables | 2.6.2 | Unlikely to impact existing buildings[1].<br><br>Increasing difficulty of construction of foundations and infrastructure in winter. |
| **Continued sea-level rise** | **Coastal flooding and storm surges – coastal erosion and site inundation leading to rockfalls, subsidence and building damage** | 4.3.2.1 | Direct and indirect effects on existing buildings.<br><br>Siting of new buildings will require careful assessment but then will not directly affect foundation design. |
| | **Higher sea levels in coastal areas/ corrosion of foundations from salt water** | 4.3.2.2 | Potential damage to existing buildings.<br><br>New buildings will require foundation design to consider corrosion potential. |

1 Wetter winters can also cause rebound of soil moisture levels leading to swelling; this is considered in Section 4.3.1

| Climate change impacts | Risks* | Discussed in detail in sections | Geohazards that could impact existing buildings and foundation design for new buildings |
|---|---|---|---|
| **Increased frequency and intensity of storms with high rainfall events** | Flooding – direct damage, erosion and site inundation | 2.6.4 | Potential damage to existing buildings. |
| | **Washout induced damage to foundations and structures** | 4.3.3 | Design of foundations for buildings in flood-prone areas will have to consider the risk of washout. |
| | Slope stability – landslips | 2.6.4.1 | Potential damage to existing buildings. |
| | **Reduction in strength associated with increase in porewater pressure on engineered structures and natural slopes** | 4.3.7 | Potential increases in porewater pressure and potential loss of effective strength will have to be considered in stability assessments during design of new developments. Potential requirement for slope stabilisation. |
| | **Dissolution and mining of chalk limestone and evaporites** | 4.3.4 (chalk and limestone)<br>4.3.5 (evaporites) | Rainwater is slightly acidic and as a result, dissolves evaporites and calcareous rocks such as chalk and limestone. This process creates underground voids and collapse and potential catastrophic surface settlements and subsidence. Some of these deposits have also been mined over millennia with resulting geohazards. All these features have the potential to be exacerbated by the effects of climate change. |
| | **Collapse settlements in earthworks and fills (principally cohesive and weak rock fills) due to inundation** | 4.3.6 | Potential damage to existing buildings.<br>Potential requirement on new developments for pre-construction consolidation of fills. |
| | Mining areas – sinkholes and other erosion leading to subsidence and building damage. | 2.6.4.2 | Potential damage to existing buildings.<br>For new developments, careful assessment of old mine entries and associated backfill required in light of potential groundwater rise. |

**Table 1** Climate change risks and associated geohazards directly relevant to the design and construction of building foundations

* Risks in bold are considered in detail within later sections of this review report

### 2.6.1 Hotter and drier summers

One of the key potential impacts on building foundations associated with hotter and drier summers is desiccation effects in shrinkable cohesive soils (clays) leading to subsidence/heave and building damage (shrink-swell). Shrink-swell is defined by the BGS[15] as the volume change that occurs as a result of changes in the moisture content of clay-rich soils. Swelling pressures can cause heave or lifting of structures, while shrinkage can cause settlement or subsidence, including differential settlement. This issue is considered in detail in **Section 4.3.1**.

As seen in the summer of 2022,[16] extremely hot and protracted dry weather can also create the conditions for wildfires in vegetated areas, such as grasslands, that can then spread, causing direct fire damage to properties. While of concern, this 'indirect' risk is not considered explicitly within this report as it does not directly concern the design and construction of foundations.

### 2.6.2 Warmer and wetter winters

Wetter winters can increase the potential risks to buildings and structures in areas dominated by clays with a high/very high potential for volume change due to heave. Wetter winters and the associated greater amount of groundwater recharge occurring over a shorter period may also be a contributory factor to increased shrink-swell effects.

There is also some anecdotal evidence that wetter conditions are leading to increased dewatering needed to construct shallow foundations and an absence of ground freezing may impair excavation work in winter due to poor ground conditions. This has implications for both design and construction of foundations.

### 2.6.3 Continued sea level rise

#### 2.6.3.1 Coastal erosion

The Futurecoast data and the National Coastal Erosion Risk Map (NCERM) shows that about 1800 km of open coast is eroding.[17] In some places, it is eroding more than 2m per year. About a quarter is eroding at more than 10 cm per year. The NCERM indicates that by 2060, about 2000 properties are at risk of being lost to coastal erosion. This assumes all current shoreline management plan (SMP) policies are implemented, which may not be the case. Examples of resulting issues are shown in Table 2, which has been extracted from Shoreline management plan guidance Volume 2: Procedures (Defra, March 2006).

| Issue | Justification | Objective |
|---|---|---|
| Loss or damage of residential properties (>100) through flooding or erosion | Homes for people. Anxiety and stress to owners and occupiers facing loss. Devaluation of neighbouring property.<br><br>Impacts on community cohesion (socio-economic) | Prevent loss or damage due to erosion or flooding |
| Potential threat to recreation areas from flooding or erosion | Important amenity areas for local residents and visitors to area (socio-economic) | Prevent loss due to flooding or erosion |

**Table 2** Examples of issues taken from Shoreline management plan guidance Volume 2: Procedures, March 2006 (Source: Defra)

In response to the risks of coastal erosion, the Scottish Government's Dynamic Coast research project, funded by the Centre of Expertise for Waters (CREW) was established to improve the evidence and awareness on coastal change and adapting to climate change. The building on the Dynamic Coast study identified the location of erodible shores and change in shoreline over 130 years; in 2021 the Dynamic Coast research project reported:[18]

- Coastal erosion currently affects 46% of soft shorelines (an increase from 38% over that reported in 2017). The increase in extent of eroding shoreline impacts on the average erosion rate of circa 0.43m/yr, a value lower than the 1m/yr previously reported.
- The extent and rate of coastal erosion, and the risk to coastal assets, is expected to increase under all emissions scenarios. Under a high emissions scenario, 75% of soft coasts are expected to be eroding by 2050. Under a low emissions scenario, erosion extent, rates and risk are lower but they remain significant.

Sea level rise impacts are considered further in **Section 4.3.2**.

### 2.6.3.2 Corrosion of foundations from salt water

Increasing sea level rise brings with it the risk of increased saline intrusion into groundwater. Consequently, foundations in coastal areas placed in non-saline groundwater may over time be exposed to salt water and its associated corrosive effects. Whereas the chloride does not have a significant adverse impact on mass concrete, it is a major factor in the failure of reinforced concrete structures. By causing the reinforcement to rust, the resultant expansion ultimately causes failure of the structural element. Consequently, sea level rise has the potential to adversely affect the performance of reinforced concrete and substructures. These issues are discussed further in **Section 4.3.5**.

## 2.6.4 Increased frequency and intensity of high rainfall events

Increases in average winter rainfall and the frequency of severe weather events are leading to a greater risk of flooding, exacerbated by increased surface water run-off in urban/developed areas with a higher proportion of hardstanding. In addition to groundwater flooding, surface water flooding ('pluvial' flooding) is potentially a greater source of flood risk.

Evidence suggests that there is already a 1% risk each year that monthly winter UK rainfall could be 20–30% higher than the maximum ever observed.[19] In one event, the flooding of summer 2007 occurred after one of the wettest May and June periods since records began in 1766, with over 55,000 homes in the Midlands and Home Counties affected by flooding. The estimated totals of households flooded in England and Wales over this period are shown in **Table 3**.

| Government Office Region | The number of households flooded* | The number of households flooded* | Total* |
|---|---|---|---|
| London | 1108 | 302 | 1410 |
| Yorkshire and Humbershire | 23479 | 3718 | 27197 |
| South East | 5896 | 129 | 6025 |
| Welsh Assembly Government | 32 | 4 | 36 |
| East Midlands | 4581 | 290 | 4871 |
| West Midlands | 8450 | 1453 | 9903 |
| South West | 4915 | 1000 | 5915 |
| **Total** | **48461** | **6896** | **55357** |

**Table 3** 2007 summer floods - Environment Agency - A table showing the approximate number of properties and businesses flooded by Government Office Region (Source: Environment Agency)

Flooding-related impacts to building foundations, i.e., washout-induced damages, are considered further in **Section 4.3.3**. Dissolution and mining of chalk limestone and evaporites due to increased rainfall are considered in **Section 4.3.4–5**.

### 2.6.4.1 Landslides

Landslides and landslips represent risks to dwellings throughout the UK and can be associated with heavy rainfall events. With the predicted increase in heavy precipitation, risks of potential landslides could also increase.

There are reported to be over 2000 coal tips in Wales, 294 of which have been identified as high risk.[20] Following heavy rain during Storm Dennis in February 2020, a major slope failure occurred at Llanwonno coal tip near Tylorstown, South Wales.[21] In 1966, after a period of heavy rainfall, the Aberfan tip, which had been placed on a natural spring, destabilised, resulting in 110,000 m$^3$ of colliery tailings spoil flowing downhill, engulfing a school and a row of houses.[22]

Slope stability is considered further in **Section 4.3.7**.

#### 2.6.4.2 Subsidence in mining areas

The CCRA technical report (CCRA3)[23] highlights that subsidence is also a risk for houses in areas with past mining activities. The report cites houses in Skewen in South Wales, where a subsidence event was triggered by heavy rainfall following Storm Christoph in January 2021. The houses were flooded following a mine shaft 'blow out' caused by water building up in the mine shaft that then collapsed. Consideration of the full range of mining-related geotechnical risks is beyond the scope of this report, although **Section 4.3.6** covers collapse settlements in earthworks and fills due to inundation.

Climate change impacts may also affect the risks from mine gas to development. This issue is considered in the CL:AIRE 2021 publication Good Practice for Risk Assessment for Coal Mine Gas Emissions.[24]

### 2.6.5 Current uncertainties and unknowns on changes to the UK climate

Further to the detail provided above based on 'standard' UK climate change predictions, there are uncertainties relating to other mechanisms that could influence the UK climate in the future, which may have significant impacts on buildings, including foundation design and construction. These known unknowns are outlined in **Appendix A.** It is further acknowledged there is additional uncertainty and potential unpredictable effects, e.g., feedback loops/tipping points, may emerge in the future through scientific observation (unknown unknowns).

## 2.7 Survey of industry practitioners

During the preparation of this guidance, RSK undertook an online survey of relevant industry contacts, including NHBC contacts and AGS members. The aim was to obtain a 'snapshot' of current industry perspectives with regard to climate change and considerations for the design and construction of building foundations. Details of the survey findings can be found in **Appendix B** and are referenced in the following sections where relevant.

# 3 Legislation and policy responses

## 3.1 Introduction

This section prides a brief summary of legislation and policy responses in the UK, including across the devolved regions, with further detail provided in **Appendix C**.

## 3.2 Government responses

The Climate Change Act 2008 sets long-term emission goals along with interim targets reported as carbon budgets and climate change risk assessments (CCRA) every five years. Responses to the risks identified by the CCRA are set out in the National Adaptation Programme (NAP). The Adaptation Sub-Committee (ASC) of the independent Committee on Climate Change (CCC) advises government and evaluates progress on adaptation.

In 2016, the Paris Agreement was ratified by the UK and on 27 June 2019, the UK became the first major economy to pass a net zero emissions law[25] requiring the government to reduce the UK's net emissions of greenhouse gases by 100% relative to 1990 levels by 2050.

The Sixth Carbon Budget published by the CCC provides ministers with advice on the volume of greenhouse gases the UK can emit during the period 2033–37. While no specific reference is made to construction and tackling climate change, the required 78% reduction in emissions by 2035 will mean that all sectors, including the construction industry, will be expected to play their part.

The Department for Environment, Food and Rural Affairs (Defra) leads on adaptation policy in England and throughout the UK on a range of reserved matters, including cross-cutting action required under the Climate Change Act 2008; however, the bulk of climate change policy is devolved for Scotland, Wales and Northern Ireland.

In Scotland, a five-year Scottish Climate Change Adaptation Programme was published in 2019, to ensure Scotland is resilient to climate change, with seven high-level outcomes. These were derived from the UN Sustainable Development Goals and Scotland's National Performance Framework and comprise communities, climate justice, the economy, infrastructure, the natural environment, the marine environment and international partnerships.

In Wales, the Well-being of Future Generations (Wales) Act 2015 sets out "Well-being Goals", including the goal of "A Resilient Wales", for public sector organisations, as well as the establishment of Public Services Boards to make well-being assessments locally. The Environment (Wales) Act 2016 has provision for climate change, including requirements around natural resources policy and a duty to protect our ecosystems.

The first Northern Ireland Climate Change Adaptation Programme (NICCAP1) was laid before the Northern Ireland Assembly in January 2014. It covers the period 2014–2019 and responds to risks and opportunities identified in the CCRA for Northern Ireland, published in 2012. A second NICCAP (NICCAP2) published in 2019 covering the period 2019–2024, sets the strategies, policies and action plans and includes adaptation actions to be implemented by local government.

## 3.3 Planning policy and strategy

Planning policy in England is outlined within the National Planning Policy Framework (NPPF), with the National Planning Framework in Scotland, Planning Policy Wales and The Strategy Planning Policy Statement in Northern Ireland. All include policies and statements aimed at responding to climate change, including reducing greenhouse gases and encouraging adaptation and mitigation to climate change (see further detail in **Appendix C**).

However, there is little evidence that the future risks from climate change in scenarios of either 2°C and 4°C global heating by 2100 are yet being integrated into planning, building design or retrofit, potentially locking in homes to some future risks.[26]

## 3.4 Local government responses

At the time of writing, around 300 local authorities have declared a climate emergency[27] and have either produced or are in the process of producing local policy and guidance in response to climate change.

While to date, local authorities have typically not addressed guidance specific to construction methods, **Appendix C** provides examples of current and proposed action, including adaptation measures for existing developments and reducing carbon in new build developments.

# 4 Effect of weather patterns

## 4.1 Introduction

This section considers in detail the occurrence of foundation failures associated with extreme weather patterns and climate change and the implications of these for the design and construction of foundations

As discussed in Section 2, climate change will cause a range of climatic effects with resulting geomorphological alterations, some of which can be predicted, others not. The impacts of these alterations will undoubtedly affect the performance of the UK's existing buildings and infrastructure. The projected design life of many of the UK's new structures will ultimately extend well into a future impacted by the effects of a warming planet, and at present, the indication is that action to improve the nation's resilience is failing to keep pace.[28] Many of the well-established consequences of climate change are yet to be integrated into planning policy, design and retrofit guidance, and consequently, there is real potential for current structures to be 'locked in' to largely avoidable risks in the future.[29]

As part of the industry survey described in **Section 2.7** and **Appendix B**, the following issues were referenced by respondents with regard to known defects to buildings resulting from climate change impacts on foundations:

- claims for cracked buildings due to clay shrinkage/heave induced by high water levels
- an increase in dissolution features in chalk and limestone, e.g., reports of sinkholes
- structural distress due to above-ground thermal movement; since this is not an issue associated with foundation performance it is not discussed further in this review
- impact on foundations as a result of changes in the nature and influence of vegetation growth and related root systems
- broken drainage; however, performance of drainage, except for its influence on foundations, is outside the scope of this review
- extremely wet winters and dry summers, both causing subsidence effects.

To understand the way in which building design, specifically foundation and infrastructure design, will need to adapt to future climate projections, it is important firstly to assess the potential impacts from the UK's existing geohazards, and then the consequent emerging changes in the risks that need to be considered in relation to ground engineering.

## 4.2 The implications of climate change for geohazards in the UK

The assessment of the effects of climate change on the natural environment poses a thought-provoking challenge to scientists and policy/decision-makers alike, and the definitive effects of global warming on geohazards that may affect prospective development sites, remain difficult to determine and predict.[30] There is a need, however, to understand and measure how climate variables affect the occurrence and severity of UK geohazards if we are to successfully adapt our planning policies and design to safeguard future construction to the changing situation.

As a country, the UK possesses a very wide spectrum of geological conditions, with rock assemblages dating from the Precambrian to the Quaternary along with examples of all major environments of deposition, formation and modification. The legacy of this assemblage and the associated geohazards, whether geotechnical, geochemical or related to geo-resources, are in evidence across the whole of the UK.[31] The country therefore has the potential to be vulnerable to a wide range of geological hazards, both naturally occurring and human-induced or exacerbated, ranging from landslides and ground dissolution in chalk soils to the collapse of former salt and coal mines.

The mechanisms by which these hazards traditionally behave are typically well researched and understood. The current planning framework requires that the full range of potential hazards be considered at the earliest stages to ensure that appropriate measures and materials are incorporated into structural and foundation design to mitigate the risks. These procedures and standards have evolved over time, based upon historical practice and experience of failure events.

The nature of the future changes, however, are without precedent. It will be essential therefore to modify existing approaches to defining hazard risk potential (both in severity and likelihood) in line with future UK climate projections, to increase the climate change resilience of buildings.

## 4.3 Foundation failure mechanisms and the changing climate

### 4.3.1 Subsidence/heave risk in shrinkable cohesive soils

Subsidence/heave risk in shrinkable cohesive soils (shrink-swell) is perhaps one of the most widely documented and detrimental geohazards experienced in Britain today. Heat waves in 2003 and 2008 led to peaks in subsidence claims. This has the potential to become more damaging through the effects of changing weather patterns/climate change impacts, as well as increased tree/canopy cover, the latter being discussed in **Section 5**.

The subsidence/heave risk is particularly pronounced in the densely occupied south-east of England, where the majority of clays with high and very high volume change potential are located.[32] Increased development of basements and undercrofts in these areas also presents an increased risk of heave or subsidence, water ingress and consequential damage. To exacerbate the issue, most modern construction is more vulnerable to differential ground movements, in part due to the adoption of cement mortars during the earlier part of this century, which while having many advantages over traditional lime mortars, are typically more brittle, causing contemporary building walls to crack more readily upon foundation movements.[33]

#### 4.3.1.1 The mechanics

Soils that are prone to shrinkage and swelling do so in response to changes in moisture content. The degree of volumetric change reflects the type and proportion of clay minerals susceptible to swelling within the soil, more specifically, expansive minerals that increase in volume upon absorption of water, and contract or shrink when water is extracted. In practice, the extent to which the ground is susceptible to shrink-swell behaviour will be determined by the water content in the near surface zone, which responds to changes in atmospheric recharge and evapotranspiration.[34]

The extent of evapotranspiration and influence on shrink-swell, especially during warm, sunny and windy weather and increased clay soil desiccation during droughts[35] is discussed below.

The incidence of drier ground conditions is expressed by the term soil moisture deficit (SMD), which is defined as the amount by which a soil's moisture content has reduced below its "field capacity" as a result of evaporation, transpiration and gravitational drainage. SMD typically builds up during summer and declines during winter. In in the absence of trees, SMD returns to zero at some point during the winter. The extent to which SMD fluctuates seasonally due to climate-induced soil moisture changes is projected to increase in magnitude under current climate change prediction scenarios in the UK.

#### 4.3.1.2 Current approaches to subsidence/heave risk in the UK

NHBC has been addressing the issue of shrinkable clays since the late 1960s, initially through its Practice Note 3 and its supplement A Quick Way to find the Right Depth of Foundation in Clay Soils. These documents were updated in 1974, but research by BRE and NHBC picked up pace following the dry summer of 1976. The outcome of this work was the publication of BRE Digest 242 (subsequently withdrawn) and later FB13 Subsidence damage to domestic buildings: A guide to good technical practice.[36]

In 1992, NHBC replaced its Practice Note 3 with Standards chapter 4.2 Building Near Trees.[37] This document, which has been updated on several occasions, most recently in January 2022, provides detailed guidance on how foundations for low-rise housing should be designed to accommodate shrinkage and swelling resulting from moisture variations both close to trees/shrubs and away from their influence. The result is that currently, the majority of new houses on shrinkable soils are designed in accordance with the NHBC Standard. This requires evaluation of three factors: the shrinkability of the soil, the proximity of the building to trees/shrubs and the moisture demand of the tree.

The NHBC Standard categorises clays into low, medium and high volume change potential and provides minimum foundation depth requirements for each. It also provides tables of increasing depth requirements as buildings are sited within the zones of influence of trees. In addition to providing protection against vertical shrink-swell movements on foundations, it recognises the need to protect lightly loaded floor slabs by incorporating voids beneath them and to provide compressible material down the side of concrete trench fill foundations in order to protect them against horizontal forces. NHBC has also developed Android and iOS apps to assist developers with their designs. It is important to note that the maximum depth of strip, pier and beam foundation that the Standard permits is 2.5m. Should the proximity to a tree require a greater depth than this, the Standard requires that a bespoke engineering design is developed.

The Standard also provides advice on the use of piled foundations designed to resist shrinkage and swelling of the ground, both acting on the pile shafts and the structures they support. Again, the standard calls for a bespoke engineering design in such cases.

The final element of the Standard is that it makes allowance for climatic variations across the UK through reducing foundation depths by 50mm for every 50 miles distance from the south-east of England.

The NHBC risk-assessed approach is based upon both science and empirical evidence from the many cases it has been involved in over the years. Based upon its claims record, this approach has proven effective, as only a small number of properties understood to have been designed in accordance with the Standards has been subject to a warranty claim. This is in marked contrast to the 10,000 reported insurance claims for all homes affected by shrink-swell following the dry summer of 2018, discussed in **Section 2.5.1**. However, predicted climate change impacts are such that the current risk-assessed approach may need to be reviewed.

### 4.3.1.3 Climate change impacts on existing and new building foundations

One of the likely implications of weather variations resulting from climate change is that longer hotter summers will increase the depth of desiccation in clay soils, leading to shrinkage. Warmer wetter winters can then also cause rebound of soil moisture levels, leading to swelling. BGS research into climate change effects on groundwater recharge[38] predicts that a greater amount of recharge will occur in a shorter period of time, i.e., shortening of the recharge season from 5-7 months (September–April) in the historical simulation (1950–2009) to 3–4 months, thereby potentially exacerbating the shrink-swell effect.

These changes are likely to give rise to a significant increase in subsidence issues and hence insurance claims for existing buildings.[39] At present, it is primarily domestic buildings that are affected by the volume change of clay soils. This is because commercial and industrial buildings tend to have deeper foundations and be more flexible or significantly more heavily loaded than domestic buildings and are therefore less likely to be affected by shrink-swell risks.

Research programmes developed in response to the evolving nature of the shrink-swell hazard are already established, such as the BGS' Climatic hazards and natural geological events (CHANGE) programme. These aim to give a better understanding of the combined impacts of climate change and geohazards on infrastructure in the UK. The initial study focuses on predicting likely future shrink-swell behaviour due to changing rainfall and temperature patterns, which in turn may affect building foundations. The findings, based upon UK Climate Projection (UKCP) scenarios (UKCP09 and UKCP18) have been used to develop predictive modelling tools, which may be utilised by planners and designers to assess future susceptibility to subsidence risks in response to changing climate variables.

The BGS GeoClimate UKCP18 study[40] outlines the potential influence of climate change on the probability of subsidence. This projects that 6.5% of properties will be affected by clay shrink-swell by 2030 (compared to 3% in 2020), rising to 11% by 2070. These BGS GeoClimate shrink-swell national datasets were developed by combining long-term UKCP scenarios for rainfall and temperature changes with the geotechnical properties of the ground, to identify areas projected to experience the largest increases in susceptibility to subsidence over the next century.

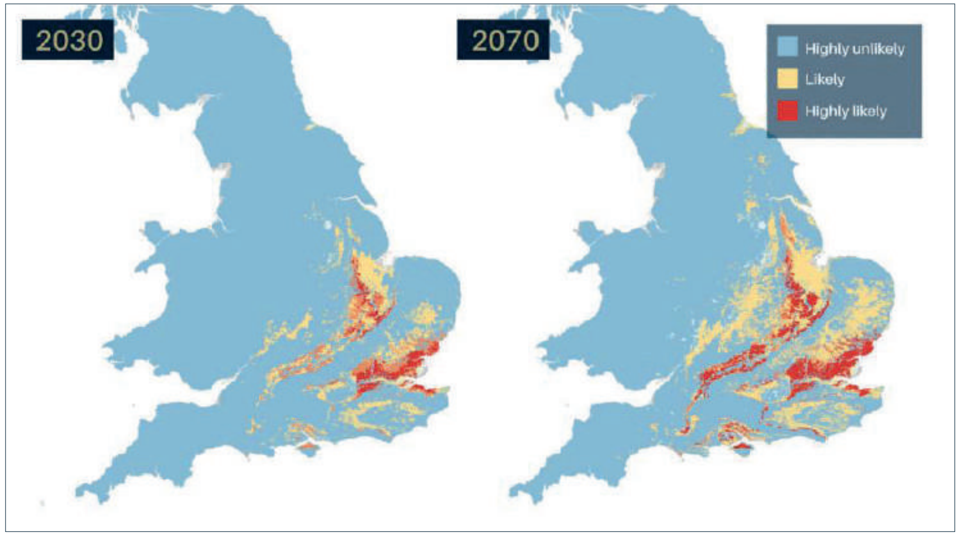


**Figure 3** GeoClimate UKCP18 Open coverage map and comparison of 2030 and 2070 projections (Source: BGS)

The GeoClimate UKCP18 Open data are provided for two time periods, the 2030s and the 2070s (see **Figure 3**). One projection is provided for each time period, based on the average outcome for the UKCP18 higher emissions scenario and the most susceptible value (the worst case) within the GeoSure grid cell. One of the key findings, as can be seen from Figure 3, is the expansion of "highly likely" and "likely" shrink-swell subsidence susceptibility due to predicted changes in climate. These are predicted to expand geographically into larger areas of south-east and southern England, East Anglia and the East Midlands.

Data analysis released by a private sector data provider in June 2022[41] (but not published in a peer reviewed paper) indicates than more than 7.65 million properties in Great Britain could be exposed to medium or high risk of soil subsidence by the 2080s due to climate change impacts. This represents an increase of over 1.89 million individual property addresses, predominantly located in the south-east of England.

It is almost certain, therefore, that the effects of climate change will lead to an increase in damages experienced by domestic properties. The impacts range from minor issues, such as the sticking of doors and windows, through to cracking of walls and damage/disruption to utility services. An example of this is shown in **Image 3a-c**.

**Image 3a-c:** Examples of building damage caused by subsidence (Source: RSK)

These geohazard risks are based upon current modelled climate predictions. It is acknowledged that there are uncertainties in the extent of change, particularly for longer time horizons. Greater changes in climatic conditions may result in significant changes in the physical and mechanical properties of the ground (relating to moisture levels within the ground), thereby causing a great deal of structural damage, particularly on lightweight constructions built on swelling soils. Therefore, the occurrence and/or magnitude of damage to houses, commercial buildings and roads due to shrink-swell may change for the worse.

#### 4.3.1.4 Implications and solutions

This type of future disruption may already be essentially 'locked in' for swathes of the existing building stock. Costly remedial options, such as widespread underpinning to impacted foundations or tree felling, are unlikely to be viable or sustainable options. Changes in the perception of the severity of the damage and tolerances or changes in the attitudes of insurers (as reflected in policy changes) to accommodate the changing climate scenarios may offer some mitigation.

However, assuming this is not the case, to mitigate the predicted increasing subsidence/heave potential, foundations for new domestic structures will need to be designed to accommodate climate change resilience across the entire lifetime of a building. This means that it is likely to some extent that new foundations to domestic properties will need to be founded at a deeper level than is currently the case to avoid damaging foundation movements. However, opportunities for changes in design and construction practice, including innovative design, may ultimately provide a more practical, economic and lower carbon solution. Examples include the adoption of mini-piles and ground beam foundations to replace the tendency to progressively deepen traditional spread foundations.

Basements and undercrofts can also be at increased risk of heave or subsidence (as well as water ingress). The potential impacts on these structures also need to be considered on a site-specific basis through thorough geotechnical evaluation.

However, as stated above, in terms of the design of new buildings, it is unclear whether the more significant risk will be associated with increased desiccation of clay soils or reduced desiccation close to trees and dieback resulting from the drought conditions., Further research is required to establish if changes are required to NHBC Standards Section 4.2 to provide resilience to climate change.

This research should consider three elements of the current NHBC Standard:

- minimum foundation depths in clay soils
- foundation depth requirements in clay soils for properties located close to trees and hedges
- a suggested 50mm decrease can be made to the foundation depth determined for every 50 miles distance north and west of London.

Although it did not come out clearly in the results of the industry survey reported in **Appendix B**, the authors are aware of anecdotal information that certain developers are increasing the minimum depth requirement in highly shrinkable clays to accommodate any planting that house owners might undertake close to their properties. This move in itself will provide some resilience to a general increase in desiccation of shrinkable soils. Since it will take some time for further research to justify changes in the NHBC Standards or Building Standards, it is recommended that all developers consider increasing their minimum foundation depths now or consider alternative methods rather than waiting for changes in standards to take place.

### 4.3.2 Continued sea level rise

As discussed in **Section 2.6.3**, current observations indicate that sea levels have already risen by nearly 200 mm between 1900 and 2000, and under the most optimistic of future climate scenarios, where aggressive action successfully reduces greenhouse gas emissions by significant margins, the global trend in sea level rise is still predicted to continue well beyond the end of this century. The worst-case predictions anticipate over a metre of sea level rise by 2100 in some areas; a rate of increase five times that of the previous century or more.[42] To substantiate projection data on sea level rise and to inform future requirements for longer-term structural assets with design lives planned to extend beyond the end of the 21st century, the Met Office has also modelled projected sea level rise up to 2300 and has assessed for low, medium-low and high emissions scenarios. Projected data for London and Cardiff, for example, indicates 1.4m to 4.3m of sea level rise by 2300[43]. It is noted that these projections do not consider the potential for substantially larger increases in sea level associated primarily with accelerations in ice mass input from West Antarctica.

Sea level rise increases the risk of two potential geohazards: coastal erosion and corrosion of foundations due to saline intrusion.

#### 4.3.2.1 Coastal erosion

The issue of coastal erosion for existing buildings can only be addressed by shoreline management plans (SMP) described in **Section 2.6.3** and is therefore not addressed further in this review. In terms of the design of new buildings, site evaluations in coastal areas should refer to any nearby SMPs to establish locations that will be beyond potential areas of erosion for the life expectancy of the buildings that are proposed.

#### 4.3.2.2 Saline intrusion

Salt water intrusion, the landward movement of seawater in coastal aquifers, has been a recognised process since the 19th century and its influence on coastal infrastructure and natural environments is predicted to grow as sea levels continue to rise due to climate change.

The degree of salt water migration inland into unconfined groundwater (saline intrusion) under future sea-level-rise scenarios will be largely controlled by a range of hydrogeological variables, including aquifer thickness, local recharge rates (which may be impacted by abstraction history), hydraulic conductivity and the rate of groundwater discharge into the sea.[44] With respect to the potential for saline intrusion to impact on existing and newly constructed substructures, including building foundations, additional factors such as coastal location, coastal elevation and topography, development type and foundation design will be influential when defining future vulnerability to saline corrosion in concrete.

Mass concrete in isolation is not significantly affected by saline groundwater and under favourable conditions, concrete provides reasonable protection against reinforcement corrosion through physical shielding. An extensive programme of review and structural inspection carried out in maritime environments by others has recorded no significant disintegration in permanently immersed reinforced concrete; however, severe damages were encountered in the splash and tidal zones.[45] In structures and foundations located within this environment, damage to concrete generally occurs as a secondary impact due to the corrosion of the internally embedded steel reinforcement. In the presence of chloride ions, the steel protective passive layer to reinforcement is locally destroyed and unprotected areas start to dissolve. The formation of corrosion products (rust) involves a substantial volume increase, i.e., the volume of corrosion products is greater than that of the original steel bar. Therefore, expansive stresses are induced around corroded reinforcement, causing the potential for cracking and in severe cases, spalling of the concrete cover, causing a loss of the bond between steel and concrete and a consequent reduction in the serviceability of the concrete structure/foundations as they deteriorate.[46]

Notwithstanding this, reinforced concrete in traditional below ground foundations is known to be less liable to attack by chlorides than that in above ground structures, as it is not exposed so readily to cycles of wetting and drying. It is therefore concluded that saline intrusion resulting from rising sea levels is unlikely to have a significant effect on conventional low rise house foundations.

### 4.3.3 Washout-induced damage to foundations and structures

The undermining of foundations and infrastructure through the washout of soil particles by flowing water (derived from both fluvial and pluvial processes) is a relatively common issue for the UK, both on construction sites during temporary works and later over the lifespan of a completed development. While many contemporary buildings and infrastructure projects are designed with flood resilience in mind, vulnerability to pluvial flooding (i.e., when an extreme rainfall event creates a flood independent of an overflowing water body) is rising, especially on construction sites, where the evolving work environment presents a changing risk profile to manage.

Significant rainfall has the power to wash away soils and inundate foundations, while concentrated flows of uncontrolled surface waters can erode slopes and retaining structures before newly planted vegetation has had the opportunity to establish. The potential setbacks and delays to construction programmes can prove costly, while requirements for additional insurance packages to protect assets will become increasingly necessary. In the most severe of circumstances, without the suitable provision of temporary and permanent drainage systems with sufficient capacity to accommodate the run-off generated by extreme rainfall events, particularly on sloping sites, the integrity and future performance of engineered structures may increasingly be vulnerable to damage.

As historically unprecedented intensive rainfall events become commonplace under future climate projections, especially during the summer months, changes to the evaluation of event probability, and therefore the need for risk mitigation, must keep pace with the predictions for the development lifetime. To use the commonly adopted flood risk figures when assessing flood event probability in return years, the use of quantitative terms such as 1 in 50 years or 1 in 500 years to describe the average time span between events of a certain magnitude are likely to become redundant in the face of the changing climate.

### 4.3.3.1 Case study: Fluvial washout-induced damage

Following a very dry start to the year, the autumn of 2012 saw a series of heavy rainfall events take place across the UK that caused significant widespread flooding and disruption to homes, businesses and travel infrastructure. In the data analysis that followed, 2012 would be crowned the UK's second wettest year to that point, eclipsed only by that of 2000. The rainfall data of England alone indicated the wettest year on record.[47]

Among the damage caused by the storms was a notable incident that took place in Newcastle upon Tyne, where a flood event resulted in catastrophic soil erosion, severely undermining the foundations to an existing four storey residential apartment block. The concentrated surge of floodwaters induced the washout of a substantial thickness of soil beneath one side of the structure, exposing large sections of the piled foundations supporting the building (see Image 4). The structural inspections that followed designated the stricken building unsafe and led to its demolition, given the extent of the damage.

The events that took place in Newcastle in 2012 provide a cautionary example of the magnitude of damage such extreme flood-induced erosion/washout events can cause. While the physical impact to the structure and the social and economic implications for those residents forced to evacuate and subsequently abandon their homes cannot be understated, it is noted that the severity of the situation may have been limited to some extent by the engineering decisions that preceded the building's construction. The piled foundations supporting the property, which were designed to transfer building loads to competent ground at depth, while likely to be damaged and no longer serviceable due to the floods, may ultimately have prevented a total structural failure, with potential loss of life.

**Image 4** Catastrophic damage caused by north-east floods, 2012 (Source: Tyne and Wear Fire Rescue Service)

### 4.3.3.2 Solutions

Considering the severity of the potential damage that can result from flash-flood-induced washout, hydraulic modelling of drainage systems and watercourses will be required in areas that could be subject to flash floods. Such models should consider the volumes of water that could be generated by extreme short-term rainfall events. In the Newcastle case described above, the single biggest factor that caused the event was the inability of the culverted part of the adjacent watercourse to carry the flow of water generated by the heavy rainfall. Consequently, the modelling must carefully evaluate the existing watercourses and in particular where these are restricted, either by natural topography or control structures such as weirs and culverts. Where it is not possible for these to accommodate projected flash flood events, the bypass areas of overland flow will have to be established and reinforced to prevent erosion.

### 4.3.4 Dissolution and anthropogenic hazards in chalk and limestone

Subsidence and ground instability hazards caused by dissolution (the susceptibility of calcium carbonate in chalk and limestone to dissolve in water containing carbon dioxide) or historical mining of limestones and chalk have long presented a challenge to the construction industry in the UK. The low rate of dissolution is unlikely to affect a development over its lifetime. However, in these settings, consideration must be given to the selection of appropriate foundation designs to accommodate zones of variable weathering within the ground profile, loose infill material collapsed from the overlying overburden and remedial treatment of man-made cavities. In addition, suitable drainage strategies have to be adopted that fulfil design requirements but do not inadvertently trigger subsidence of loose or weathered material or destabilisation of open voids.

The most vulnerable environments to potential natural dissolution hazards are typically encountered where the feather edge of low-permeability cover deposits are located over sub-cropping chalk or limestone. This stratigraphical environment enables concentrated flows of surface water to penetrate the slightly soluble calcareous rock dissolving its surface. Over time, this leads to the creation of a range of dissolution features. It is common for overlying cover deposits or rocks to settle down into the zone of solution, leading to loosening of the natural soils. In stronger chalk and limestone, actual cavities can form (called karsts in limestone). These themselves can be unstable, allowing upwardly migrating voids or loosened material and potentially triggering eventual sudden collapses at the surface. The risks to new developments are therefore both of settlement of loosened overburden material or more radical formation of sinkholes at the surface.

Typically, anthropogenic features in chalk and limestone (which are not restricted to areas where there is an edge of overlying low permeability material) include 'deneholes' (ancient small workings), disused shafts and workings associated with historical extraction of chalk for agriculture and brickworks.[48] Although some of the more recent mines and shafts are recorded, the locations of many older (and all ancient) workings are unknown.

While natural and man-made cavities can be present at depth in a stable or potentially unstable condition, the latter can be triggered to cause ground instability by the introduction of percolating water. Equally difficult to predict are areas where overburden has been loosened by the dissolution of weak rock below. Such materials can be in a metastable condition and significant settlement can be triggered by the introduction of water. For these reasons, dissolution, and ground stability hazards in soluble chalk/limestones together with anthropogenic workings, are highly susceptible to increase as a result of predicted climate changes, specifically, projections of increased rainfall totals and a greater frequency and intensity of extreme rainfall events.

**Image 5** shows an example of extensive damage to a property that was caused by a possible solution feature or denehole within the underlying chalk strata and led to the property being demolished.

**Image 5** Damage to housing caused by a solution feature or denehole (Source: RSK)

### 4.3.4.1 Case study: Unprecedented development of new sinkholes

In February 2014, the UK Met Office reported on the winter storms of December 2013 to January 2014. It advised that this was one of the most, if not the most, exceptional periods of winter rainfall in the last 248 years for England and Wales. The combined rainfall total for December and January over that period amounted to 287.6 mm for the south-east and central southern regions of England, which constituted the wettest two-month period since modern records began in 1910. Twelve storms hit the south and south-east during January and February 2014, making it one of the stormiest periods of weather that the UK has experienced across the last 20 years.[49]

During this same period, an exceptional number of sinkholes and subsidence events (19 in total), both derived from naturally occurring cavity collapses and the collapse of anthropogenic workings, were reported across the UK to the BGS. These had a significant impact on infrastructure and property. The sustained period of wet weather is suspected to have been the trigger for the unusually high number of sinkholes and collapse subsidence features that occurred. A heightened media, public, stakeholder and governmental interest developed in response to the unprecedented nature of the events, which required addressing by the BGS in the form of improvements to its karst mapping and database collections.[50]

### 4.3.4.2 Case study: Subsidence on the M25

On the evening of 10 June 2019, a road closure between junctions 4 and 5 on the M25 due to a road traffic accident led to the discovery of two sinkholes within the central reservation. The subsidence was preceded by extremely heavy rainfall, which in some parts of the country equated to a month's worth of rain falling within only a couple of days. The adverse weather conditions, causing large volumes of percolating rainwater to enter through the chalk, exacerbated by vibration and surface loading associated with the carriageway, are likely to have triggered the collapses.

### 4.3.4.3 Commentary

In both cases described above, the increasing severity and reduced predictability of the weather patterns that preceded the events were deemed to have had the potential to impact on the occurrence of the geohazards.

With respect to foundations and subsidence risks, the level of vulnerability to dissolution-related hazards generally depends on the type of substructure. Spread or piled foundations bearing potentially loose or metastable infilled solution cavities within cannot be adopted because of the risks of slumping after periods of heavy rainfall.[45] CIRIA's C574 Engineering in Chalk[51] indicates that the greatest risks are associated with isolated pad footings and ground-bearing floor slabs, while the fewest subsidence risks may be attributed to suspended ground floor slabs supported on end-bearing piled foundations below the depth of any solution features. Certain engineering activities common on construction sites can contribute to subsidence or collapses and certain construction activities can exacerbate instability issues associated with solution features. For example, these include:

- exposure of clay soils during excavation, leading to desiccation and crack formation during drought periods, which can allow increased percolation from subsequent rainfall into vulnerable chalk below
- point discharges from highways, drains or soakaways can destabilise adjacent solution features
- sustainable urban drainage systems (SuDS), which are designed to minimise flow on development sites by the retention of water in oversized pipes and surface features. If these schemes do not take account of the vulnerability of the underlying ground, they can cause infiltration and destabilise solution features.

The projected increases in rainfall and storm frequency and intensity will increase the risks discussed above, leading to an escalation in subsidence/collapse associated with sites located on weak calcareous rocks.

#### 4.3.4.4 Solutions

When designing foundations in these areas, the presence of anthropogenic and solution features should be evaluated. Certain records of natural and man-made cavities do exist (e.g., Natural Cavities and Mining Datasets – Stantec[52]), but currently are only sufficiently comprehensive for a few areas underlain by chalk. Consequently, subsidence risk hazard mapping is also limited. In response to the changing nature of risk, it will be increasingly important to promote the comprehensive investigation of sites considered to be vulnerable to dissolution or historic workings, to identify geotechnical hazards at the onset of construction projects and to obtain the necessary data to inform design, construction and any requirements for mitigative measures. These evaluations must take account of the projected increases in storm events and associated rainfall projected to occur over the lifetime of the development.

### 4.3.5 Evaporite dissolution

Evaporites, including gypsum (or anhydrite) and salt, are readily soluble minerals that dissolve both at the surface and underground, creating subsidence and karst-like features similar to those discussed above. These can also locally result in major subsidence and sinkholes. Unlike the calcareous rocks, however, dissolution rates in evaporite minerals are rapid and cavities and caves can enlarge and collapse on a human generational timescale.[53] Conversely, the natural or induced hydration and recrystallisation of anhydrite to gypsum may be accompanied by considerable expansion in volume and the associated pressures can result in uplift and heave, posing a risk to substructures located in evaporite dissolution areas.

The UK's evaporite deposits are primarily located in the Triassic strata of the Midlands and south-west, and in the Permian strata of the north-east and north-west of England. The mechanism by which gypsum dissolves through exposure to flowing water and suitable groundwater conditions can result in the development of rapidly enlarging cave systems that can form large chambers that are susceptible to eventual collapse. The presence of such cave systems is documented in the Vale of Eden, Cumbria, and beneath Ripon, North Yorkshire, where a vast complex of water-filled caves have propagated to the subsurface. The periodic collapse of these chambers produces breccia pipes that migrate vertically through the overlying strata to break through at the surface, forming subsidence hollows. The subsidence problems documented in Ripon (see the following case study) are understood to be due to this phenomenon.

A further consideration in such areas relates to where chemical reactions of concrete or cement stabilisation binders occur with sulphate-rich groundwater associated with gypsum, anhydrite or pyritic materials. These reactions can cause detrimental damages to concrete foundations and infrastructure.

### 4.3.5.1 Case study: Ripon sinkhole

On 17 February 2014, large cracks appeared in the brickwork of a detached house in Ripon, later leading to the partial collapse of a section of the structure. The cause of the collapse was due to the formation of a surface sinkhole induced by the dissolution of thick gypsum deposits beneath the area.

**Image 6a-b:** Sinkhole damage, Ripon, February 2014 (Source: BGS)

The sinkhole was roughly oval in shape, measuring 11m by 15m across, while the subsidence recorded within the property's garden amounted to 0.7m vertical displacement. The structural damage suffered by the building was substantial, with a crack widening from ground level that reached to the building's roof, causing severe damage to the rear third of the house. The crack continued to widen over the following days, while 40 metres to the east-north-east of the property, a historical sinkhole that formed in 1979/1980 also showed signs of movement through reactivation cracks.

The BGS investigation[54] (see **Image 6** and **Figure 4**) indicated that a combination of factors was likely to have triggered the subsidence, namely the enlargement of Ripon's caves due to continuing dissolution within the subsurface, surface water infiltration and seasonal fluctuations in groundwater level.

The input mechanisms attributed to the development of the Ripon sinkhole are, like many of the other geohazards discussed within this section, likely to be sensitive to the projected climate changes the UK will experience over the coming decades. Variations in hydrogeological regime due to seasonal fluctuation are expected to escalate, while surface water percolation, either derived from greater rainfall intensity or drainage problems in urban environments, may serve to intensify dissolution rates within evaporite deposits or cause dissolution in areas that had previously been unaffected.[55] Increases to carbon dioxide levels in the atmosphere also have the potential to increase the acidity of rainwater, accelerating the rate of solution.

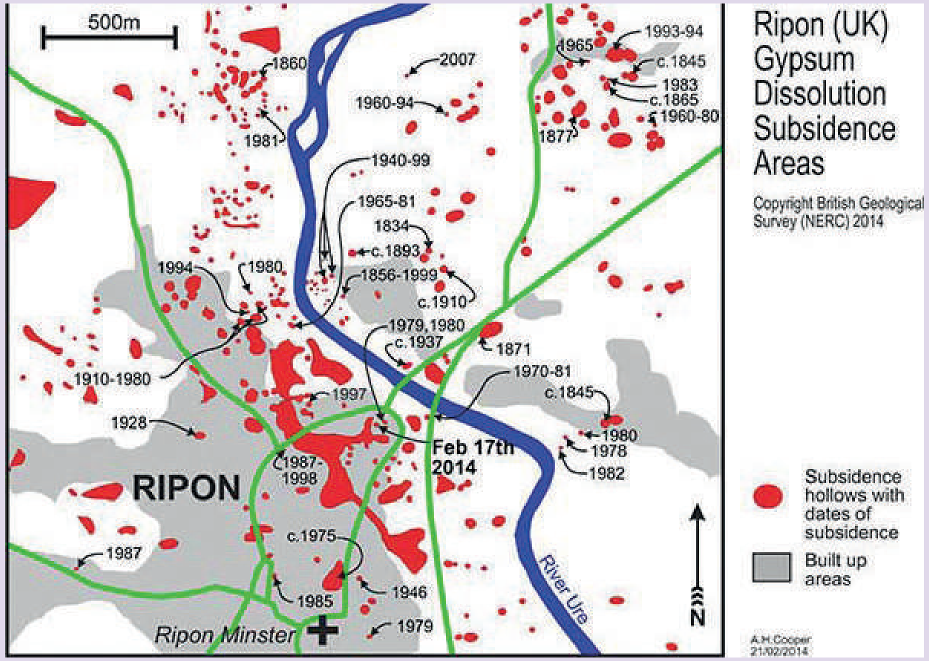


**Figure 4** Map of the Ripon area, showing the distribution of sinkholes, with the dates of reported collapses. The large areas are amalgamations of sinkholes

mainly filled with peat and clay (Source: BGS)

#### 4.3.5.2 Solutions

In the main evaporite subsidence-prone areas, the current planning system has typically evolved to accommodate the subsidence risks, with new developments in Ripon, for example, requiring extensive site investigation and development design to limit ground disturbance. In addition, foundations for new structures are commonly reinforced to reduce the risks associated with differential settlement, or in the worst case scenario of sinkhole development, reduce the risk of total collapse of the structure. The Ripon bypass embankment that traverses gypsum deposits includes layers of geotextile tensile membrane reinforcement to promote stability and maintain serviceability in the event of subsidence,[56] while the new Ure Bridge was designed to withstand the sudden loss of one upright support.[57] The adoption of such preventative and mitigatory measures to overcome engineering problems and ensure resilience to a potential increase in subsidence due to climate changes will increasingly have to be considered to ensure resilience of new buildings in these areas.[58]

### 4.3.6 Collapse settlements in earthworks and fills (principally cohesive and weak rock fills) due to inundation

A substantial proportion of low-rise construction in Britain today is built on filled ground, and problems occurring due to subsidence and heave within bulk fills have been documented.[59] Inundation or collapse settlements are triggered when fills placed during relatively dry conditions become saturated, typically from inundation by a rising groundwater table at the base of a fill layer, or to a lesser extent, by downward infiltration of surface waters, often provoked by construction works in which appropriate temporary or permanent drainage design has been overlooked.[60] Ground movements due to collapse settlements can be large and vertical compressions in the order of 3–5% total fill depth are not unusual. The resulting settlements at the ground surface have been greater than 0.5m at some sites. The settlement caused by inundation is unlikely to be uniform and serious damage to building foundations and infrastructure is a likely outcome.

#### 4.3.6.1 Collapse settlement mechanics

The mechanisms by which collapse settlements occur are generally well understood, typically comprising a relationship between the following factors:

- the initial water content of the soil (or air voids)
- the compactive effort applied during filling works
- the overburden/confining pressure (i.e., the pressure due to overlying fill and foundation loads).

For cohesive fills of a given plasticity compacted to a low compactive effort and dry density of optimum condition, collapse settlements may be expected to occur at high confining pressures, the trigger usually being inundation by groundwater rising into the base of the fill. Conversely, for fine fills compacted to a high compactive effort, and on the dry side of optimum moisture content, heave may be expected to occur at low confining pressures, the trigger mechanism again being inundation by water.

Historically, collapse settlements were considered relatively unusual within natural soils situated across north-western Europe, which typically maintain their undrained condition due to the temperate nature of our present-day climate. The projected changes to our weather systems, however, which are forecast to include intensified heat and prolonged periods of drought during summer, with the winter season typified by wetter conditions, are likely to lead to significant variations in soil moisture deficit and consequently the physical and mechanical properties of UK soils. The greatest variations may be expected in the south/south-east of England where the highest levels of warming are predicted to occur.

Further reductions in soil moisture content may be expected within excavated and stockpiled fills during earthworks projects, increasing the likelihood of significant material desiccation during the summer months. Future cut and fill projects carried out under these conditions are increasingly likely to be susceptible to issues arising from fill placements in excessively dry conditions and when placed under relatively light compaction, leaving high air void spaces within the fill layers. These materials are potentially vulnerable to collapse and subsidence upon subsequent wetting or inundation.



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Groundwater naturally fluctuates in response to seasonal variation, as demonstrated by falling water tables during the summer months in response to dry conditions and reduced recharge rates, while levels typically rise across the winter period as lower temperatures and increased rainfall become the dominant weather pattern. Variations in groundwater elevation experienced due to seasonal fluctuation are anticipated to escalate in response to the projected impacts of climate change, when periods of abnormally high rainfall will probably result in raised water tables or potentially the emergence of groundwater at or near the surface.[61] Groundwater inundation at the base of poorly compacted fills, the trigger mechanism primarily responsible for the inducement of collapse settlements, is therefore increasingly likely to occur during significantly wet and flood-prone years in our future climate.

### 4.3.6.2 Fill containing weak rock fragments

Large collapse settlements in fill containing fragments of weak rock (for example, chalk fill and colliery spoil) can occur because of softening of the weak fragments upon contact with water. The bridges between intact fragments within the fill structure are destroyed upon wetting and the solids readily collapse into the air voids. CIRIA C574[51] indicates that settlement issues on chalk sites are often most pronounced where pavements approach bridges, where the chalk has been stockpiled and placed shortly before the end of a road construction contract or where batter trimmings are used in wedges adjacent to bridge abutments (both circumstances are indicative of potential double handling and prolonged periods of natural drying). The most significant issues are often noted to occur when heavy autumn rains follow a particularly dry earth moving season, a pattern we are likely to experience with increased intensity and frequency under current projections of our future climate.

More general research into the performance of deep fills was undertaken by Watts and Charles of the BRE over a period of 25 years. The third edition of their report Building on fill: geotechnical aspects,[62] which was published by BRE in 2015, contains several case studies where settlement monitoring was undertaken over significant periods of time. They report that collapse settlements were recorded along the banks of the Danube in 1940 when the river level rose 2m. Their own monitoring recorded collapse settlement on seven sites underlain by a variety of opencast backfills. Settlements of between 1% and 7% were recorded, which were triggered in three cases by rising groundwater, in three cases by downward infiltration of surface water and in one case by the injection of grout and water.

The occurrence of subsidence due to inundation or surface water percolation can potentially take place over a significant time period.[59] Long-term collapse settlement may continue after the water source has been removed, because water already within the fill continues to percolate downwards. Evidence may be drawn from examples linked to the engineered backfilling of former quarries and open cast sites where the restoration of former voids is typically carried out to provide a stable development platform. Issues can arise where either the existing groundwater table has been artificially lowered to facilitate historical workings or when poorly designed drainage systems are ineffective, resulting in inundation of the fill material during heavy rainfall events. It can take a number of years after cessation of dewatering historical excavations for the localised groundwater table to fully recover.[62] The collapse of basal fill layers upon groundwater inundation is therefore likely to be time dependent, with subsidence rates largely controlled by the rate at which the wetting occurs and in some cases, this may be experienced many years after development has been completed.

Understanding groundwater and surface water behaviour in response to climate change will be a progressively influential factor on the design and successful operation of future earthworks projects. It will be essential to ensure that engineered fills placed and compacted to support buildings and infrastructure are specifically designed and controlled to eliminate collapse potential.[63] The careful management of field operations to ensure fill materials are suitably protected from the elements and the installation of sufficient temporary and permanent drainage systems designed with future climate resilience in mind will be essential in reducing the probability of potential settlement issues in construction fills. Capturing worst-case groundwater conditions during current seasonal fluctuation under long-term monitoring programmes may assist fill design in the interim, but it will be equally important to consider the impacts of seasonal and weather extremes from climate change predictions over lengthier timescales.

#### 4.3.6.3 Solutions

Watts and Charles[62] discuss appropriate methods to evaluate settlement risk when designing a development on filled ground. With the poorly compacted fills described above, the potential for collapse settlement must be evaluated on a site-specific basis. Groundwater level monitoring is required to assess whether it is rising, and this process must now include a prediction of whether weather variations could cause additional increases during the lifetime of the development. However, as illustrated by the Watts and Charles case studies, inundation by infiltration of water from the surface is an equal problem. Consequently, investigations should consider inundation tests to replicate surface water infiltration by discharging water into trenches and boreholes while monitoring settlements at surface and at depth. Should this demonstrate a risk of collapse settlement occurring, Watts and Charles consider options for stabilising fill, which include:

- preloading/surcharging
- dynamic compaction/rapid impact compaction
- vibro-compaction/replacement.

Although these solutions all have their merits, Watts and Charles conclude that for deep fills, preloading is the most effective solution, while the two forms of compaction by surface treatment are appropriate for shallower fills.

Where inundation settlement is a risk, consideration can also be given to reduce the potential for infiltration from the surface. This involves identifying areas where there is a potential for infiltration, such as low spots that could flood, areas where surface water is to be stored and areas beneath drainage systems. Once identified, these areas can be protected by the placement of an impermeable layer, such as a reasonable thickness of well-compacted clay, extending at or close to the surface. If using a clay layer, it must extend to sufficient depth to ensure that it is not subjected to desiccation in dry summers.

### 4.3.7 Reduction in soil strength associated with increases in porewater pressure

The build-up of excess porewater pressure, due, for example, to prolonged and heavy periods of rainfall or a rise in groundwater levels,[63] generally exerts a strong influence on the stability of natural landforms and engineered structures, including building foundations. Climate conditions and the distribution of pore pressures in the soil are intrinsically linked, and unusually wet or dry periods are known to have potentially detrimental effects on structures such as embankments and retaining walls, as well as natural and man-made slopes. Where pore pressures increase, effective stresses and strength in the soil reduce, which may lead to a loss of stability and under the worst circumstances, failures occur.

The forecast of rainfall events of greater intensity means even those locations traditionally associated with drier conditions during the summer months may experience rapid increases in porewater pressures within the ground profile and consequent rapid decreases in strength. For example, the particularly wet winter of 2000–2001 caused the porewater pressures in some embankments on the London Underground network to increase to unprecedented levels.[64] It was also indicated that the reduction in porewater pressures that tall deciduous trees were assumed to provide could not be relied upon during this period. These sorts of imbalances to traditionally relatively stable and predictable cycles in soil mechanics are destined to become more significant under climate change projections, and the incorporation of appropriate preventative steps to control excess pore pressures building within sensitive structures will be critical in ensuring their future serviceability.

It is also noted that current approaches to foundation design rely in part upon empirical methods; for example, the derivation of bearing capacity factors in cohesive soils for use in the design of spread and piled foundations, adhesion factors derived from the ratio of undrained shear strength to effective overburden pressure and angles of shearing resistance derived from standard penetration test determined ‘N’ values.[45] If climate change has a significant effect on stress conditions, it may be necessary to reconsider the applicability of empirical methods to longer-term engineering solutions, while the factor of safety margins may require modification to reflect the future uncertainty.[65]

### 4.3.7.1 Solutions

Sensitivity, in terms of the degree to which slopes can cope with these rates of change, needs to be assessed. Examples of such assessments include Numerical Analysis of Rainfall Effects on Slope Stability[66] by Fei Cai and Keizo Ugai, published in the International Journal of Geomechanics in 2004. The report identified that while (as anticipated) slope stability was reduced due to infiltration of rainfall, whether slope failure takes place depends on the hydraulic characteristics of soils, rainfall intensity and duration and the shear strength of soils. The slopes with low permeability were found to fail only if the rainfall lasted a sufficient duration, even if the rainfall had a great intensity. For slopes with comparatively large permeability, the slope failures possibly took place under the rainfall with a shorter duration and a greater intensity.

Well-established technologies and methods are available within the industry to facilitate the effective removal of excess porewater pressures. These can be applied to situations assessed to be at risk of loss of stability due to climate change impacts. Such methods aim either to induce greater rates of consolidation within fills or are applied within engineered structures or slopes to control the build-up of excessive pore pressures. Internal drainage systems, such as prefabricated vertical band drains, can be installed to act as preferential drainage paths to remove porewater from fine soils and thus prevent the loss of stability. It is important to ensure these drainage systems are suitably designed to inhibit the inflow of surface waters while being free draining to enable effective removal of water. Sufficient surface water drainage should also be provided to prevent any ponding at ground level.

There are also innovative techniques available for stabilising slopes involving electrokinetic geosynthetics.[67] This technique has been used to stabilise failed and failing slopes in a variety of settings. It works by combining the remedial actions of soil strengthening, reinforcement and drainage and is based around the design code for soil nailing.

# 5 Effects of increased canopy cover

## 5.1 Introduction

Tree canopy cover can be defined as the area of leaves, branches and stems of trees covering the ground when viewed from above.[68] Research suggests that even moderate increases in canopy cover within cities can aid adaptation to the adverse effects projected under a changing climate.[69] Properly managed trees also make important contributions to the planning, design and management of sustainable, resilient landscapes, as they help make cities safer, more pleasant, more diverse and attractive, wealthier and healthier. However, the impacts of increasing canopy cover on building foundations need to be considered.

This section starts with a summary of the advantages of increasing canopy cover in more detail. Direct and indirect risks to foundations associated with the influence of trees in both shrinkable and non-shrinkable soils are then considered, along with the influence of tree selection and location at masterplanning stage for new developments and for new planting on existing sites. The section then identifies the key implications of the above for foundation solutions, future trends and current uncertainties and unknowns. Consideration is also given to a transition away from conventional deep concrete strip foundations to more sustainable piling solutions.[70] The section concludes with alternatives to trees/canopy cover that provide some of the benefits but may have less of an effect on foundations, such as green walls and green roofs.

## 5.2 Advantages of increased canopy cover

Beneficial services provided by urban trees include the following:[71]

### a) Regulating services

- Carbon sequestration and storage: Increasing the number of trees slows the accumulation of atmospheric carbon, a contributor to climate change.
- Temperature regulation: Trees are good reflectors of short-wave radiation and canopy cover also shades surfaces that would otherwise absorb radiation, reducing surface heat. Evapotranspiration also converts solar energy into latent heat, cooling the surrounding air.
- Water regulation: Trees regulate storm water by intercepting rainfall, which subsequently evaporates, or slow the travel time to groundwater. Trees also improve infiltration around the stem.
- Air purification: Trees remove air pollutants from the atmosphere via dry deposition.
- Noise mitigation: Trees can scatter and absorb sound waves, obstructing the pathway between noise and receiver.

### b) Cultural services

- Health: Trees can assist in providing an environment encouraging physical wellbeing, mental restoration, escape and enjoyment.
- Nature/landscape connections: Benefits arise from the visual aspects, providing a sense of place, physical interactions and a feeling of connection with nature.
- Social development: Activities within an area of trees can strengthen social relationships.
- Education and learning: Trees can provide opportunities for informal and formal learning.

### c) Provisioning services

- Fuel (wood fuel) provision: Through the process of harvesting and combustion, woody biomass can be used as a source of heat, electricity, biofuel and biochemicals.
- Timber provision: Timber can be used for construction, veneer and flooring, as well as chip and pulp for boards and paper.
- Food provision: Trees can directly provide food, such as fruits, nuts and berries, or indirectly via animals such as deer that reside in wooded areas.

In addition to the services provided above, developers have reported that they were able to recover the extra costs of preserving trees through higher sales prices for houses and that homes on wooded plots sell sooner than homes on unwooded plots.

## 5.3 Additional considerations for mitigation

Notwithstanding the above, it must be appreciated that the drive for increased canopy cover could have a significant impact on development layouts and increased incidences of vegetation and trees near houses. Potential additional considerations for mitigation of increased canopy cover include the following:

- visual impairment: trees and vegetation can block the line of sight and affect highway safety and visibility splays
- potential for shading of buildings: a particular problem where rooms require natural light and open spaces, which should receive direct sunlight for at least part of the day
- direct damage: either below ground damage resulting from incremental root and stem growth or above ground damage to neighbouring trees and/or structures by the continuous whipping of branches
- indirect damage (direct risks to foundations): the risk of new planting removing moisture from load bearing shrinkable clay soils
- seasonal nuisance: caused by trees naturally growing and shedding organisms, such as leaves blocking gullies and gutters, fruit causing slippery patches and/or accumulation of honeydew, damaging surfaces and/or vehicles.

Direct and indirect damage are discussed in more detail in **Section 5.6**.

## 5.4 Policy drivers for increased tree/canopy cover

Given the potential range of benefits associated with increasing canopy cover, it is unsurprising that there are a number of emerging policies aimed at promoting an increase in canopy cover within developed and/or developing areas. The CCC has recommended woodland creation, including the enhancement of urban and peri-urban wood density, to reduce climate-change-related risks.

As noted in **Appendix C3**, the UK government, the devolved administrations and local authority policies have identified green infrastructure as contributing to tackling climate change. For example, in England, the National Planning Policy Framework (NPPF) acknowledges the importance of trees with respect to climate change adaptation and mitigation. Under paragraph 131, it states: "planning policies and decisions should ensure that new streets are tree-lined, that opportunities are taken to incorporate trees elsewhere in developments (such as parks and community orchards), that appropriate measures are in place to secure the long-term maintenance of newly-planted trees, and that existing trees are retained wherever possible." The Town and Country Planning (Tree Preservation) (England) Regulations 2012 require that local planning authorities (LPA) consider the protection and planting of trees when granting planning permission for development. If necessary, LPAs may issue a Tree Preservation Order to protect trees in the interests of amenity.

## 5.5 Factors for consideration in development layouts

Canopy cover within new development layouts should be designed to ensure space for future growth of roots, stems and canopies to maturity, mitigating risk of direct contact to structures, causing obstruction of access, light or nuisance. BS 5837:2012 states: "where tree retention or planting is proposed in conjunction with nearby construction, the objective should be to achieve a harmonious relationship between trees and structures that can be sustained in the long term."

### 5.5.1 Retention of existing trees

It is obviously advantageous to retain any existing trees within development layouts to maximise the existing canopy cover. BS 5837:2012 provides guidance for developers and local authorities on how to survey trees to determine suitability for retention. Once complete, an initial measurement of on-site canopy cover associated with retained trees should be completed.

### 5.5.2 Requirements and specification of new tree planting

Once the area of retained canopy cover has been established, it is necessary to calculate how new planting can be included within the development layout to achieve the canopy cover target. The number, size and shape of trees should be considered to ensure the absence of conflict within the development. The assessment should include consideration of the canopy cover in both its juvenile and mature state.

The quality and quantity of the soil will dictate the speed and size to which a tree can grow. Planting specifications should therefore be provided for each individual species and subspecies of new planting.

### 5.5.3 Time to canopy cover target achievement

Unless the total canopy cover target is entirely made up of retained trees, it will be necessary for trees to reach maturity to maximise canopy cover. Consequently, focus should be towards ensuring the correct conditions are provided for healthy growth.

### 5.5.4 Layout design

Design of layout to accommodate the future growth of trees without conflict is essential. It is imperative that arboriculturists and landscape architects are coordinated with urban designers from an early stage and throughout the design process to ensure the target can be met in an appropriate manner.

The nature and level of detail of information required in the master-planning process (to properly consider the development implications) varies between stages and in relation to what is proposed. For illustrative purposes, a flow diagram has been constructed to help visualise the requirement (Figure 5).

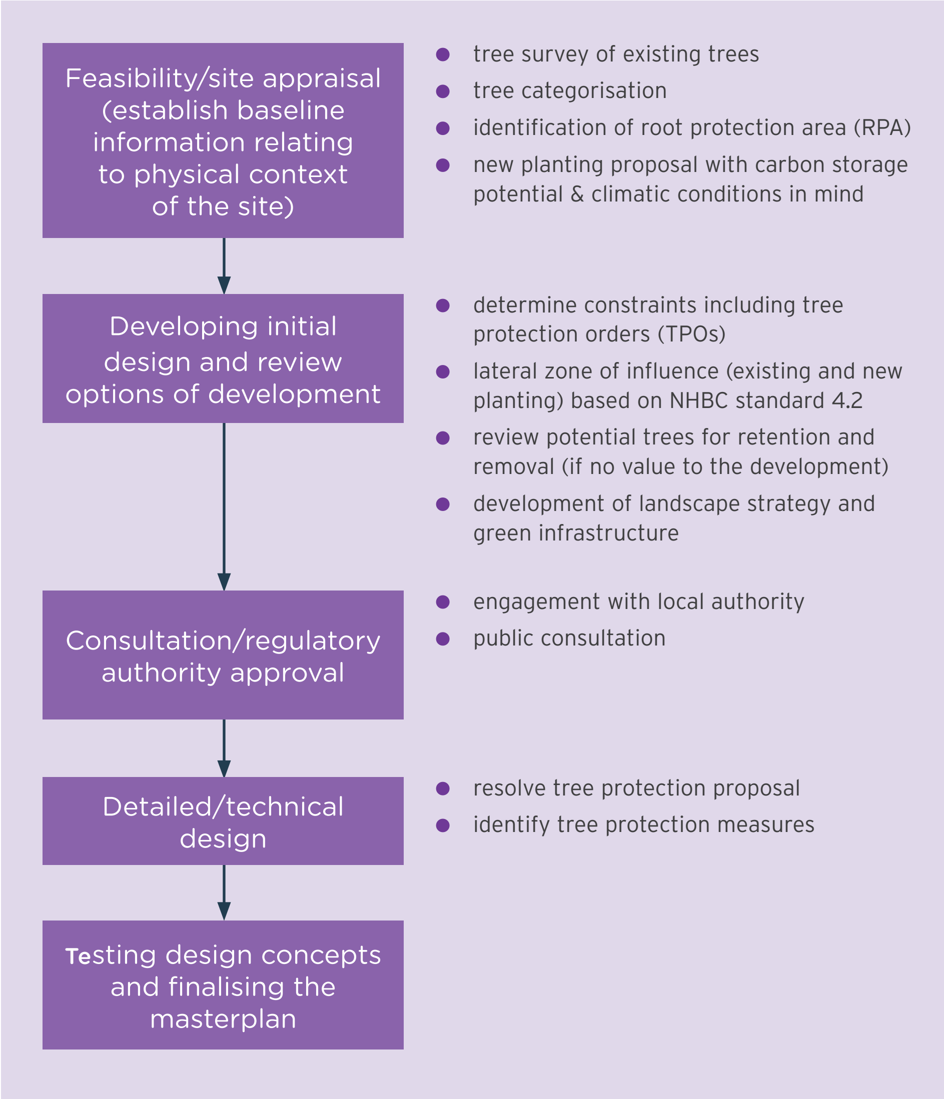


**Figure 5** Flow chart of the planning process for layout design (Source: RSK)

## 5.6 Specific risks posed by increased incidence of trees and vegetation in proximity to existing building foundations and infrastructure

It is well known that trees can cause damage via direct action in all soil types, including disruption of underground utilities and displacement and distorting of structures. This generally takes the form of direct pressure exerted by the tree roots; however, the pressure generated is relatively small and roots are only able to cause damage to lightly loaded structures.

### 5.6.1 Direct risks

Trees can cause direct damage to structures in all soil types by:

- disruption of underground utility apparatus
- displacement, lifting or distorting
- the impact of branches
- structural failure of the tree.

#### 5.6.1.1 Mitigation of direct risks

The following sections summarise the options available to mitigate the direct risks posed to structures due to the proximity of trees and vegetation.

#### Separation

In order to mitigate direct risks posed by new planting to existing structures, Table A.1 of BS 5837:2012 prescribes minimum planting distances. This table has been reproduced as **Table 4** for reference. The minimum distances prescribed within the table may be adopted in non-cohesive soils for all new planting proposed in proximity to existing building foundations and/or structures to avoid direct damage unless specific measures are adopted to accommodate the potential risks.

| Type of structure | Minimum distance between young trees or new planting and structure, in metres (m) | | |
|---|---|---|---|
| | Stem dia. <300mm | Stem dia. 300mm to 600mm | Stem dia. >600mm |
| Buildings and heavily loaded structures | - | 0.5 | 1.2 |
| Lightly loaded structures such as garages, porches etc. | - | 0.7 | 1.5 |
| Services <1m deep | 0.5 | 1.5 | 3.0 |
| Services >1m deep | - | 1.0 | 2.0 |
| Masonry boundary walls | - | 1.0 | 2.0 |
| In-situ concrete paths and drives | 0.5 | 1.0 | 2.5 |
| Paths and drives with flexible surfaces or paving slabs | 0.7 | 1.5 | 3.0 |
| Stem diameter measured at 1.5m above ground level at maturity | | | |

**Table 4** Reproduction of Table A.1 of BS 5837:2012 prescribed minimum planting distances to avoid direct damage to a structure from future tree growth (Source: BSi)

### 5.6.1.2 Canopy reduction

The most commonly adopted canopy reduction techniques to reduce the risks posed to structures from direct contact with trees above ground are crown reduction and crown thinning.

- Crown reduction: this technique reduces the volume of the crown but enables its natural shape to be retained. It is achieved by removing the outer portions of all major branches to achieve reduction of both height and spread.
- Crown thinning: this technique reduces the number of lateral branches coming off all the major branches and does not affect the original volume of the tree.

Decreasing water uptake by trees is believed to lessen subsidence risk by conserving soil moisture and reducing clay subsoil shrinkage. Specifically, reducing the canopy leaf area by pruning was believed to lessen water uptake and cyclical pruning was recommended in a risk limitation strategy for tree root claims developed by the London Tree Officers Association.

However, results of the Horticulture LINK Project no. 212 observed that while crown reduction reduced soil dryness by trees during the year of pruning, the effects were generally small and disappeared within the following season, unless the reduction was severe, in which case the effects were larger and persisted for up to two years. Crown thinning was not observed to reduce soil drying.

The Horticulture LINK Project indicated that there was justification for modifying previously adopted pruning regimes for London plane trees to reduce the risk of subsidence by reducing rather than thinning the crowns and using techniques that produce compact crowns.

Restriction of roots by the methodologies discussed within Section 5.6.1.3, which include root barriers, root deflectors, chemical inhibitors and root pruning, may also offer benefits in reducing the lateral extent of the tree's root systems, consequently reducing the lateral extent of moisture reduction within the soils and controlling the growth of the tree itself.

### 5.6.1.3 Root restriction

Existing structures and infrastructure may be protected from the direct risks posed by roots by adoption of one or more of the following methods.

- Root barriers: typically consisting of woven geotextiles or welded fibre sheets installed to encapsulate the extent of root growth. Stronger roots can, however, penetrate weaknesses within barriers and commonly over time the barriers fail to prevent root growth. Some evidence suggests that retrospective installation of root barriers can actually promote the growth of roots and they can grow more readily through the surrounding soils, which have become disturbed and uncompacted during installation. However, research completed as part of the Horticulture LINK Project 212 in 2004 observed that root restriction for newly planted trees proved a very effective method of controlling growth.
- Root deflectors: typically more robust vertical plastic or metal barriers installed to deflect root growth from sensitive structures and/or infrastructure.
- Chemical inhibitors: textiles that have been impregnated with chemical growth inhibitors to limit root growth are installed within the ground. Such techniques do, however, become less effective over time as the concentration of the chemical inhibitor reduces.
- Root pruning: this can be completed to prevent the growth of roots towards sensitive structures and infrastructure. However, this should only be completed by a specialist in order to prevent damage to the tree and/or destabilisation.

## 5.6.2 Indirect risks

Figure 6 extracted from BRE publication FB13 Subsidence Damage to Domestic Buildings: A Guide to Good Technical Practice (2007)[36] shows the locations of the principal formations that contain soils most prone to shrinkage and swelling, resulting from changes in moisture. The change in volume within the soils occurs as moisture content fluctuates seasonally and as a result of other factors, including the action of roots from trees and to a lesser extent, hedges, large shrubs, crops and vegetation.

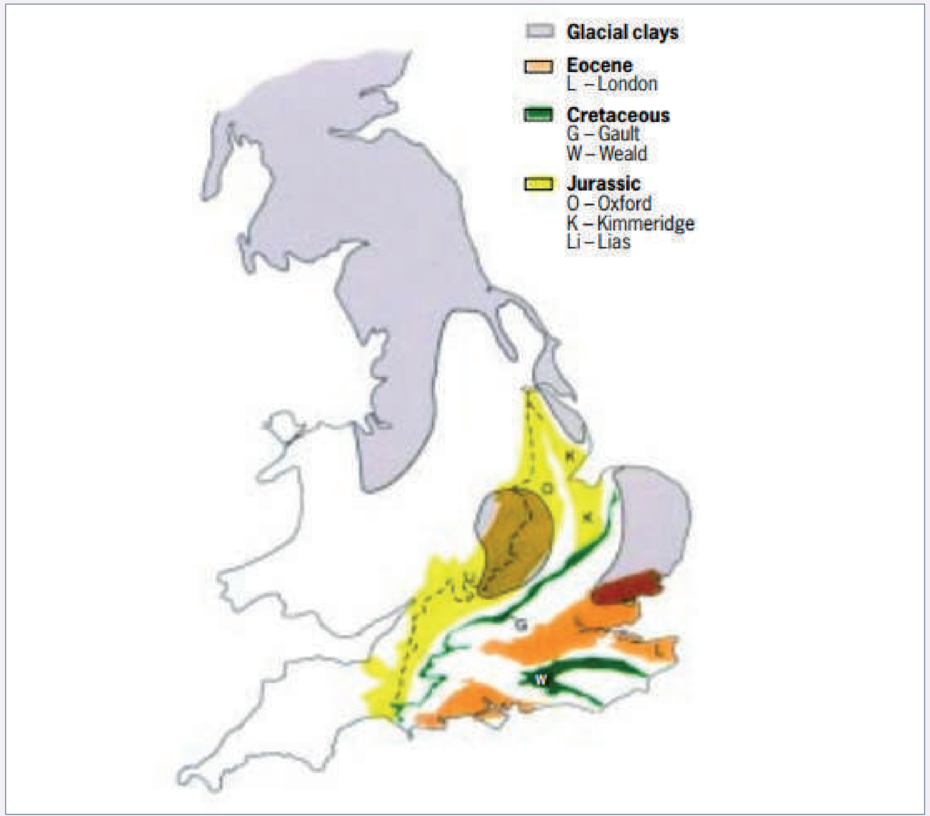


**Figure 6** The distribution of shrinkable clays in England (Source: BRE)

It can be seen that the outcrops of strata shown in this figure align with the BGS data reproduced in Figure 3 in section 4.3.1.3 above. Specifically, in respect to trees, the zone of soil influenced by the roots increases in depth and lateral extent as the tree grows. Although the degree and extent of the desiccation in this zone varies according to the size and species of the tree – as well being influenced by the prevailing climate and soil type (i.e. volume change potential) – certain tree species (all elms, eucalyptus, hawthorn, oaks, poplars and willows) require more water than others to survive. These are described as high-water-demand trees by the current NHBC Standards.

A full categorisation (low/medium/high) of the water demand of broadleaf and coniferous trees by species and the average mature height to which healthy trees of the species may be expected to grow is presented within Table 3 of NHBC Standards, clause 4.2.4: The effects of trees on shrinkable soils.

### Separation distance from trees

One way to avoid tree root problems is to maintain a 'safe' distance between the tree and the building so that the tree cannot influence the soil beneath the building. Table 1 of BRE Digest 298 Low-rise building foundations: the influence of trees in clay soils (April 1999, now archived)[72] records the distance between tree and building within which between 75% and 90% of the cases of damage occurred for each tree species, based on data collected by the Royal Botanic Gardens, Kew. The digest suggests that on high volume change potential soils, 90% distances be adopted for oak species and that the 75% distance be adopted for the remainder of tree species. In terms of tree height rule of thumb, the specified distances typically relate to values between 0.5 H and 1 H where H = mature tree height.

Notwithstanding the above, a slightly more conservative approach based on wider data would be to adopt the recommendations for no tree planting zones, specified within Table 3a of NHBC Standards clause 4.2.7, which specifies a lateral distance of 1.25 x mature height for high water demand trees, 0.75 x mature height for moderate water demand trees and 0.5 x mature height for low water demand trees. As also recommended within NHBC Standards clause 4.2.7, similar lateral distances should be adopted for shrubs that have a maximum mature height of 1.8m and for climbing shrubs that require wall support and have a maximum mature height of 5 m. Exceptions are Pyracantha and Cotoneaster (that have mature heights exceeding 1.8m), which should be planted at least a lateral distance of 1 x mature height. All other shrubs should be planted at least 0.75 x mature height from foundations.

### 5.6.3 Accommodating risk

The potential for existing structures and/or infrastructure to accommodate the risks identified above is commonly seen as a last resort, considered only after damage has occurred. While measures such as underpinning, pressure injection of grout/geopolymer resins, and inclusion of heave precautions within existing buildings can be adopted, the cost implications can be extremely high. Similarly, changes to structures or infrastructure to improve flexibility are commonly cost-prohibitive.

It is noted that while UK insurance policies commonly allow the holder to claim for subsidence to residential housing, this is subject to policy terms, which may exclude a history of ground movement due to close proximity to trees.; t. Within countries such as the United States of America and Australia, where the frequency and magnitude of ground movement can be much higher, the absence of available insurance cover results in the acceptance of tolerable damage within buildings and structures far greater than in the UK.

### 5.6.4 Summary

Introducing and increasing green infrastructure is recognised as supporting adaptation to climate change. Benefits include carbon sequestration, temperature regulation and social and community health benefits. However, trees (both new and existing) pose significant risks, both direct and indirect, to existing structures and infrastructure, including foundations. While the separation of trees from structures and infrastructure within areas of the UK underlain by non-shrinkable soils may be feasible, the distances are unlikely to be permissive within areas underlain by shrinkable soils. Within such areas, tree species should be carefully selected to minimise the tolerable lateral separation between the tree and the existing structure in order to prevent damage. Where such distances cannot be achieved, measures to restrain the growth of the tree and its roots will need to be employed unless perception of tolerable damage can be changed.

## 5.7 Specific risks posed by increased incidence of trees and vegetation in proximity to new building foundations and infrastructure

### 5.7.1 Risks

Potential risks posed to new buildings and infrastructure from the increased incidence of trees and vegetation are principally the same as those discussed within Section 5.6 for existing buildings and infrastructure. Similarly, measures to separate and/or mitigate them remain the same. The exception is the ability to appropriately design the foundations for the building and/or the building or infrastructure itself. Consequently, this section is dedicated to discussing the measures that could be incorporated within the design of new foundations and infrastructure to mitigate or accommodate the risks.

### 5.7.2 New building foundations and structures

New building foundations may be constructed in relatively close proximity to existing or planned trees and vegetation where soils are non-shrinkable. Appropriate distances of separation are detailed within **Section 5.6.1**, based on the recommendations contained within British Standard BS 5837:2012. It is noted, however, that where traditional strip foundations are proposed in close proximity to existing trees, this can result in significant root damage and consequently should be avoided. Piled foundations offer the ability to avoid or at least minimise damage to existing roots, assuming initial excavations are made by air spade or similar to ensure piles are appropriately located around the roots. In general, piles with the smallest diameter should be adopted to minimise damage.

Greater distances of separation are required where soils are shrinkable, as detailed within **Section 5.6.2**, which are based on current NHBC Standards. By increasing foundation depths and inclusion of heave precaution measures in strict accordance with the current NHBC Standards, separation distances may be reduced significantly. The separation distances are proportionate to the volume change potential of the soil, the water demand of the tree and the depth of the foundation. Alternatives to simple deepening of traditional spread foundations include adoption of short-bored piles (designed to resist potential heave forces in tension) or stiffened rafts, more capable of accommodating ground movements. Such measures to mitigate the risks will clearly increase the cost of building, which is likely to preclude their adoption unless policy is adopted to mandate the requirement for increased trees and vegetation on new developments in close proximity to buildings. Further research and development are required by the construction industry to ascertain the most commercially viable alternative foundation solutions to enable trees and vegetation to be planted in closer proximity to structures in shrinkable soils.

An alternative to minimising structural movements by improving foundation design would be to consider adopting more flexible structures than traditional brittle masonry construction. Timber framed and timber boarded structures are known to be more commonly adopted in areas outside of the UK to accommodate the risks posed by ground movements. As the industry adopts more framed and prefabricated modular construction techniques and customers appear more willing to accept them, designers should investigate the potential to incorporate more flexibility and articulation within the structures to accommodate the anticipated magnitude of potential ground movements.

As it appears unlikely that customers within the UK will be more willing to accept any visible cracking or distortion within the structures, even if such small movements are not detrimental to the performance of the structure or its facade, it will remain essential for the design to prevent or mask any such issues. The construction industry also has a responsibility to research and develop new or emerging construction techniques as more efficient and low carbon alternatives to simply deepening foundations, and these will need to be considered by warranty providers.

### 5.7.3 New hard surfacing and light structures

Where the installation of new paths or light structures near to young trees is unavoidable, their design needs to take the growth of trees into consideration. Specifically, where walls or similar structures are constructed over roots greater than void formers around the root and by adoption of a reinforced lintel above to transfer loads around the root.

Where hard surfacing is proposed, unbound granular material may provide a suitable surfacing as it allows future growth to occur and may be simply regraded as necessary to accommodate any ground movements. Where bound or rigid construction materials are proposed, these should be used in a manner to enable infiltration and distortion along defined joints to occur.

## 5.8 Likely future trends, current uncertainties and unknowns

It is not clear from the current research information available whether drier summers will cause the desiccating effects of trees to increase or not. The low permeable nature of clay soils makes it inherently difficult to draw moisture out of them. Hence, in drier conditions, it is possible that trees will be put under stress, as they are unable to draw sufficient water from the ground to meet their needs. As a consequence, one indirect impact of climate change could be the loss of trees. For example, evidence from the dry summer of 1976 shows that the drought put significant stress on the beech tree population in England to the point that in certain areas it is no longer the predominant species.

When tree loss happens, the clay slowly recovers its moisture content and swells with resultant impacts on foundations that were constructed in the trees' vicinity. This can therefore affect the shrink-swell risk to foundations unless replanting takes place.

Most tree species that are currently well suited to the soil are likely to continue to be suitable under steady-state climatic conditions. However, longer-term changes in precipitation or temperature arising from climate change may lead to longer periods of stress (either via drought or waterlogging) on trees. Certain native trees may not be able to tolerate such distress, e.g., higher winter precipitation may result in more active root pathogens, so roots will be more seriously damaged. Then, when the root systems come under stress in the hotter summers, more trees and shrubs may die back. Subsequently, ground movement could increase, as wetter winters swell soils and drier summers lead to trees extracting more water than at present, leading to damaging soil shrinkage.

Increased frequency and intensity of storm events will also lead to direct damage to trees, which can cause both direct and indirect damage to buildings, the latter including indirect effects on foundations.

## 5.9 Alternatives to trees/canopy cover with less of an effect on foundations

To reduce the impacts typically associated with tree canopy/cover, consideration may be given to alternative green infrastructure, such as living roofs and walls. These can similarly enhance biodiversity, reduce the risk of flooding (by absorbing rainfall), improve a building's thermal performance, thus reducing associated energy costs and help counter the 'urban heat island' effect associated with higher temperatures and hot summers. Some options for this are outlined below.

### 5.9.1 Green roofs (living roofs)

There are generally three types of green roof systems: extensive, semi-intensive and intensive, which are made up of a number of layers, as illustrated in **Figure 7**.

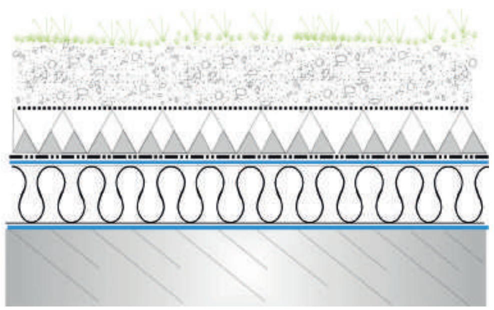


**Figure 7** Typical green roof cross-section (Source: CIRIA)

Intensive roofs are often referred to as roof gardens, as the vegetation can consist of a variety of plant types, such as ground cover, herbaceous plants, grasses, woody shrubs and small trees. This type of roof requires regular maintenance and irrigation, and the depth of the growth medium is generally greater than 200mm. They are principally designed to provide amenity and are normally accessible for recreational use. Owing to the plants used and the combined growing and drainage properties of the substrate, the weight of the intensive green roof system can be considerable. Substantial reinforcement of an existing roof structure or inclusion of extra building structural support may be required, with a consequent impact on foundation design.

Semi-intensive roofs are an intermediate green roof type with characteristics of both extensive and intensive roofs. They tend to have a wider range of plants, including shrubs and woody plants, compared to extensive roofs. In general, the depth of the substrate is between 100mm and 200mm. The guidance varies with regard to the requirements for irrigation and maintenance.

Extensive roofs have a shallow growing medium and are designed to be relatively self-sustaining. In most cases, they are planted with, or colonised by, mosses, wild flowers and grasses that are able to survive on the shallow low-nutrient substrates that form their growing medium. They require minimal management and usually no irrigation or fertilisation, although these may be required initially until plants become established. Based on information from BRE,[73] they usually comprise:

- mat-based systems: these have very shallow soils, typically between 20 and 40mm, are pre-grown to provide 100% instant cover and generally consist of Sedum species. The shallow substrates of mat-based systems retain less rainfall and have less thermal mass.
- substrate-based systems: these are generally between 75mm and 150mm in depth, and consist of either a porous substrate or similar reused aggregates. In the UK, such systems are generally planted with a variety of Sedum species, whether as plugs, cuttings or seeded, although on continental Europe it is more common to use species of wild flowers that are typical of dry meadow habitats. As substrate-based systems are deeper than those that are mat-based, they have the potential to support a greater variety of species, hold significantly more rainfall, have a greater thermal mass and have greater evapotranspiration properties. A potential disadvantage is that they are heavier than mat-based systems and take time to establish full vegetation cover, should that be required.

### 5.9.1.1 Case study: Kidbrooke Village

Kidbrooke Village comprises an ongoing 109-hectare development by Berkeley Homes, located within the Royal Borough of Greenwich in south-east London (see The majority of the blocks within the development will provide extensive biodiverse green roofs. Berkeley Homes[74] commented that the rationale for installing biodiverse green roofs included requirements of planning, corporate responsibility, contribution to sustainable drainage strategies and to enhance biodiversity. In terms of wider benefits, the green roofs provide visual amenity for people in apartments at higher levels and the intensive green roofs provide amenity space for residents. Both also provide habitats for wildlife and support increased biodiversity.

**Image 7** shows an example for a living roof in an urban setting.

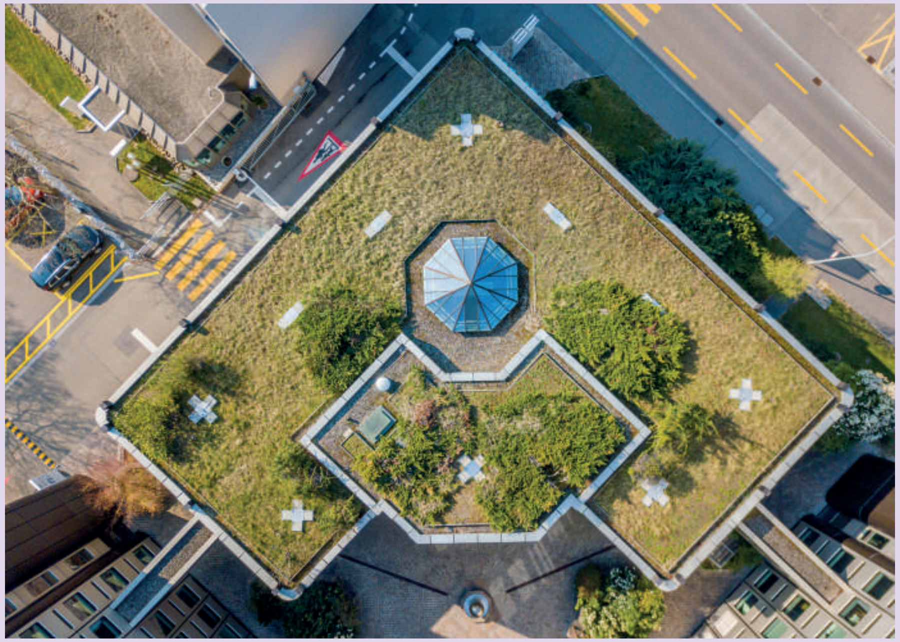

**Image 7** Aerial view of a living roof in an urban residential area (Source: Shutterstock)

## 5.9.2 Green walls

Green walls, also referred to as living walls, are deliberately vegetated facades. There are fewer established guidelines on their use. Broadly speaking, the effect is achieved in a number of ways.

- Climbing plants can be grown directly against the wall or trained against a trellis. A trellis of steel wires or mesh is used as a support for climbing plants, which can be rooted into the ground or substrate-filled planters, which can be supported at height if required. Such systems are usually irrigated but can survive without irrigation if rooted into the ground.
- Hydroponic green walls: these systems are usually constructed from plastic mesh, geotextiles, fabrics or horticultural mineral wool or combinations of materials fixed to supporting frames or boards. Plants grow without substrate or soil and rely on irrigation and nutrients added to irrigation water.
- Modular green walls: usually manufactured from purpose-made HDPE modules containing cells that are filled with growing medium and planted. Modules are fixed to a wall or frame and may be combined to cover large areas. Irrigation water is usually delivered to the top of each module via irrigation lines. Nutrients can be contained in soil or added to the irrigation supply.

### 5.9.2.1 Case study: Parliament Hill School

**Image 8** Living wall, Parliament Hill School, Camden (Source: Scotscape)

Parliament Hill School is located in Camden, London. The green wall shown in **Image 8** is a modular green wall, which was supplied and installed by Scotscape. The wall contains many native species to help support local biodiversity. The densely planted structure also contributes to insulating the building and helps with the amelioration of air pollution.

## 5.9.3 Limitations

There are a number of limitations to implementing green roofs/walls and these include

- a lack of UK standards. The major suppliers of green roofs in the UK are signed up members of the German FLL, the Landscape Research, Development and Construction Society. This body provides standards for landscaping in Germany.
- damage to waterproofing. Historically, flat roofs have been perceived as more vulnerable to leakage due to the effects of the climate (frost and ponding) on waterproofing systems. Most established green roof suppliers provide FLL-rated root barriers, which protect waterproofing membranes from the potential negative impact of roots. Furthermore, established companies will leak test before the implementation of the green roof element.
- a lack of policy. The implementation of living roofs is not being informed by policy guidance. Very few are being established in order to capture the energy- and water-management-related benefits that can accrue. For these benefits and particularly those relating to climate change to be achieved in full, there has to be wide-scale uptake of the technology: something that will only happen when firm policy guidance is available.
- damage to trees/vegetation due to wind loading. This may potentially impact the stability of trees.
- the potential risks associated with green walls, that are a major barrier to widespread use, particularly a lack of clarity with regard to compliance with parts of the Building Regulations. For example, satisfactory mitigation of the fire risk is one area that is yet to be fully developed.

### 5.9.4 Summary

Increased canopy cover, especially within an urban setting, has recognised environmental and social benefits, including managing temperature, water regulation, air quality and community wellbeing. However, the close proximity of trees has the potential for direct damage from roots impacting building foundations and services. There is further potential impact on buildings and structures from new planting and existing trees, resulting in removing moisture from load-bearing shrinkable clay soils.

Standard BS 5837:2012 prescribes minimum planting distances to avoid direct damage in non-shrinkable soils, assisting planners and developers in accommodating the retention and introduction of trees. NHBC Standards Chapter 4.2 recognises the potential implications on soils susceptible to shrink–swell and provides recommendations on tree standoff distance and foundation depth.

The benefits and implications of increased canopy cover; the impact on soils susceptible to shrink–swell and adaptation; and the resilience of building design to mitigate the anticipated long-term changes in weather due to climate change are all understood but would benefit from consistency and standardisation of approach.

Alternative solutions to increasing canopy cover include the development of green roofs and walls; however, this is subject to adequate building design and structural integrity.

# 6 Low carbon foundation solutions

## 6.1 Introduction

Ongoing pressure on the construction sector in the UK to reach net zero by 2050 means that lower carbon solutions need to be considered throughout the design process. This needs to start from the ground investigation phase and feed into the design and implementation of all construction projects.

In 2017, the House of Commons' Housing, Communities and Local Government Committee on Modern Methods of Construction (MMC)[75] reported that "to meet its target to eradicate the UK's net contribution to climate change by 2050, the Government should embrace every opportunity to reduce carbon emissions. It should be ambitious in setting carbon reduction targets for the built environment both during construction and in use."

It should be noted that the term 'net zero carbon' differs from 'carbon neutral' developments. Carbon neutral is defined by PAS 2060[76] as a "condition in which during a specified period there has been no net increase in the global emission of greenhouse gasses to the atmosphere as a result of the greenhouse gas emission associated with the subject during the same period."

Both net zero carbon and carbon neutral developments require measurement against scope 1 (direct emissions), scope 2 (indirect energy emissions) and scope 3 (indirect other emissions). However, carbon neutral developments under PAS 2060 aim to avoid increasing carbon emissions by purchasing offsets (carbon credits) equivalent to the total carbon footprint, whereas net zero carbon developments need to reduce the carbon emissions throughout the process with offsetting as a last resort. This section focuses on net zero carbon, as offsetting is increasingly seen as an unviable long-term approach.

This section initially considers relevant carbon calculator tools and estimated relative embodied carbon between different foundation options. It then goes on to consider a range of possible ways to reduce embodied carbon within foundations,[77] including the following established and emerging options:

- modern methods of construction (MMC)
- reducing the load
- alternatives to and reduction of concrete/cement
- alternative low-carbon options
- pre-cast piles
- combining piled foundations with ground source heating
- reuse of existing foundations.

**N.B. reference is made in this section to a range of organisations and proprietary products. These have been used as examples in support of the options discussed. This is not an endorsement of these organisations or products, nor does this confer NHBC acceptance on any of these products or services.**

This section concludes with reference to the findings of the industry survey and interactions between resilience and low carbon design.

## 6.2 Relevant carbon emissions

There are an increasing number of carbon calculators available or in development that are applicable to the construction sector. In preparing this review, more than ten carbon calculator tools were identified to be potentially applicable. These include the European Federation of Foundation Contractors-Deep Foundations Institute (EFFC-DFI) Carbon Calculator, the Environment Agency Carbon Calculator and the IStructE Structural Carbon Tool. However, these have varying degrees of relevance to calculating the carbon cost of foundations design for residential development. Leap Environmental[78] has designed a carbon calculator for foundation design for new residential developments, which was recently published. The most relevant tools currently available are summarised here but it is acknowledged that there are gaps in the tools available to enable the practical calculation of embodied and whole-life carbon for all relevant foundation options.

### 6.2.1 EFFC-DFI Carbon Calculator

One tool that is particularly relevant to the geotechnical sector and this review is the EFFC-DFI Carbon Calculator.[79] The tool is specifically designed to calculate the $CO_2$ emissions of foundation and geotechnical works and to enable designers, contractors and commissioning organisations to assess the carbon footprint of their projects. In addition, the tool allows the user to compare the $CO_2$ emissions of different approaches within the same project. The tool, first developed in 2012, includes a carbon accounting methodology for a variety of techniques (see **Figure 8**).

The figure details the emissions source breakdown for each of the techniques, the main contributors being materials, energy and waste. This would imply that the easiest way to tackle carbon reduction in foundations is to look at the materials selected, their transport to site, the energy involved in their production and installation and the wastes produced.

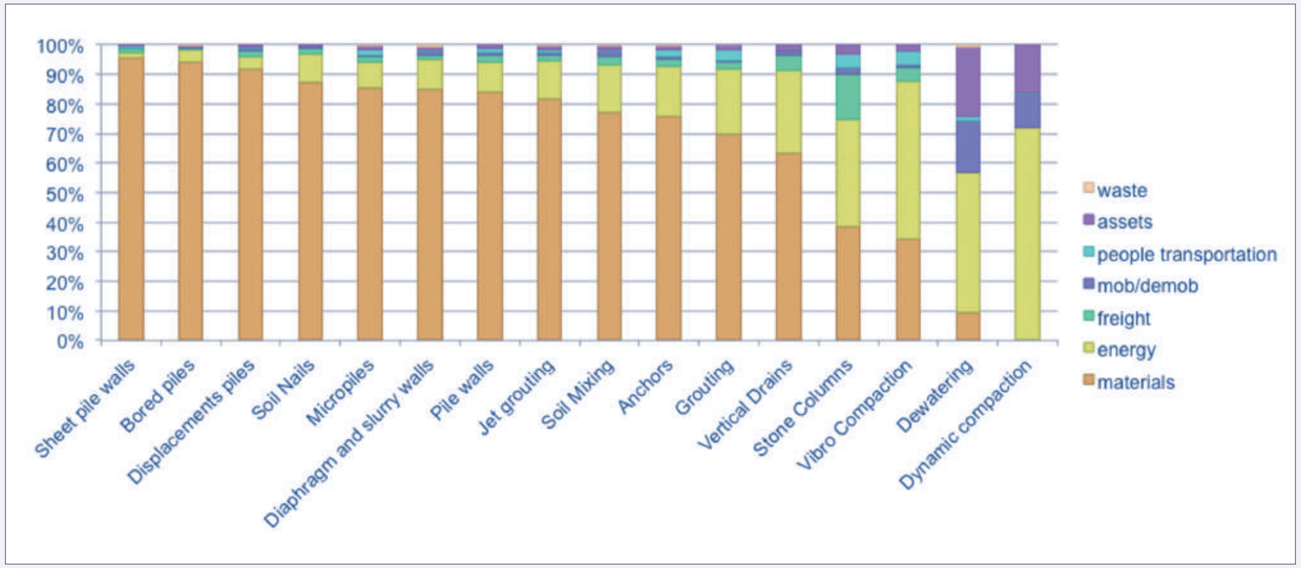


**Figure 8** EFFC-DFI Carbon Calculator Tool: Emission breakdown – average results based on samples studied to develop the methodology (Source: EFFC-DFI)

### 6.2.2 Leap Carbon Calculator

Leap Environmental, a RSK company, has designed a carbon calculator tool for foundation design for new residential developments. The calculator focuses on embodied carbon associated with the construction phase, rather than a whole-life carbon assessment. It is based on site-specific data obtained as part of a ground investigation.

A simplified ground model is used within the tool to select from a range of different soil types, including high and low plasticity index (PI) clay, sand, gravel and chalk. The calculations also consider any made ground present, whether this is contaminated or not and its suitability for reuse. The tool calculates the total embodied carbon of the earthworks activities and both on-site and off-site transport. It considers traditional shallow foundations and continuous flight auger (CFA) piling methods, allowing a comparison between the two.

For shallow foundations, the width and depth of the foundation are input along with the use of reinforcement. The calculations also consider the type of cement used within the foundations to enable low carbon options to be used.

For a piled solution, the pile diameter and pile length are input, together with the number of piles and distance between them. As with the traditional footings, the steel reinforcement and cement type can also be changed. In addition, for the piled solution, the piling mat size and thickness is included in the calculation of the equivalent carbon for the earthworks required prior to the piling works.

An example using the carbon calculator for shallow and pile foundations can be found in **Appendix D**.

## 6.3 Embodied carbon in foundations

At the time of writing, there is no technical specification for the carbon embodied in foundation materials. The principal contributor to embedded carbon in the majority of foundation works is concrete, specifically the production of cement. The $CO_2$ emissions due to calcination are formed when the raw materials (mostly limestone and clay) are heated and $CO_2$ is liberated directly from the decomposed minerals and indirectly from the $CO_2$ emitted in the power generation used in heating the raw materials. Steel used in reinforcement is also a major contributor due to high embodied carbon associated with its manufacture.

Depending on the ground conditions, various foundation types may be available. The most cost-effective foundation solution may not necessarily be the one with the least environmental impact. For example, trench fill foundations are a common foundation solution for low rise structures. For a typical three-bedroom semi-detached house, concrete (across the foundation and slab and superstructure if applicable) comprises around 18m$^3$, or the equivalent of around 3000 kg of embodied carbon dioxide.[80]

In the context of reducing carbon in the construction phase as a whole, low embodied carbon solutions should be compared with traditional high volume concrete solutions, such as deep trench and raft foundations. In poor ground conditions or where high building loads are to be applied, traditional piling techniques may offer the most energy-efficient solutions. The advantages gained above ground with modular and prefabricated system ground floor construction can be further enhanced as these foundation and flooring systems are compatible with most piling systems, including driven precast concrete or steel piles, continuous flight auger (CFA), segmental flight auger (SFA) or continual helical displacement (CHD) and steel helical (screw) piles. An emerging technology is also to combine ground source heating and piling for foundations, referred to as 'energy piles' (see **Section 6.10**).

However, it needs to be borne in mind that piles are normally used in conjunction with a reinforced concrete ground beam, whereas trench fill may be built on directly. Some proprietary piled foundation/ground floor systems exist that efficiently provide both the ground floor slab and perimeter beams for the walls.

## 6.4 Modern methods of construction (MMC)

According to the NHBC Foundation's 2016 report NF70 Modern Methods of Construction: Views from the Industry,[81] 98% of large- and medium-sized housebuilders and housing associations have used or considered at least one form of MMC. The survey undertaken as part of this review also highlighted that approximately 30% of housebuilders and 10% of housing associations had experience of using prefabricated foundations; however, the report does not refer to climate change or carbon as reasons for considering MMC, with the survey reporting faster build programme, improved build quality and improving health and safety as key factors in its selection.

The House of Commons' Housing, Communities and Local Government Committee on Modern Methods of Construction (MMC) report in 2017 stated that "MMC should be used to deliver more efficient homes now, to avoid costly retrofitting of homes later, to comply with more rigorous energy efficiency targets." The committee also stated that a significant proportion of homes must be built using MMC if the UK is to meet the target to deliver 300,000 homes annually.

In 2017, a cross-industry working group was established by the UK government,[82] tasked with developing various outputs, including the categorised definition framework or different forms of innovative construction methodologies. In total, seven MMC categories were identified, including those relating to pre-manufactured (off-site construction), performance- and productivity-based improvements compared to traditional building and process-led systems. RICS has confirmed that it will integrate the MMC definition into supporting guidance for the new Home Survey Standard, New Build Valuation Guidance, and the next revision of the International Construction Measurement Standards.

In 2018, the NHBC Foundation followed NF70 with the release of NF82 Modern methods of construction: who's doing what?,[83] in which a survey confirmed that of 36 active MMC developers, over 50% of their development output used MMC, with only 8% stating they had no plans to expand their use of MMC. Quality (86%) and efficiency (81%) were the two highest reported reasons for utilising MMC and while there was no specific question relating to climate change or carbon, over half (53%) of developers stated sustainability as a factor for the use of MMC.

## 6.5 Reducing the load: Lightweight building construction

### 6.5.1 Lightweight concrete floor

The Block Research Group at ETH Zurich, in conjunction with building materials company Holcim, has developed a new floor system[84] using a technique and design that has the potential to reduce material (70%) and associated embodied energy in material production[85] using fewer materials/ concrete and 90% less reinforced steel compared to standard block and beam construction, which is currently the most commonly used option in new build houses. The Rippmann Floor System (RFS) uses off-site 3D-printing techniques to construct an unreinforced concrete floor made up of a thin funicular vault stiffened by a series of spandrel walls.[86] The floor is completed with tension ties that link the supports and absorb the horizontal thrusts of the funicular shell. In 2021, the first example of this innovative floor design was built as part of the NEST HiLo project on the Empa campus in Dübendorf, Switzerland.

While the application of this technology to date is limited to the single full-scale construction project at NEST and exhibited prototypes, the potential for this MMC technique to assist in reducing embodied carbon through building design is considered significant.

### 6.5.2 Cross-laminated timber

Cross-laminated timber (CLT) is an MMC for producing structural, prefabricated panels used to form walls, roofs and floors.[87] Typically made from spruce, pine or larch, the sheets of wood are laid in layers at 90 degrees to the layer below and glued, producing a 'super plywood' (see **Figure 9**).

CLT has a high strength-to-weight ratio compared to concrete and steel and therefore offers the benefit of reduced loading on foundations and infrastructure services.

According to the RICS 2018 report, the first high-density housing building in the UK was the Stadthaus in London (see **Image 9**). A high-density housing building built from prefabricated CLT panels, the nine-storey building was commissioned by Metropolitan Housing Trust and developed by housebuilder Telford Homes.[88]

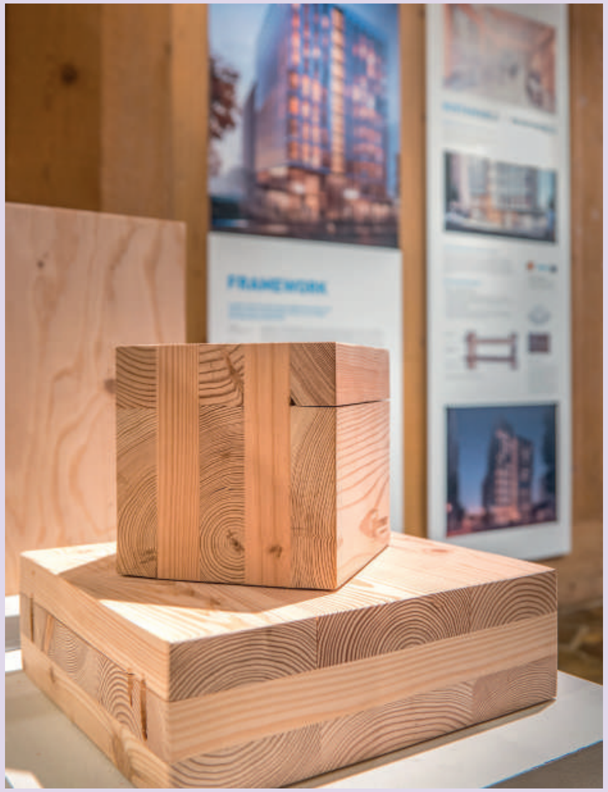

**Figure 9** Cross Laminated Timber (CLT) Exhibit (Source: Shutterstock)

**Image 9** Stadthaus, London (Source: Waugh Thistleton Architects and Will Pryce)

## 6.6 Alternatives to and reduction of concrete/cement

Installation of concrete foundations has high embodied carbon generally, requiring heavy machinery and the transportation of concrete and other materials to site. Additionally, if they are not designed with reuse in mind, their removal can add a large amount to the whole-life carbon impact.

### 6.6.1 Reduced carbon cement

The cement manufacturing industry in the UK has recognised the importance of reducing carbon in the production of its products and has been active in producing a range of 'green' cements. Examples of these products in comparison to their traditional counterpart are presented in **Table 5**.

| Producer | Product | Carbon reduction compared to standard concrete mix |
|---|---|---|
| Cemex UK[89] | Vertua© Classic | 30-50% |
| Hanson[90] | EcoPlus® | At least 35% |

**Table 5** Example low carbon concrete products

### 6.6.2 Alternatives to and reduction of concrete/cement use

Alternatives to and reduction of concrete/cement use include:

- **ashcrete**: Fly ash is a by-product of combustion and is generally discarded to landfill. When mixed with lime and water it can make a suitable alternative to conventional cement.
- **ground granulated blast furnace slag (GGBS)**: A cement substitute manufactured from a by-product of the iron-making industry. Using one tonne of GGBS in concrete reduces the embodied $CO_2$ by around 900 kg compared to using one tonne of Portland cement.[91]
- **micro silica**: This is commonly used in hot climate countries to reduce heat generation and slow setting time in deep foundations, thereby avoiding explosive spalling.
- **aggregate replacement**: Examples include Papercrete, i.e., replacing the aggregate portion with waste paper; concrete debris, i.e., reusing old concrete (crushed) to replace virgin raw materials to reduce the consumption of new resources; post-consumer glass; and plastic waste.
- Of the above options, ashcrete is dependent upon products of combustion, typically coal from energy generation, which the UK is committed to phase out by 2025. The United Kingdom Quality Ash Association (UKQAA) reported in 2020[92] that fly ash generation in 2019 was 257,454 ktonnes compared to sales of 255,445 ktonnes with landfill/stockpile of 902,284 ktonnes, suggesting the availability of this source of material in the UK will diminish after 2025 with the loss of coal-fired power stations, a situation that has already occurred in Scotland.

The availability of GGBS may also reduce over time with the reduction of iron making via this route in the UK.

All of the above options, while reducing the carbon footprint of the cement, do not reduce the carbon involved in the physical process of transporting to site and installing.

Driven timber or steel piled foundations could also be a viable alternative, as discussed in the next subsection.

## 6.7 Alternative low-carbon options

While alternatives to cement are an option for reducing the carbon cost of concrete, there are other non-concrete solutions that would also lower the carbon cost of a project, as detailed below.

### 6.7.1 Timber piles

Timber piles sourced from sustainable forests could be an option for short life structures with low bearing capacities and soft strata. There are three classes of timber pile based on the quality and dimensions.

- **Class A**: Minimum diameter of 14 inches (355 mm) and used for heavy loads
- **Class B**: Minimum diameter ranges between 12 and 13 inches (300–330 mm) and used for medium loads
- **Class C**: Minimum diameter of 12 inches (300 mm) and used for temporary structures.

### 6.7.2 Concrete-free piles

RapidRoot[93] has developed a heavy duty concrete-free footing system termed a 'hybrid root pile' (see Image 11). It is an adjustable system comparable to screw piles and ground anchors. The solution is suitable for most soil types and as with timber piles, offers an alternative potential solution to deep trench footings in overcoming tree-induced desiccation, as noted in **Section 5.6.2**.

#### 6.7.2.1 Case Study: RapidRoot – a public walkway amongst 'champion' trees

A common construction problem is building among and around trees. Apart from dealing with the tree roots themselves and the health of the tree, the potential for soil expansion and contraction and the stability of the foundations is also a major cause for concern (**Section 5.5.2**). RapidRoot systems are non-invasive and do not disturb the soil. Being hollow sections, they core into the soil without significantly displacing the ground (see **Image 10**).

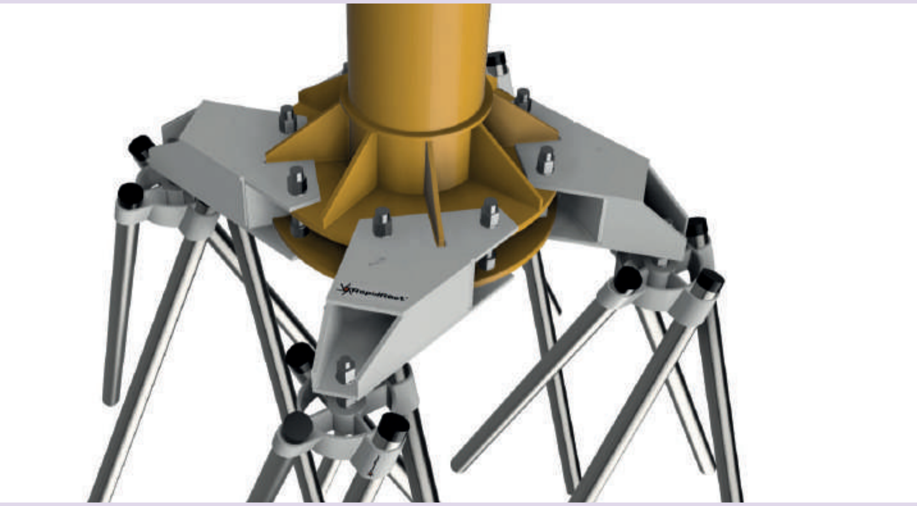

**Image 10** RapidRoot pile design (Source: RapidRoot)

RapidRoot enables the ground to be left intact, apart from slightly sinking the pile caps for aesthetic reasons. The system avoids the need for excavation and thus greatly reduces installation equipment and displaced spoil. The installation equipment and relative light weight of the system enables installation within areas of restricted access. An example is shown in **Image 11**.

**Image 11** RapidRoot installation along a public garden walkway (Source: RapidRoot)

### 6.7.3 Screw piles

The use of steel screw or helical piles can reduce carbon emissions when compared to concrete foundations. They are generally constructed from galvanised steel and can penetrate through dense ground conditions where standard excavation can be difficult.

### 6.7.4 Incorporated ring beam

The option of an incorporated ring beam obviates the need for a concrete (either pre-cast or in-situ poured) ring beam to be constructed on site. Additional steel is incorporated into the steel frame (floor), removing the need for a concrete ring beam on site. The structural load is transferred to the foundations via point loads. An example is shown in **Image 12**.

This innovation results in a reduced site construction time from avoiding the concrete ring beam pour (that requires 28+ days to cure) – although the time benefit varies, depending on the foundation type used. The potential impact/benefits with associated carbon savings include:

- reduction in on-site works
- reduction in concrete required for foundations
- reduction in excavating waste for transport off-site
- reduced site construction time/cost
- reduced site deliveries (and associated carbon impact).

**Image 12** Inbuilt ring beam foundation (Source: Elevate FBE Ltd.)

## Future Found trenchless solution

Future Found[94] is an MMC trenchless system, manufactured in the UK, that uses high-density expanded polystyrene (EPS) formwork, designed and cut to suit the individual project design (see **Figure 10**). The Future Found system is certified as an "Innovative Product" that can meet NHBC Standards; however, additional requirements must be met for it to qualify for Buildmark cover.

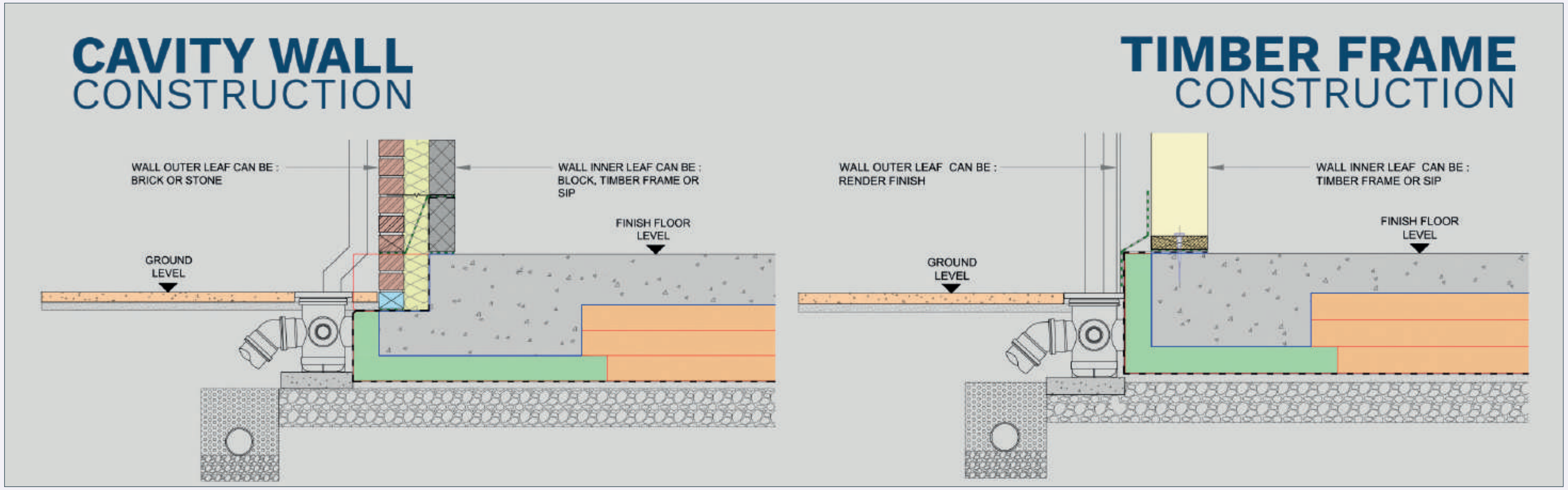


**Figure 10** Future Found trenchless system (Source: Build-Lite (UK) Ltd)

The product arrives as a ready-made framework, that once constructed, enables the concrete to be poured in one operation. This saves on machine time and waste, making it not only cost-effective but also lower carbon.

## 6.8 Pre-cast piles

Pre-cast or hollow piles may be utilised to reduce material and transportation carbon costs of concrete to site.

### 6.8.1 Driven pre-cast piles

Driven pre-cast piles can be considered a lower carbon alternative to cast-in-situ piles (See **Figure 11**). While transportation is still required for equipment and materials, the amount of waste produced is low.

The higher strength of concrete required for driven piles tends to counteract the greater volume of concrete used for CFA piles, with the $CO_2$ cost of concrete for driven piles being 177kg versus 230 kg for CFA piles (BRE Environmental Profiles database). The steel reinforcement adds a further 83 kg of $CO_2$ to each type of pile.

As well as being a lower carbon alternative to cast-in-situ piles, pre-cast piles are also suitable for high water tables, which is a likely result of climate change in many areas of the UK.

Apart from the embodied carbon cost incurred during manufacture of the products, the main disadvantage to this technique is the vibration and noise produced during installation. The impact on surrounding buildings would need to be considered on a site-specific basis.

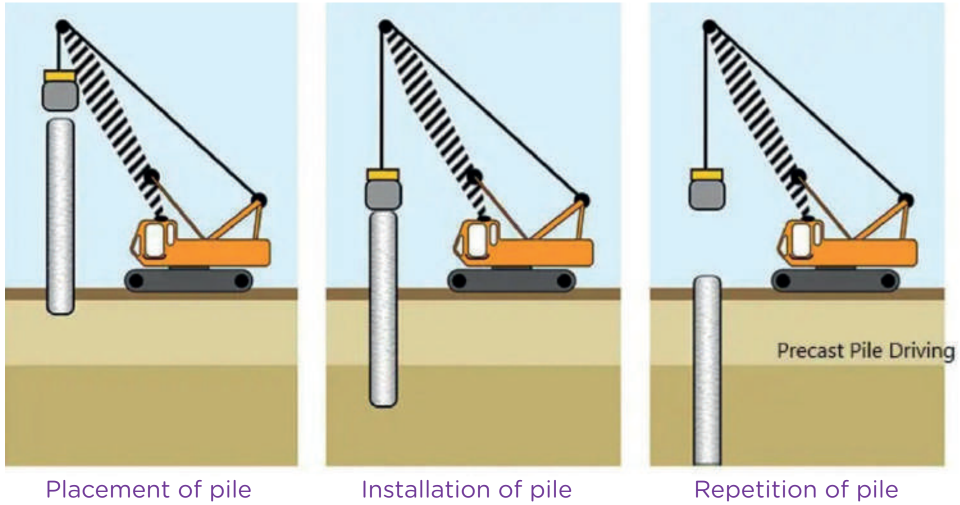


**Figure 11** Example of one method used for installing pre-cast piles (Source: Structural Guide)

Of course, driven piles may not be suitable for all sites, in particular, their use may cause problems such as ground heave or may push contaminated soils through aquicludes or into aquifers. The performance of CFA piles can be improved by using casing, which avoids the removal of excess soil from around the bore. Other low carbon alternatives include vibro-stone columns, which have approximately 10–25% of the embodied carbon of normal concrete piles, or stone trench foundations or screw piles. Vibro-stone columns can create pathways for gas migration to the surface or contamination to migrate to groundwater at depth. Therefore, site-specific applicability needs to remain an important consideration in foundation selection alongside carbon and other important factors such as cost and programme.

### 6.8.2 Hollow piles

Developed by Balfour Beatty Ground Engineering and City University of London, the City SuRe PileTM is a reusable hollow pile.[95] The concept is that the pile is the same size and shape as a standard pile but with a hollow centre, which results in less concrete being used than in the standard pile.

The ground is bored or augered in the standard way; however, prior to the concrete pouring, a hollow steel tube is placed in the centre. The concrete is poured around the void between the tube and the soil. Once completed, specially designed pile caps are cast to ensure the load is distributed to the correct sections. Currently, the inner steel tube remains in place, but it is hoped that future methodologies would permit removal of the inner steel tube liner from the piles.

## 6.9 Combining piled foundations with ground source heating ('energy piles')

Ground source heat pumps are an efficient and low carbon renewable heating, cooling and ventilation system. Combining the ground heat exchanger with a geotechnical structure (e.g., a pile) can lead to a lower capital cost and in turn lower carbon, particularly where piling is the preferred foundation solution.

The NHBC Foundation report NF5 Ground source heat pump systems: Benefits, drivers and barriers in residential developments, published in October 2007, discusses the combining or incorporation of pipes into piled foundations as an emerging technology. This has been used in commercial buildings but is less common in housing due to a lack of scale effects. This approach requires rigorous quality control of the installation of the pipework, the joints in the pipework and the connections at the top of the pile, as after casting they cannot be easily repaired.

### 6.9.1 Thermal screw piles

Utilising the previously mentioned screw piles, a thermal screw pile aims to provide two jobs in one solution: the pile doubles up as a heat exchanger for underground thermal energy storage (UTES). Developed by ENVIGA Geothermal, the Thermo Screw Pile™[96] is a "pre-assembled energy-pile, which can be easily removed and recycled". This makes the solution a potentially good option to lower embodied carbon in a foundation design.

### 6.9.2 HIPER® Pile

The HIPER® Pile[97] is a solution designed to reduce embodied carbon and enhances the use of thermal energy. HIPER® is an acronym meaning hollow, impression, precast, energy-generating and reusable, and the piles potentially combine the following known solutions:

- hollow piles: The pile is hollow, thereby reducing the material required for construction. This, coupled with low carbon concrete solutions, could significantly reduce the amount of embodied carbon in a design.
- impression piles: These piles are designed to increase the shaft friction and thereby capacity of the pile, enabling the designer to reduce the length of piles required for a given structure. By reducing the length, in turn, the use of materials and the waste created during construction are reduced. The downside to these piles is they are generally only suitable in cohesive soils.
- pre-cast piles: The pile is pre-cast, which reduces the amount of material being transported to sites during construction, as bulk materials can be utilised in a factory setting. Pre-cast piles also aid in waste reduction.
- energy piles: These piles incorporate a ground source heat pump to harness thermal energy to heat and cool structures, reducing the need for fossil fuel heating.
- reusable piles: In congested urban sites, it is becoming more and more common to test and reuse existing foundations as an alternative to removing and installing new ones. The HIPER® pile has been specifically designed with this purpose in mind with the "ability to inspect and survey piles during building occupancy".

### 6.9.2.1 Case study: Keltbray – large-scale commercial office, London

This original scheme, constructed in 2016 with works completed for Principal Contractor, Mace,[98] comprised 47 1800-mm-diameter piles, 39m deep. Each pile was constructed with traditional geothermal heat exchanger loops attached to the cage, extending to the toe of the pile, and were installed during the pile installation works (see Image 13).

**Image 13** Keltbray team installing traditional geothermal loops within solid piles (Source: Keltbray)

This project was retrospectively analysed to quantify the benefits of replacing conventional solid piles with HIPER® Piles including 46% less carbon. A value-engineered solution was developed, incorporating all in-situ elements of the HIPER® Pile using temporary works liners to form the 1300 mm void, and the results are presented in the table in **Table 6**.

| Producer | Conventional as-built pile | HIPER® Pile | Benefit |
|---|---|---|---|
| Bored : Void Diameter | 18:0 | 18:1.4 | |
| Average Bored Length | 39 | 36 | 8% saving |
| Average Concrete Length | 28 | 25 | 11% saving |
| Nodule Volume ($m^3$) | | 0.18 | |
| Total Volume Muck Away (m) | 5131 | 4736 | 8% reduction |
| Total Muckaway Vehicles | 571 | 527 | 8% reduction |
| Total Concrete Volume ($m^3$) | 3349 | 1181 | 65% reduction |
| Total Concrete Vehicles | 447 | 158 | 65% reduction |
| Total Vehicle Movements | 1018 | 685 | 33% reduction |
| Steel Tonnage | 190 | 65 | 66% saving |
| Piling Programme Days | 34 | 27 | 21% saving |
| Energy Generation (MWhrs/yr) | 1650 | 3253 | 97% increase in capacity |
| EFFC $CO_2$ calculation ($tCO_2e$) | 1100 | 590 | 46% reduction |
| Comparison between the as-built piling package and a HIPER® Pile value engineered. | | | |

**Table 6** Comparison between conventional and HIPER® piles (Source: Keltbray)

## 6.10 Reuse of foundations

If existing foundations can be reused as part of a redevelopment, this would result in the foundations of the new building having low to zero embodied carbon, as well as achieving wider carbon savings in the construction phase. However, there are risks with using foundations past their design life that may affect resilience to climate change impacts and other factors.

According to the IStructE paper A short guide to reusing foundations,[99] successful foundation reuse depends on the relationship between the existing configuration and future needs. This includes consideration of the building height/number of storeys; massing, i.e., existing use in relation to proposed use (floor-to-ceiling height and loading); and the ability of the foundations to support additional or different loading requirements.

Published studies into the reuse of foundations are summarised below.

### 6.10.1 CIRIA C653

CIRIA guidance C653 published in 2007[100] provides "concise guidance for the economic, safe and appropriate reuse of foundations in urban environments where existing foundations are often encountered during redevelopment of buildings and infrastructure". The guide follows a decision-making process with two possible outcomes: yes or no to reuse. Following the 'no' result there is further consideration to be made regarding the potential future use of new foundations.

When creating foundations for new developments where there are already existing deep foundations, there are four options for the new foundation construction. Options 3 and 4 would be the most carbon efficient, owing to an element of reuse, followed by option 1, then 2 having the highest carbon impact due to the waste created following removal in addition to newly constructed foundations (see **Figure 12**).

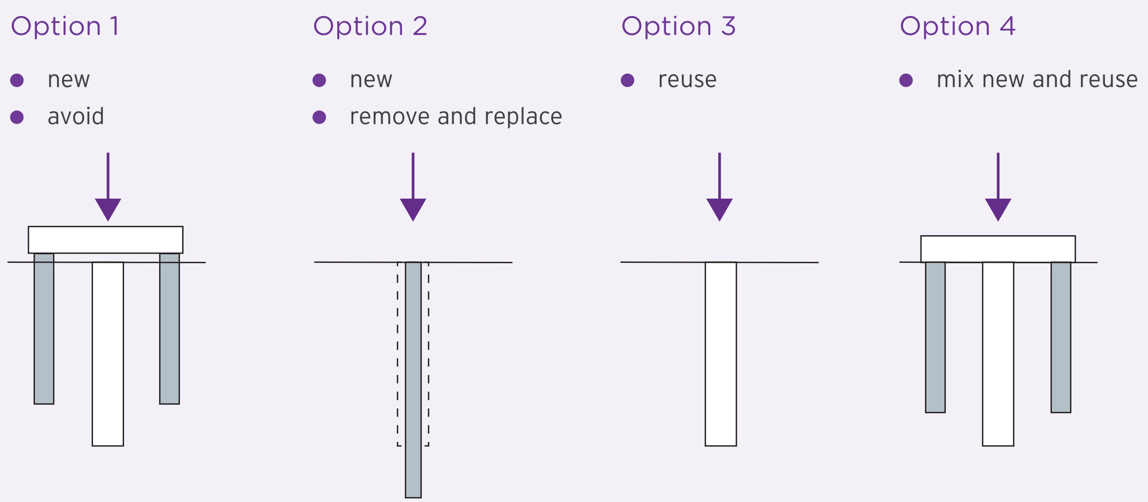


**Figure 12** Options for new piled foundations, CIRIA C653 (Source: CIRIA)

## 6.10.2 RuFUS

The Reuse of Foundations for Urban Sites (RuFUS[101] best practice handbook was developed by the BRE in 2006. The handbook was developed as part of a research project part-funded by the European Commission and draws together experience on the reuse of foundations across Europe. It provides advice on investigation, design and construction when reusing foundations.

## 6.10.3 Hybrid method

A paper developed by the Institution of Civil Engineers (ICE) in 2014[102] looks at the RuFUS and CIRIA assessment methods for the reuse of foundations and combines information from both into a hybrid assessment method. The assessment has three possible outcomes, as shown in **Figure 13**, i.e.:

- design for partial or total reuse
- design for partial or total reuse with supplemental elements
- install new foundations. Consider future development and reuse of foundations.

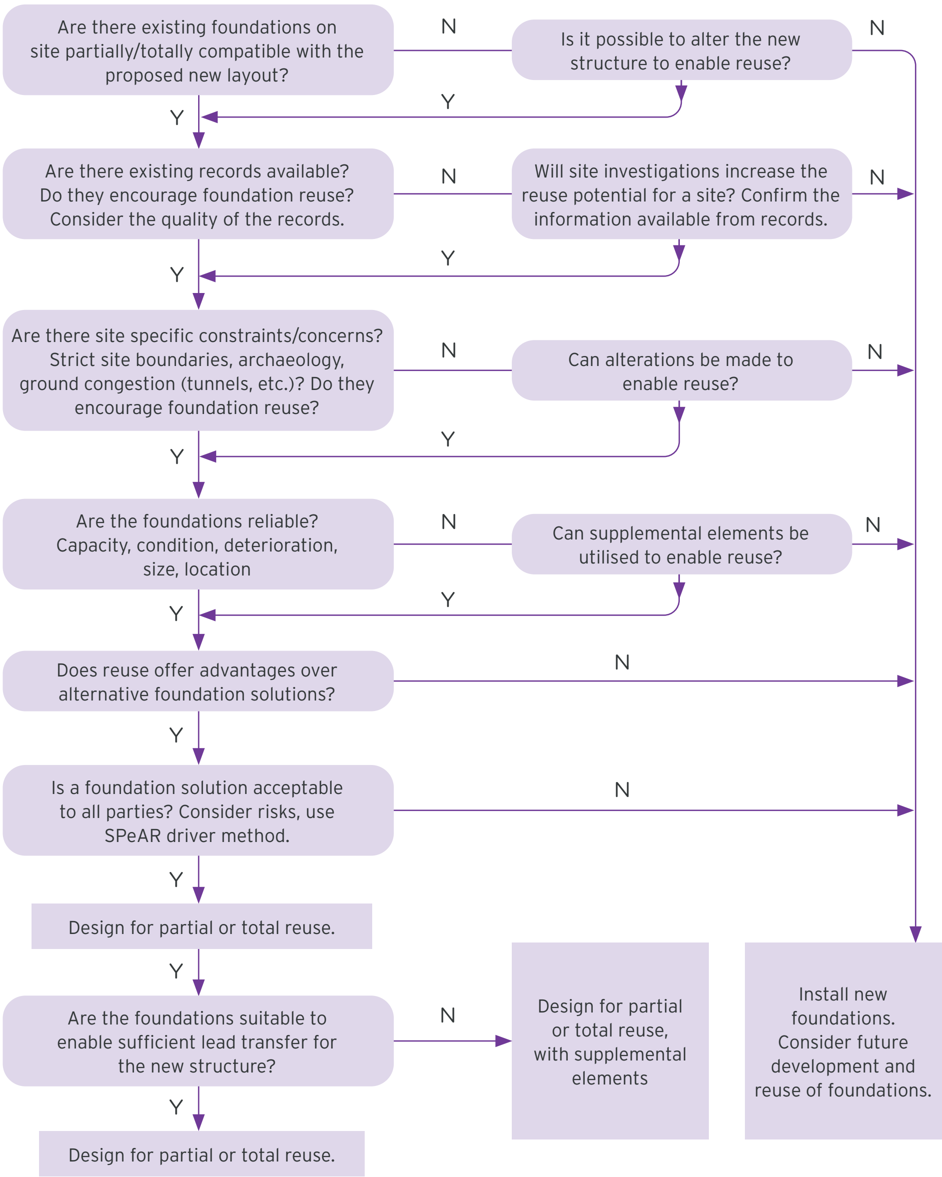


**Figure 13** A hybrid method for foundation reuse evaluation (Source: ICE Publishing)

### 6.10.3.1 Case Study: Sir John Lyon House, London

This development was on the site of the former Sir John Lyon House in Central London, which comprised three six-storey interlinked offices with basement space that was built in the 1960s. The proposed scheme was to construct a six-storey residential unit on one of the former office blocks, reusing existing foundations (see **Image 14**).

In considering the potential to reuse the existing foundations, the design team had to establish accurate position and size of all existing foundations and presence of under-reams beneath the piles, followed by determining the geotechnical and structural capacity of the piles and shallow foundations and the composition and condition of the foundation materials. In addition to confirming details for design purposes, sufficient evidence was required to satisfy the local planning authority.

A site investigation was undertaken of the proposed residential development, which included:

- cross-hole geophysics to determine the depth of the piles
- trial pits excavated to expose existing foundations
- coring piles to establish the pile length and to obtain samples
- dynamic pile testing for capacity and settlement integrity testing of piles
- geotechnical and geoenvironmental laboratory testing of selected soil samples
- materials testing of selected concrete samples, including microscopic examination
- reviewing the concrete and steel durability.

**Image 14** Residential development on the site of the former Sir John Lyon House (Source: RM Architects)

Results from the investigation confirmed that, with the exception of limited additional piling, the existing foundation could be reused as part of the development. While a calculation of embodied and whole-life carbon was not undertaken as part of the project, the outcome that all the existing piles were reused in the new scheme would have resulted in a reduced level of additional carbon being required to complete the scheme and successful completion of the development supporting reuse of foundations as an acceptable alternative method for construction.

## 6.11 Industry survey findings

As part of the industry survey described in **Section 2.7**, those respondents who confirmed they were aware of materials and techniques providing low carbon solutions to foundation construction mentioned the following solutions:

- low carbon concrete and steel
- aerated concrete to reduce volume/mass of concrete/cement in trench fill foundations
- low density fill
- ground improvement (e.g., vibro-stone columns, vibro-compaction)/soil stabilisation
- ground granulated blast furnace slag (GBBS) concrete in piles
- raft foundation system using recycled aggregate and low cement
- lean design
- moving away from brick/block and mortar construction towards more flexible and sustainable construction materials, allowing shallower foundations
- incorporation of ground source heating in foundations and gardens/open space areas
- use of recycled and secondary aggregates
- choice of foundation solution
- lighter superstructure, e.g., timber.

As such, it is clear that the more enlightened industry practitioners are already considering a wide range of options to reduce carbon associated with foundations and wider construction, including many of the emerging techniques discussed above.

## 6.12 Interaction between climate change resilience and low carbon design

The review has identified the impacts of climate change on UK weather and subsequent geohazards, for which adaptation and the resilience of existing and planned developments will be of increasing importance. The review also highlights the international, national and local commitments to decarbonisation, which in turn are driving innovation, the development of MMC and the use of new materials to deliver climate change resilience with low carbon design. As noted above, the results from the survey undertaken as part of the review confirmed that, of those organisations incorporating low carbon into their designs, there is a wide range of approaches being considered, including MMC and low carbon materials.

Cost and programme considerations have not been considered in this review, which is intended as a technical evaluation of the relationship between climate resilience and embodied carbon in construction.

Based upon the results from the online survey, it is clear that traditional shallow undations have a significant place in the housebuilding sector with cost, knowledge and trust in alternative techniques factors supporting the status quo. Although relatively low in embodied carbon, the need to increase climate resilience of buildings may result in designers and developers opting for traditional piled solutions or deeper foundations. However, as these options involve a greater use of concrete and steel, they come with a higher carbon intensity.

The reuse of foundations, particularly for larger residential developments in an urban setting and reusable piles, offers a higher carbon saving primarily due to the use of less material; however, potential constraints and considerations may limit the wider adoption of this technique for low rise housing.



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Alternatives to concrete, including the use of structural timber for both substructure and superstructure, have the potential for higher resilience to climate change both in terms of lower carbon and adaptability to future climate-related constraints (provided the timber is sustainably sourced). Use of this technique as noted in **Section 6.8.1** supports the practical application, and in parts of the UK, for example Scotland, the use of timber frame is more widely adopted.[103] However, it would require a significant shift in the industry towards MMC, supply chain and changing perceptions to achieve widespread adoption.

Some proprietary piled foundation/ground floor systems are available that efficiently provide both the ground floor slab and perimeter beams for the wall. Such designs offer lower embodied carbon with high resilience across the whole structure rather than the foundations alone.

In addition to reducing embodied carbon within a building in the construction phase, carbon reduction commitments focus on increasing energy efficiency during its operational life. Development of energy pile systems, including the examples in **Section 6.9**, provide the potential to have both a foundation design resilient to climate change and to provide energy-saving benefits.

**Section 6** confirms industry is responding to the challenge of tackling climate change mindful of reducing carbon and adaptation to current and future constraints. The review also highlights that there are areas of best practice, but equally, there are gaps in knowledge and the availability of consistent standards and guidance and support that can be referred to nationally by industry, regulators and decision-makers.

# 7 Conclusions and recommendations

## 7.1 Key considerations

### 7.1.1 Climate change impacts

Climate change is here and the effects are being felt already and across all sectors. The UK's annual average temperature has risen by around 0.6°C above the average of the 1981–2000 period, consistent with a trend of around 0.3°C per decade since the 1980s. Episodes of extreme heat are becoming more frequent, with the chance of a hot summer like 2018 now up to 25% per year compared to less than 10% a few decades ago. In July 2022, we experienced another hot summer with temperatures of 40°C observed for the first time in the UK. By 2050, it is predicted that the heatwave of summer 2018 will be a typical summer. Cold extremes have also decreased in frequency and intensity.

Sea levels around the UK have risen by 16 cm since 1900 and by around 6.5 cm since the 1981–2000 period. Data for heavy rainfall generally show an increase in very wet days across the UK, although there are challenges in distinguishing between human-induced climate change and the large interannual variability in the observational record at a UK-wide scale. There is some evidence that human-induced climate change has increased the likelihood of some observed UK precipitation extremes linked to significant flooding impacts.

This review has focused on the risks to buildings and specifically the implications for the design and construction of their foundations. Taking as a starting point the climate change predictions for the UK published by the UK Climate Change Committee (CCC), those identified to be relevant to building foundations include hotter and drier summers; warmer and wetter winters; continued sea level rise; and an increased frequency and intensity of storms with high rainfall events. The review has considered a range of potential impacts on buildings and specifically their foundations; how climate change impacts may affect the risks and their occurrence; and potential solutions that are available.

### 7.1.2 Key legislation and policy drivers

Climate change adaptation is led through UK Climate Change Risk Assessments, which under the Climate Change Act 2008 are required to be completed every five years. These set out the risks and opportunities from climate change, combined with a National Adaptation Programme to address those risks. In addition, the net zero emissions law requires the government to reduce the UK's net emissions of greenhouse gases by 100% relative to 1990 levels by 2050 with the Net Zero Strategy detailing a range of actions and commitments. These include the need to reduce embodied carbon in buildings and infrastructure through substitution of materials and to reduce carbon consumption during construction.

The National Planning Policy Framework in England, and its equivalents in the devolved administrations, requires new developments to take a proactive approach to mitigating and adapting to climate change and to reduce greenhouse gas emissions to achieve net zero.

### 7.1.3 Industry survey findings

The findings of a survey of construction industry contacts undertaken as part of this project suggest that there are currently variable levels of knowledge and engagement with these issues by developers and foundation designers. This is influenced by a current lack of regional and national level policy and standards specific to foundations design in response to the impact of climate change.

### 7.1.4 Risks to building foundations and their mitigation

Due to its very wide spectrum of geological conditions, the UK has the potential to be vulnerable to a wide range of geological hazards, both naturally occurring and human induced. The review considers a range of potential impacts on buildings and specifically their foundations, how climate change impacts may affect the risks and their occurrence and available potential solutions. The key risks are highlighted below.

- Subsidence/heave in shrinkable cohesive soils (shrink–swell)
- Washout-induced damage or settlement
- Reduction in soil strength associated with increases in porewater pressure
- Dissolution and anthropogenic hazards of chalk and limestone and evaporites and other mining areas
- Collapse settlements in earthworks and fills
- Higher sea levels in coastal areas/corrosion of foundations from salt water.

The mechanisms by which these hazards traditionally behave are typically well understood. The current planning framework requires that the full range of potential hazards be considered at the earliest stages, to ensure that appropriate measures and materials are incorporated into structural and foundation design to mitigate the risks. These procedures and standards have evolved over time, based upon historical practice and experience of failure events; however, the nature of the predicted changes from climate change are without precedent. It will be essential, therefore, to modify existing approaches to defining hazard and risk potential (both in severity and likelihood), in line with future UK climate projections, in order to increase the climate change resilience of buildings through the design of building foundations.

Furthermore, increasing green infrastructure, such as canopy cover/tree planting, in urban areas is recognised as supporting adaptation to climate change and is promoted through planning policy UK-wide. The benefits include carbon sequestration, temperature regulation by increasing shade and reducing surface heat and reducing the impact of storm water, as well as the social and community health benefits. However, trees – new and existing – pose significant risks, both direct and indirect, to existing structures and infrastructure, including foundations. This is particularly the case for areas affected by shrink–swell, where careful selection of suitable tree species and design of layouts to accommodate future growth of trees without conflict is essential to minimise the potential risk of structural damage to buildings.

The effects of climate change are therefore expected to lead to an increase in damages experienced by domestic properties. These are likely to comprise the cracking of walls, sticking of doors and windows and potential disruption to utilities. Insurance claims for subsidence are noted to have increased significantly following the hot summer of 2018 and this may well be the case for 2022.

This type of future disruption may already be essentially ‘locked in’ for swathes of the existing building stock designed and constructed without considering climate-related impacts. Costly remedial options, such as widespread underpinning to support impacted foundations or tree felling, are unlikely to present a practicable or sustainable option, although alternatives such as injection of expanding geopolymer resins are noted to be available.

The geohazard risks identified relating to climate change impacts are based upon current modelled predictions. It is acknowledged that there are uncertainties in the extent of change, particularly for longer time horizons. Greater changes in climatic conditions may result in significant changes in the physical and mechanical properties of the ground (relating to moisture levels within the ground), thereby causing a great deal of structural damage, particularly on lightweight constructions built on swelling soils. Therefore, the occurrence and/or magnitude of damage to houses, commercial buildings and roads due to shrink-swell will probably change for the worse.

### 7.1.5 Low-carbon options

The drive to net zero and the required 78% reduction in emissions by 2035 in the Sixth Carbon Budget means that all sectors, including the construction industry, will be expected to play their part. Alongside the need for climate change adaptation, foundations represent a significant component of carbon emissions relating to construction. This needs to be reduced to achieve net zero and the range of current approaches that are available is described.

Use of lower carbon cement products or alternatives to cement could result in a carbon reduction of between 30 and 50% compared to standard concrete. Reducing carbon within foundations is being achieved in a variety of other ways, including utilising MMC and other approaches to develop innovative lightweight building components leading to reduction in embodied and construction carbon; increased use of timber both in the substructure and superstructure; and retaining and reusing existing foundations, which is a viable option for higher density urban development. Newer approaches, including combining piled foundations with ground source heating ('energy piles'), are also described.

Available carbon calculation tools for foundations have been presented, which assist designers to make choices on the materials, design and construction practices for construction and the whole life of the building. Example calculations are provided for the relative embodied carbon for shallow strip foundations versus piles using a tool developed by Leap Environmental and the University of Surrey.

### 7.1.6 Conclusions

In conclusion, the report recommends that for new build, designers of building foundations and developers should consider the identified climate change risks and associated geohazards and how these may vary over the lifetime of each development. Since it will take some time for further research to justify changes in the NHBC Standards or Building Standards, it is recommended that developers consider increasing their minimum foundation depths now to increase climate resilience rather than waiting for changes in standards to take place. However, this needs to be balanced against net zero considerations and the need to reduce, rather than increase, embodied carbon associated with building construction, so alternative foundation options should also be considered.

## 7.2 Recommendations for further research

As a result of the findings of this review, the following recommendations are made with respect to further research and assessment:

1. Further research should be undertaken on climate change risks and sustainable solutions for foundation design and construction.
2. Research into the resilience, economic, technical performance and ease of assessment of embodied carbon of foundation designs and materials is needed.
3. There is a review and research requirement to inform updating of the current NHBC Standards Chapter 4.2 Building Near Trees and to establish where changes are needed to the precautions specified.

# Appendix A Changes to the UK climate

## A.1 Tipping points

According to the Met Office Hadley Centre,[104] "something that is currently not well understood is what different tipping points in combination might result in or whether we should expect different outcomes if one precedes another. Kriegler et al. 2009 and Lenton et al. 2008 both note the probability of some tipping points can vary depending on whether another has already occurred."

While global tipping points have been identified and changes to them can be measured, there are significant uncertainties and unknowns regarding how they will affect global and UK climate, and in turn, what adaptations to mitigate risk and changes to building and foundation design are required, as discussed in later sections.

The Met Office Hadley Centre report includes a global map (reproduced in **Figure A1**) of tipping points that could be important for UK climate impacts. Those represented in red are large-scale shifts in climate patterns, resulting in regional climate change, including changes in the position of the jet stream. Cryosphere changes increasing global sea level risk and subsequently UK sea levels are represented in blue. Carbon-cycle or biogeochemical feedbacks that result in additional global warming with associated increased impact on the UK climate are highlighted in green.

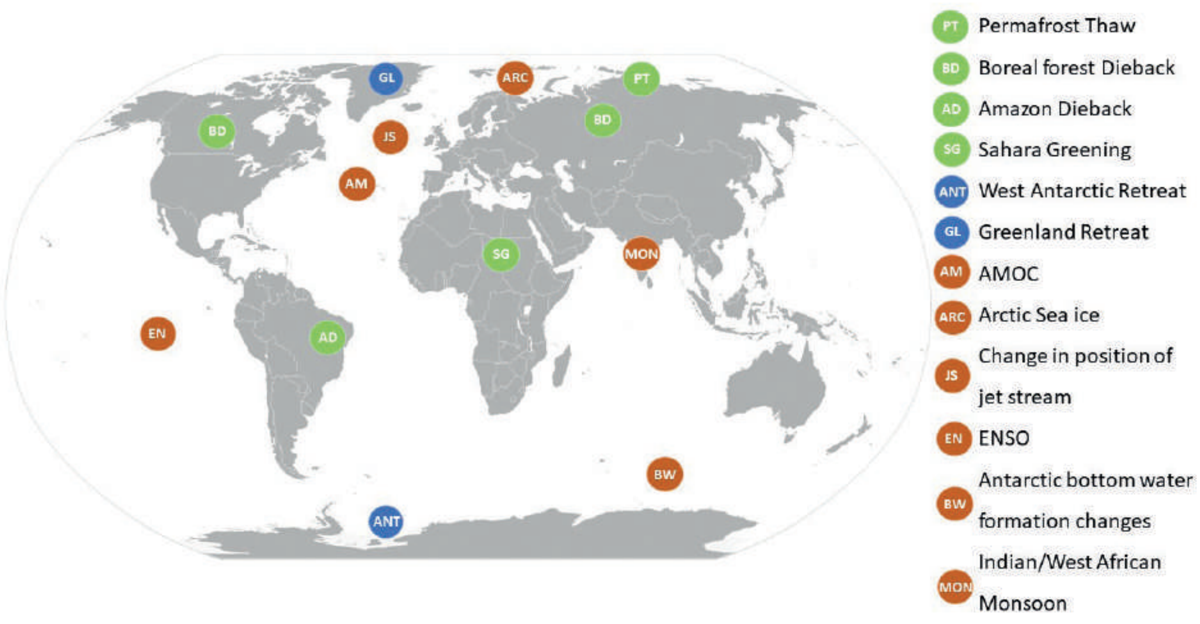


**Figure A1** Effect of potential climate tipping points on UK impacts (Source: Met Office Hadley Centre)

### A.1.1 Weakening of the Gulf Stream

According to the Met Office, as warm water flows from the equator to the poles, it cools and increases in density, eventually sinking as part of a global process of continually mixing the world's oceans and distributing heat and energy to all parts of the earth. In terms of the UK, this results in an approximate 5°C difference in temperatures, resulting in milder winters. A weakening of the Gulf Stream would see a reduction in the moderating effect on weather conditions with potential for significantly colder winters.

The Intergovernmental Panel on Climate Change reported in 2021[105] that the key circulation system of the Atlantic Ocean, known as the Atlantic Meridional Overturning Circulation (AMOC) is very likely to weaken over the 21st century for all emissions scenarios. While there is high confidence in the 21st century decline, there is only low confidence in the magnitude of the trend. However, in the event the AMOC were to stop, the UK is likely to encounter more severe cold winters. This is not a scenario that is currently being considered in adaptation planning as the latest UK climate projections are indicating the opposite, with milder winters and fewer cold-weather impacts most likely in a warmer climate (Hanlon et al 2021). However, there is medium confidence that there will not be an abrupt collapse before 2100.

### A.1.2 Changes to the Jet Stream

The Jet Stream is a core of strong winds around 5 to 7 miles above the Earth's surface, moving from west to east. The strength and direction of the Jet Stream affects atmospheric pressure, influencing areas of high and low pressure. The position of the Jet Stream is the main factor affecting the path weather systems and storms take across the North Atlantic towards the UK. Consequently, the position and strength of the Jet Stream has a big impact on UK weather, influencing the frequency/magnitude of extremes, especially in winter.[106] UK weather is influenced by the polar Jet Stream, which forms due to the difference in the temperatures between the pole and equator. Colder air is focused on the northern side, with warmer air to the south. The location of the Jet Stream is therefore an important factor affecting the type of weather encountered in the UK. Any significant change to the natural movement and location of the Jet Stream, for example, could result in a wider range of effects. However, uncertainties in this scenario based upon analysis of future weather patterns with current projections suggest mild/unsettled weather in the UK in winter and drier settled weather in future summers. As such, this influence is the opposite to the effect suggested in the event of a weaker Gulf Stream leading to cold spells, meaning the occurrence of a tipping point that leads to change in the Jet Stream could have a different outcome than that currently expected from projections.

### A.1.3 Accelerated Antarctic melting

Contrary to the projected impact of climate change outlined by BGS UKCP18 and IPCC, as discussed earlier in this section, uncertainties in this scenario are presented by studies undertaken by Deconto and Pollard[107] that suggest sea levels could rise far quicker, resulting in a tipping point of sea level rise of up to 2m by 2100 around the UK. **Figure A2** shows UKCP18 projections of sea level change up to 2100 at four locations around the UK, scaled with Deconto and Pollard estimates.

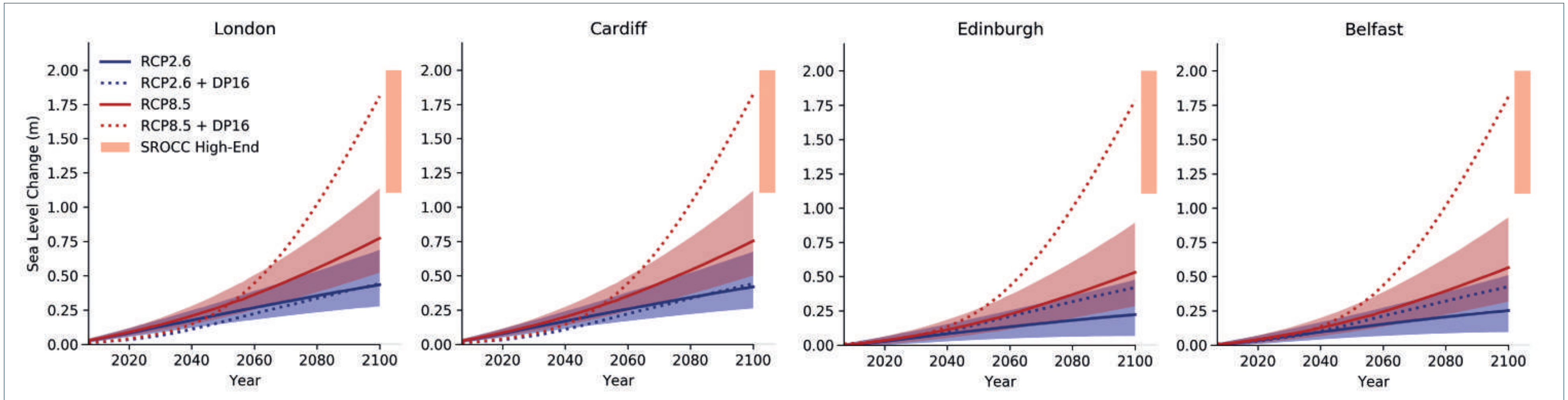


**Figure A2** UKCP18 projections of sea level change up to 2100 at four locations around the UK, scaled with Deconto and Pollard estimates (Source: Met Office Hadley Centre)

### A.1.4 Permafrost thaw

Permafrost thaw is considered a possible carbon source to the atmosphere (Schuur et al. 2015),[108] that would be larger if thaw is abrupt (Turetsky et al. 2020).[109] The impact to the UK would be indirect, with permafrost thaw affecting overall global temperatures through the release of additional greenhouse gases more rapidly than considered in current climate forecasts. This also means it could indirectly affect other tipping points that are sensitive to global temperature rise.

Permafrost thaw can cause direct building damage but is not relevant to the UK context of this report.

# Appendix B Industry survey

There were 38 responses overall to the industry survey completed as part of this study, with respondents' principal business being mainly national or regional developers and designers/consultants. The relatively low survey response rate is potentially indicative of low levels of awareness or engagement with these issues currently. However, of those who did respond, there was some understanding of the key impacts in relation to building foundations and recognition that this increasingly needs to be addressed.

The types of respondents and some of the key findings are illustrated in **Figure B1**.

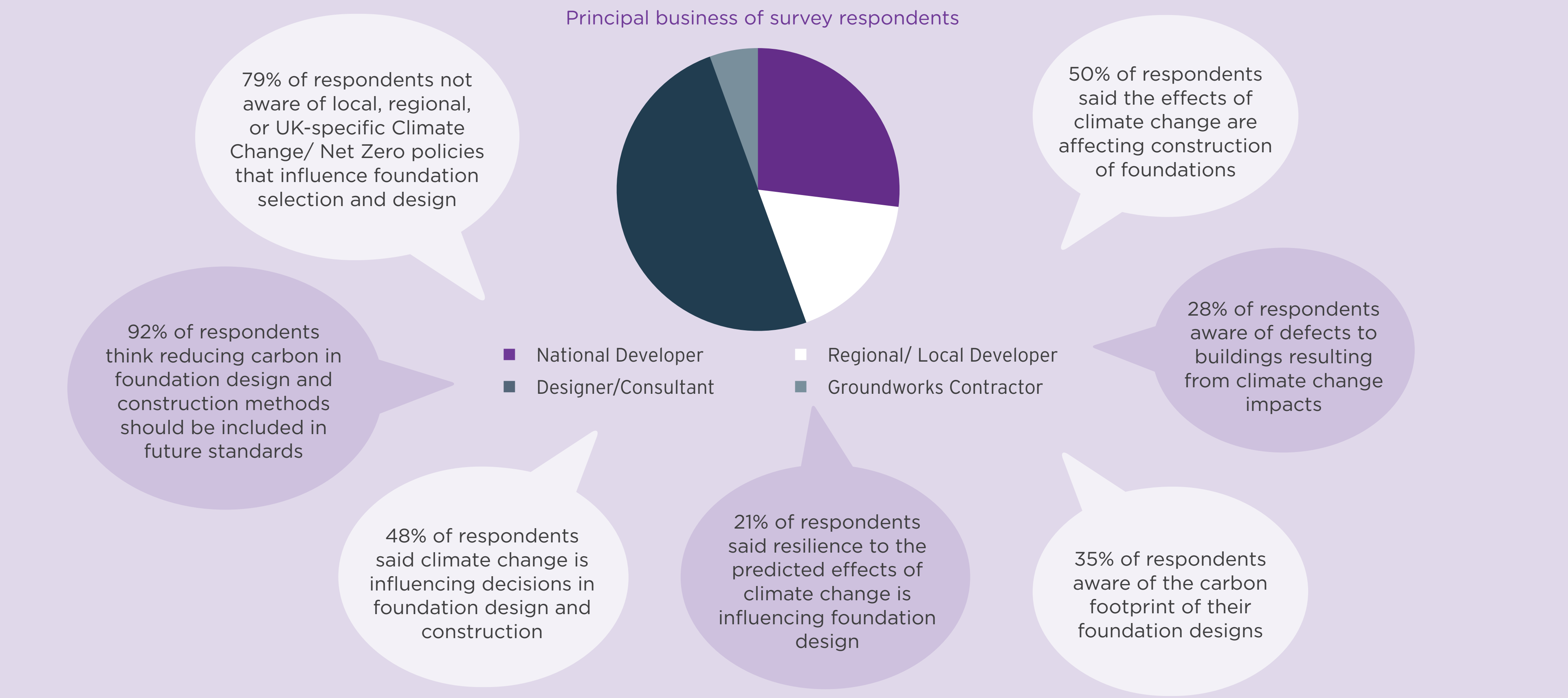


**Figure B1** NHBC/RSK industry survey, key findings (Source: RSK)

The following responses to two of the survey questions are also broadly indicative of the range of responses received. The first question about whether climate change is currently influencing decisions in foundation design and construction gives a good illustration of the wide range of responses from industry practitioners, as illustrated in **Figure B2**.

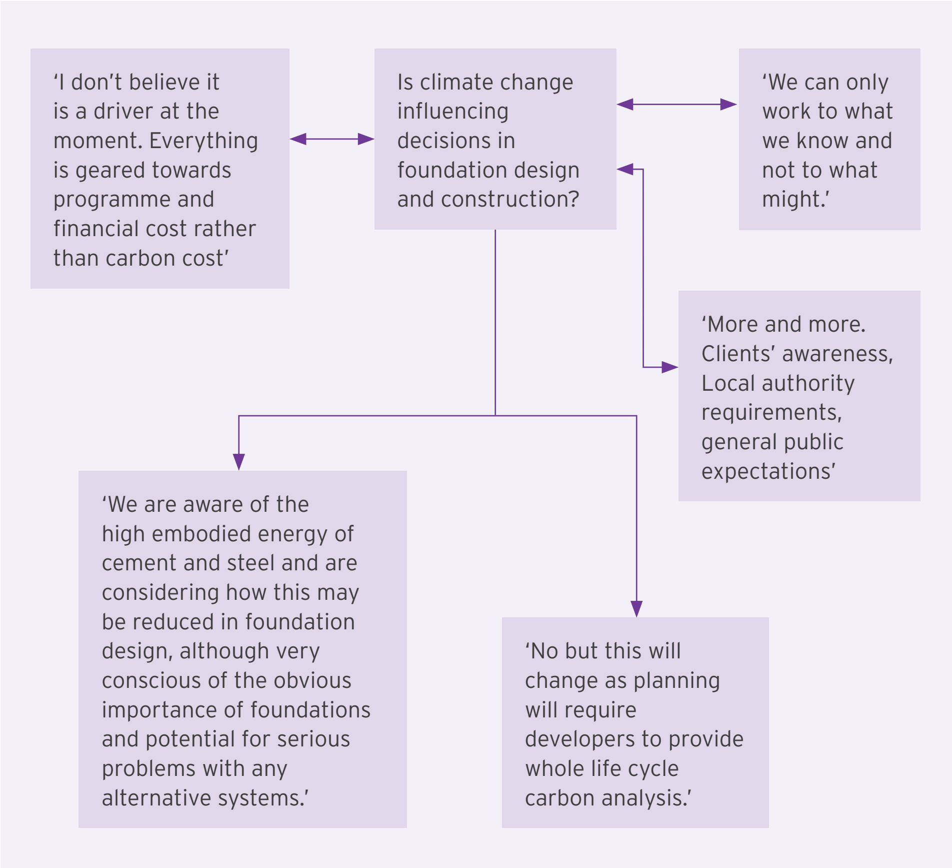


**Figure B2** NHBC RSK industry survey sample example responses (Source: RSK)

Respondents were also asked to pick the top three effects of climate change on their business from a list and provide additional comments. The responses are provided as a 'wordmap' in **Figure B3**, in which the text size increases in proportion to the popularity of responses.


**Figure B3** NHBC RSK industry survey wordmap of responses to the question "What are the three top effects of climate change on your business?" (Source: RSK)

# Appendix C Legislation and policy

## C.1 UK government responses to the climate emergency

### C.1.2 The Climate Change Act 2008

The Climate Change Act 2008[110] set a target of reducing GHG emissions by at least 80% by 2050, relative to the baseline year of 1990. The Act further established the Climate Change Committee (CCC) as an independent, statutory body, whose purpose is to advise the UK and devolved governments on emission reduction targets while also reporting to Parliament on the progress made to date in relation to these.

The Climate Change Act mandates the production of UK Climate Change Risk Assessments every five years, which set out the risks and opportunities facing the UK from climate change, combined with a National Adaptation Programme to address those risks.

### C.1.3 Environment Act 2021

The Act provides the basis for the implementation of the 25-year Environmental Plan and of the Office for Environmental Protection, which will be responsible for overseeing plan targets. Targets within the Environmental Plan are to be reviewed every five years by local authorities and annual reports are to be made on progress. Long-term targets will have a duration of a minimum of 15 years. Housing and new development areas are likely to be impacted by drainage and biodiversity net gain requirements.

In August 2021, a legally binding target to "halt the decline in species abundance by 2030" was set for the UK, due to the biodiversity loss incurred between the 20th and 21st centuries. There is a requirement for developers to achieve a 10% net increase in biodiversity, maintained over the course of at least 30 years, referred to as "biodiversity net gain". These conditions can be met through the creation of additional biodiversity value on- or off-site or through the purchase of biodiversity credits.

In November 2020, the UK government released the Prime Minister's 10 Point Plan for a Green Industrial Revolution, outlining its commitment to tackling climate change. Relevant aspects of this document include Point 7 Greener Homes and the construction of homes to the Future Homes Standard.

In October 2021, the UK government published its Net Zero Strategy[111] building on the 10 Point Plan. In relation to housing, the Net Zero Strategy outlines a range of actions and commitments. Those of most relevance to this review include:

- supporting the construction sector by improving reporting on embodied carbon in buildings and infrastructure with a view to exploring a maximum level for new builds in the future and reducing embodied carbon through substitution of materials
- working with Homes England and delivery partners to explore ways to increase timber use in the delivery of housing programmes
- growing the heat pump market to support 600,000 installations per year by 2028.

Further details on the development and use of low carbon solutions are covered in **Section 6**.

The CCC advises, monitors and reports on whether the UK is on course to meet its carbon budgets. The committee also reports on Scotland's progress in reducing greenhouse gas emissions against its annual carbon targets. In its June 2021 Progress Report to Parliament, the committee demonstrated that UK emissions had fallen during the COVID-19 pandemic lockdown period. That being said, it suggested that sectors such as infrastructure, air quality and property flood resilience remain in need of further progress to achieve 'notable' results.

The Adaptation Committee (of the CCC) reports to Parliament every two years on the UK government's progress in adapting to the impacts of climate change through the National Adaptation Programme (NAP). The NAP focuses on the whole of the UK for a small number of reserved policy areas and focuses on England for devolved matters. This is because the devolved administrations (Scotland, Wales and Northern Ireland) make policy independently on devolved matters, which make up the majority of the policy areas relating to climate change adaptation.

### C.1.4 UK's Sixth Carbon Budget 2020

The UK's Sixth Carbon Budget requires a 78% reduction in emissions by 2035, relative to 1990 levels. This budget supports a trajectory that is consistent with both the Climate Change Act (as amended) and the Paris Agreement. In addition to setting this target for reduction, the budget provides recommendations, including:

- encouraging the take up of low-carbon solutions
- expanding low carbon energy supplies
- reducing demand for carbon-intensive activities
- supporting land-based sequestration through woodland creation and peatland restoration.

The UK government has committed to reducing emissions by at least 100% of 1990 levels by 2050 and contributing to global emissions reductions aimed at limiting global temperature rise to well below 2°C and to pursue efforts to limit temperatures to 1.5°C above pre-industrial levels.

The path to net zero calls for adaptive measures to meet national decarbonisation needs. The 'Balanced Net Zero Pathway' described anticipates manufacturing and construction sector emissions being reduced by 70% by 2035 and 90% by 2040 from 2018 levels. This is based on adoption of fuel switching, carbon capture and storage, and improvements to resource and energy efficiency. Changes are expected to occur in fuel combustion and process emissions (cement, steel and chemicals subsectors), including capture and sequestration of $CO_2$ emissions, material usage (increased use of wood in construction), efficiency (design optimisation) or substitution (recycled glass, clinker). Examples of these potential changes are provided in **Section 6**.

## C.2 Planning policies

### C.2.1 National Planning Policy Framework (NPPF) for England

The most recent revision of the NPPF was published by the UK government in July 2021. The NPPF outlines government planning policies for England and is a framework against which locally prepared plans for housing and other developments should be produced. In response to climate mitigation and adaptation, it states "plans should promote a sustainable pattern of development that seeks to meet the development needs of their area; align growth and infrastructure; improve the environment; mitigate climate change (including by making effective use of land in urban areas) and adapt to its effects."

The NPPF also recognises the provisions and objectives of the Climate Change Act 2008 by requiring local planning authorities to take a proactive approach to mitigating and adapting to climate change, considering the long-term implications for flood risk, biodiversity and landscapes and the risk of overheating from rising temperatures.

## C.2.2 Devolved administrations

Scotland plans to cut emissions to net zero by 2045,[112] and generate over 50% of Scotland's overall energy consumption from renewables by 2030.

Similar to the NPPF, Scotland has a National Planning Framework (NPF3) that outlines the policies relating to land use planning matters, including with respect to cities and towns, rural areas, coast and islands and national developments. In response to climate change, NPF3 states that "development facilitates adaptation to climate change, reduces resource consumption and lowers greenhouse gases." A new revision of the NPF is due to be released in which "development proposals for new, or alterations to, buildings, infrastructure and spaces should be designed to be adaptable to the future impacts of climate change. Proposals to sensitively incorporate climate adaptation and mitigation measures for existing buildings, infrastructure and spaces, should generally be supported."

Wales has committed to reduce greenhouse emissions by 95% by 2050, with an ambition to get as close to net zero as possible. Planning Policy Wales[113] outlines a number of key planning principles, including making best use of resources, noting the causes and impacts of climate change through location, design, build, operation, decommissioning and restoration and supporting decarbonisation and the transition to a low carbon economy.

Northern Ireland is targeting 35% lower emissions by 2025 under its Greenhouse Gas Action Plan and is developing plans for its own Climate Change Act. The Strategy Planning Policy Statement sets out a range of policies relating to planning matters. Of note, it states that local development plans (LDP) "should seek to identify and promote green and blue infrastructure [including street trees] where this will add value to the provision, enhancement and connection of open space and habitats in and around settlements." Additional detail of green and blue infrastructure is provided in the Regional Development Strategy 2035, in which it states "urban areas generate, absorb, and store a lot of heat energy which could be a big problem for people living there." The influence of encouraging green infrastructure is covered in **Section 5**.

## C.2.3 Local government

According to the Local Government Association,[114] around 300 out of a total of 333 of England's District, County, Unitary and Metropolitan councils (approximately 90%), had declared a climate emergency at the time of writing. The National Audit Office Report into Local Government and Net Zero[115] identified £1.2 billion in specific grant funding available in 2020–2021 for local authorities to act on climate change. This includes funding through the Public Sector Decarbonisation Scheme, the On-Street Residential Chargepoint Scheme and the Green Recovery Challenge Fund.

Of the sample reviewed, climate action plans largely favoured mandatory biodiversity net gain for new developments with a considerable minority calling for increased canopy cover through tree planting. The creation of green infrastructure is seen as a key step in increasing biodiversity and is favoured due to benefits such as natural flood management.

The action plans reviewed focused on in-use emission reduction in new dwellings. There was little to no mention of before use emissions, including embodied carbon.

A few notable example local authority responses are highlighted below.

### C.2.3.1 Greater London Authority – New London Plan

The London Plan[116] is the statutory spatial development strategy (SDS) for Greater London published on 2 March 2021. As part of developing the SDS, the London Plan recognises the balance of population and economic growth across the city region with the consequences of climate change and promoting a circular low carbon economy.

The London Plan includes six 'Good Growth' (GG) objectives including GG6 increasing efficiency and resilience, of which it states developers must "ensure buildings and infrastructure are designed to adapt to a changing climate, making efficient use of water, reducing impacts from natural hazards like flooding and heatwaves, while mitigating and avoiding contributing to the urban heat island effect."

### C.2.3.2 Manchester City Council – Climate Change Action Plan 2020–2025

The Climate Change Action Plan[117] summarises the specific actions that are required to ensure the council reduces its direct emissions by at least 50% by 2025. In relation to development, the action plan recognises the importance of reducing carbon for new development, including proposed major housing schemes. Blue-green infrastructure is promoted by the plan, including climate change adaptation and carbon sequestration through city-wide tree and hedge planting schemes.

### C.2.3.3 Lancaster City Council supplementary planning documents

Lancaster City Council has drafted supplementary planning documents (SPD),[118] with an aim of supporting developers with a range of topics, including sustainable building and green-blue infrastructure. The draft SPDs were issued for an eight week consultation between June and August 2022.

### C.2.3.4 Glasgow City Council – Climate Adaptation Plan 2022–2030

Glasgow City Council has produced a Climate Adaptation Plan,[119] outlining the importance of building local resilience to the unavoidable consequences of a changing climate. The plan includes adaptation actions, including identifying climate change impacts, minimising potential negative effects and responding appropriately. The plan aims to address climate adaptation action in the city, building our understanding of climate risks and increasing our adaptive capacity, helping to make the city more resilient to current and future climate events such as flooding and overheating.

## C.3 Policy and guidance on canopy cover

Green infrastructure and the benefits of increasing canopy cover in urban areas are referenced in current and evolving climate change policy and guidance in England and the devolved governments.

### C.3.1 England

With respect to canopy cover, the NPPF acknowledges the importance of trees for climate change adaptation and mitigation. Trees in developments are recognised within the NPPF, which sets out what local planning authorities (LPA) will require when setting local policies and also considering planning applications for all developments. Under paragraph 131, it states: "Planning policies and decisions should ensure that new streets are tree-lined, that opportunities are taken to incorporate trees elsewhere in developments (such as parks and community orchards), that appropriate measures are in place to secure the long-term maintenance of newly-planted trees, and that existing trees are retained wherever possible."

This is backed up by other government and local guidance such as the National Model Design Code N 3 iii, Street Trees of the Guidance notes for Design Codes ('Design Code'),[120] which states: "All schemes will be expected to follow national policy by achieving a 10% net gain in biodiversity. All new streets should include street trees." The Design Code outlines a number of principles with respect to street tree design that may be included in design codes, modelled on the characteristics of well-designed places as set out in the National Design Code. With respect to street trees, these are:

- species: codes may include a list of species as a palette for use by developers, including non-native species that can provide valuable habitat. These help to establish different area types and need to take account of local climate, shape and size, fruit and pollen.
- position: careful positioning to allow space for the mature trees without interfering with property, infrastructure street lighting or junction sightlines. This can be on median strips, verges or interspersed with parking bays but only on pavements where the mature tree will not block access.
- services: coordinating tree planting with utilities providers and service ducts early in the lifetime of a scheme can ensure that trees do not interfere with underground services.
- specification: care is needed in heavily trafficked areas to avoid the compaction of the soil around the tree. Guidance on tree planting, pits, guards and other technical specifications are widely available and have a significant impact on the tree's survival prospects.

The use of design codes can be an effective way to achieve an increased standard of green infrastructure design, and the National Model Design Code is a useful tool in that regard.

As with the NPPF, the England Trees Action Plan[121] reinforces the government's commitment to all new streets being lined with trees. Specifically, the action plan states that the "developer should work with local authorities to plan, plant and manage these trees, and agree how they will be funded – including through developer contributions such as Biodiversity Net Gain". The action plan proposes to develop new National Model Design Code guidance on how trees can be included in the built environment, including design parameters for the placement of street trees.

The Town and Country Planning (Tree Preservation) (England) Regulations 2012 require that LPAs consider the protection and planting of trees when granting planning permission for development. If necessary, LPAs may issue a Tree Preservation Order to protect trees in the interests of amenity. More specifically, an order prohibits the cutting down, topping, lopping, uprooting, wilful damage and wilful destruction of trees without written consent. Protected trees can be of any size or species.

In line with UK climate policy, the 2020 Forestry Commission guide, and Defra Tree Action Plan 2021, the CCC recommended woodland creation, including the enhancement of urban and peri-urban wood density to reduce climate-change-related risks.

The UK government launched the 25 Year Environment Plan in 2018, which sets out its objectives for improving the environment. It details how the government will work with communities and businesses in order to achieve this. With particular reference to trees, there is a strong emphasis to provide "more and better-quality green infrastructure". Under Section 3, it clearly states that a framework will be in place to develop key green standards (anticipated to be launched in 2022), ensuring that new developments include accessible green spaces and provision of trees to achieve a preliminary target of 12% by 2060.

The CCC recommended in 2020 increasing woodland cover in the UK from 13% to a minimum of 17% by 2050, and possibly to 19% to ensure the country achieves net zero carbon emissions. It has recommended a significant expansion of trees outside woods to achieve net carbon zero, including agroforestry (trees integrated into farming systems) and hedgerows. This is in addition to any new woodland cover.

On average, only 11% of urban areas are currently covered by trees outside woods. These trees tend to be a varied selection of native and non-native species. In many urban areas there is huge potential to expand the tree canopy cover and deliver multiple benefits for both people and wildlife.

## C.3.2 Scotland

In Scotland, the Climate Change Plan 2018–2032 aims to introduce a stepped increase in the annual woodland creation rates from 2020–2021 to enhance the contribution that trees make to reducing emissions through sequestering carbon. It also aims to increase the use of sustainably sourced wood fibre to reduce emissions by encouraging the construction industry to increase the use of wood products, where appropriate.

There is no reference to canopy cover in relation to building foundations within NPF3, though it does aim to increase woodland creation throughout Scotland by 100,000 hectares within the next ten years and acknowledges that "a more integrated approach and 'greening' of the urban environment through green infrastructure and retrofitting can improve quality of life within our towns and cities, alongside enhancing their longer-term environmental performance and climate resilience."

Likewise, the NPF4 draft out for consultation makes no direct reference to canopy cover; however it builds on the green infrastructure aims outlined by NPF3 by stating places should be greener, healthier and more resilient to climate change, including reference to urban trees and green roofs and walls.

Under the 2010 regulations, an LPA may issue a Tree Preservation Order in the interest of amenity and/or if the trees are of cultural or historical significance. An order prohibits the cutting down, topping, lopping, uprooting, wilful damage or wilful destruction of trees except with the consent of the LPA, though there are a number of exemptions to this, including if:

- it is necessary for the prevention or abatement of a nuisance
- it is urgently necessary in the interests of safety
- it is in compliance with any obligation imposed under an Act of Parliament or an Act of the Scottish Parliament.

The Third Land Use Strategy acknowledges the importance of urban forestry as a means of maintaining and expanding green networks throughout towns and cities. It references the Scottish Forestry Strategy 2019–2029, which outlines the intention to increase tree canopy cover in towns and cities throughout Scotland.

### C.3.3 Wales

Planning Policy Wales (PPW) sets out the land use planning policies of the Welsh Government. It is supplemented by a series of Technical Advice Notes (TAN), Welsh Government circulars, and policy clarification letters which, together with PPW, provide the national planning policy framework for Wales. No direct reference is made to canopy cover, but PPW does identify the benefit of urban tree retention and planting for improving wellbeing and urban cooling.

Amending the Town and Country Planning (Trees) Regulations 1999 and their subsequent amendments, the 2017 regulations make provisions for Tree Preservation Orders and for applications for consent to carry out work on trees subject to an order.

TAN12 sets out advice for promoting sustainability through "good design" and "Planning for sustainable building". No direct reference is made to canopy cover; however, it does recommend "consideration should be given to retaining existing landmarks, established routes, mature trees and hedgerows within housing areas as well as introducing new planting appropriate to the area." It also recognises the 'natural cooling' associated with green corridors and urban planting.

### C.3.4 Northern Ireland

Presently in its draft form, the Green Growth Strategy for Northern Ireland[122] issued on 21 October 2021 by The Department for Agriculture, Environment and Rural Affairs (DAERA) highlights the intention to plant 18 million trees or 9000 hectares of new woodland over the next ten years through its Forests for Our Future programme.

## C.4 Future legislation

### C.4.1 Climate and Ecology Bill

At the time of writing, the Climate and Ecology Bill is proceeding through its second reading in the UK Parliament. Its aim is to create core climate and nature targets, rooted firmly in the latest scientific evidence, that are essential to effectively address the climate and ecological emergency.

The Bill requires the UK government to reduce the UK's GHG emissions at a rate consistent with limiting the global mean temperature increase to 1.5°C above pre-industrial levels, taking account of its international commitments under the UNFCCC and the Paris Agreement.

The Bill also requires the UK government to halt and reverse the UK's overall contribution to the degradation and loss of nature in the UK and overseas, consistent with its international commitments under the UN Convention on Biodiversity.

The Bill provides for the creation of an emergency climate and nature strategy, including the 'red lines' that are essential for the strategy to meet the climate and nature targets.

## C.5 Emerging standards and technical guidance for the housing and building sector

### C.5.1 British Standards Institution

The British Standards Institution (BSI) in its The journey to carbon neutrality: A guide to progress with standards document published in 2021,[123] outlines a range of standards. While not specifically related to foundation design, it does provide guidance on the broader topic of environmental management, sustainability and carbon, including:

- BS EN ISO 14001 Guidance for environmental management systems.[124] This document maps out a framework that an organisation can follow to set up an effective environmental management system, including policies and objectives.
- PAS 2080:216 Carbon management in infrastructure.[125] This document looks at the whole life cycle of the carbon used on projects and promotes reduced cost infrastructure delivery and innovation.
- PAS 2060:2014 Specification for the demonstration of carbon neutrality.[126] This document specifies the requirements to be met by any entity seeking to demonstrate carbon neutrality through the quantification, reduction and offsetting of greenhouse gas emissions from a uniquely identified subject.
- BS ISO 15392 2019 Sustainability in buildings and civil engineering works.[127] This document identifies and establishes general principles for the contribution of buildings, civil engineering works and other types of construction works to sustainable development, including whole life assessment.
- BS 8004 2015: Code of practice for foundations provides recommendations for the design and construction of foundations for a 'normal' range of buildings.[128] Of note in this standard is reference to long-term changes in groundwater that are likely to occur during the design life of the structure, including those due to climate change.

Similar to the findings of the industry survey undertaken as part of this review, BSI research quoted in the reference above[133] indicates only 10% of respondents stated they fully understood the relevant terminology related to carbon neutrality, reinforcing the need for additional guidance and support for those involved with construction.

## C.6 NHBC responses

In January 2023, the NHBC launched the latest edition of its Technical Standards, covering new homes with an NHBC warranty where foundations are begun on or after 1 January 2023. Pertinent to this review and noted in **Section 2** above, is NHBC's long-held recognition of climate and the effect of trees on foundations. Of note is Section 4.2 of the Standards and the zoning of the UK, reflecting the geographical diminishing risk associated with soil movement/shrink-swell, which is covered in greater detail by **Section 4**.

The NHBC has committed to supporting the UK government's ambition to achieving net zero carbon by 2050. Working with the housebuilding industry, the Future Homes Standard will set commercially and technically viable requirements to ensure the interests of homeowners are protected.

To support the decarbonisation of new developments, NHBC published the report Biodiversity in new housing developments: creating wildlife-friendly communities (April 2021)[129]. The publication focuses on the practicalities of building homes in a sustainable way that enhances wildlife and supports the development of climate resilience. The report offers nature-based solutions that combat pollinator decline, carbon emissions, water pollution, soil erosion and water run-off. Key messages in the report focus on using natural materials to combat flooding, reducing soil disturbance and using the correct mix of trees to encourage nectar-rich landscapes. On canopy cover, it published research that found that where tree canopy cover is over 25% but open enough for people to feel safe (and not suppress the vegetation beneath), social deprivation and crime rates are lower, plot values are higher and there are education and employment benefits.

The NHBC has contributed to the UK government's consultation on local planning policy, which calls for uniformity in the requirements of local plans with the view to ensuring consistency within planning policy.

Other NHBC Foundation publications of relevance include NF9 Zero carbon: what does it mean to homeowners and housebuilders?[130] published April 2008 and NF3 Climate change and innovation in house building: Designing out risk[1] published in August 2007.

# Appendix D Carbon calculations

As described in **Section 6.2.2**, Leap Environmental has developed a carbon calculator tool for foundation design for new residential developments. This estimates relative embodied carbon associated with the construction phase for traditional strip foundations versus piling. It is based on site-specific data, obtained as part of a ground investigation.

Using the tool, the model was run for a 'model' standard site to compare the different foundation options as an example. The embodied carbon calculations assumed the following input parameters:

| Model | Design parameter |
|---|---|
| Single detached house | 10m x 10m footprint |
| Reinforcement used in foundations? | No |
| Concrete type | C30/37 UK average ready-mixed concrete (35% cement replacement) |
| Ground conditions | |
| Topsoil | 0.0m to 0.3m below ground level (bgl) |
| Clay soil with high Plasticity Index (PI) | 0.3m to 20m bgl |
| Soil reuse | 100% topsoil and natural soil reused on site<br><br>50% made ground reused on site |
| Vegetation | Trees with zone of influence requiring foundation depth greater than minimum foundations |
| Option 1: Strip foundation | |
| Strip foundation | Foundation depths 0.9, 1.5 and 2.5m, all modeled 0.6m wide |
| Option 2: Piled foundation | |
| Pile type | CFA |
| Pile size | 0.3m diameter by 7.5m long[1] |
| Pile mat thickness | 0.6m |

**Table D1** Model input parameters

1 Based upon pile size dimensions proposed by NHBC Foundation

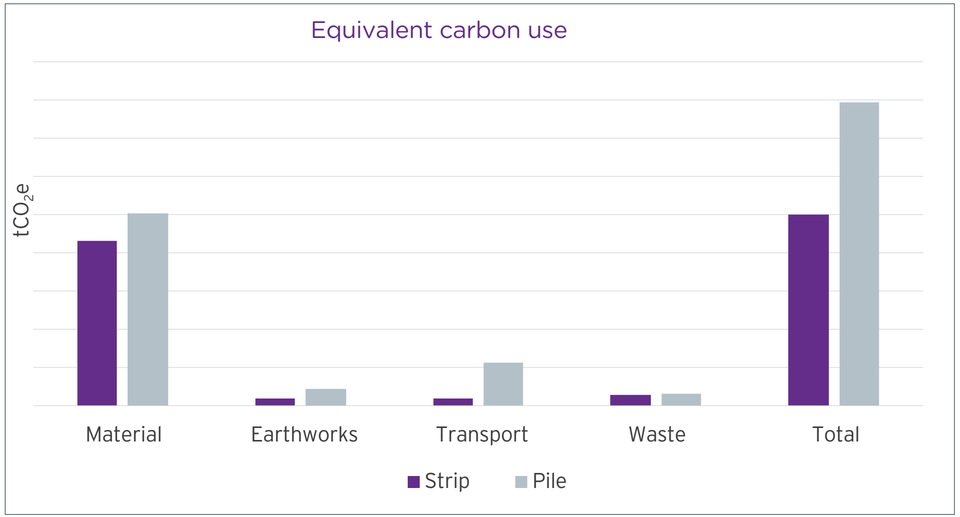


**Figure D1** Output from Leap Environmental tool carbon calculator tool showing relative equivalent carbon use for strip versus pile foundations for a high PI clay with 0.9m deep foundation (Source: Leap Environmental)

The results for this scenario, as shown in **Figure D1 – D3**, highlight the equivalent carbon emissions produced for strip foundations in a 0.9m, 1.5m and 2.5m deep foundation compared to a 7.5m long x 0.3m diameter piled foundation. This takes into account the materials used in the foundations, the associated transportation of soils and materials and the waste created.

The point at which a piled foundation solution has a lower tonnes of embodied carbon equivalent (tCO2e) than shallow foundations is when the shallow foundations on site would be required to be deeper than 1.5m bgl. This applies for the scenario of soil with high PI and the other factors detailed above and may differ for other scenarios.

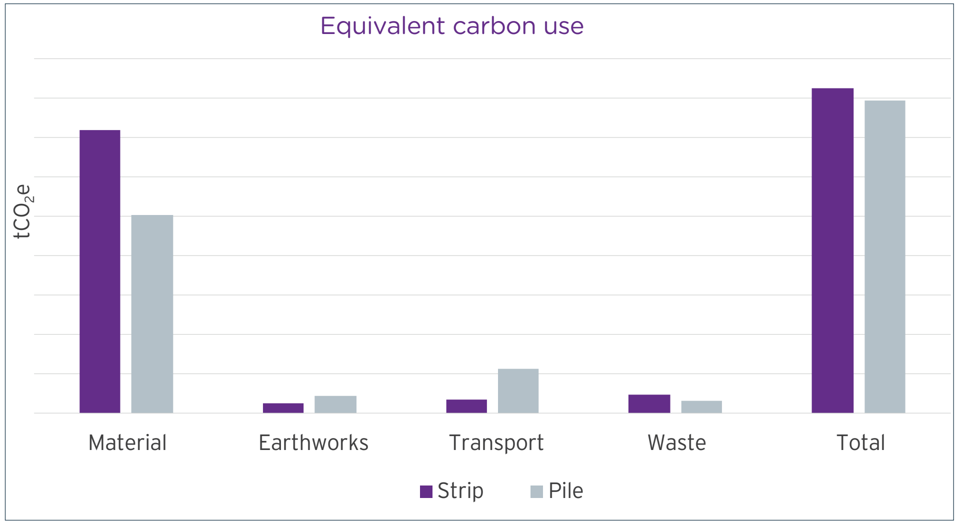


**Figure D2** Output from Leap Environmental tool carbon calculator tool showing relative equivalent carbon use for strip versus pile foundations for a high PI clay with 1.5m deep foundation (Source: Leap Environmental)

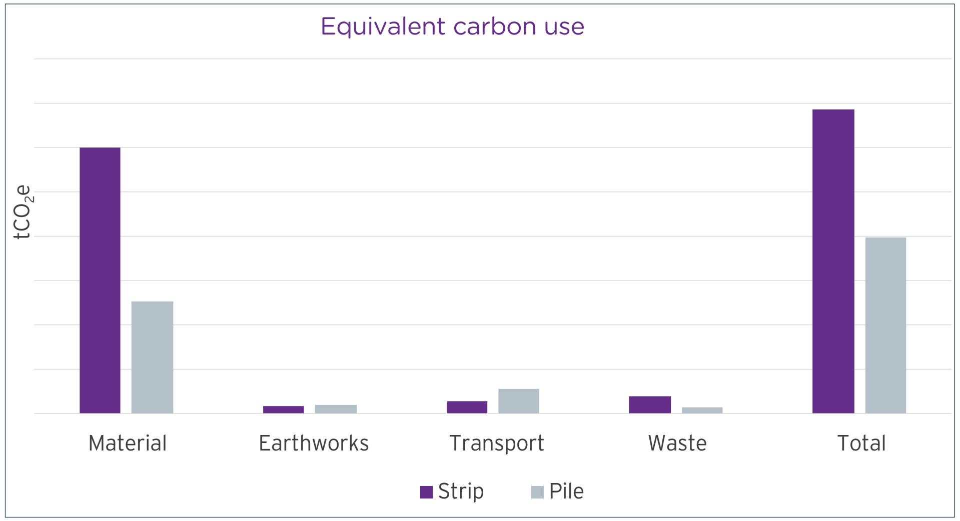


**Figure D3** Output from Leap Environmental tool carbon calculator tool showing relative equivalent carbon use for strip versus pile foundations for a high PI clay with 2.5m deep foundation (Source: Leap Environmental)

# Image credits

## Front cover

- © Tyne and Wear Fire and Rescue Service, 2012.

## Section 2: Background to the climate change emergency

- **Image 1:** IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, **https://www.ipcc.ch/report/ar6/wg1/**, © Intergovernmental Panel on Climate Change 2021
- **Image 2:** COP26, Glasgow, **https://ukcop26.org/**, © Crown Copyright 2021
- **Figure 1:** Observed changes in aspects of UK climate, Independent Assessment of UK Climate Risk (CCRA3), June 2021, **https://www.theccc.org.uk/publication/independent-assessment-of-uk-climate-risk/** and **https://www.ukclimaterisk.org/**, © Climate Change Committee 2021
- **Figure 2:** Observed and projected changes in UK hazards due to climate change, Independent Assessment of UK Climate Risk (CCRA3), June 2021, **https://www.theccc.org.uk/publication/independent-assessment-of-uk-climate-risk/** and **https://www.ukclimaterisk.org/**, © Climate Change Committee 2021
- **Table 2:** Examples of issues taken from Shoreline management plan guidance Volume 2: Procedures, March 2006, © Defra, 2006
- **Table 3:** 2007 summer floods - Environment Agency - A table showing the approximate number of properties and businesses flooded by Government Office Region **https://webarchive.nationalarchives.gov.uk/ukgwa/20140328091400/http://www.environment-agency.gov.uk/research/library/publications/33887.aspx**, Environment Agency 2007.

## Section 4: Effect of weather patterns

- **Figure 3:** GeoClimate UKCP18 Open coverage map and comparison of 2030 and 2070 projections: GeoClimate UKCP09 and UKCP18 – British Geological Survey (bgs.ac.uk), © UKRI BGS
- **Image 3:** Examples of building damage caused by subsidence, © RSK, 2022
- **Image 4:** © Tyne and Wear Fire and Rescue Service, 2012
- **Image 5:** Damage to housing caused by a solution feature or denehole © RSK, 2022
- **Image 6a-b:** Ripon sinkhole February 2014 case study, BGS Research – Sinkholes and karst research **https://www.bgs.ac.uk/geology-projects/sinkholes-research/sinkhole-at-magdalens-close/**, © UKRI BGS, 2014
- **Figure 4:** Ripon sinkhole February 2014 case study, BGS Research – Sinkholes and karst research **https://www.bgs.ac.uk/geology-projects/sinkholes-research/sinkhole-at-magdalens-close/** © UKRI BGS, 2014.

## Section 5: Effect of increased canopy cover

- **Figure 5:** Flow Chart of planning process for layout design © RSK, 2022
- **Table 4:** Reproduction of Table A.1 of BS 5837:2012 prescribed minimum planting distances to avoid direct damage to a structure from future tree growth, © BSI 2012
- **Figure 6:** Building Research Establishment, FB13 Subsidence damage to domestic buildings: A guide to good technical practice, 2007 (Figure 2), the distribution of shrinkable clays in England, © BRE, 2007
- **Figure 7:** Green roof typical cross-section CIRA Building Greener (C644), **http://www.ciria.com/buildinggreener/gr_introduction.htm**, © CIRIA
- **Image 7:** Aerial view of a living roof in an urban residential area (Source: Shutterstock)
- **Image 8:** Living Wall, Parliament Hill School Camden, **https://www.scotscape.co.uk/projects/parliament-hill-school**, © Scotscape

## Section 6: Low carbon foundation solutions

- **Figure 8:** EFFC-DFI Carbon Calculator Tool V4.0, **https://www.effc.org/how-we-operate/eco%e2%82%82-foundations/**, © EFFC-DFI/Carbone 4
- **Figure 9**: Cross Laminated Timber (CLT) Exhibit (Source: Shutterstock)
- **Image 9**: Stadthaus, © Waugh Thistleton Architects and Will Pryce
- **Image 10**: RapidRoot Pile Design, © RapidRoot, 2019
- **Image 11**: RapidRoot installation along a public garden walkway, © RapidRoot, 2019
- **Image 12**: Inbuilt ring beam foundation, © Elevate FBE Ltd
- **Figure 10**: Future Found trenchless system, © Build-Lite (UK) Ltd
- **Figure 11**: Example of one method used for installing pre-cast piles **https://www.structuralguide.com/pile-foundations**, © Structural Guide, 2022
- **Image 13**: Keltbray team installing traditional geothermal loops within solid piles, © Keltbray Holdings Ltd
- **Table 6**: Comparison between conventional pile and HIPER pile, **https://issuu.com/keltbraygroup/docs/keltbray_-_hiper__pile?fr=sNTQ0ZTIxNjEzMzU**, © Keltbray Holdings Ltd
- **Figure 12:** Options for new piled foundations, CIRIA Reuse of foundations (C653), © CIRIA
- **Figure 13:** A hybrid method for foundation reuse evaluation, Environmental Geotechnics, 2 (4): 224-236, (2014), Laefer, Debra F.; Farrell, Kelly-Ann (Figure 4), © ICE Publishing 2022
- **Image 14:** Sir John Lyon House, **https://rm-architects.com/sir-john-lyon-house**, © RM Architects, 2015

## Appendix A: Changes to the UK climate

- **Figure A1:** Global tipping points – Figure 1, Effect of Potential Climate Tipping Points on UK Impacts, © Met Office Hadley Centre, 2021
- **Figure A2:** Figure 10, UKCP18 projections of sea level change up to 2100 at four locations around the UK, scaled with Deconto and Pollard estimates, © Met Office Hadley Centre 2021

## Appendix B: Industry survey

- **Figure B1:** NHBC/RSK Industry survey key findings, © RSK, 2022
- **Figure B2:** NHBC/RSK Industry survey sample example responses, © RSK, 2022
- **Figure B3:** NHBC RSK Industry survey wordmap of responses to question, © RSK, 2022

## Appendix D: Carbon calculations

- **Figures D1-D3:** Outputs from Leap Environmental tool carbon calculator tool © Leap Environmental Ltd, 2022

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**NHBC Foundation**
NHBC House
Davy Avenue
Knowlhill
Milton Keynes
MK5 8FP
Tel: 0344 633 1000
Email: info@nhbcfoundation.org
Web: www.nhbcfoundation.org
Twitter: @nhbcfoundation

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