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Systematic review CEE10-005 (SR90)

THE IMPACT OF CHANGES IN THE WATER TABLE AND SOIL MOISTURE ON STRUCTURAL STABILITY OF BUILDINGS AND FOUNDATION SYSTEMS

Draft Review

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Cover Sheet

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Executive Summary

This Systematic Review aims to consider the impact of changes in the ground water table and soil moisture regime on structural stability of buildings and foundation systems. The possible changes in the water table levels and soil moisture conditions are expected as a result of environmental change.

Building and infrastructure damage occurs where differential movements exceed the thresholds that the buildings or infrastructure can sustain. At locations where uniform vertical settlement dominates, buildings often move vertically with the subsiding ground surface and little damage occurs. It is when excessive differential deformation occurs that buildings and infrastructure are more prone to damage. A number of criteria for damage risk assessment are described.

The expectation is that that settlement (downward movement of the ground surface) will occur during groundwater lowering and heave (upward movement of the ground surface) during groundwater rise. However, no cases of damage due to heave resulting from groundwater level rise *per se* were found in the literature reviewed. However, there were a significant number of cases of damage due to collapse settlements due to inundation during groundwater level rise. Collapse settlements in fill materials due to rising ground water levels are of major concern in the UK.

Capillary rise may occur in soil above the water table. Capillary rise can cause deterioration to structures formed from monumental sandstone through dissolution of cementing minerals reducing the strength of stone and recrystallisation of dissolved salts leading to expansion of the stone.

Flooding, where surface water exists above the ground surface, can be one circumstance that can lead to wetting and ground water table rise within the soil. In the first stage of flooding, the building structure is subject to the destructive impacts of water streams. In the aftermath of flooding, when water levels subside, the subsoil remains saturated with water. A further effect of flooding is that of soil erosion and scour which can do significant damage to foundations.

Rises in groundwater level, can cause reductions in strength of the soil that can lead to failures of slopes. In regions of significant slope instability, significant damage to buildings can occur as a result of landslides.

Lowering of the groundwater table can cause the soil to consolidate, which induces settlement. With softer, more compressible soils, settlements can become large. Many of the cases of damage reported are due to large scale land-surface subsidence induced by ground water abstraction. In some of these examples, the ground surface has fallen by as much as 8m. Other cases deal with more localised ground water control measures, usually associated with dewatering during construction of a tunnel or deep excavation such as an underground car park or metro station. The evidence suggests that significant consolidation settlements can be induced by groundwater lowering. In soft compressible soils, very large settlements can be induced. Settlements of the order of metres can be induced by large drops in groundwater level (30+ metres). Even land subsidence of less than 1 metre can induce significant damage to buildings.

Much of the damage reported that is associated with groundwater lowering occurs in buildings on shallow foundations. However, deep foundations on piles can also be affected. If soil settles relative to the pile, this can result in downdrag on the pile (known as “negative skin friction”). This additional load could potentially overstress the pile and lead to failure. A further particular problem occurs with wooden piles when the groundwater level is lowered. If the water table is lowered, this exposes the upper part of the pile to aerobic conditions and rotting and decay can start to take place. There are examples of building damage due to rotting of wooden piles.

Karstic conditions exist in soluble rocks such as limestone and dolomite, where ground water flow causes dissolution of the rock leading to the formation of caverns. Sinkhole formation and ground surface subsidence due to dissolution of soluble rocks is a major cause of damage to buildings in karstic areas. This is often associated with groundwater lowering changing the dynamics of the hydrogeology in calcareous rocks. However, there are examples where damage has resulted from additional flow under high water table conditions, as the greater flow causes more dissolution of the soluble rocks and erosion or removal of clay filling from the fissures.

Shrinkage and swelling of clay soils is the single most common cause of foundation-related damage to low-rise buildings in the UK. Vegetation, particularly larger trees, has a significant effect of removing water from the soil and inducing shrinkage. Seasonal shrinkage and swelling will be a major factor of concern if climate change produces drier summers and wetter winters, as predicted for the UK, since greater extremes of wetting and drying will induce greater cycles of swelling and shrinkage. The evidence suggests that shrinkage during periods of drought causes the greatest degree of damage. There is evidence from France that soil conditions are becoming progressively drier and this is consistent with a long-term drying trend predicted for the UK.

Peat poses particular geotechnical problems due to its high compressibility. It is made from decaying vegetation and can be very fibrous with a very open, compressible structure. Due it its high compressibility, any changes in stress resulting from groundwater level changes are likely to result in large surface settlement or heave.

To be able to assess the future implications of damage to structures due to environmental change it is important to understand the economic cost of damage to buildings due the mechanisms of groundwater level change, shrink/swell etc. The costs of damage due to shrink/swell movements on clay soils have resulted in economic losses of over £1.6 billion in the UK during drought years in the 1990s. Similar figures are evident from France where losses have been as high as 3.3 billion € (£2.7 billion) in a single year. In China, losses due to land subsidence in Shanghai are estimated to be about £10 billion over a decade with £0.3 billion a year in losses in three other cities.

Consideration has been given by researchers and strategists to the impacts of climate change on the UK built environment and what might be needed for adaption. A consensus is that potential problems to foundations could be addressed through higher specification of foundations, including greater depths for foundations, as well as by new construction methods. It is also possible that higher [increasing] minimum temperatures and fewer cold days could reduce problems associated with frost heave. It may be that an increase in the number of properties suffering damage could result in changes in the perception of the severity of damage and householders may become willing to accept minor levels of damage.

Discussions about building performance in New Zealand also lead to the suggestion that risks of future climate change to buildings should be managed and this means that building codes and practices around the world will need to change to suit new climate conditions. However, changing codes and practices requires a good foundation of evidence and research. This is difficult to establish given the uncertainty of current climate change scenarios and their long timescale. There is also an awareness that buildings built now will still be in use in 50-100 years time. This produces a need for early action in the construction sector.

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1 Background

This Systematic Review aims to consider the impact of changes in the ground water table and soil moisture regime on structural stability of buildings and foundation systems. The possible changes in the water table levels and soil moisture conditions are expected as a result of environmental change. The IPCC 4th Assessment Report provides evidence to support the view that with the advent of industrialisation since 1750, the subsequent increase in greenhouse gas production has influenced global warming (IPCC (2007)). The implications of this, as the report states, are: "Continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century". This now represents the consensus view of many climate scientists, although, of course, there are continuing debates around the body of evidence and the subsequent conclusions drawn by both scientific and political communities.

There is evidence of environmental changes that are already in process. The last decade has demonstrated the occurrence of extreme climate events. In the UK, the winter of 2000/1 was the wettest on record; the period May-July 2007 was the wettest for 250 years (resulting in extensive flooding in Gloucestershire, Worcestershire and Yorkshire); flooding in Cumbria in 2009 was reported as the worst for 1000 years. Whether or not these extreme events are attributable to global warming is debatable but they are evidence of environmental change. Current climate models lead to the conclusion that future weather patterns will involve more flooding (Evans*, et al.* (2008)). This carries implications for existing infrastructure as well as defining standards for new-build projects. Therefore there is an urgent need to ensure that engineering professionals responsible for our built environment are fully informed about the potential effects to ensure they can plan, design and respond to these events and possibly more extreme future scenarios.

Engineers face two major concerns in the professional assessment of buildings and structures: Firstly, are the foundations safe and serviceable in the current climate conditions and secondly, will the foundations maintain their serviceability when faced with changes in climate patterns. UKCP09 climate projections (Murphy (2009)) predict that by 2080, based on medium emissions of greenhouse gasses, the UK could face increased rainfall during winter periods (50% probability level of 11-20% increase), higher temperatures and reduced rainfall during summer seasons (50% probability level of 2.5-3°C increase in temperature and 4-9% reduction in rainfall) and more extreme storm events (heavy rain days to increase by a factor of between 2 and 3.5 in winter, and 1 to 2 in summer).

The intention of this review is to assess the published literature in order to identify the current state of knowledge about the impact of changes in the water table and soil moisture on structural stability of buildings and foundation systems.

2 Objective of the Review

The original question was framed as part of the *Living with Environmental Change* initiative (www.lwec.org.uk) to address questions which relate to how environmental change could impact on the construction industry. As a result of a scoping study carried out by the review team, the following research question was agreed for the full systematic review:

Question: What is the impact of changes in the water table and soil moisture on structural stability of buildings and foundation systems?

To address this question, the ***subject*** of concern was buildings and structures or foundation systems for other forms of construction (bridges, dams, roads, railways). The ***exposure*** element was changes in hydrological regime, ground water table or soil moisture conditions induced by environmental change. The ***outcome*** was building movement or damage (that were also identified by surrogate terms such as "failure", "subsidence", "settlement" etc.).

For this type of engineering problem, there are no controlled experiments that have directly investigated the research question. Instead, the evidence has to be pieced together from observations and case histories of real buildings and structures that have been exposed to changes in ground water regime imposed by the vagaries of nature. The ***comparators*** are soil type and foundation type, as direct comparisons can only be made between case studies where these two elements are similar.

The study focussed on the implications of environmental change for the UK. However, an international literature search was carried out as there are relevant case studies from other parts of the world that help to provide a fuller picture of the outcomes resulting from changes in groundwater regime. Although geological conditions and construction methods vary between countries, lessons can be learnt by comparing cases where soil type and foundation type are similar.

3 Methods

To conduct the review, an International review team was assembled by the lead reviewer. The review team comprises 5 leading international geotechnical engineers and hydrogeologists with specialist knowledge of environmental impacts.

Stakeholder bodies with complementary expertise and with interests in the review were willing to contribute. Their contributions brought a wider pool of knowledge to the scoping process. These were:

- British Geological Survey (BGS)
- Environment Agency (EA)
- National House Building Council (NHBC)
- Atkins
- Golder Associates
- Mott MacDonald

BGS and EA are Government funded institutions (BGS is funded through NERC). NHBC is an independent, non-profit distributing company that is the standard setting body and leading warranty and insurance provider for new and newly converted homes in the UK. Atkins, Golder Associates and Mott MacDonald are major Civil Engineering companies whose work involves design and overseeing construction of civil engineering works in the UK and overseas.

A scoping study was carried out by the Review Team to assist in the selection of search terms. A workshop to discuss the scoping study was held at Durham University, 25-26 March 2010 (http://www.dur.ac.uk/geo-engineering/iasworkshop/). This was attended by 40 people with contributors from UK Stakeholders (British Geological Survey; Climate North East; Environment Agency; Scottish Crop Research Institute; Transport Research Laboratory; UK Climate Impacts Programme), UK Universities (Durham; Loughborough; Newcastle; Portsmouth; Queen's Belfast; Southampton) and International Researchers (Bangladesh Agricultural University; Deltares, The

Netherlands; Ecole des Ponts, France; Hong Kong University of Science and Technology). This allowed the presentation of the review strategy and provided engagement with a wide range of experts and stakeholders.

3.1 Search strategy

The search strategy relied upon electronically searchable databases. The search terms in Table 1 were used in the searches. These were developed by the review team within the scoping study.

Table 1. Search Terms

Subject terms Building; Structure; Construction; Foundation
Exposure terms Water table; Ground water; Flood; Drought; Soil moisture
Outcome terms Instability; Failure; Collapse; Shrinkage; Swelling; Heave; Subsidence; Settlement

The search strings combined the individual subject, exposure and outcome terms with "OR". To ensure that at least one term from each category is included, the subject, exposure and outcome groups were combined with "AND". Wildcards were used for alternate terms e.g. swell* can be used to check for "swell", "swelling", "swelled" etc.

The search string used was:

((building) OR (structure) OR (construction) OR (foundation))
AND ((water table) OR ((ground water) OR (groundwater)) OR (flood*) OR (drought*) OR (soil moisture))
AND ((instability) OR (failure) OR (collapse) OR (shrink*) OR (swell*) OR (heave*) OR (subsidence) OR (settle*))

The following databases were used:

- Web of Science (ISI) (20/8/2010)
  1764 references found (4 duplicates removed – 1760 imported)
- GEOBASE (OCLC First Search) (20/8/2010)
  969 references. Top 100 imported, sorted by Relevance. (33 duplicates with WoS and 3 incomplete records removed)
- GeoRef (EBSCO) (20/8/2010)
  2916 references (2000 with abstracts). Top 100 imported, sorted by Relevance. (25 duplicates with WoS removed)
- InformaWorld (Taylor and Francis Online Journals) (20/8/2010)
  1851 references. Top 100 imported, sorted by Relevance. (8 duplicates with WoS removed)
- JSTOR (ITHAKA) (24/8/2010)
  219718 references. Top 100 imported, sorted by Relevance. ((1 duplicate with WoS removed)
  Note: since wildcards could not be used for JSTOR the following research string was adopted: [Search string: ((((building) OR (structure) OR (construction) OR (foundation)) AND ((water table) OR ((ground water) OR (groundwater)) OR (flood) OR (flooding) OR (drought) OR (soil

moisture))) AND ((instability) OR (failure) OR (collapse) OR (shrink) OR (shrinkage) OR (swell) OR (swelling) OR (heave) OR (heaving) OR (subsidence) OR (settle) OR (settlement)))]

- ECO (Electronic Collections Online) for Journal Articles (OCLC First Search) (24/8/2010)
  268 references. Top 100 imported, sorted by Relevance. (52 duplicates with WoS, 1 duplicate with IngentaWorld and 2 incomplete records removed)
- ScienceDirect (Elsevier) for Journal Articles (24/8/2010)
  422033 references. Top 100 imported, sorted by Relevance. (9 duplicates with WoS removed)

The following databases were accessed, but nor used in the final search:

- IngentaConnect. *Not used as search string length too limited to allow full search.*
- Springerlink (Springer). *Not used due to difficulties in exporting citations and identifying source.*

For "grey literature", the following web-based unstructured keyword search engine was used:

- http://www.google.com

From the Google search, the first 50 references were recovered, as is normal practice for Systematic Review. An Excel macro was written to read the saved **.htm** files generated from the search. This allowed the abstraction of essential information, such as *URL, Title, Abstract* (the short preview paragraph presented by the Google search) and allowed it to be imported into the Endnote library.

3.2 Study inclusion criteria

The studies included in the review were selected on the following criteria.

- **Relevant subject(s):**
  Buildings, structures and foundation systems
- **Types of exposure:**
  Changes in hydrological regime, water table or soil moisture conditions
- **Types of outcome:**
  Building movement or damage (failure, subsidence, settlement etc.)
- **Types of study:**
  Observational studies and case histories; Experimental studies (full-scale and model-scale); Numerical models and simulations.

Each reference was evaluated by two members of the review team for the above inclusion criteria. The team members had access to author/date/title/source information and in the majority of cases, a full abstract, on which to base their decision.

The included papers are reviewed in the following section. The individual cases of building damage or foundation problems are tabulated in Table 5 to Table 10, categorised according to the type of exposure and outcome or according to specific soil types.

4 Review Findings

4.1 Damage to buildings

Building and infrastructure damage occurs where differential movements exceed the thresholds that the buildings or infrastructure can sustain. At locations where uniform vertical settlement dominates, buildings often move vertically with the subsiding ground surface and little damage occurs. It is when excessive differential deformation occurs that buildings and infrastructure are more prone to damage.

Preene (2000) reviews ways to assess settlements induced by groundwater control and provides clear guidelines on assessing the damage caused by differential settlements. He notes that no study has concentrated on damage from groundwater control induced settlements. He refers to Burland and Wroth (1975) who summarise the literature on the magnitude of deformations which result in the onset of varying degrees of damage. He provides Table 2 taken from Lake*, et al.* (1996).

Table 2. Tentative limits of building settlement and tilt for damage risk assessment (Lake, et al. (1996))

Risk category	Maximum settlement: mm	Building tilt	Anticipated effects
Negligible	<10	<1/500	Superficial damage unlikely
Slight	10-50	1/500-1/200	Possible superficial damage, unlikely to have structural significance
Moderate	50-75	1/200-1/50	Expected superficial damage and possible structural damage to buildings; possible damage to rigid pipelines
Severe	>75	>1/50	Expected structural damage to buildings and expected damage to rigid pipelines or possible damage to other pipelines

Crilly (2001) refers to the criteria given in BRE Digest 251 (BRE (1995)) which is given in Table 3.

Table 3. Classification of visible damage to walls with particular reference to ease of repair of plaster and brickwork or masonry

(Crack width is one factor in assessing category of damage and should not be used on its own as a direct measure of it)

Category	Description of typical damage of damage *Ease of repair in italic type*
0	Hairline cracks of less than about 0.1 mm which are classed as negligible. *No action required*.
1	Fine cracks which can *be treated easily using normal decoration*. Damage generally restricted to internal wall finishes; cracks rarely visible in external brickwork. Typical crack widths up to 1 mm.
2	*Cracks easily filled. Recurrent cracks can be masked by suitable linings*. Cracks not necessarily visible externally; *some external repointing may be required to ensure weather-tightness.* Doors and windows may stick slightly and *require easing and adjusting*. Typical crack widths up to 5 mm.
3	Cracks which *require some opening up and can be patched by a mason. Repointing of external brickwork and possibly a small amount of brickwork to be replaced*. Doors and windows sticking. Service pipes may fracture. Weather-tightness often impaired. Typical crack widths are 5 to 15 mm, or several of, say, 3 mm.
4	Extensive damage which *requires breaking-out and replacing sections of walls*, especially

	over doors and windows. Windows and door frames distorted, floor sloping noticeably*. Walls leaning or bulging noticeably*, some loss of bearing in beams. Service pipes disrupted. Typical crack widths are 15 to 25 mm, but also depends on number of cracks.
5	Structural damage which *requires a major repair job, involving partial or complete rebuilding*. Beams lose bearing, walls lean badly and require shoring. Windows broken with distortion. Danger of instability. Typical crack widths are greater than 25 mm, but depends on number of cracks.

** Local deviation of slope, from the horizontal or vertical, of more than 1/100 will normally be clearly visible. Overall deviations in excess of 1/150 are undesirable.*

Feng*, et al.* (2008) report the Chinese Government criteria for Building Damage Level (BDL) based on the slope of the deformed surface (S_T) (Table 4). Categories I-IV map quite closely onto categories 2-5 of the BRE (1995) classification, based on crack width. It is assumed that the S_T values are expressed as percentage, in which case values of 3, 6 and 10% would be equivalent to 1/33, 1/17 and 1/10 respectively. These are significantly greater slopes than those quoted in Table 2.

Table 4. Building damage level (BDL) (after Feng*, et al.* (2008)).

Building Damage Level (BDL)	**Surface Slope (S_T)**	**Description**
I	≤3	Rare cracks on the wall and the width is less than 4 mm
II	3<S≤6	Wall cracks and their width are greater than 4 mm but less 15 mm, slight window and door deformation
III	6<S≤10	Wall cracks and their width are greater than 16 mm but less than 30 mm. serious window and door deformation, slight wall incline
IV	>10	Serious wall inclination and structure damage, even collapse

Papadopoulos*, et al.* (2004) reports on three case studies in Boston, USA where settlements were of the order of 10-30mm. These settlements were within tolerable values for the structures and no damage was seen. Peterson and Wade (1997) describe settlements of buildings in Alberta, Canada where significant settlements (up to 270mm) did occur. However, the angular distortion (building tilt) was low, equivalent to 1/300, and the building showed no signs of damage, although there were hairline cracks in the floor slabs. These are consistent with the suggested limits in Table 2.

Özdemir (2008) describes the collapse of the Zümrüt Building in Konya, Turkey in 2004 which resulted in 92 fatalities. The author argues that the collapse was due to unacceptable differential settlements with one side of the building calculated to settle by 249mm and the other side by 80mm, inducing angular distortions of the order of 1/150. This angular distortion is less than would be expected to cause severe structural damage from Table 2, although the overall settlement was large.

4.2 Groundwater rise

A rise in groundwater level can produce changes in the foundation stress conditions. Effective stresses reduce as groundwater rise causes the pore-water pressures to increase. The expectation is that that settlement (downward movement of the ground surface) will occur during groundwater lowering and heave (upward movement of the ground surface) during groundwater rise. However, Varosio (2000) notes that in complex hydrological conditions, with confined aquifers, transient states can result in wetting of a layer above the compressible layer, thus inducing settlement, as the total stresses above the compressible layer can increase during this transient phase.

A reduction in effective stress can also produce reductions in strength of the soil. Powrie (2008) notes that increases in pore-water pressure towards a new equilibrium condition by transient groundwater flow can cause an initially stable trench, slope or retaining wall to fail in the medium to long term. Ground movements due to slope or retaining wall failure can impact on nearby buildings, inducing damage. Case studies of slope instabilities relating to groundwater rise are discussed later.

There can also be changes in soil properties resulting from changing moisture conditions produced by rising ground water levels. Cajka and Manasek (2005) report on the effect of moisture content increase in clay soils in the Czech Republic, causing significant reductions in the angle of shearing resistance and modulus of deformation. They suggest that an increase in moisture content from 20% to 30% could cause sufficient reduction in modulus of deformation to cause the foundation settlement to increase by 2-4 times.

Kieffer and Goodman (1999) describe numerical modelling of a gravity dam on the Eel River, California during reservoir filling. The model predicted upstream tilting of the dam during construction, followed by downstream tilting during reservoir filling, showing a clear influence of groundwater level rise.

No cases of damage due to heave resulting from groundwater level rise *per se* were found in the literature reviewed. There are instances of damage to buildings due to cycles of wetting and drying in active clay soils, and these will be discussed later. Even here, most damage seems to be associated with shrinkage settlements rather than heave on wetting.

However, there were a significant number of cases of damage due to collapse settlements due to inundation during ground water level rise. These are reviewed in the following section.

4.2.1 Collapse settlements

Some soils are liable to collapse (reduce in volume) when inundated by water. Collapse is a phenomena that occurs when a soil exists in a loose state, with large inter-particle voids, supported either by suctions in the pore-water, by cemented bonds between particles or by clay “bridges” between particles (that are themselves supported by suctions). If the soil is wetted, the suctions reduce and/or the cementing is dissolved or removed and the loose state can no longer be supported. When the support between the particles is lost, the soil “collapses” causing a sudden reduction in volume resulting in surface settlements.

Soils that are susceptible to collapse are anthropogenic fill materials (collapsible fills are likely to contain clayey fines, rather than clean granular fills), loess (a fine-grained wind-blown deposit), residual soils or weakly cemented soils. Chapman (1999) suggests that collapse settlement is generally only a problem for fill materials in the UK.

Collapse is initiated by an increase in the degree of saturation (wetting) that produces a reduction in suction. El-Ehwany and Houston (1990) found that, in an infiltration test on a natural collapsible soil, the degree of saturation averaged about 50% behind the wetting front. Laboratory tests indicated that a degree of saturation of 50% produced about 85% of the full collapse potential. There was full collapse with a degree of saturation above 70%. Charles and Watts (1996) note that a partially saturated fill that has previously had a higher degree of saturation, but has never been fully saturated with consequential compression, can still demonstrate a substantial potential for compression on wetting.

Charles and Watts (1996) identify that about 20% of low-rise construction in Britain (which includes house building) takes place on filled ground (i.e. artificial soil placed to raise ground levels). Therefore, potential problems posed by collapse compression of fills due to wetting are of major significance (Table 5). Collapse compression occurs when a partially saturated fill undergoes a reduction in volume due to an increase in water content. They noted that inundation can be due to either submergence from a rising groundwater level or river level or water infiltrating downwards from the ground surface. The rate at which collapse compression takes place will be largely controlled by the rate at which the fill is wetted. They also reported that collapse compression can occur many years after the fill was placed (with dates ranging from 5 years to 246 years in their case studies, see Table 5).

Peterson and Wade (1997) describe collapse settlements of buildings in Alberta, Canada constructed on mine waste. The settlements resulted from unanticipated groundwater rise. The building, on 12-15m of reclaimed mine waste showed settlements varying between zero and 270mm about 15 years after construction. However, the building showed no signs of damage since the angular distortion was equivalent to 1/300, although there were hairline cracks in the floor slabs. The amount of settlement was estimated to approach 5% of the wetted thickness.

Bally (1988) reports on a number of extremely useful case histories of collapse settlements in loessial soils in Romania and the former USSR. Considerable settlements were induced by wetting. The settlements in some cases were attributed to collapse on wetting; in other cases due to weakening of the soil on wetting such that bearing pressures exceeded the yield stress. Interestingly, Bally notes that settlements on loess soils may continue after flooding has occurred, when the soil is draining, and this may continue for a number of years after the flooding event. Bally also reports the observation by Abelev (1948) that raising of the water level results in a smaller settlement of the loess formation than falling water levels.

Kushner (2008) reports on a case study from Ukraine where the ground water level beneath a 4 story concrete framed structure rose by 13.5-17m over 40 years causing large settlements up to 538 mm. The building was founded on loess soils. Although considerable bending of beams and columns was observed, there was surprisingly little significant cracking or concerns about structural integrity apart from a limited number of beams, columns and walls. The authors attribute the lack of damage to the slow deformation process which allowed the structural components to adapt to deformations as well as high initial safety factors for the structural components.

Vilar and Rodrigues (2011) report on damage caused to the town of Pereira Barreto, São Paulo, Brazil as a result of ground water level rise of 20m associated with reservoir filling for the Três Irmãos dam and canal construction. Initially the water level rose within a non-collapsible residual clay soil and no settlement resulted. However, as the water rose within very loose sand layers, settlements of over 100mm were induced, causing damage to over 300 buildings, many of which had to be demolished and rebuilt.

Gutierrez and Cooper (2002) discuss the effects of flooding problems on the historic city of Calatayud in NE Spain. Most of the old buildings in the city have been damaged by subsidence. One cause of subsidence is hydrocollapse of gypsiferous silt in the alluvial fan deposits although the authors suggest that evaporite bedrock dissolution is the main process responsible for the subsidence.

Clearly, collapse settlements in fill materials due to rising ground water levels are of major concern in the UK, with 5 cases tabulated in Table 5. Collapse of loess, residual soils and cemented soils (eg gypsiferous soils) due to rising ground water levels are likely to have major impacts in other parts of the world where these soil types are common.

4.2.2 Capillary rise

Kelman and Spence (2004) note that capillary rise may occur in soil above the water table. They quote Whitlow (1983) who suggests that soil saturated with capillary water may occur up to 0.5 m above the water table and partial saturation with capillary water may occur more than 10 m above the water table for fine soils such as clay.

Ahmed*, et al.* (2007) reports on the effects of rising ground water levels resulting from the construction of the Aswan High dam in 1970. This has resulted in damage to structures in the archaeological sites of Upper Egypt. The rise in ground water level was 0.5-1.0 m as a result of an increasing trend which was observed to be 5-30 cm/year from 1995-1999. This led to damage through capillary rise and crystallisation of salts and in some cases caused collapse.

Ahmed*, et al.* (2007) notes that the groundwater rise caused deterioration to structures formed from monumental sandstone through: (i) dissolution of cementing minerals reducing the strength of stone (ii) recrystallisation of dissolved salts leading to expansion of the stone. Since the climate of the Nile Valley is characterised by low precipitation and high evaporation, the capillary zone extends to the surface, resulting in upward transport of salt. Particular damage was caused by extensive diurnal variations in temperature; high daily temperatures causing evaporation from the stone surface, producing a concentration of water soluble salts, while low temperatures at night caused condensation of water which penetrated the stone by capillary action. This repeated dissolution and crystallisation of salt produces large stresses that can damage even competent stone.

A coarse grained granular layer can be used beneath foundations to act as a capillary break preventing water being drawn upwards by capillarity. Rantala and Leivo (2008) note from studies in Finland that the relative humidity of granular fill layers beneath building foundations is close to 100%. They also report on temperature variations beneath a heated building. Temperatures under the slab were 10-20°C even when the outside air temperature dropped below -20°C. It was found that fungal or bacterial growth occurs in the warm, humid conditions within the fill layer. However, they concluded that the detection of microbes in the fill layer was not a sign of moisture damage to the ground slab.

4.2.3 Flooding

Flooding, where surface water exists above the ground surface, can be one circumstance that can lead to wetting and ground water table rise within the soil. Cajka and Manasek (2005) discuss numerical modelling of the effects of flooding on structures. Disastrous floods hit the Czech Republic in 1997, 2000 and 2002. They note that in the first stage of flooding, the building structure is subject to the destructive impacts of water streams. In the aftermath of flooding, when water levels subside, the subsoil remains saturated with water. The foundation stress conditions change as a result of the changing ground water levels and changes in soil properties result from changing moisture conditions.

Ahmed*, et al.* (2007) notes that damage was caused by floods in Egypt where water carrying sediments rose to 3m above ground level. This led to swelling and subsequent shrinkage and cracking of clay shales. Ahmed*, et al.* (2007) also note that runoff water after flooding led to dissolution of sulphates in the shale beds, forming acidic water that caused corrosion of limestones.

Crystallisation of salts in monumental stones also caused damage by alveolar (honeycomb) weathering.

Kelman and Spence (2004) review flood actions on buildings although they do not pay particular attention to impacts on foundations. Similarly, Khan and Jamal (2000) present a risk assessment for dams, including the effect of extreme floods. While they consider possible damage scenarios this is done in a generic way.

Apart from the effects of ground water rise and soil wetting due to flooding that are considered elsewhere, a further effect of flooding is that of soil erosion and scour. This is considered in the following section.

4.2.4 Soil Erosion and Scour

Cajka and Manasek (2005) note that, in the aftermath of flooding, in loose sandy soils, water flow can wash away soil grains. These effects can result in foundation subsidence. Cajka and Manasek (2005) suggest that water velocities of greater than 0.6-1.2 ms^{-1} could cause scour for gravel soils from the Bečva River in the Czech Republic. Wash out around pile foundations can reduce the load carrying capacity. They recommended using more piles, each of smaller dimensions, as the probability of a pile group failing is lower than for individual piles. They did note, however, that the exposed head of a smaller pile may be more easily damaged by buckling and lateral loading due to flowing water.

Kelman and Spence (2004) consider erosion and scour as a result of flooding, identifying two principal phenomena: entrainment of sediment in water and horizontal movement of the entrained sediment. Nadal*, et al.* (2010) considers flood damage on building and notes that there is no methodology to estimate local soil scour at a building foundation.

Thomas and van Schalkwyk (1993) identify bridge failures caused by geological hazards as a result of intense rain and flooding in Natal, South Africa. During floods in 1987/88, damage was recorded at 28 bridge sites, 130 bridge approaches and 40 causeways. Geological factors played a part in only sixteen bridge failures; three failures were due to a change of river course and thirteen failures were the result of foundation failures. The major factors causing foundation failures were scour and debris build-up against structures during flooding. None were due to a change in groundwater level *per se* but due to flood waters above ground level.

Wardhana and Hadipriono (2003) report on over 500 failures of bridge structures in the United States between 1989-2000. 226 of the failures (53%) were associated with flood events. Scour is a major feature of the failures due to floods. It is not possible from the data reported to identify failures directly associated with changes in groundwater levels.

4.2.5 Slope Instability

As has already been noted, rises in groundwater level, usually as a result of heavy rainfall, can cause reductions in strength that can lead to failures of slopes. There is a large literature of rainfall-induced landslides that will not be reviewed here. Only cases of building or infrastructure failure associated with slope instability will be considered (Table 6).

Meisina*, et al.* (2006) discuss geological hazards in Oltrepo Pavese in Northern Italy, an area particularly prone to shallow and deep landslides, swelling/shrinkage of the clayey soils and subsidence in the Po plain. More than 1200 residential buildings have experienced damage and landslides account for 46% of this damage.

Kelly*, et al.* (1995) describe deformation of a bridge structure in Saskatchewan, Canada resulting from a landslide. An upward ground water gradient lowered effective stresses causing sliding on two surfaces. Slow movements of the abutments and piers have continued since construction in 1968. The authors note that stabilisation by dewatering would take several years to take effects due to the 24m thickness of shales between the two sliding surfaces.

Mejia-Navarro*, et al.* (1994) report on 21 debris flows and floods in Glenwood Springs, Colorado that caused damage to buildings, highways and railways. In particular in 1977 a heavy thunderstorm resulted in a debris flow that spread over more than 80 ha of the city. Debris flows have caused millions of dollars of damage to structures during years when extremely heavy rainstorms occur. The 1977 event was triggered by a storm of 27mm, 22 mm of which fell in about 30 minutes.

Lohnes and Kjartanson (2002) describe 11 slope failures (mudflows) in loess in Iowa, USA that resulted in State Highway US-275 and the Burlington Railroad being damaged. The landslides were triggered by unusually high precipitation of 191mm with intensities of 76.5 mm/h. Water contents greater than the liquid limit were measured in the mudflow. They note that greater infiltration occurred on gentler slopes.

Metternicht*, et al.* (2005) suggest that thermal remote sensing techniques can assist in the identification of zones with different water content indicative of high risk hydrogeological situations. Their interest was landslides in mountainous environments in Switzerland. Yost (2004) discusses slope stability issues associated with a flooded open-pit copper mine in Maryville, California, USA. The assessment considered slope failures only and no buildings were affected.

Zhou*, et al.* (2006) discuss the effects of rising groundwater levels on slopes reinforced with soil nails, based on centrifuge model tests. Rising water levels induced shallow failures in unreinforced slopes, whereas the soil nails prevented this.

There are cases where building failures have resulted from slope instabilities (Table 6). In regions of significant slope instability, such as the region of Northern Italy described by Meisina*, et al.* (2006), more than 500 residential buildings have experienced damage due to landslides. Debris flows and mudflows can also cause significant damage to individual buildings or whole towns.

4.3 Groundwater lowering

A simple overview of the effects of changing water tables is given by Chapman (1999). Lowering of the water table can cause the soil to consolidate, which induces settlement. With softer, more compressible soils, settlements can become large.

Many of the cases of damage reported are due to large scale land-surface subsidence induced by ground water abstraction (Table 7). In some of these examples, the ground surface has fallen by as much as 8m. Other cases deal with more localised ground water control measures, usually associated with dewatering during construction of a tunnel or deep excavation such as an underground car park or metro station.

Lesser and Cortes (1998) report on land surface settlement in Mexico City, where the ground surface level reduced by 8m between 1900 and 2000. The ground conditions of the plain of Mexico City are very compressible clays that are ancient lake sediments. The ground surface fell at a rate of 25 cm/yr during the period 1936-1956 when ground water abstraction was increased to 3.5 m^3/s. The rate of subsidence reduced to below 10 cm/yr when abstraction was reduced.

Pacheco, et al. (2006) report on land subsidence in Central Mexico. In several cities in the region, ground failures have produced severe damage to civil infrastructure, that range from fissured roads to houses and building losses. In one city alone (Aguascalientes), more than 2500 houses are reported to be damaged through ground subsidence (Zermeño (2005)). Critical values of water table drawdown were between 4 and 6.6 m/year and common drawdowns are around 3 m/year. The cumulated level of subsidence is unknown, but levelling suggests more than 0.6 m/year of subsidence. The authors attribute areas of damage to differences in the hydrologic basement rocks and attempt to correlate this with gravity surveys. They do note the presence of swelling clays but do not consider the consequences of these in the discussion.

Loupasakis and Rozos (2009) report on land subsidence induced by water pumping in Kalochori village, Greece. Intense water abstraction over 25 years caused a 37m drop in the water table resulting in surface subsidence of up to 3-4m. This extreme land subsidence caused a marine invasion, approaching close to the village and requiring embankments to be built to protect the village. The ground conditions comprise 150-400m of marine and lacustrine sediments.

Phien-wej*, et al.* (2006) discusses land subsidence induced by deep well pumping that has been affecting Bangkok, Thailand for the past 35 years. Piezometric levels of the main aquifers have lowered as much as 70 m. Parts of the city have been subsiding at the rate of 30 to 120 mm/year and some areas still continue to subside at 20 mm/year. Long-term differential settlement of buildings is a significant issue for Bangkok.

Feng, et al. (2008) report on land-surface subsidence caused by long-term excessive extraction of groundwater in the residential areas of Datun coal mining district in East China. Datun area is located in the delta of the abandoned Yellow River where alluvial and Quaternary flood deposits include clay, sand-clay, silt-clay, sand and gravel. The thickness of these sediments varies from 167-305 m with an average thickness of 185 m. Groundwater extraction caused a cone-shaped depression of the water table centred on the Datun area, where the fall has exceeded 40 m. The recorded maximum level of subsidence in the area since 1976 to 2006 was 863 mm. Over ten cases of building damage (cracking) due to ground subsidence were observed. The estimated building damage level in Datun has reached BDL III in some areas (See Table 4), as evidenced by cracks in buildings and underground utility infrastructures. Land subsidence has also increased the risk of surface water floods in the depressed area.

Walker and Indraratna (2009) also refer to subsidence of the Saga Plain on the Japanese island of Kyushu reported by Sakai (2001). Groundwater pumping in summer for agriculture, and winter recharge causes seasonal changes in groundwater levels. At 27.5m depth the water level changes were of the order of 3m and at 54m depth groundwater level changes of the order of 13m were observed. These changes resulted in subsidence of about 45mm.

Preene (2000) reviews ways to assess settlements induced by groundwater control. He notes that relatively few definitive case histories exist with data on groundwater control induced drawdowns, settlements and damage. He notes that differential settlements can be increased by variations in soil conditions or foundation types beneath buildings. Preene and Roberts (2002) review groundwater control methods for construction in the Lambeth Group in the UK where permeable water-bearing layers may cause problems during construction, resulting from groundwater inflows, instability or uplift and base heave due to unrelieved pore water pressures. However, the case studies reported do not provide data on building foundations.

Papadopoulos*, et al.* (2004) report on the effects on adjacent buildings of dewatering for the construction of a highway tunnel at 35m depth in Boston, USA. Settlements were measured and were within tolerable values for the structures (See Table 7). The authors note that although consolidation settlements can be significant (due to their magnitude and permanence), elastic settlements can also be an important contributor to total settlement.

Roy and Robinson (2009) report on a case study of construction of a 16m deep underground car park in soft soil conditions in Vancouver, Canada. The structure intersected an aquifer in bedrock under artesian pressure. Permanent dewatering was needed for the underground structure and this resulted in settlements as large as 360 mm occurring within 5.75 years of construction.

Walker and Indraratna (2009) discuss a series of test embankments constructed to assess the behaviour of thick compressible subsoil as part of the Second Bangkok International Airport (30 km east of Bangkok, Thailand) reported by Bergado*, et al.* (1998). The surface settlements were monitored at the middle of two embankments incorporating vacuum loading and vertical drains. Settlements of 0.4-0.8m were induced by vacuum loading of -60 kPa (equivalent to 6m reduction in ground water level).

Zhou*, et al.* (2010) look at metro station construction in the soft soils of Shanghai, China. They consider the implications of the dewatering when building a metro station in a deep excavation. The metro station considered is Hangzhong Road where the excavation depth is 15.59-17.52m and the amount of ground water lowering necessary is 10.28-13.82m. They used numerical modelling to predict settlements, based on different designs of dewatering scheme. The worst case prediction for ground surface settlement is 43mm.

Kerh*, et al.* (2003) discuss the likely impact of construction of the mass rapid transit system in Kaohsiung, Taiwan. One of the lines will pass under part of the city with a high density of population and buildings. The construction requires a temporary or long-term groundwater lowering to 17-20m below the ground surface. The line is situated in the recent alluvial sediments including mainly sandy silt and low compressibility clays. The theoretical predictions suggest that for a drawdown depth of 5 m, there are about 10-20 cm settlement. If the drawdown was 10 m, the settlements would be almost three times larger. However, for the anticipated drawdown depth of 20m, the average settlement was predicted to be 66 cm although settlements could reach up to 1 m in some regions. Regions with a higher initial ground water level or a thicker clay layer in the soil profile will result in the most severe settlements.

Zangerl, et al. (2008a) and Zangerl, et al. (2008b) consider consolidation settlements above the Gotthard highway tunnel in Central Switzerland. Normally subsidence would not be of concern in crystalline rock masses. However, settlements of 12cm were observed. This can be explained by fault closure and consolidation of intact rock blocks. These mechanisms are associated with water pressure reduction due to flow into the tunnel, even though there is no evidence of a lowering of the ground water table near the ground surface.

Xie*, et al.* (1996) discusses the implications of mining under thick water-bearing strata. Although they refer to an example of subsidence caused by water loss due to mining, no details are provided.

Özdemir (2008) describes the collapse of the Zümrüt Building in Konya, Turkey in 2004 which resulted in 92 fatalities. One hypothesis for the collapse was abstraction of groundwater but the investigation showed that groundwater levels had actually increased over the life of the building. The author argues that the collapse was due to unacceptable differential settlements. Similarly, Qian, *et al.* (2003) refer to a case study of the excavation of basement ("foundation pit") for the China Mansion in Wuhan, China. Although they suggest ground water level lowering can affect buildings, the damage to nearby buildings reported seems to have resulted from the excavation in soft soils.

The evidence suggests that significant consolidation settlements can be induced by groundwater lowering (Table 7). In soft compressible soils, very large settlements can be induced. Settlements of the order of metres can be induced by large drops in groundwater level (30+ meters). Even land subsidence of less than 1 metre can induce significant damage (Feng, et al. (2008)).

4.3.1 Piled Foundations

Much of the damage associated with groundwater lowering occurs in buildings on shallow foundations. It might be expected that foundation on deep pile foundations would not be affected. However, if soil settles relative to the pile, this can result in downdrag on the pile (known as "negative skin friction"). This additional load could potentially overstress the pile and lead to failure.

Lee and Chen (2003) investigated the effect of lowering of the ground water table on the negative skin friction on piles, using centrifuge modelling. Tests were carried out in a low plasticity clay/silt. They simulated the effect of 1m diameter pile in a 22.5m deep bed of clay subject to a 6m drop in ground water table. They found that the axial load in the pile increased during water table lowering. However, the axial load reduced rapidly when the water table started to rise and decreased to a value lower than before the water table was lowered.

Moormann (2003) and Moormann and Katzenbach (2003) report on the effects of groundwater lowering on piled raft foundations in layered Frankfurt clays. The case studies described are for two high-rise buildings of 240m and 110m height respectively. The effect of ground water lowering was not only on the settlements of building but also in the distribution of loads within the foundation. The loss of buoyancy forces caused a significant increase in pile forces by up to 60%, as load share was transferred to the piles.

Xiang, *et al.* (2008) discuss the effects on a pile-supported overpass in Beijing of dewatering and tunnelling associated with construction of a metro station. Settlement of the piled foundation approached 10mm (with differential movement of 4mm between adjacent piers) before underpinning was carried out. Maximum settlements were 20mm (with 9mm differential movement). However, it is not clear how much of the settlement was tunnelling-induced rather than the result of dewatering.

López Gayarre, et al. (2010) suggest that land subsidence and negative skin friction experienced by the piles as a result of artificially lowering the groundwater table were contributory factors to a foundation failure in Gijón (NW Spain). However, rotting of the head of the wooden piles was the major factor, as discussed in the next section.

4.3.2 Attack of Wooden Piles

A particular problem occurs with buildings founded on wooden piles when the groundwater level is lowered. Providing the timber is maintained in anaerobic conditions below the water table it will not be affected by rotting and bacteriological/fungal attack. However, if the water table is lowered, this exposes the upper part of the pile to aerobic conditions and decay can start to take place.

López Gayarre, et al. (2010) report on a case history of a foundation failure in Gijón (NW Spain) resulting from artificially lowering the groundwater table, which occurred during the construction of a nearby building. This led to rotting of the head of the wooden piles of the foundation causing major damage of the building. This study also considers the land subsidence and negative skin friction experienced by the piles as a result of artificially lowering the groundwater table were contributory factors.

Gordon*, et al.* (1999) discusses the impact that groundwater lowering for the construction of the Copenhagen Metro had on neighbouring buildings. They developed a risk assessment strategy to identify potential damage within the zone where the groundwater lowering was greater than 0.5m. In addition to settlement they identified bacteriological and fungal attack of wooden foundations as a potential source of damage. The paper does not report on any damage cases.

Kalm (2007) reports on cases of building damage due to ground water fluctuations in Tatu, Estonia. The records show a peak in the rate of building subsidence (at 4.8 mm/yr) in 1973 when water levels fell by 3.5m as a result of ground water abstraction. Damage to timber piles by *Cossonus parallelepipedus* worms and 14 different species of fungus was detected above the water table, although it was not possible to relate directly the damage of the timber piles to the subsidence of the buildings.

4.4 Karst

Karstic conditions exist in soluble rocks such as limestone and dolomite, where ground water flow causes dissolution of the rock leading to the formation of caverns. If the roof of the underground cavern collapses, this can lead to a sinkhole forming where the ground surface drops. If such features form below a building they can result in significant damage to the structure.

Providing the underground caverns remain full of water, this provides support to the walls and roofs of the cavern and prevents collapse. However, if the ground water is lowered, the water support can be removed potentially leading to collapse and formation of a sinkhole.

Feng and Luo (2007) examine the effects of ground water level change on inducing collapse in karst formations in Wuhan City, China. They describe the repetitive cycle of collapse – filling – washing - collapse of caves due to groundwater movement. They note that past karst collapses in Wuhan city have sometimes happened in high water season when the ground water level was high due to rainfall and high river levels (in the Yagtse River). However, other karst collapses have occurred in the low-water season when groundwater exploitation causes falling groundwater levels. From physical and numerical models they explained that high hydraulic gradients are the main factor in instigating karst collapse.

Gutierrez and Cooper (2002) discuss the effects of flooding problems on the historic city of Calatayud in NE Spain. Most of the old buildings in the city have been damaged by subsidence. Dissolution of the evaporite bedrock in the urban areas causes subsidence and triggers rock-falls from the gypsum cliffs overlooking the city. Subsidence is also caused by the hydrocollapse of gypsiferous silt in the alluvial fan deposits. However, the authors suggest that evaporite bedrock dissolution is the main process responsible for the subsidence.

Kim, et al. (2007) report on cracking of houses and buildings in a densely populated area of Muan-eup, a small city in Korea affected by ground subsidence and development of sinkholes. The number of ground subsidence reports has been greatly increasing since the 1990s, implying that the ground subsidence in this area is closely related to the amount of pumping of groundwater (which has increased) not just the presence of subsurface limestone cavities. It is suggested that clay filling the limestone cavities or dissolved zones may be pumped out during excessive pumping of groundwater. Numerical modelling suggested that when groundwater is excessively pumped, so that the groundwater level becomes significantly drawn down to 20m below ground level, an abrupt cave-in or sinkhole development could be instigated. Very large ground surface subsidence of 6-12m was predicted.

Wang (1998) reports on the effect of construction of the Dayaoshan Tunnel, in Nanling area of Guandong Province, China. The tunnel passes through Devonian limestone karst terrain. During construction, large volumes of water flowed into the tunnel lowering the groundwater levels in the region. This caused loss of support to solution cavities and fissures in the limestone that had been previously flooded, resulting in surface collapses. The surface area of collapse features reached 500 m^2 in 1987 with the largest collapse being 30m deep. Damage to houses and rice paddies occurred.

Lin (2000) describes ground subsidence in karstic areas of Guangzhou City, China resulting from over-exploitation of groundwater. On 18th April 2000 an area of 200m^2 subsided and the ground surface dropped by nearly 10m, during installation of piles for a residential area. No details of resulting damage are reported.

Ouyang*, et al.* (2006) provide a very general overview of ground water effects on causing subsidence. They refer to collapse of Beiming River Iron Mine in Hebei Province, China due to collapse pits (sink holes) which they attribute to ground water pumping changing the dynamics of the hydrogeology in calcareous rocks. Wang*, et al.* (2004) discuss the potential problems associated with karst collapse associated with the Laixin expressway in Shandong Province, China. Grouting and other stabilisation methods were used to prevent karst collapse.

Gonzalez-Nicieza*, et al.* (2008) report on a foundation failure in Oviedo (Spain) in gypsiferous ground. A major crack appeared in the buildings reaching some 10 cm in width. In all, 362 apartments were affected and declared in ruins, with the consequential social and economic impact of rehousing 300 families. The ground conditions comprised fill overlying a clayey Quaternary system composed of clays, muddy clays, marly clays and marls with abundant organic matter. The thickness of this Quaternary system varied between 8 and 12 m. This overlay karstic gypsum and calcarenite. The failure was blamed on the construction of a nearby underground car park provoked a depression of “several meters” in the ground water of the karstified gypsum aquifer. However, the authors’ conclusion is that the failure was due to consolidation settlement and not due to the water table depression.

Schenk and Peth (1997) report on damage to residential housing built over a 13th Century cellar system in Oppenhein, near Frankfurt, Germany. Water infiltration due to a broken water pipe resulting in a dramatic collapse due to cavern formation in the underlying limestones.

Sinkhole formation and ground surface subsidence due to dissolution of soluble rocks is a major cause of damage to buildings in karstic areas (Table 8). This is often associated with groundwater lowering changing the dynamics of the hydrogeology in calcareous rocks. However, there are examples where damage has resulted from additional flow under high water table conditions, as the greater flow causes more dissolution of the soluble rocks and erosion or removal of clay filling from the fissures.

4.5 Shrink/Swell in Active Clay Soils

Active clay soils (also referred to as "expansive clays") are clays that are particularly sensitive to soil moisture changes. As the water content of the clay increases during the wet season, the soil will swell causing surface heave. During the dry season, the clay will shrink producing downward settlement of the ground surface. This seasonal shrink/swell cycle can cause significant damage to buildings directly founded on the clay (Table 9). Crilly (2001) and Sanders and Phillipson (2003) note that shrinkage and swelling of clay soils is the single most common cause of foundation-related damage to low-rise buildings in the UK.

The wetting is usually induced by precipitation (rainfall) in the wet season and drying is induced by evaporation from the ground surface or abstraction of water by the roots of vegetation (grasses or trees) in the dry season. This may be accompanied by a rise/fall in the ground water table level. However, water content changes can be produced by surface infiltration of rainwater and evapo-transpiration, without necessarily significantly affecting the long-term groundwater level.

The important soil properties determining shrink/swell movements are: the depth of soil, the amount of swelling clays present and the soil's ability to take up water (Corti*, et al.* (2009)). These factors determine the amount of vertical soil movement that occurs as the soil alternates between wet and dry conditions, potentially harming buildings or other infrastructure.

Crilly (2001) reports on a database of clay subsidence/heave damage set up by the Building Research Establishment (BRE) to provide a collection of data on individual cases of damage due to the swelling or shrinkage of clay subsoils. As reported in 2001, the database included 484 records of individual cases of damage. Most cases of damage (68%) were attributed to clay shrinkage due to vegetation, while a further significant proportion (21%) was attributed to seasonal shrinkage and swelling, but in the absence of significant vegetation. The most common ground conditions where damage was recorded were in London Clay (nearly 30% of all records). Other ground conditions with relatively high numbers of cases of damage were on glacial till, Lias clay, Weald clay and clay-with-flints.

Crilly (2001) notes that around 76% of all of the cases of UK house damage from shrink/swell of clays recorded in the BRE database had levels of damage that fit into Category 2 (Typical crack widths up to 5 mm) or Category 3 (Typical crack widths are 5 to 15 mm) of BRE Digest 251 (Table 2). Few cases had damage levels associated with Category 1 damage (fine cracks), though there were a significant number (about 10%) with Category 4 (extensive) damage.

Droughts can induce important building damage due to shrinking soils (Corti*, et al.* (2009)). The amount of damage due to soil subsidence in France peaked in 2003, when the summer drought caused unprecedented damage. Simulations by Corti*, et al.* (2009) suggest that the damage due to shrink/swell in France in 1989-2002 doubled compared to the period 1961-1990. This is consistent with a strong shift in soil moisture conditions since the beginning of the 1990s, with much drier conditions than in the thirty preceding years. This is explained to be controlled by an increase in temperature and consequently additional evapotranspiration, rather than a change in precipitation as this had changed much less noticeably.

Sanders and Phillipson (2003) consider the impact of climate change on water contents in the UK and hence the effect on buildings. Their observations were based on the UK Climate Impacts Programme UKCIP02 scenarios (Hulme*, et al.* (2002)). The prediction suggests that the average soil moisture content in South East England will fall by between 20 and 40% by the 2080s, following a similar drying trend as has been observed in France (Corti*, et al.* (2009)).

There is evidence that the relationship between damage to buildings and the soil moisture deficit (a measure of how dry the soil is) is non-linear (Corti*, et al.* (2009)). This non-linearity explains the significant increase in damage to properties in France after 1989. Even though the changes in soil moisture conditions were moderate, once the soil moisture deficit fell below 200 mm damage started to occur. In the exceptional drought in 2003, the soil moisture deficit exceeded 200mm all over France and regions that were previously spared from soil subsidence were thus affected for the first time, resulting in the peak in damage costs recorded in that year.

Geremew*, et al.* (2009) also investigated the swell–shrink behaviour of clayey soils in France. The objective of the study was to investigate the swell–shrink behaviour responsible for damage observed on buildings in the Paris region. Their experimental data showed that when subject to repeated wetting and drying, the swelling rate of the soil became faster. They explained this by an increase in permeability of the soil due to the development of cracks on drying providing preferential flow paths. With an increasing number of cycles, a permanent increase in the volume of the samples was found. From studying the pore size distribution they observed that after five cycles, the soil original structure was totally lost and a disoriented homogeneous and a loose structure with more homogeneous pore spaces was observed.

Santos and Cuellar (2005) describe problems with shrinkage problems in clay soils and marls in Spain. They note that in severe droughts ("several" successive years), ground shrinkage may extend to depths in excess of 6m. This had resulted in cracking and induced settlement in building foundations. They report experiences in the 1970s in Southern Madrid where architects introduced air ventilation below the buildings to protect them from swelling problems. This change in construction methods resulted in detrimental settlements, particularly on southern façades of the buildings where longer exposure to sun led to greater desiccation and shrinkage. They suggest that soils that have a large difference between the plastic limit and the shrinkage limit are more likely to show significant cracking and will pose problematic behaviour due to drying.

Meisina*, et al.* (2006) discuss geological hazards in Oltrepo Pavese in Northern Italy. More than 1200 residential buildings have experienced damage with single storey family residences being mostly affected. The single storey buildings are founded on conventional concrete shallow strip footings founded 1-2 m below ground level. Volume change in clay soils account for 20% of the cases of damage. The expansive/shrinking soils are colluvial, alluvial soils and aeolian soils. Water content profiles were used to provide a qualitative estimate of the magnitude of seasonal movements of around 50–70 mm.

Kovacs*, et al.* (2003) report on ground surface measurements on clay soils in the Bükkábrány region of Hungary for the years 1973-2001 together with the monthly and annual precipitation values. In 1991 and 1999 the precipitation was significantly above average whereas 1992 was an arid year. They show that with a precipitation of over 600 mm there is generally a 4-10 mm rise in the surface level, while with annual precipitation values below 400-450 mm per year there is generally 5-10 mm subsidence. They also show seasonal variation of movement of a storehouse in Hungary. There was a rise in spring of 4-8mm and subsidence of 4-10mm at the end of the summer. The higher values were from the southern side of the storehouse, where there was a greater variation of soil water content.

Kovacs*, et al.* (2003) also report on data by other authors: Rétháti (1995) showed that during a 3-4 year period of substantial precipitation a 40-60 mm movement could be detected on an open surface and 100-120 mm in a covered area. Barados and Bozozuk (1957) reported a movement of over 60 mm during a 4 year period of substantial precipitation in Canada. Szorocsan (1974) reported 6-8 mm surface rise for a year of substantial precipitation, and altogether 20-30 mm surface subsidence for the subsequent two dry years. Burov*, et al.* (1966) reported a 15-30 mm rise in a foundation for a period of substantial precipitation in spring and early summer when compared to the expected seasonal variation within a year.

Zhang and Briaud (2010) report on a field site on expansive clays near Arlington, Texas. Two foundations 2m × 2m and 0.6m deep were constructed. Water content profiles were monitored to a depth of 3m over a period of 2 years. Minimum water contents were around 15% and maximum values were around 25%. Water levels varied between 4 and 4.8m below ground level during this period. The foundations showed a maximum 50mm heave in autumn and a settlement of 30mm in the summer. The maximum movement from summer to winter for any one foundation was 40mm.

Sanders and Phillipson (2003) note that most cases of subsidence and heave on clay soils are associated with trees because the effect of their root systems can extend further and deeper than other vegetation. They note that predictions of subsidence due to climate change may be complicated by second-order effects such as some species of tree dying back, reducing their water uptake. However, the death of trees can also cause damage to buildings through the consequent wetting up of moisture sensitive soils.

Misra and Sands (1993) also examined the role of vegetation by monitored water content profiles near to trees in Melbourne, Australia. The trees were English Elm (*Ulmus*) and Prickly paperbark (*Melaleuca*) growing in a sandy loam/ loamy sand. It was observed that seasonal variation in water content and density was restricted to the upper 0.5m, but this could have been affected by changes in texture at this depth. They note that building damage due to vegetation may be greater in moderately expansive soils than highly expansive clay soils. This is because moderately expansive soils allow easier establishment of vegetation and better rooting.

Navarro*, et al.* (2009) investigates the effects of trees on soil moisture changes and hence foundation movements. They report a case study of 25 low-rise buildings in Alcazar de San Juan (Central Spain). Sixty-seven chinaberry trees (*Melia Azedarach*) were planted close to the properties and after the summer of 2003, which was especially hot and dry, the residents began to notice cracks opening in their homes. Cracks were concentrated in the first bay near the building façades. The cracks of the load-bearing walls between buildings were diagonal, from the floor to the façade. The crack opening advanced more rapidly in summer which would be consistent with shrinkage induced by the trees causing the damage.

Sikh (1994) discusses the impacts of domestic irrigation on buildings in Southern California built on expansive clay soils. It is noted that the typical amount of irrigation is equivalent to an annual rainfall of 178cm, compared to a natural annual rainfall of 28 cm in San Diego. This produces a progressive wetting of the soils leading to swelling. The depth of water content change was 2.0 to 3.5m based on observations at six sites.

Tang, et al. (2009) report on heave observed on the railway roadbed of the French high-speed train (TGV) at Chabrillan in southern France. One of the mechanisms for damage was swelling of the marls beneath the railway roadbed. Heave of over 80mm was observed in the railway roadbed during a 6-year period from 2001 to 2007. However, the majority of this swelling could be attributed to unloading due to a deep excavation (9-34m deep) at the site. The movement due to climate effects were thought to be only ±3 mm.

Tang, et al. (2009) note that structural and pavement damage due to expansive clays have been observed in numerous countries such as Saudi Arabia (Abduljauwad*, et al.* (1998); Al-Mhaidib (1999); Al-Shamrani and Dhowian (2003)), Australia (Fityus*, et al.* (2004)), Poland (Kaczynski and Grabowska-

Olszewska (1997)), Turkey (Erguler and Ulusay (2003)), Oman (Al-Rawas and Qamaruddin (1998)), China (Shi*, et al.* (2002)).

Seasonal shrinkage and swelling is the most common cause of foundation-related damage to low-rise buildings in the UK. It will be a major factor of concern if climate change produces drier summers and wetter winters, as predicted for the UK (Murphy (2009)), since greater extremes of wetting and drying will induce greater cycles of swelling and shrinkage. The evidence suggests that shrinkage during periods of drought causes the greatest degree of damage. There is evidence from France that soil conditions are becoming progressively drier (Corti*, et al.* (2009)) and this is consistent with a long-term drying trend predicted for the UK (Sanders and Phillipson (2003)).

Vegetation, particularly larger trees, has a significant effect of removing water from the soil and inducing shrinkage. Building damage due to vegetation may be greater in moderately expansive soils than in highly expansive clay soils as moderately expansive soils allow easier establishment of vegetation and better rooting (Misra and Sands (1993)). The effect of climate change may be further complicated by second-order effects such as some species of tree dying back, reducing their water uptake (Sanders and Phillipson (2003)). However, the death of trees can also cause damage to buildings through the consequent wetting up of moisture sensitive soils.

4.6 Peat

Peat poses particular geotechnical problems due to its high compressibility. It is made from decaying vegetation and can be very fibrous with a very open, compressible structure. Due it its high compressibility, any changes in stress resulting from groundwater level changes are likely to result in large surface settlement or heave.

Varosio (2000) describes a case study of an annual cycle of lowering of groundwater level by 6m in a soil profile containing compressible peat and the resulting settlement and heave produced in an industrial building (Table 10). The expectation is that that settlements will occur during groundwater lowering and heave during recovery. However, Varosio (2000) notes that in complex hydrological conditions, with confined aquifers, transient states can result in wetting of a layer above the peat (before the peat itself starts to wet) thus inducing settlement, as the total stresses on the peat increase during this transient phase.

Kalm (2007) reports on cases of building damage due to ground water fluctuations in Tatu, Estonia. The ground conditions are Holocene alluvial and bog deposits (with up to 6m of peat) overlying late glacial varved soils. The records show a peak in the rate of building subsidence (at 4.8 mm/yr) in 1973 when water levels fell by 3.5m as a result of ground water abstraction. When groundwater abstraction was reduced from 1974-1994, water levels recovered, and the rate of building subsidence reduced to 1.5-2 mm/yr.

4.7 Types of failures and repair costs

Crilly (2001) reports that brickwork buildings are the structures most affected by shrinkage and swelling of clay soils, as recorded in the Building Research Establishment (BRE) database of clay subsidence/heave damage in the UK. Properties built prior to 1900 appear less susceptible to damage (perhaps built with more flexible lime mortars) and there appears to be a downward trend in susceptibility to damage with age for properties built in the 20th century. The suggestion is that the reduction in susceptibility to damage in the 20th century is due to improved foundation construction. The perception of damage typically took place about 50 years after construction, while only about 7% of cases occurred in the first ten years after construction.

Marshall (1999) reports that claims to Home Warranty programmes in Canada from foundation failures in new residential construction were \$2,134,000 per year. 36% of the failures were due to swelling clays. Marshall (1999) suggests that appropriate foundation design could eliminate 70% of these failures. The damage induced by foundation problems resulted in horizontal and vertical cracks, bowed walls, damaged doors and in-operable windows.

Lin and Scott (2005) look at seven types of building failure in Australia including foundation failure. Based on nine case histories they report the probability of failure due to settlement to be 16.7%. The repair cost to building value was 2-46% (average 24%) for settlement failure. Meisina*, et al.* (2006) suggest that for Northern Italy, economic losses due to volume changes of clay soils have been estimated at around 20% of the building costs.

Gimenes and Lemos (2005) report on structural damage induced by rising water tables due to reservoir filling operations. They discuss the impact on a densely populated town with a population of about 20,000 in mid-eastern Brazil adjacent to a reservoir to be filled. They attempt to correlate the likely damage caused with cost of repair using a relationship between angular distortion and repair costs. They suggested that average repair costs would be 2.4-5.0% of initial construction costs.

4.8 Economic Losses

To be able to assess the future implications of damage to structures due to environmental change it is important to understand the economic cost of damage to buildings due the mechanisms of groundwater level change, shrink/swell etc.

Mills (2003) reports that subsidence losses from two droughts in the 1990s resulted in losses of US\$2.5 billion (£1.6 billion, 2 billion €) in France and even more in the UK (Figure 1) (Vellinga*, et al.* (2001)). Sanders and Phillipson (2003) quote a value for insurance claims for subsidence and heave damage to private domestic properties of about £400 million per annum in the UK based on the data for insurance claims as used by Vellinga*, et al.* (2001) .

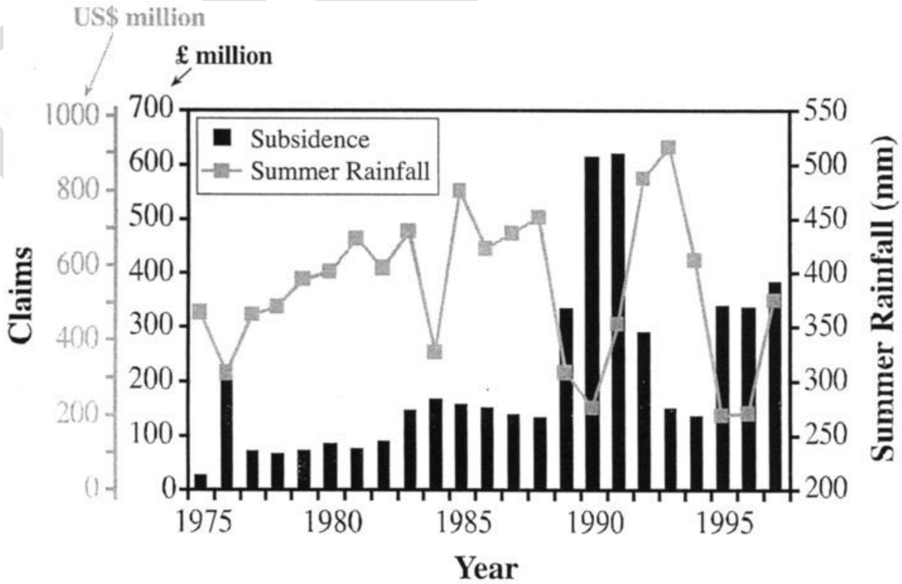

Figure 1 Correlation between soil subsidence and periods of drought. Summer rainfall and subsidence claims in the UK 1975-1997 (Vellinga*, et al.* (2001))

Corti*, et al.* (2009) note that droughts can induce important building damages due to shrinking and swelling of soils, leading to costs as large as for floods in some regions of France. Geremew*, et al.* (2009) reports that in France, the damage caused by shrink-swell in clay soils was estimated to be more than 3.3 billion € (£2.7 billion) in 2002. However, Corti*, et al.* (2009) suggests the amount of damage due to soil subsidence peaked in 2003, when the summer drought caused unprecedented damage of over 1 billion € (£0.8 billion) (CCR (2007)). They note a significant upturn in damage from drought-induced soil-subsidence damage in France from 0.25 billion € (£0.2 billion) for the period 1989-2002 to 1.06 billion € (£0.9 billion) in one year in 2003. Simulations by Corti*, et al.* (2009) suggest that the damage in 1989-2002 had doubled compared to the period 1961-1990.

Hu*, et al.* (2004) report on the economic losses due to land subsidence in China. In Tianjin, the total economic loss was RMB 189.6 billion (£19 billion) from 1959 to 1993. The direct loss was RMB 17.2 billion (£2 billion) and the related loss was RMB 172.4 billion (£17 billion). In the three cities of Suzhou, Wuxi and Changzhou, the total economic loss is about RMB 3.3 billion per year (£0.3 billion). The direct economic loss is about RMB 300 million (£3 million) per year and the related economic loss is RMB 30 billion per year (£3 billion). Feng*, et al.* (2008) identify that land subsidence in Shanghai has caused economic losses worth more than 100 billion RMB (£10 billion) (China Daily, Feb. 14, 2007) and is estimated to be about 24.57 billion RMB (£2.5 billion) for the first decade of the 21st century.

Marshall (1999) reports that claims to Home Warranty programmes in Canada from foundation failures in new residential construction were $2.13 million (£1.34 million) per year. Mejia-Navarro*, et al.* (1994) reports that debris flows have caused millions of dollars of damage to public and private structures in Glenwood Springs, Colorado, USA during years when extremely heavy rainstorms occur.

The costs of damage due to shrink/swell movements on clay soils have resulted in economic losses of over £1.6 billion in the UK during drought years in the 1990s. Similar figures are evident from France where losses have been as high as 3.3 billion € (£2.7 billion) in a single year. In China, losses due to land subsidence in Shanghai are estimated to be about £10 billion over a decade with £0.3 billion a year in losses in three other cities.

4.9 Adaption to Climate Change

Hertin*, et al.* (2003), Mills (2003), Sanders and Phillipson (2003) and Steemers (2003) have all given thought to the impacts of climate change on the UK built environment and what might be needed for adaption.

Hertin*, et al.* (2003) explore how climate change could affect the UK house-building sector as revealed through in-depth interviews in five house-building companies in the UK. They note that it was perceived that gradual change such as drier summers, wetter winters, more wind and coastal erosion had greater potential to create impacts rather than extreme events (storms, droughts, river flooding, tidal flooding). The impacts related to foundations were thought to be: ground instability due to more variable ground water levels and higher maintenance cost/devaluation of managed buildings due to subsidence. The suggestion was that reduced ground stability through more variable water tables and greater disruption caused by heave could be addressed through higher specification of foundations as well as by new construction methods, but no details of these suggested changes are provided.

Mills (2003) notes that weather-related disaster losses from natural disasters have increased dramatically since 1950. More intense precipitation events and increased summer drying and associated risk of drought could have an impact on property, although higher [increasing] minimum temperatures and fewer cold days could reduce problems associated with frost heave. Damage to buildings and pipelines due to soil subsidence is an important but often overlooked class of event.

Sanders and Phillipson (2003) suggest that to adapt to climate change, foundations for new domestic buildings will need to be deeper than is currently the case or redesigned with increased stiffness in order to avoid damaging foundation movements. They recommend new foundation technologies such as prefabricated strip or pile-and-beam foundations could be employed for domestic buildings. However, they also argue that an increase in the number of properties suffering damage could result in changes in the perception of the severity of damage and that householders may become willing to accept minor levels of damage.

Steemers (2003) refers to Graves and Phillipson's report (Graves and Phillipson (2000), Graves and Phillipson (2001)) that addresses ways to adapt to climate change. It recommends that design teams should increase foundation depths in clay by 0.5m. Steemers (2003) notes that in the context of climate change – typically spanning a century – new buildings will have an increasingly important role as older buildings are replaced. Within the next 50 years one might expect half the existing buildings to have been replaced (assuming a replacement rate of 1.0–1.5% annually). Thus, in the timeframe of climate change predictions new buildings will accumulatively account for an equal or greater fraction of the building stock and should be designed to enable adaptation to climate change. He does observe that over their lifetime, buildings will undergo shorter refurbishment cycles, when adaptive improvements can be implemented. However, it is unlikely that changes to foundations could be implemented in this way, so this will need to be implemented at the build stage.

Camillieri*, et al.* (2001) discuss the impacts of climate change on building performance in New Zealand. They note that, while argument still persists about whether or not recent changes in climate can be attributed to anthropogenic greenhouse gas emissions, this does not alter the fact that the climate has changed significantly over the last century, and the best predictions available suggest that more changes are on the way. They suggest that risks of future climate change to buildings should be managed and this means that building codes and practices around the world will need to change to suit new climate conditions. However, they note that changing codes and practices requires a good foundation of evidence and research. This is difficult to establish given the uncertainty of current climate change scenarios and their long timescale.

Camillieri*, et al.* (2001) note that a major difficulty is that buildings built now will still be in use in 50-100 years time. This produces a need for early action in the construction sector. They suggest that the construction industry and the public should be shown how adaptation can produce immediate and short term benefits in both performance and costs. They recommend that the 'barely legal' requirements defined by building codes and standards should be replaced by 'best practice' as climate change impacts would be reduced by higher quality construction practices.

Larsson (2003) consider the need to adapt to climate change in Canada. They postulate that more frequent and extreme droughts may lead to increased foundation problems in areas of clay soils. They also note that winter snow loads may change, requiring changes to building codes.

Shimoda (2003) discusses the impact of climate change on the urban heat island in Japan. It is noted that the effect of the urban heat island in winter lowers the relative humidity. The average relative humidity in Tokyo in January is 50%, which is the lowest figure in Japan's large cities. However, this is no discussion of the implications of this for foundations.

du Plessis*, et al.* (2003) reviews the impact of climate change on the built environment in South Africa. However, there is no discussion of the implications for building foundations. Twomlow*, et al.* (2008) discusses building adaptive capacity to cope with future climate change in Southern Africa. However, the paper focuses on impacts on agricultural land and there is no discussion of effects on civil engineering structures.

4.10 Other reviewed publications

A number of publications were identified by the search that did not directly relate to the topic under consideration.

A number of papers related to damage due to ground freezing. Salnikov (2000) discusses deep seasonal freezing and thawing of ground below foundations in Southern Tansbaikalie, Russia. The depth of freeze/thaw is 2.5-3.5m. Heave movements reach 80mm near the surface. It is noted that differential movements of foundations due to thawing are greater than those due to heave when freezing. Tart (2000) discusses damage to roads in Alaska due to freezing conditions. While freezing causes changes in the groundwater regime, drawing up water to the freezing zone, the damage discussed is due to ice lens formation rather than groundwater changes *per se*. Yang*, et al.* (2006) discusses frost heave associated with artificial ground freezing. Zhang*, et al.* (2006) discuss damage to the Qinghai–Tibetan railway resulting from permafrost.

Other papers addressed general issues relating to foundations, including liquefaction failures due to earthquakes. Valeev and Bogdanov (1976) argued that piled foundations were being adopted uneconomically in Russia and other solutions should be considered. There is no discussion of the role of changes in ground water regime. White and Hoevelkamp (2004) describe a case study of a box culvert construction to eliminate replacement of a deteriorating bridge. Large settlements occurred, but these were not due to groundwater level changes. Sancio, et al. (2002) report on foundation failures in Adapazari, Turkey during the 1999 Kocaeli earthquake. They note that shallow soils that liquefied had Liquid Limit LL<35% and water content w_n> 0.9LL i.e. high liquidity indexes. Uzuoka*, et al.* (2008) discusses liquefaction-induced failures of piled foundations. The failures discussed are due to earthquake shaking rather than changes in ground water conditions.

Other papers relate to groundwater flow, but are not relevant to the issue of building failures. Semprich and Scheid (2001) discusses the effect of air injection into soils below the groundwater level associated with tunnelling. Although this can cause damage to buildings, the mechanism is not relevant to this study. Shaqour and Hasan (2008) report on a case study of groundwater lowering for the construction of a pumping station in Jahra, near Kuwait City. The problems associated with the study were in the estimation of the hydraulic permeability, which resulted in an inappropriate dewatering technique being adopted.

Saunders and Fookes (1970) review the relationship between rock weathering and climate. Although they note the effect of groundwater, there is no discussion of foundation problems or building damage. Suzuki*, et al.* (2007) report on changes to soil structure in agricultural soils in North-east Thailand. There is no discussion of civil engineering structures. Preene and Powrie (2009) discuss ground energy systems that use the ground and groundwater beneath a building as a heat source or sink. However, the “failures” they discuss relate to failure of the ground energy system, not the foundation.

5 Conclusions

Damage to building foundations can be brought about by a rise or fall in the groundwater table or through seasonal wetting/drying processes. The expectation is that that settlement (downward movement of the ground surface) will occur during groundwater lowering and heave (upward movement of the ground surface) during groundwater rise. However, no cases of damage due to heave resulting from groundwater level rise *per se* were found in the literature reviewed.

There are a significant number of cases of damage due to collapse settlements due to inundation during ground water level rise. Collapse settlements in fill materials due to rising ground water levels are of major concern in the UK. Rises in groundwater level, can also cause reductions in strength of the soil that can lead to failures of slopes or retaining walls. In regions of significant slope instability, significant damage to buildings can occur as a result of landslides.

Lowering of the groundwater table can cause the soil to consolidate, which induces settlement. With softer, more compressible soils, settlements can become large. Many of the cases of damage reported are due to large scale land-surface subsidence induced by ground water abstraction. In some of these examples, the ground surface has fallen by as much as 8m. Other cases deal with more localised ground water control measures, usually associated with dewatering during construction of a tunnel or deep excavation such as an underground car park or metro station. The evidence suggests that significant consolidation settlements can be induced by groundwater lowering that can lead to building damage.

Much of the damage reported that is associated with groundwater lowering occurs in buildings on shallow foundations. However, deep foundations on piles can also be affected. However, if soil settles relative to the pile, this can result in downdrag on the pile (known as “negative skin friction”). This additional load could potentially overstress the pile and lead to failure. A further particular problem occurs with wooden piles. If the water table is lowered, this exposes the upper part of the pile to aerobic conditions and rotting and decay can start to take place.

Sinkhole formation and ground surface subsidence due to dissolution of soluble rocks is a major cause of damage to buildings in karstic areas. This is often associated with groundwater lowering changing the dynamics of the hydrogeology in calcareous rocks. However, there are examples where damage has resulted from additional flow under high water table conditions, as the greater flow causes more dissolution of the soluble rocks and erosion or removal of clay filling from the fissures.

Shrinkage and swelling of clay soils is the single most common cause of foundation-related damage to low-rise buildings in the UK. Seasonal shrinkage and swelling will be a major factor of concern if climate change produces drier summers and wetter winters, as predicted for the UK, since greater extremes of wetting and drying will induce greater cycles of swelling and shrinkage. The evidence suggests that shrinkage during periods of drought causes the greatest degree of damage. There is evidence from France that soil conditions are becoming progressively drier and this is consistent with a long-term drying trend predicted for the UK.

Potential problems to foundations as a result of environmental change can be addressed through higher specification of foundations, including greater depths for foundations, as well as by new construction methods. Many of the buildings built now will still be in use in 50-100 years time. This produces a need for early action in the construction sector to address these issues.

6 Potential Conflicts of Interest and Sources of Support

Funding for the study was obtained from the Natural Environment Research Council under the *Living with Environmental Change* initiative. There are no conflicts of interest for the review team.

Table 5. Cases associated with Collapse Settlement

Structure	Location	Soil type	Exposure	Damage	Source
A block of eight two-storey houses	Ilkeston, UK	12m thickness of stiff clay opencast backfill	Heavy rain	A total settlement of 0.3m. The block was never occupied and had to be demolished	Charles and Watts (1996)
Single storey factory	West Aukland, UK	18 m deep opencast mining backfill composed of clay with shale fragments	A 2-3 m rise in groundwater table due to cessation of pumping when local mines were closed	Serious differential settlement with a maximum settlement of 0.21 m. This was due to 4.7% vertical compression of the newly saturated fill	Charles and Watts (1996)
Industrial estate	Brighton, UK	6 m deep chalk fill in the form of a loose rubble with high air voids	Combined effect of new loading from sand and gravel fill and subsequent wetting from soakaways, just after the buildings had been roofed, following periods of heavy rain	Settlement of 110 mm was observed causing damage and delay to construction	Charles and Watts (1996)
A low rise hospital development	North Tyneside, UK	20 m deep clay and shale fill that had been placed without systematic compaction	Wetting up of the fill	The buildings suffered significant settlements of up to 160 mm, requiring some remedial work	Charles and Watts (1996)
A stone tower built in the thirteenth century	York, UK	15 m high mound made up of horizontal layers of a fill comprising stones, gravel and clay	Severe floods in 1315-6	The tower was 'cracked from top to bottom in two places'. The tower was underpinned in 1903	Charles and Watts (1996)
Test pit	Building Research Establishment, UK	A granular colliery spoil from Bentinck Colliery in the North Nottinghamshire coalfield	Base of fill submerged by 1m followed by surface inundation. Water content rose from 8.8% to 11%	7% compression on basal wetting followed by similar amount on surface inundation	Charles and Watts (1996)
Test pit	Building Research Establishment, UK	Glacial till (boulder clay). A matrix dominated till with numerous angular flints and soft chalk clasts	Water level rise of 1 m followed by surface inundation to wet the upper 1 m of partially saturated fill	12% collapse settlement during water table rise with further collapse settlement on surface inundation	Charles and Watts (1996)

Houses	Southern California, USA	Sandy clay fills up to 30 m deep were placed to a specification which required 90% of modified Proctor dry density at moisture contents close to optimum	Irrigation produced a change from a natural annual precipitation of 200 mm to an equivalent annual rainfall of 1800 mm	In areas where the fill was shallow, heave was observed. Five years after construction, some structures built on deeper fill began to suffer distress due to settlement. Ten years after construction some areas had settled as much as 0.45 m.	Charles and Watts (1996)
Mine building	Alberta, Canada	12-15m of reclaimed mine waste	Unanticipated groundwater rise. The amount of settlement was estimated to approach 5% of the wetted thickness	Settlements varying between zero and 270mm about 15 years after construction. However, the building showed no signs of damage since the angular distortion was equivalent to 1/300, although there were hairline cracks in the floor slabs	Peterson and Wade (1997)
3 story Hospital Building	Romania	Dry loess	The change of its use (from school to hospital) needed an extensive water supply system that gave way to wetting of the ground	Structure existing for more than 25 years without serious difficulties. Large uneven settlements seriously damaged the structure. The rate of settlements varied between 2-7 cm/year.	Bally (1988)
11 storey dwelling, including two independent and similar structures with plan dimensions of 16 x 22 m	Romania	Loess	Deep wetting	2-3 years after construction, uneven settlements were recorded. Measurements during a period of 12 years (1973-1985) showed a maximum of 30 cm.	Bally (1988)

-	Farhad, U.S.S.R	Loess	Wetting	Settlements continued for 30 years after construction. Attributed to the slow yielding of the structural resistance of the wetted loess and consequently to its slow compaction	Bally (1988)
Buildings of Electro-chemical plant (mean foundation pressure 120-150 kPa).	Iavansk, U.S.S.R	Soft wetted loess (with gravel cushions 0.7-2 m thick) Water level 1.5-6 m below ground surface	Wetting	The maximum settlement was 25 cm and the differential settlement up to 12 cm. Where thin gravel cushions were used, the rate of settlement reached 2.5-3 mm/month 1.5-2.5 years after construction. However, the structures were not damaged by the large and uneven settlements	Galitsky, *et al.* (1983) (in Bally (1988))
The receiving basin from a pumping station at the starting canal of a new irrigation system	Romania	Foundation pits were excavated through the upper, intensely collapsible horizon of a loessial formation until a silty-clay non-collapsible layer was inserted in the loess deposit	The foundation soil was wetted	The settlement of the structure reached 48-101 cm. This was not due to collapse settlement of the ground. The settlement resulted from the thrust of the foundation pits in loess soil that was weakened by wetting	Bally, *et al.* (1973) (in Bally (1988))
Canal	Romania	Loess	Flooding (canal filling)	Maximum settlements of 55-95 cm	Bally (1988)
Five storey block in a residential district	Romania	Thick and intensely collapsible loess	The ground water level was rising in the lower part of the loess deposit. The water level rose by 4 m (with a sloping surface along the building)	A five year survey of the settlement showed a maximum of 18 cm and a 3.5% increment of tilting. Nevertheless the low rate of displacements prevented the building from damage	Bally (1988)

A structure on shallow foundation beams, 60 cm wide, with mean pressures above 250 kPa	Romania	30m thickness of loess with the upper 6m having been compacted (poor compaction only achieved densities of 1.50-1.55 Mg/m^3). The water table was initially very deep.	Water injection caused wetting to 8m below foundation level. The injection caused an increase of the soil moisture content from 14 to 25%. 90 days after injection ended the moisture content had already returned to 18%.	Settlement developed slowly, associated with the slow diffusion of the injected water. The mean settlement increment was 15 cm; 3 cm took place in the (poorly) compacted loess and the other 12 cm in the 2 m uncompacted and still not submerged underlying natural loess	Bally and Ottulescu (1980) (in Bally (1988))
An area of 43 ha for a water treatment station	Romania	Thick collapsible loessial deposit	The site was flooded to allow settlements to take place before construction	Non-uniform ground surface deformations with a maximum of 2m were recorded during flooding. After flooding, during self drainage, an increment of settlement of 20-30 cm took place. The deformation continued for 5 years after flooding although the supplementary settlement was less than 25cm	Beleş, *et al.* (1969) (in Bally (1988)).

A four-story industrial building with a five-story annex to one side and a basement to the other side, built in 1952	Pridneprovsk Chemical Plant in Dneprodzerzhinsk, Ukraine	Loess clayey loam (thickness varies from 27.5 m to 34 m) overlying clay and sandy loam. The initial water table was at the top of the sandy loam layer at 32.5-35m depth.	Since construction the ground water level had risen by 13.5-17 m so that it varied from 11.5 m (above the clay) and 30 m (above the sandy loam)	The building suffered significant non-uniform settlements which totalled 157 to 538 mm. These began during construction in 1951 and continued over a period of more than 40 years before stabilising by 1994. Despite significant deformations (bending and deflection of the columns and beams), there was no significant impact on the integrity of the structure and virtually no cracks were observed	Kushner (2008)
Residential buildings	Pereira Barreto, São Paulo, Brazil	A top layer of laterized colluvium, which is very loose clayey fine sand, with thickness varying between 5 and 10 m. This overlies residual sandstone soil, clayey fine sand, ranging from very loose to medium dense	Groundwater levels rose by 20m from 1987-1994 due to construction of Três Irmãos dam and canal	Settlements of up to 100mm occurred when ground water levels rose to within the collapsible soil layer. This resulted in 300 buildings needing to be refurbished and many homes had to be demolished	Vilar and Rodrigues (2011), Filho (2002) (in Gimenes and Lemos (2005))

Table 6. Cases associated with Slope Instability

Structure	Location	Soil type	Exposure	Damage	Source
Single storey family residences founded on conventional concrete shallow strip footings founded 1-2 m below ground level	Oltrepo Pavese in Northern Italy			More than 1200 residential buildings have experienced damage and landslides account for 46% of this damage	Meisina, *et al.* (2006)
Deer Creek Bridge	Saskatchewan, Canada	Cretaceous Clay shales	Active landslide caused by an upward groundwater gradient	Closure of expansion joints due to landslide movements, recorded by inclinometers to be of 13-80 mm.	Kelly, *et al.* (1995)

Table 7. Cases associated with Groundwater Lowering

Structure	Location	Soil type	Exposure	Damage	Source
Chulalongkorn site	Bangkok, Thailand	Soft Bangkok clay to 13m, with 3m crust, overlying stiff clay 13-20m depth	A 20m drawdown of ground water taking place between 1960 and 1990	200mm settlement recorded 0-27.1m with 5mm taking place in the upper 1-10m	Phienwej, *et al.* (2004) (in Phien-wej, *et al.* (2006)
Houses and roads	Querétaro Valley, Central Mexico	The reported ground conditions are "granular material of lacustrine and alluvial origin". The presence of clays is noted (with thicknesses of up to 15m) but the consequences are not considered in the discussion. Underlying this are tuffs and sequences of andesitic lavas	Land subsidence caused by ground water lowering. Critical values of water table drawdown are between 4 and 6.6 m/year and common drawdowns are around 3 m/year. Maximum drops in water levels between 1970 and 2002 are about 160 m in the central part of the valley	The cumulated level of subsidence is unknown, but levelling suggests more than 0.6 m/year of subsidence. More than 2500 houses are reported to be damaged in the town of Aguascalientes alone.	Zermeño (2005), Pacheco, et al. (2006)
Residential buildings (over 10 cases)	Datun coal mining district, East China	Alluvial and Quaternary flood deposits include clay, sand-clay, silt-clay, sand and gravel in the delta of the abandoned Yellow River. The thickness of these sediments varies from 167-305 m with an average thickness of 185 m.	Long-term excessive extraction of groundwater caused a cone-shaped depression of the water table centred on the Datun area, where the fall has exceeded 40 m.	The recorded maximum level of subsidence in the area since 1976 to 2006 was 863 mm. Over ten cases of building damage (cracking) due to ground subsidence were observed.	Feng, et al. (2008)
11 storey reinforced concrete building founded on 42 belled caissons to 10-11m depth	Boston, USA	Hard blue clay. The clay is 18m thick overlying glacial till and shale bedrock	Ground water lowering due to excavation of nearby highway tunnel was 6.5-7m	Maximum settlements were 25-32mm. This was within tolerable limits and no damage was incurred	Papadopoulos, *et al.* (2004)

46 storey steel framed commercial office tower with 2-level basement car park. Founded on 1.8-2.4m thick reinforced concrete raft at 10m depth	Boston, USA	Glacial deposits. 15m of cohesive till overlying 10m of granular till over shale bedrock	Ground water lowering due to excavation of nearby highway tunnel was 18-19m	Maximum settlements were 7-9mm. This was within tolerable limits and no damage was incurred	Papadopoulos, *et al.* (2004)
Railway station founded on wooden piles to 14m depth	Boston, USA	Glacial deposits	Ground water lowering due to excavation of nearby highway tunnel was 7-16.5m	Maximum settlements were 17-25mm. This was within tolerable limits and no damage was incurred	Papadopoulos, *et al.* (2004)
Five-storey 16m deep underground car park constructed as a reinforced concrete frame	Vancouver, Canada	8m of soft soils (soft and compressible peat and clayey silt or silty clay) overlying 8m of sandstone and siltstone bedrock	An under floor drainage system was installed with a pumped sump for continuous removal of collected water. The sump continued to be dewatered after construction. The structure intersects an aquifer in bedrock under artesian pressure.	Settlements of up to 300mm were observed 3 years after construction, increasing to over 350mm after 5.75 years. This lead to severe operational problems for the commercial properties around the underground structure	Roy and Robinson (2009)
Zeuzier arch dam	Western Switzerland	Fractured marly-limestone	Driving of an investigation adit 1.5km away from the dam through a confined aquifer caused groundwater lowering	13 cm of vertical settlement was observed at the dam site. Cracks in the dam required the impounded reservoir to be emptied whilst the dam was repaired over a period of several years	Lombardi (1992) (in Zangerl, *et al.* (2008b))

115m high rise building "Japan Center" on a piled raft foundation	Frankfurt, Germany	Quaternary sands and gravels down to 6-10m underlain by slightly overconsolidated Frankfurt Clay; a highly plastic, stiff clay intercalated with silty sand and limestone layers	Ground water was lowered by 21m at a nearby excavation causing the pore water pressure below the raft to drop from 103 to 52kPa.	The loss of buoyancy caused redistribution of load resulting in pile loads increasing by 27%	Moormann and Katzenbach (2003)
5-7 storey buildings	Gijón (NW Spain)	Fill material of clay, sand, gravel, pieces of debris, stones, bricks and some peat (0.6 and 1.8 m in thickness) overlying peat with thickness varying between 3.0 and 7.0 m.	Ground water level reduction due to adjacent basement construction. Ground water table fell from 0.4m below ground level in 1980 to 5.0m in 2005	Major cracking of buildings leading to demolition. This was concluded to be due to deterioration of wooden piles exacerbated by land subsidence (estimated to be 20cm) and negative skin friction	López Gayarre, et al. (2010)
2 apartment blocks containing 362 apartments	Oviedo, Spain	The ground conditions comprised fill overlying a clayey Quaternary system composed of clays, muddy clays, marly clays and marls with abundant organic matter. The thickness of this Quaternary system varied between 8 and 12 m. This overlay karstic gypsum and calcarenite	The failure was blamed on the construction of a nearby underground car park provoked a depression of "several meters" in the ground water of the karstified gypsum aquifer. However, the authors' conclusion is that the failure was due to consolidation settlement and not due to the water table depression	A major crack appeared in the buildings reaching some 10 cm in width. In all, 362 apartments were affected and declared in ruins, with the consequential social and economic impact of rehousing 300 families	Gonzalez-Nicieza, *et al.* (2008)

Table 8. Cases associated with Karst

Structure	Location	Soil type	Exposure	Damage	Source
San Pedro de los Francos Church, an 11th to 14th century church	Calatayud, NE Spain	Situation at the foot of a gypsum scarp	Evaporite dissolution subsidence. Natural subsurface drainage causes the dissolution and subsidence, which is aggravated by leakage from water and sewage pipes.	The church has been seriously damaged by subsidence. The most striking effect is the tilting of the 25 m high tower, which leans towards and overhangs the street by about 1.5 m	Gutierrez and Cooper (2002)
Colegiata de Santa María la Mayor with a 72 m high tower (constructed between the 13th and 18th Centuries)	Calatayud, NE Spain	Recent alluvial deposits underlain by gypsum and other soluble rocks	In 1996, the fracture of a water supply pipe flooded the cloisters and the church with 100 mm of water. Ten years earlier a similar breakage and flood had occurred. These breaks in the water pipes are most likely related to the subsidence movements of the ground. Once they occur, the massive input of water to the subsurface may trigger other subsidence-inducing subsurface processes including dissolution, piping and hydrocollapse	Large blocks have fallen from the vault of the "Capitular Hall" and cracks up to 150 mm wide have opened in the brickwork	Gutierrez and Cooper (2002)
Residential housing built over a 13th Century cellar system	Oppenhein, near Frankfurt, Germany	8m thickness of Pleistocene loess overlying Oligocene limestones	A broken water pipe in 1986 resulted in uncontrolled water outflow	Settlement damage was observed along a street of buildings. Caverns were produced with an average diameter of 3m. These caves sometimes collapsed in a dramatic manner (a car is shown fallen into a collapsed cavern).	Schenk and Peth (1997)

Table 9. Cases associated with Shrink/Swell of Clays

Structure	Location	Soil type	Exposure	Damage	Source
484 records of damaged properties in BRE database	UK	The most common ground conditions where damage was recorded were in London Clay (nearly 30% of all records). Other ground conditions with relatively high numbers of cases of damage were on glacial till, Lias clay, Weald clay and clay-with-flints.	Most cases of damage (68%) were attributed to clay shrinkage due to vegetation, while a further significant proportion (21%) was attributed to seasonal shrinkage and swelling, but in the absence of significant vegetation.	Around 76% of all of the cases of UK house damage from shrink/swell of clays recorded in the BRE database had levels of damage that fit into Category 2 or Category 3 of BRE Digest 251 (BRE (1995)). Few cases had damage levels associated with Category 1 damage, though there were a significant number (about 10%) with Category 4 damage.	Crilly (2001)
25 low-rise buildings	Alcazar de San Juan (Central Spain)		Sixty-seven chinaberry trees (Melia Azedarach) were planted close by followed by an especially hot and dry summer	Cracks of load-bearing walls between buildings occurred that were diagonal, from the floor to the façade. The crack opening advanced more rapidly in summer, consistent with shrinkage induced by the trees causing the damage	Navarro, *et al.* (2009)
Railway roadbed of the French high-speed train (TGV)	Chabrillan in southern France	Expansive clayey marl	One of the mechanisms for damage was swelling of the marls beneath the railway roadbed	Heave of over 80mm was observed in the railway roadbed during a 6-year period from 2001 to 2007. However, the majority of this swelling could be attributed to unloading due to a deep excavation (9-34m deep) at the site. The movement due to climate effects were thought to be only $\pm$3 mm	Tang, et al. (2009)

Table 10. Cases associated with Peat

Structure	Location	Soil type	Exposure	Damage	Source
Industrial building with a precast reinforced concrete structure constructed on 540mm dia. Franki piles. Lightly loaded and interior floors were placed directly on fill	Angri, Italy (near to Naples)	Peat overlying low permeability tuff, interbedded with marine, alluvial and pyroclastic sediments.	A 6m lowering of groundwater table during summer months (1989-1995) linked to water abstraction	Slabs on fill underwent settlements of 30-40cm after construction. The interior walls were damaged and equipment on the slab was inoperable. Plant damage after construction was a consequence of settlement due to groundwater movements with annual cycles of movement of about 3cm.	Varosio (2000)
Building	Tatu, Estonia	The ground conditions are Holocene alluvial and bog (with up to 6m of peat) deposits overlying late glacial varved soils	Ground water fluctuations	The records show a peak in the rate of building subsidence (at 4.8 mm/yr) in 1973 when water levels fell by 3.5m as a result of ground water abstraction. When groundwater abstraction was reduced from 1974-1994, water levels recovered, and the rate of building subsidence reduced to 1.5-2 mm/yr.	Kalm (2007)

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