Geohazards have particular significance in urban areas where, in addition to endangering human life, their consequences may affect large developments, individual homes, transport and services. The British Geological Survey has an ongoing programme to assess geohazard susceptibility and record geological hazard events in Britain. An integral part of this programme is the study and understanding of the processes and mechanisms involved. Those geohazards considered to be of particular relevance to the Lias Group are: landslides, shrink/swell potential, sulphate attack on buried concrete structures, and radon. These are discussed below.

### Landslides

#### General

Britain does not suffer from landslide hazards on the physical or human scale experienced in some parts of the world. However, there are a large number of landslides (believed to be in excess of 10 000) existing largely as a result of Britain’s glacial and periglacial history, and as a consequence of coastal erosion. Records of known landslides are maintained as part of the BGS’s National Landslide Database; which incorporates data acquired from an earlier national study for the Department of the Environment by Geomorphological Services Ltd. (Jones & Lee, 1994[1]). Contrary to popular belief, landslides have caused fatalities in Britain, albeit in most, but not all, cases as a result of consequential rail or traffic accidents. Many landslides on the coast are associated with coastal erosion, particularly in eastern and southern England, the great majority of which are unrecorded. The presence of these landslides raises economic and planning issues and, in some cases, safety issues. It is apparent that Lias Group rocks are markedly landslide-prone and include a particular form of mass movement known as ‘cambering’.

**Cambering** is a mass movement process whereby a competent, relatively brittle caprock layer overlying a weak, ‘extruding’ clay layer, at the edge of a plateau or hilltop, is subject to ‘hinging’ or ‘slumping’ downward and outward, and subsequent gradual break-up. These masses then become involved in landslides on the slope. One effect of cambering is to exaggerate the apparent caprock thickness, and conversely reduce the apparent thickness of the substratum. A good example of cambering is found on Bredon Hill, Worcestershire (between Tewkesbury and Evesham) where the base of the Inferior Oolite limestone caprock (overlying Whitby Mudstone) drops up to 53 m, from its original elevation. Associated with cambering are ‘gulls’. These are open or infilled tension cracks within the caprock, usually formed along pre-existing joints and running mainly parallel with the valley or escarpment. In some cases, gulls may be ‘bridged’, that is they occur only in the lower beds of the caprock and are not visible at surface. Such gulls occur in the Great Oolite Formation of the Bath area where they form a network of orthogonal ‘gull caves’ deep within the hillside (Self, 1985[2]).
Landslides in the Lias Group

There are many recorded landslides either within the Lias Group outcrop or involving materials derived from it. A small number of these are well documented. These are found particularly in the Cotswolds, the Bath area, the East Midlands, the North Yorkshire Moors, and the Dorset coast.

A total of 1,316 landslides involving Lias Group rocks were recorded as part of the DoE/GSL national database (Jones & Lee, 1994[i]). The Lias Group landslides were shown to represent 15% of all those recorded in Britain with the most common landslide types found to be ‘rotational’, ‘flows’, ‘compound’, and also ‘cambers’. The ‘Upper Lias’ was found to be the most susceptible to landslides (distinction by Formations was not made in the DoE/GSL database; see Glossary for correlations), accounting for 50% of the Lias Group landslides, and with a density of 42 landslides per 100 km$^2$ of outcrop. This compares with 28 and 10 landslides per 100 km$^2$ for the ‘Middle’ and ‘Lower Lias’ respectively. [Note: These figures include major coastal landslides]. Along with the London Clay, The Lias Group is probably the most widely studied with regard to landslides in Britain (Jones & Lee, 1994[i]). It has been estimated (Butler, 1983[iii]) that as much as 51% of the Upper Lias outcrop area in the Cotswolds is affected by either landsliding or cambering.

Inland landslides

The principal regions and types of inland landslides within the Lias Group are:

- Avon – Somerset-Wiltshire (multiple rotational, cambering, debris slides)
- Cotswold Hills (multiple rotational, cambering, debris slides, mudslides)
- East Midlands (cambering, rotational, mudslides, slab slides)
- North York Moors (multiple rotational, cambering, toppling, debris flows)

Note: For landslide types refer to: Varnes (1978[iv]) and Cruden & Varnes (1996[v]).

Avon-Somerset-Wiltshire

The landslides surrounding the city of Bath, in Avon and West Wiltshire, are well documented (Chandler et al., 1976[vii]; Hawkins, 1977[ii]; Anson, 1996[viii]; Cook, 1973[iix]) and represent some of the best examples of their type. The Lias Group here forms the lowest part of a two-level landslide domain extending upward to the limestones of the Great Oolite Group forming the plateaux around the city. The Hengrove Wood landslide in the Limpley Stoke valley is a characteristic example (Figure 5.1).

Figure 5.1  Slope cross-section: Hengrove Wood landslide, Limpley Stoke valley, Bath (Hobbs, 1980[x]).

Note: Likely slip surfaces shown in red.
Here the Charmouth Mudstone Formation (Lias Group) is overlain by the Inferior Oolite Group limestones, which in this instance produce a prominent escarpment and appear un-cambered. The lower parts of this landslide have been active in recent times, and have involved the A36 road and the Kennet & Avon canal (Hobbs, 1980[10]). However, evidence of cambering of the Inferior Oolite Group on the Lias in the Swainswick valley, Bath, was obtained by site investigations during the 1970’s and 1980’s for the A46 road re-alignment on the east side of the valley. A large number of continuously cored boreholes were drilled, several of which revealed no Inferior Oolite. These were interpreted as having been drilled through wide ‘gulls’ which had become infilled both from above by the Fuller’s Earth Formation of the Great Oolite Group, and below by the Bridport Sands Formation (formerly Midford Sands) of the Lias. A landslide map of the Bath and Bristol area, showing the outcrop of the Lias Group in light brown is shown in Figure 5.2.

Figure 5.2 Landslides and Lias Group strata in the Bath/Bristol area. [Key: grey = Lower Lias, yellow = Middle Lias, purple = Upper Lias, hatching = landslide].

Cotswold Hills
The Cotswold Hills are well known for their escarpments, outlier hills, and the many examples of landslides and cambering associated with them (Goudie & Parker, 1996[11]; Jones & Lee, 1994[1]; Whitworth et al., 2003[12]; Seedhouse, 1987[13]). To the south, the Great Oolite is the main scarp-forming caprock and the Fuller’s Earth Formation (Great Oolite Group) provides a weak underlying mudstone. To the north, however, the Inferior Oolite becomes the main caprock and the Lias Group mudrocks the substrate. Landslide frequency is strongly influenced by this change in geology, which occurs in the area of Stroud; the frequency increasing from south to north (Figures 5.3, 5.4 and 5.5).
Figure 5.3  Landslides and Lias Group strata in the Cotswolds (northern section).
[Key: grey = Lower Lias, yellow = Middle Lias, purple = Upper Lias, hatching = landslide].

Figure 5.4  Landslides and Lias Group strata in the Cotswolds (central section).
[Key: grey = Lower Lias, yellow = Middle Lias, purple = Upper Lias, hatching = landslide].
Landslides and Lias Group strata in the Cotswolds (southern section).

[Key: grey = Lower Lias, yellow = Middle Lias, purple = Upper Lias, hatching = landslide].

Whilst the landslides mainly date from times of periglacial conditions, some areas are currently active, and examples in the Lias occur at Broadway (Rowlands et al., 2003\textsuperscript{[14]}, Whitworth et al., 2003\textsuperscript{[12]}), Moreton-in-Marsh, and around Cheltenham. The principal (though not the only) mode of slope failure in the Lias Group is as shown in Figure 5.6 taken from Butler (1983)\textsuperscript{[3]}:

![Figure 5.6](image)

Mass movement processes in the Cotswolds (modified after Butler, 1983\textsuperscript{[3]}).
Landslide type is linked to slope angle and geology. Typical of Lias in the Cotswolds, the slopes around Blockley, Gloucestershire (Figure 5.7) feature both landsliding and cambering, elements of which remain active. Mudslides in Dyrham Formation have been recorded at Churchdown Hill, Leckhampton Hill, and Ebrington Hill, Gloucestershire (Butler, 1983[15], Hutchinson, 1988[15]).

East Midlands
In the Midlands, Lias Group landslides were investigated at Uppingham in Whitby Mudstone Formation (Chandler, 1970[16]) and on the A45 Daventry By-pass at Fox Hill and Newnham Hill, again within the Whitby Mudstone Formation overlain by the Northampton Sand Formation (Biczysko, 1981[17]).

The influence of weathering on slope stability has been examined by Chandler (1972)[18]. Sites at Culworth, Stowehill, Gretton, and Rockingham (Northamptonshire), and at Wothorpe (near Stamford, Lincolnshire) were studied for relationships between degree of weathering and strength, in the light of landslides and cambers at the sites. The author noted that persistent instability of a road cut at Wothorpe appeared to be related to fabric disturbance of the Whitby Mudstone Formation, probably associated with cambering of the overlying ironstone (Northampton Sand Formation), and linked it with similar observations in the Bath and Wellingborough areas. The author also proposed a weathering scheme for the Whitby Mudstone Formation (Upper Lias Clay) (Chandler, 1972[18]). Periglacial freeze/thaw effects on the Lias have been described (Kovacevic et al., 2007[19]). These have resulted in a distinctive brecciated fabric and highly variable geotechnical properties (see Physical weathering).

Landslides feature on the Lincolnshire Limestone Formation and Marlstone Rock Formation escarpments of the East Midlands, for example in the Grantham area (Forster, 1992[20], Berridge et al., 1999[21], Melton Mowbray area (Carney et al., 2002[22]), and on the Lincoln Scarp (Penn et al., 1983[23]). Shallow slumps and mudflows characterise slope instability within the underlying Whitby Mudstone Formation between Grantham and Lincoln, and also to the southwest of Grantham bordering the Vale of Belvoir. These become readily re-activated and result in a hummocky surface. Cambering of the Marlstone Rock Formation has also been observed in the Grantham area (Berridge et al., 1999[21]). In Rutland there are scattered landslides on the Whitby Mudstone Formation, between Uppingham and Oakham. Further south, landslides have been investigated at Rockingham,
near Corby [at SP 874 918 and between SP 874 918 and 889 925] (Chandler, 1972). In the Market Harborough area, there are shallow landslides of shallow successive rotational slide type within the Whitby Mudstone Formation overlain by Northampton Sand Formation at Medbourne [SP 803 933] (Figure 5.8) and Slawston Hill [SP 782 941] (Poole et al., 1968).

**Figure 5.8** Active shallow successive landslides in Whitby Mudstone Formation at Medbourne, Leics. (Feb 2003) [SP803 933].

The Lincoln Scarp has been modified by periglacial activity, including landsliding and cambering (Penn et al., 1983). Here, the scarp is formed by weathered and cambered Northampton Sand and Lincolnshire Limestone Formations (Inferior Oolite Group). These have supplied water to the slopes below underlain by Whitby Mudstone Formation, Marlstone Rock Formation and Charmouth Mudstone Formation strata, and Head deposits, resulting in phases of shallow slumping, mudslide, and solifluction lobe re-activation. The cambering, and associated gull formation, is small-scale and oriented sub-parallel with the scarp due to jointing.

**Cambering and valley bulging**

Cambering was first identified in Britain at ironstone quarries and river sections in the Shipton valley of Northamptonshire during the 1940’s (Hollingworth et al., 1944). Subsequently, significant investigations and reviews into cambering, and the associated phenomena of ‘valley bulging’ and ‘gulls’, have been carried out (Hutchinson, 1988; Parks, 1991; Humpage, 1996). Other investigations involving the Lias Group include:

- Empingham Dam, Leicestershire [cambering & valley bulging] (Figure 5.9) (Horswill & Horton, 1976; Vaughan, 1976; Kovacevic et al., 2007)
- Pinbury Park, Stroud, [valley bulging] (Ackermann & Cave, 1967)
- Upper Slaughter, Cotswolds (Briggs & Courtney, 1972)
Elsewhere, cambering of the Lincolnshire Limestone and Northampton Sand Formations at Little Ponton, Wellingborough, Oundle, Eye Brook, Hollowell, Rothwell, Kettering, Thrapston, Kingsthorpe, Hunsbury Hill, and Little Addington have been described by Hollingworth et al. (1944)\cite{25}, Hollingworth & Taylor (1951)\cite{32}, and Poole et al. (1968)\cite{24}. Most of these examples, but not all, are accompanied by valley bulging, usually involving Lias Group formations as the basal bed; the plastic extrusion or faulted displacement of which into the valley floor initiates the cambering process. Examples where valley bulging features are exposed at the present day are rare. Historically, evidence would have been perhaps more abundant due to the proliferation of mining, quarrying, dam building etc.

The pattern of cambering is usually the same throughout, though the severity varies, as does the presence of tensional features such as ‘dip and fault’ structures. Severe cambering is usually accompanied by basal shearing and landsliding. Hollingworth & Taylor (1951)\cite{32} noted that occasionally ‘multi-formational’ cambered layers were present in the same valley section. Cambering does not necessarily affect both sides of a valley equally. In some cases it may be absent on one side or replaced by conventional landsliding, as at Blockley [SP416235]. Vertical displacements due to valley bulging of as much as 30 m have been noted by Hollingworth & Taylor (1951)\cite{32}. They also noted that the axis of the bulge may be off-line with the current river valley, as a result of stream migration. Severe upward extrusion, due to valley bulging, of Whitby Mudstone Formation clays at Irthlingborough [SP 935 703] in the Nene Valley has apparently coincided with a fault on the northern perimeter of a limestone quarry (Hollingworth & Taylor, 1951\cite{32}, pp. 34, 180, fig. 17).

Cambering at a site in Radstock, Avon, was described by Hawkins and Privett (1981)\cite{33}. The site investigation for a housing development revealed hidden extension gulls associated with cambering of Blue Lias Formation limestones over Westbury Formation and Cotham Member (Penarth Group) clays and mudstones, and Mercia Mudstone Formation. The gulls were frequently bridged, and hence concealed, by Head deposits. Hawkins & Privett (1981)\cite{33} proposed a four-way classification of gulls based on the observations made during the investigation. Similar bridged gulls are found in the Limpley-Stoke valley near Bath, Avon (Hobbs, 1980\cite{10}), within the Great Oolite Series limestones. One of these is illustrated in Figure 5.10.
Geophysical investigation, using ground-probing radar and resistivity imaging, of superficial structures mappable at the surface in the Windrush and Eye valleys of the Cotswolds was described by Raines et al. (1999). This survey successfully imaged gulls in Mid-Jurassic limestones overlying the Whitby Mudstone Formation. However, the mechanism of cambering suggested by the geophysical data was not the classic one of ‘draped’ strata dipping valleywards as described in Parks (1991) and Hutchinson (1988), but rather a version, possibly modified by post-cambering landslides, where blocks are backtilted.

Valley bulging is a process of valley bottom uplift, extrusion or folding typically parallel to the valley axis, produced by erosive stress relief, probably during Pleistocene times. The process is linked to cambering and many occurrences are present within the Whitby Mudstone Formation. The process tends to fold and shear the relatively weak (possibly saturated) clay strata at the valley bottom, and may result in Lias outcropping above its normal position. The structures produced by valley bulging are often planed off by erosion or obscured by alluvium. Ackerman and Cave (1967) described examples from the Frome valley near Stroud. Examples of severe ‘contortion’, principally a ‘tight anticlinal fold’ aligned parallel with the Fishpool Brook valley, within the Barnstone Member (formerly the Hydraulic Limestone) of the Scunthorpe Mudstone Formation seen in former cement workings at Barrow-upon-Soar (Lamplugh et al., 1908), are probably attributable to valley bulging (Figure 5.11).
Cambering/valley bulging and landsliding in the Lias Group rocks typically result from a process known as progressive failure. This is due to over-consolidation by overburden (including ice) followed by overburden erosion (or post-glacial ice melting) and stress relief, resulting in weakening of the rock mass. These factors are often associated with a delay in failure following slope alteration. This type of failure mechanism is believed to be common in cut slopes in overconsolidated clays. Coastal landslides in over-consolidated clays often differ significantly, due to the wide range of time scales of coastal erosion and the effects of this on pore pressure equilibration, and hence effective stress and stability. Whilst negative pore pressures have been demonstrated for cliffs in Tertiary clays (Dixon & Bromhead, 2002[37]), it may also apply to some coastal Lias Group landslides where the erosion rate is particularly high and the landslide type is of low complexity.

**Coastal landslides**

The principal areas of coastal landslides within the Lias Group (with their typical modes of failure) are:

- Lyme Bay, Dorset (mudslides, mudflows, earthflows, multiple rotational, block slides)
- Watchet Bay, Somerset (debris slides, rockfalls)
- Glamorgan, South Wales (rockfalls, topples, translational)
- North Yorkshire coast (rock fall, debris slide)
- Inner Hebrides (multiple rotational, block slides, rock fall)

**Lyme Bay**
Dorset’s Lyme Bay coastline, from Axmouth to Burton Bradstock, has many famous examples of large and complex landslides in which the Blue Lias, Charmouth Mudstone, and Dyrham Formations feature. Many of these are active and have caused considerable damage in built-up areas. These include Bindon (Pitts & Brunsden, 1987[38]), Lyme Regis (Sellwood et al., 2000[39]; Lee & Clark, 2002[40]), Black Ven (Brunsden, 2002[41], Conway, 1974[42]), Stonebarrow Hill (Ramli et al., 2000[43]), Warbarrow, and Seatown (Atherton & Burbidge, 2000[44]).

The well-known Black Ven landslide between Charmouth and Lyme Regis is large and complex. It is characterised by a series of benches (Figure 5.12) on which discrete landslides occur, and over which mudflows and mudslides move more or less continuously (Gibson, 2005[45]). The upper platform and backscar consist largely of sands (‘Foxmould’ and ‘Chert’ of the Upper Greensand) on a thin layer of highly plastic Gault Formation clay. These strata are the principal source of groundwater to the landslide, and the origin of major rotational movements. The Stonebarrow Hill landslide (Figure 5.13) immediately to the east differs slightly in profile due to the eastward dip of the strata. Here the Belemnite Marl Formation provides a relatively stable bench caprock and, with the underlying Black Ven Marl Formation, the near-vertical sea cliff. The aftermath of a major re-activation in 2000 is shown in Figure 5.13. Landslides in the area are not confined to sea cliffs, and are also found on the slopes of the River Char valley (Jones & Lee, 1994[44]).

*Figure 5.12* Cross-section through Black Ven landslide, Charmouth, Dorset (Conway, 1974[42]) [SY 354 932].
As an interesting footnote with respect to Dorset coast landslides, there have been many instances reported of spontaneous combustion of shales within the Shales-with-Beef Member of the Charmouth Mudstone Formation, in particular in 1908 at the Spittles, Black Ven (Jukes-Brown, 1908). These appear to be similar to combustion events observed in the Kimmeridge Clay Formation at Kimmeridge, Dorset. The fires have been associated with recent landsliding (exposure of fresh rock), and wet conditions, and may therefore be initiated by the oxidation of pyrite, followed by ignition of bituminous material and vapour (West, 2003). The Lias Group rocks concerned typically have about a third the organic content of the bituminous Blackstone Member of the Kimmeridge Clay Formation.

**Watchet Bay**
The Somerset coastline of Bridgwater Bay, between Watchet and Burnham-on-Sea, features landslides on cliffs formed from an outlier of thick undifferentiated Langport Member (Rhaetian), Blue Lias Formation and Charmouth Mudstone Formation. These consist of limestones, shales, and bituminous shales. The Blue Lias east of Watchet is about 145 m thick.

**Glamorgan**
The 22 km Glamorgan Heritage Coastline, between Ogmore-by-Sea and Barry, features landslides on 15 to 80 m high cliffs in the Porthkerry and Lavernock Shale Members of the Blue Lias Formation (Williams et al., 1993; George, 1974). Examples of coastal exposures are shown in Figures 5.14 and 5.15.
North Yorkshire

Lias Group rocks are exposed on the 50 km section of the North Yorkshire coast from Robin Hood’s Bay (Figure 5.16) to Redcar. A variety of landslides are found here. Whilst these principally occur within till, and other superficial deposits, overlying the Lias and other formations, the Lias Group formations may be involved. The Lias Group rocks of North Yorkshire are generally stronger and more durable than their equivalents on the Dorset or Bristol Channel coasts (refer to Chapter 7 and Kemp et al., 2005[50]). Contemporary landslides are consequently less numerous, less spectacular, and less active. Considerable thicknesses of till and other superficial deposits are found frequently occupying the entire cliff section. These tend to concentrate ground water, and are particularly prone to rotational landslides and mudslides. Landslides within the Lias Group cliffs tend to be ‘rock
falls’, ‘debris slides’, or ‘topples’, although in the geological past some deep-seated landslides have occurred.

Figure 5.16  Cliff and wave-cut platform and deep-seated landslides (distant, left) at Ravenscar, Robin Hood’s Bay, N. Yorkshire, in Whitby Mudstone, Cleveland Ironstone, Staithes Sandstone, & Redcar Mudstone Formations).

Inner Hebrides
A few of the many large landslides on the Isles of Skye and Raasay involve Lias deposits. Notably, Dun Caan on the east coast of the Isle of Raasay (P002267 & P002833) and Ben Tianavaig on the east coast of Skye, south-east of Portree and facing Raasay. These landslides are sliding on the relatively weak Portree Shale, Scalpay Sandstone, and Pabay Shale Formations of the Lias Group. Dun Caan is described as having been active in historical times (Anderson & Dunham, 1966[51]). The extensive and structurally complex Trotternish landslide zone on the east coast of Skye extends from the famous Quiraing (Flodigarry) in the north [NG 449 716], via the Cleat and the Storr, to Ben Tianavaig (near Portree) in the south [NG 512 410] (Benn and Ballantyne, 2000[52]), a distance of 23 km. However, only the southern part of this zone involves Lias Group rocks. Landsliding has been linked with de-glaciation around 17 500 years BP, but one landslide has been dated at only 6,500 years BP. It is thought that earthquakes may have been a factor (Benn and Ballantyne, 2000[52]).
View of Dun Caan landslide, east coast of Raasay, Inverness-shire.
[NG 586 392].
*Note: Landslide in foreground. Loch a' Chada-charnaich (right) is a pond filling a depression formed at the rear of a back-tilted block.*

North part of Dun Caan landslide, east coast of Raasay, Inverness-shire [NG 585 401].
**Shrink/swell**

**General**

The mineralogy of the clay component of a rock or soil is the most significant factor determining its shrink/swell hazard. Swelling and shrinkage are the two sides of the volume-change ‘coin’, both result from changes in water content of the soil/rock fabric. A decrease in water content causes shrinkage (an overall volume decrease) and an increase in water content causes swelling (an overall volume increase). These conditions are neither permanent nor reversible. They are not intrinsic properties of the soil or rock, but respond to prevailing environmental conditions. The relationship between shrink/swell and water content is also not linear, but follows a so-called ‘characteristic’ curve such as that shown for a remoulded laboratory test specimen in Figure 5.19. Thus a moderately dry summer will not necessarily result in major shrinkage of a clay soil, whereas a drought will. This may result in structural damage for buildings with shallow foundations, and disruption to services such as gas and water mains. The amount of seasonal water content change is partly dependent on the type and location of vegetation, particularly trees, adjacent to a building or service (Building Research Establishment, 1993).

*Figure 5.19*  Shrinkage characteristic curve (idealised) showing Atterberg Limits (shrinkage limit, SL, plastic limit, PL, & liquid limit, LL) Refer to sections 7.2.4 and 7.2.11 for definitions.

The capacity of a mudstone or clay to shrink or swell with water content change is largely a function of the following:

- Material composition
- Clay mineral type
- Over-consolidation/induration/weathering
- Current effective stress
- Time

The proportions and types of clay minerals present, and the way in which the distinctive surface properties of clay minerals react with ‘free’ water, is particularly significant in mudstones with a
high clay content. The degree of over-consolidation, induration, and weathering principally affects the material stiffness, and thus the way in which the mudstone responds to stress changes including suction caused by desiccation. The effective stress is the relationship between total stress and pore water pressure. Changes in effective stress can be brought about by changes in either, or both, of these elements. A change in effective stress results in a change in strength, which in turn may cause a change in volume. The shrinkage shown in Figure 5.19 is in direct response to an effective stress increase caused by a water content decrease (suction increase). This relationship is non-linear.

Figure 5.20  Linear shrinkage vs. Plasticity index by Formation (Hobbs et al., 2007[54]).

There are tests available to directly measure the shrink/swell behaviour of soils, but these are seldom employed. More often, indirect properties such as plasticity index are used as a guide to shrink/swell behaviour (See Geotechnical properties). This is partly because direct tests, either in the field or in the laboratory, are more difficult and expensive to carry out. The two British Standard laboratory shrinkage tests are the ‘shrinkage limit’ (volumetric shrinkage) test and the ‘linear shrinkage’ test (BS1377:1990, Tests 6.3 & 6.5, respectively); the former representing a specific water content on the characteristic curve and the latter a percentage length reduction of a remoulded specimen. Two British Standard swelling tests are described in BS1377 1990: the swelling pressure test and the swelling (strain) test (BS1377:1990, Tests 4.3 & 4.4). These tests are described in detail in Head (1998)[55] and Hobbs & Jones (1995)[56].

The linear shrinkage test has a positive correlation with plasticity index (Figure 5.20) (Hobbs et al. 2007[54]).

Lias Group shrink/swell behaviour

In the absence of direct shrink/swell data, the plasticity index (difference between liquid and plastic limits) is typically used as a guide to likely shrink/swell behaviour. A summary of Lias Group median values of plasticity index and derived shrink/swell rating is given in Table 5.1:

| Plasticity index median values | and shrink/swell hazard rating. |

Table 5.1
### Formation, Plasticity index (%), Shrink/swell rating

<table>
<thead>
<tr>
<th>Formation</th>
<th>Plasticity index (%)</th>
<th>Shrink/swell rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridport Sand</td>
<td>17</td>
<td>low</td>
</tr>
<tr>
<td>Whitby Mudstone</td>
<td>29</td>
<td>Medium</td>
</tr>
<tr>
<td>Dyrham</td>
<td>26</td>
<td>Medium</td>
</tr>
<tr>
<td>Charmouth Mudstone</td>
<td>30</td>
<td>Medium</td>
</tr>
<tr>
<td>Scunthorpe Mudstone</td>
<td>24</td>
<td>Medium</td>
</tr>
<tr>
<td>Blue Lias</td>
<td>29</td>
<td>Medium</td>
</tr>
</tbody>
</table>

The degree of over-consolidation or induration of the several Lias Group mudstones vary, and this variation imparts different shrink/swell behaviour and anisotropy, other factors being equal. Over-consolidation tends to result in greater lateral than vertical volume change. Increased induration tends to reduce the amount of overall volume change due to improved stiffness and the development of cementation. Weathering tends to have the reverse effect, whereby stiffness and stress-related anisotropy are reduced, thus tending to increase shrink/swell movement in the vertical plane.

A small number of swelling and shrinkage tests were carried out on Lias Group samples by BGS and reported in Hobbs et al. (2007)\(^{[54]}\). The results of one particular test, the 3-D swell strain test, are summarised in Table 5.2. These show that the more thinly bedded and shaly specimens within (e.g. All Blue Lias; Whitby Mudstone, Sidegate Lane 1) produced greater swell strain anisotropy (up to 8 \(x\)) in a 50 mm cube-shaped specimen at natural initial water content, than more uniform, non-shaly or thicker bedded, specimens (e.g. Charmouth Mudstone, Blockley Site 1; Whitby Mudstone, Brixworth 1).

#### Table 5.2 Results of 3-D swelling strain test; values represent maxima.

<table>
<thead>
<tr>
<th>Sample location</th>
<th>Formation</th>
<th>(\varepsilon_1) (%)</th>
<th>(\varepsilon_2) (%)</th>
<th>(\varepsilon_3) (%)</th>
<th>Strain, (\Delta) (%)</th>
<th>(\Psi) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bishop's Cleeve 1</td>
<td>Blue Lias F.</td>
<td>1.29</td>
<td>0.62</td>
<td>0.74</td>
<td>2.7</td>
<td>91</td>
</tr>
<tr>
<td>Southam 1</td>
<td>Blue Lias F.</td>
<td>2.24</td>
<td>0.25</td>
<td>0.25</td>
<td>2.8</td>
<td>804</td>
</tr>
<tr>
<td>Stowey 1</td>
<td>Blue Lias F.</td>
<td>0.39</td>
<td>0.26</td>
<td>0</td>
<td>0.7</td>
<td>208</td>
</tr>
<tr>
<td>Blockley Site 1</td>
<td>Charmouth Mudstone F.</td>
<td>0.35</td>
<td>0.85</td>
<td>0.58</td>
<td>1.8</td>
<td>-52</td>
</tr>
<tr>
<td>Dimmer 1</td>
<td>Charmouth Mudstone F.</td>
<td>0.98</td>
<td>0.62</td>
<td>0.6</td>
<td>2.2</td>
<td>61</td>
</tr>
<tr>
<td>Brixworth 1</td>
<td>Whitby Mudstone F.</td>
<td>1.82</td>
<td>2.13</td>
<td>2</td>
<td>6.1</td>
<td>-10</td>
</tr>
<tr>
<td>Sidegate Lane 1</td>
<td>Whitby Mudstone F.</td>
<td>7.13</td>
<td>2.9</td>
<td>2.02</td>
<td>12.5</td>
<td>194</td>
</tr>
</tbody>
</table>

**NOTE:** Strain vectors are orthogonal, \(e_1\) is perpendicular to bedding.

### Sulphate

#### General

Sulphates and sulphides are very common in British stratigraphic formations, occurring naturally in a variety of forms in mudstones and other sediments, including Lias Group mudstones and clays. The distribution and classification of sulphate in British rocks and soils is described in BRE Digest 363 (Building Research Establishment, 1991, 1996)\(^{[57]}\, [58]\) and Forster et al. (1995)\(^{[59]}\). Typically, sulphate content varies with depth and weathering state. The damaging effects of sulphate salts on concrete, particularly below the water table, are well documented. For example, during construction of the M40 motorway in Oxfordshire, England, heave of the carriageway was caused when lime...
stabilisation of pyrite-bearing Charmouth Mudstone Formation (formerly the ‘Lower Lias Clay’) was attempted. The layer concerned had to be removed (Anon, 1991b).

The best-known forms of sulphate in mudrocks are gypsum and anhydrite formed by the oxidation of sulphides. Sulphides, particularly pyrite (FeS₂), are formed in anaerobic conditions through the action of sulphate-reducing bacteria and are generally found as dispersed microscopic minerals. Pyrite oxidation is complex but may be summarised as follows:

a. Oxidation of pyrite to form ferric oxide (Fe₂O₃) and sulphuric acid (H₂SO₄),
b. Reaction of sulphuric acid with calcium carbonate to form gypsum (CaSO₄·2H₂O),
c. Reaction of sulphuric acid with clay minerals, if calcium carbonate is lacking, leaching them of exchangeable cations.

One of the end products of this process may be the formation of the sulphate mineral thaumasite. Oxidation of pyrite associated with weathering may be a slow process. However, buried concrete structures within Lias Group mudrocks are prone to thaumasite sulphate attack (TSA), particularly where the concrete is in contact with saturated un-weathered Lias-derived fill (Longworth, 2002). The result is a transformation of the concrete fabric into a weak paste, which has serious consequences for the integrity of the concrete, and may result ultimately in failure. TSA was notable on bridge foundations where concrete contacted pyritic Lias Group clays and clay-fill on the M5 motorway in Gloucestershire (Floyd et al., 2002). This topic is discussed in detail in Sulphate attack of concrete.

The effects of stockpiling conditions on the sulphur content of Lias (and other) clays has been discussed in Czerewko et al. (2003). Inappropriate storage conditions (viz. excessive duration, insufficiently low temperatures) were found to result in much reduced sulphide values, much increased sulphate values, and consequent changes in geotechnical properties.

**Lias Group sulphates**

There are three types of sulphate content test routinely used in geotechnical laboratories (BS1377:1990, Part 3, Test 5), results from which are contained in the Lias Group database of properties compiled for this study:

a. Total sulphate [solids]: ‘acid extraction test’ (preparation 5.2)
b. Water soluble sulphate [solids]: ‘2:1 aqueous extract test’ (preparation 5.3)
c. Dissolved sulphates in ground water [water]: (preparation 5.4)

BRE Digest 363 (Building Research Establishment, 1991; 1996) suggested that if total sulphate is greater than 0.24% then aqueous sulphate tests should be carried out. The ‘total sulphate’ test does not test for sulphides, as these are destroyed in preparation, and is not now considered a good guide to sulphate attack (Longworth, 2004). Different sulphates have different rates of dissolution, and hence degrees of hazard with respect to concrete foundations. A rigorous analysis, going beyond the simple ‘geotechnical’ tests listed above, would require geochemical tests to identify the full potential of this geohazard. A new sulphate classification has been developed and described in BRE Special Digest 1 — Concrete in Aggressive ground (Building Research Establishment, 2005). This is summarised in Table 5.3 with the addition of a verbal descriptor.

The overall total sulphate content median value (for the Lias Group formations for which data were available) is 0.16%. The equivalent ‘water-soluble’ and ‘ground water’ values are 1.01 and 0.14 g/l, respectively. This places the Lias Group median within the new sulphate class DS-2 (low) (Building Research Establishment, 2005). However, individual results lie in the range DS-1 to DS-4, i.e.
very low’ to ‘high’ (Table 5.4). The Lias Group dataset is dominated by mudstones, in particular the Charmouth Mudstone and Whitby Mudstone Formations. The Charmouth Mudstone Formation demonstrated the highest overall aqueous extract sulphate values and hence the greatest sulphate geohazard potential, whilst the Scunthorpe Mudstone Formation recorded the highest median total sulphate content (Table 5.4).

NOTE 1: The Lias Group database revealed poor correlation between different sulphate test results. NOTE 2: Sulphates present in ground water may have originated in other formations outside the area of interest.

Sulphate attack of concrete

Thaumasite (derived from the Greek word ‘thaumasion’ meaning surprising) may be formed by sulphate attack on concrete and has been found on twenty to thirty year old concrete structures on the M5 and other major trunk roads in Gloucestershire, Somerset and Wiltshire, in the Charmouth Mudstone Formation. Of the concrete structures investigated 75% had been damaged, with abutments and columns being the most severely affected members. In each case Charmouth Mudstone Formation backfill had been used. There has been some confusion in the past regarding the classification schemes, based on the different sulphate tests described in BS1377:1990[66], their precision, and their relationship to TSA (Longworth, 2004[64]). In the majority of cases, the sulphate class limits based on soil extract tests were both lower than sulphate class based on sulphate in groundwater and were also low when compared to the actual occurrence of TSA. The new limits given in BRE Special Digest 1 bring sulphate classification based on 2:1 water/soil extract tests into parity with the groundwater based tests.

Table 5.3 Table of old and new sulphate classes based on 2:1 soil extraction test (Building Research Establishment, 2005[65]).

<table>
<thead>
<tr>
<th>Sulphate class</th>
<th>Old limits g/l SO₄²⁻</th>
<th>New limits mg/l SO₄²⁻</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS-1</td>
<td>&lt;1.2</td>
<td>&lt;500</td>
<td>Very low</td>
</tr>
<tr>
<td>DS-2</td>
<td>1.2–2.3</td>
<td>500–1500</td>
<td>Low</td>
</tr>
<tr>
<td>DS-3</td>
<td>2.4–3.7</td>
<td>1600–3000</td>
<td>Medium</td>
</tr>
<tr>
<td>DS-4</td>
<td>3.8–6.7</td>
<td>3100–6000</td>
<td>High</td>
</tr>
<tr>
<td>DS-5</td>
<td>&gt;6.7</td>
<td>&gt;6000</td>
<td>Very high</td>
</tr>
</tbody>
</table>

Table 5.4 Table of Lias Group sulphate medians with new classification based on SO₄²⁻ (aqueous extract) test data: medians and maxima.

<table>
<thead>
<tr>
<th>Formation</th>
<th>SO₄²⁻ (total) (%)</th>
<th>SO₄²⁻ (aqueous extract) (mg/l)</th>
<th>SO₄²⁻ (water) (%)</th>
<th>New (median) sulphate classification (BRE, 2005)</th>
<th>New (maximum) sulphate classification (BRE, 2005)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue Lias</td>
<td>0.06</td>
<td>340</td>
<td>0.17</td>
<td>DS-1</td>
<td>DS-3</td>
</tr>
<tr>
<td>Charmouth Mudstone</td>
<td>0.19</td>
<td>1060</td>
<td>0.20</td>
<td>DS-2</td>
<td>DS-4</td>
</tr>
<tr>
<td>Dyrham</td>
<td>0.07</td>
<td>220</td>
<td>0.05</td>
<td>DS-1</td>
<td>DS-1</td>
</tr>
<tr>
<td>Scunthorpe Mudstone</td>
<td>0.38</td>
<td>1230</td>
<td>0.10</td>
<td>DS-2</td>
<td>DS-3</td>
</tr>
<tr>
<td>Whitby Mudstone</td>
<td>0.18</td>
<td>710</td>
<td>0.14</td>
<td>DS-2</td>
<td>DS-3</td>
</tr>
</tbody>
</table>

The following is a summary of the findings of a Building Research Establishment study (Longworth, 2002[61]) and also those of Bensted (1999)[67], Floyd et al (2002)[62], and Hobbs & Taylor (2000)[68].

Thaumasite sulphate attack (TSA) is characterised by softening and expansion of the concrete
The surface has a white pulpy appearance, or occasionally a ‘crust’ of apparently ‘fresh’ concrete, beneath which the coarse aggregate is surrounded by white rings or halos of reaction products.

Thaumasite can be identified by a combination of petrographic examination and scanning electron microscope (SEM) microprobe analysis. The process of thaumasite formation, leading to TSA, was found to create four zones within structural quality concrete with a sharp reaction front. Rust staining and chloride contamination, associated with reinforcement corrosion, were present in TSA affected structures several metres below ground level. The degree of TSA at each site could be classified using depth of attack and area of softening. The typical pattern of attack to buried vertical members was found to be: no attack within 1 m of ground level, local patches of softening or blistering at mid-height and increasingly severe attack towards the base. The position of these areas of attack appears to be associated with groundwater level. At Tredington Ashchurch Road Bridge, one of the worst affected structures investigated, the maximum depth of softening and amount of expansion were approximately 45 mm and 33 mm, respectively. Concrete cast directly against undisturbed Charmouth Mudstone Formation clay was often found to have sulphate contents in excess of 5% by mass of cement but there was no evidence of TSA. The degree of thaumasite attack appeared to be related to the availability of water. Bituminous coatings appeared to have provided partial protection to some structures. Visual assessment of the depth of TSA had limitations for estimating the concrete to be removed prior to repair work as sulphate contents in excess of 5% by mass of cement occur within apparently sound concrete.

The formation of thaumasite follows the hydration of cement:

\[
6\text{CaO}.\text{SiO}_2 + 6\text{H}_2\text{O} = (\text{Ca}_3\text{Si}_2\text{O}_7.3\text{H}_2\text{O}) + 3\text{Ca(OH)}_2 \quad (1)
\]

Following the reaction with sulphate, bicarbonate and hydrogen ions (acid), all present in oxidising Charmouth Mudstone Formation, thaumasite is formed.

\[
(\text{Ca}_3\text{Si}_2\text{O}_7.3\text{H}_2\text{O}) + 3\text{Ca(OH)}_2 + 2\text{SO}_4^{2-} + 2\text{HCO}_3^- + 20\text{H}_2\text{O} + 6\text{H}^+ = 2[(\text{Ca}_3\text{Si(OH)}_6\times12\text{H}_2\text{O})(\text{SO}_4)(\text{CO}_3)] \quad (2)
\]

Thaumasite was found to form where the backfill consisted of heterogeneous, predominantly reworked and gravel size lithorelicts of unweathered and weathered Charmouth Mudstone Formation. This was found to contain calcite, pyrite and clay minerals (see Mineralogy).

- There was a decrease in pyrite content and an increase in acid-soluble sulphate as the Charmouth Mudstone Formation was weathered, because of the reaction of pyrite oxidation to form sulphuric acid, which was buffered by calcium carbonate to precipitate gypsum (selenite) crystals (see reactions (1) and (2)). The process was confirmed by laboratory storage tests.
- In the study area the gypsum concentration was greatest approximately 3 to 4 m below ground level in the Charmouth Mudstone Formation.

No significant relationships were found between chemical, mineralogical or physical soil parameters and distance from concrete or degree of thaumasite attack. However, several trends in the data with proximity to concrete were identified (Longworth, 2002[61]).

The pH value and calcium carbonate concentration were found to increase towards concrete (both vertical members and footings) at less than 1.5 m offset, possibly due to leaching of calcium hydroxide from the concrete. Total sulphur and moisture content also increased. Water-soluble magnesium decreased with proximity to concrete; there was an inverse relationship between water-soluble magnesium and pH.
There was less pyrite and sulphide in thaumasite damage zone 3 (full attack) than in zones 1 and 2 (none and partial attack). This suggested that most thaumasite attack occurred where there was the most pyrite oxidation, generally in the deepest and wettest section of fill at each structure. Water-soluble sulphate, acid-soluble sulphate and total sulphur increased with increasing thaumasite attack (associated with individual structures and bridge piers). In general, thaumasite was not found where there were lower values of the water-soluble sulphate and acid-soluble sulphate and, to a lesser degree, total sulphur. The highest values occurred where there was partial attack (with the values decreasing away from the face) and consistently high values occurred where there was a major attack. Again, this may have been partly related to groundwater level.

Gypsum results were limited but values were higher where there was partial attack but lower where there was full attack. The pH value increased with increasing thaumasite. Water-soluble magnesium decreased with increasing thaumasite attack.

The extent of thaumasite attack was strongly related to groundwater level. Thaumasite damage zones correlated with the maximum and minimum groundwater levels measured at the structures over the 12 to 18-month monitoring period. Generally the concrete was not attacked above the maximum water level (i.e. permanently dry, except for percolating water); greatest attack usually occurred below the minimum water level (i.e. permanently wet), and partial attack where the groundwater level was between a maximum and minimum value. **Also, sufficient groundwater sulphate and carbonate were both found to be required in order to form thaumasite.**

Over twenty structures were investigated including over-bridges, under-bridges and culverts. Soil and groundwater sampling and testing was undertaken in conjunction with exposure, inspection and testing of the buried concrete.

All of the structures investigated were founded on undisturbed Charmouth Mudstone Formation, with backfill predominantly of reworked Charmouth Mudstone Formation, occasionally mixed with some alluvium. All of the backfill contained lithorelicts of Charmouth Mudstone Formation (generally fine to medium gravel size) in a clay matrix.

The majority of the structures investigated were constructed during 1968–1971, using Grade C35–C40 in situ concrete containing limestone coarse aggregate and meeting BRE 363 sulphate resistance Classes 1 to 2.

**Radon**

**General**

Radon (Rn-222) is a naturally occurring radioactive gas, resulting from the radioactive decay of uranium, which is released from bedrock and ground water. If radon is allowed to collect, for example beneath buildings, it may constitute a health hazard. This is assessed, in areas of known risk, according to a Government Action Level, above which remedial measures have to be carried out. The areas of risk broadly correspond with geology and exposure of the bedrock at any particular location. Since 1987 the National Radiological Protection Board (NRPB) has carried out tests and produced maps of Britain based on a 5 km square grid. The Lias Group rocks have a high radon hazard (either a ‘full’ or ‘basic’ radon hazard rating); the ironstones and ferruginous limestones of the Marlstone Rock Formation and Northampton Sand Formation being particularly highly rated (Berridge et al., 1999[21]; Sutherland & Sharman, 1996[69]), with the Charmouth and Scunthorpe Mudstone formations ranking slightly lower in this respect. These conclusions are borne out by airborne High-Resolution radiometric surveys recently carried out by the BGS in the East Midlands.
Radon tends to migrate from the source rocks by association with other gases, in particular methane and carbon dioxide. It may also be transported in groundwater, returning to a gas phase in areas of water turbulence or pressure decrease (e.g. waterfalls and springs). Radon may therefore occur in high permeability rocks present above a source rock. Major faults can act as conduits for radon migration while impermeable surface deposits, such as till, may form a surface capping, reducing levels of radon reaching the ground surface. Although concentrations of radon in open air normally do not present a hazard, in poorly vented confined spaces the gas can accumulate and may cause a health hazard, including lung cancer, to individuals exposed to it for long periods of time. 

*Advice on potential radon hazard and measures for the alleviation of radon build-up in properties can be obtained on application to the Enquiries Desk at the British Geological Survey, Keyworth.*

**References**


35. Ackermann, K. J., and Cave, R. 1967. Superficial deposits and structures, including landslip,


46. ↑ Jukes-Browne, A J. 1908. The burning cliff and the landslip at Lyme Regis. *Proceedings of Dorset Natural History and Antiquarian Field Club* 29, 153–160. *[by A J Jukes-Browne, F G S, read July 22nd, 1908. With 4 plates, including two photographs of the Lyme Volcano and one illustration of the Burning Cliff at Ringstead. With a map showing the exact location of the cliff fire, the burning mound.]*


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