



Programme Area: Nuclear

Project: Natural Hazards Phase 3

Title: Volume 7: Seismic, Volcanic and Geological Hazards

Abstract:

This technical volume addresses:

- Introduction
- Description of the main phenomena; seismicity, volcanicity, geological instability including landslides, ground dissolution, shrink-swell clays, mining
- Observations, measurements techniques and modelling tools
- Methodologies
- Related phenomena; seismicity, volcanicity, geological instability
- Regulation
- Emerging trends

Context:

The Natural Hazards Review project will develop a framework and best practice approach to characterise natural hazards and seek to improve methodologies where current approaches are inefficient. This is to improve energy system infrastructure design and the project is intended to share knowledge of natural hazards across sectors. The project will be completed in three stages. Phase one will focus on a gap analysis. Phase two will look at developing a series of improved methodologies from the gaps identified in phase one, and phase three will demonstrate how to apply these methodologies. Finally, phase 3 will develop a “how to” guide for use by project engineers.

Enabling Resilient UK Energy Infrastructure:
Natural Hazard Characterisation Technical Volumes
and Case Studies

Volume 7:
**Seismic, Volcanic
and Geological
Hazards**



LC 0064_18V7



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Version	Date	Details
0.1	21/02/18	Submitted for IPR
0.2	15/04/18	IPR comments addressed and submitted to CTO
1.0	04/05/18	CTO comments addressed and submitted to ETI
2.0	31/07/18	ETI and NHP3 Steering Committee comments addressed

This document forms part of the Energy Technologies Institute (ETI) project 'Low Carbon Electricity Generation Technologies: Review of Natural Hazards', funded by the ETI and led in delivery by the EDF Energy R&D UK Centre. The aim of the project has been to develop a consistent methodology for the characterisation of natural hazards, and to produce a high-quality peer-reviewed set of documents suitable for use across the energy industry to better understand the impact that natural hazards may have on new and existing infrastructure. This work is seen as vital given the drive to build new energy infrastructure and extend the life of current assets against the backdrop of increased exposure to a variety of natural hazards and the potential impact that climate change may have on the magnitude and frequency of these hazards.

The first edition of *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies* has been funded by the ETI and authored by EDF Energy R&D UK Centre, with the Met Office and Mott MacDonald Limited. The ETI was active from 2007 to 2019, but to make the project outputs available to industry, organisations and individuals, the ETI has provided a licence to the Institution of Mechanical Engineers and Institution of Chemical Engineers to exploit the intellectual property. This enables these organisations to make these documents available and also update them as deemed appropriate.

The technical volumes outline the latest science in the field of natural hazard characterisation and are supported by case studies that illustrate how these approaches can be used to better understand the risks posed to UK infrastructure projects. The documents presented are split into a set of eleven technical volumes and five case studies.

Each technical volume aims to provide an overview of the latest science available to characterise the natural hazard under consideration within the specific volume. This includes a description of the phenomena related to a natural hazard, the data and methodologies that can be used to characterise the hazard, the regulatory context and emerging trends. These documents are aimed at the technical end-user with some prior knowledge of natural hazards and their potential impacts on infrastructure, who wishes to know more about the natural hazards and the methods that lie behind the values that are often quoted in guideline and standards documents. The volumes are not intended to be exhaustive and it is acknowledged that other approaches may be available to characterise a hazard. It has also not been the intention of the project to produce a set of standard engineering 'guidelines' (i.e. a step-by-step 'how to' guide for each hazard) since the specific hazards and levels of interest will vary widely depending on the infrastructure being built and where it is being built. For any energy-related projects affected by natural hazards, it is recommended that additional site- and infrastructure-specific analyses be undertaken by professionals. However, the approaches outlined

aim to provide a summary of methods available for each hazard across the energy industry. General advice on regulation and emerging trends are provided for each hazard as context, but again it is advised that end-users investigate in further detail for the latest developments relating to the hazard, technology, project and site of interest.

The case studies aim to illustrate how the approaches outlined in the technical volumes could be applied at a site to characterise a specific set of natural hazards. These documents are aimed at the less technical end-user who wants an illustration of the factors that need to be accounted for when characterising natural hazards at a site where there is new or existing infrastructure. The case studies have been chosen to illustrate several different locations around the UK with different types of site (e.g. offshore, onshore coastal site, onshore river site, etc.). Each of the natural hazards developed in the volumes has been illustrated for at least one of the case study locations. For the sake of expediency, only a small subset of all hazards has been illustrated at each site. However, it is noted that each case study site would require additional analysis for other natural hazards. Each case study should be seen as illustrative of the methods outlined in the technical volumes and the values derived at any site should not be directly used to provide site-specific values for any type of safety analysis. It is a project recommendation that detailed site-specific analysis should be undertaken by professionals when analysing the safety and operational performance of new or existing infrastructure. The case studies seek only to provide engineers and end-users with a better understanding of this type of analysis.

Whilst the requirements of specific legislation for a sub-sector of energy industry (e.g. nuclear, offshore) will take precedence, as outlined above, a more rounded understanding of hazard characterisation can be achieved by looking at the information provided in the technical volumes and case studies together. For the less technical end-user this may involve starting with a case study and then moving to the technical volume for additional detail, whereas the more technical end-user may jump straight to the volume and then cross-reference with the case study for an illustration of how to apply these methodologies at a specific site. The documents have been designed to fit together in either way and the choice is up to the end-user.

The documents should be referenced in the following way (examples given for a technical volume and case study):

ETI. 2018. *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies*, Volume 1 — Introduction to the Technical Volumes and Case Studies. IMechE, IChemE.

ETI. 2018. *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies*, Case Study 1 — Trawsfynydd. IMechE, IChemE.

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1.1 Seismicity

A seismic hazard is an earthquake-induced natural phenomenon, such as ground shaking, soil liquefaction or a tsunami, that has the potential to cause adverse effects on something or someone. However, the term seismic hazard is also often used to describe risk, i.e. the probability of exceedance of a ground motion intensity threshold, in a given geographic area, within a given period.

The UK is generally an area of low seismic activity. Seismic design may not be considered for facilities that are classed of low importance by stakeholders, where safety or damage are not critical, or the facilities/contents are not considered sensitive to seismic vibrations. However, small earthquakes occur on a regular basis (*Figure 1*) and certain structures (e.g. nuclear power plants) require design to withstand earthquakes regardless of the perceived level of threat; this is likely to involve site-specific analyses, such as Probabilistic Seismic Hazard Assessment (PSHA). The foreword to Eurocode BS EN 1998-1 *Eurocode 8 – Design of Structures for Earthquake Resistance – General Rules, Seismic Actions and Rules for Buildings* states 'There are generally no requirements in the UK to consider seismic loading, and the whole of the UK may be considered an area of very low seismicity in which the provisions of Eurocode EN 1998 need not apply. However, certain types of structure, by reason of their function, location or form, may warrant an explicit consideration of seismic actions'.

BS EN 1990 defines three consequence classes: CC1, CC2 and CC3 (*Table 1*). Consequence Class CC1 is described as low consequence for loss of human life; economic, social or environmental consequences small or negligible, e.g. agricultural buildings where people do not normally enter. Consequence Class CC2 is described as medium consequence for loss of human life; economic, social or environmental consequences considerable, e.g. residential or office buildings where the consequences of failure are medium. Finally, Consequence Class CC3 is described as high consequence for loss of human life; economic, social or environmental consequences very great, e.g. public buildings where consequences of failure are high. It is recommended that structures with Consequence Class CC3 should be considered for seismic design (PD 6698:2009 *Recommendations for the Design of Structures for Earthquake Resistance to BS EN 1998*).

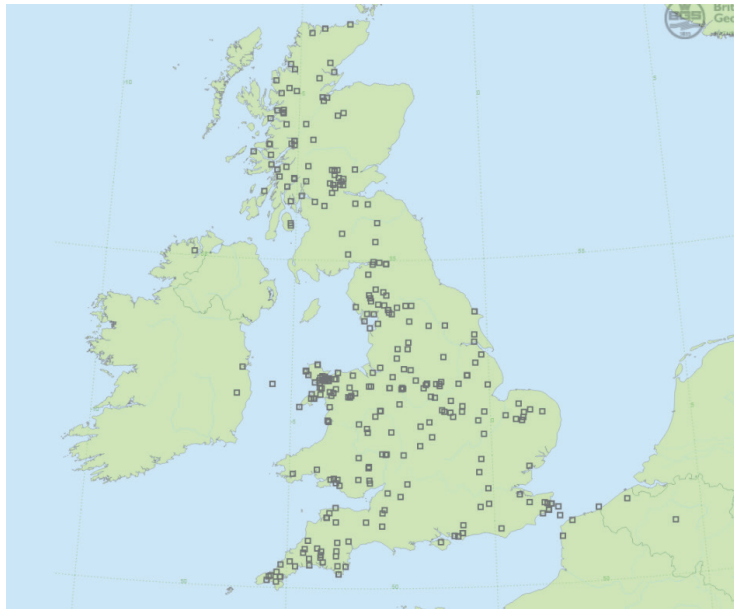


Figure 1. Map showing the location of UK earthquakes since 1048 AD. (UK Historical Earthquake Database, BGS (2018a), reproduced with the permission of the British Geological Survey © NERC. All rights reserved.)

Table 1. Extract from BS EN 1990 Table B1 showing definitions of consequence classes.

Consequence Class	Description	Example of buildings and civil engineering works
CC3	High consequence for loss of human life; economic, social or environmental consequences very great	Grandstands, public buildings where consequences of failure are high (e.g. a concert hall)
CC2	Medium consequence for loss of human life; economic, social or environmental consequences considerable	Residential and office buildings, public buildings where consequences of failure are medium (e.g. a car park)
CC1	Low consequence for loss of human life; economic, social or environmental consequences small or negligible	Agricultural buildings where people do not normally enter (e.g. storage buildings, greenhouses)

Seismic design is therefore required for structures/facilities where:

- structural failure poses a large threat of death or injury, e.g. nuclear power plant;
- a structure forms a major part of national infrastructure, e.g. a major bridge;
- a failure of the structure would impede the regional and national ability to deal with a disaster;
- the structure is supporting the strengthening or upgrading of a historic structure which forms part of national heritage.

1.2 Volcanicity

The UK is no longer volcanically active but remains subject to the influence of distant volcanic eruptions due to atmospheric dispersion of air-borne erupted fine particulates (ash), which may remain in atmospheric suspension or be deposited at ground level.

This technical volume considers the potential for volcanic ash hazards associated with a volcanic event; in the context of the UK, this includes the risk of:

- clogging of air and water intake, handling and filtration systems;
- adverse impact upon mechanical and electrical plant, including water treatment plant;
- flashover electrical short of power lines and transformers;
- impact upon external communication equipment;
- obscuring of road markings;
- increased corrosion of components;
- respiratory health impact.

The incidence and distribution of these hazards within the UK is primarily a function of the occurrence of a volcanic event (within relative global proximity and of sufficient explosivity) to generate large volumes of fine ash projected into the upper atmosphere, together with a sustained weather pattern permitting the transport of suspended ash over the UK.

The most recent notable incidences are the eruption of the Icelandic volcanoes Grímsvötn in 2011 and Eyjafjallajökull in 2010; the latter causing major disruption to UK (and worldwide) air traffic. Total losses have been calculated in the region of \$5 billion (*Oxford Economics, 2010*). Although recording stations registered ash dust particles at ground level, no significant adverse ground-level impacts were documented.

Historical records describe prolonged eruptions at the Icelandic Laki fissure and volcanically associated Grímsvötn volcano from 1783 to 1784. This had the foremost impact on Iceland, with significant loss of life due to direct and indirect causes. In Europe and North America there was extreme and unusual weather for two to three years, with the 'Laki haze' of fine ash and sulphuric acid aerosol affecting the northern hemisphere for months.

Within the recent Holocene geological history of approximately 10,000 years, ash from numerous volcanic eruptions in Iceland can be found in peat bogs and lake sediments across Scotland and the rest of northern Europe.

1.3 Geological instability

Geological instability, where there is a loss of ground support, may be caused by natural or man-made hazards. The potential for geological instability is widespread within the UK, with a consequent risk of:

- significant damage to infrastructure, and associated plant and equipment;
- loss of serviceability, i.e. loss of, or reduction in, function;
- loss of access routes external to the infrastructure site;
- injury/death;
- requirement for future mitigation.

The character and magnitude of the ground movements, as well as the nature of the infrastructure and its sensitivity to movement, is of importance as it will determine the significance of the impact. The utilisation of best practice design may provide sufficient mitigation for the development of new infrastructure, but existing infrastructure may be vulnerable to prevailing conditions.

Geological instability may be broadly classified within the following categories:

- natural ground instability, e.g. landslides;
- natural ground movement, e.g. shrink-swell clays;
- man-made ground instability, e.g. mining.

The incidence and distribution of these hazards within the UK is primarily a function of the underlying geology, but additional factors of influence include topography, weather, and human activities including land use, construction and resource exploitation.

The British Geological Survey (BGS) reports that shrinking and swelling of the ground caused by shrink-swell clays (often reported as subsidence) is one of the most damaging geohazards in Great Britain today, costing the economy an estimated £3 billion over the past decade. Landslides — the movement of rock, earth, or debris down a sloped section of land — although not having the same financial cumulative impact, have individually had significant adverse impacts with loss of life or loss of key access routes. The most notable landslide disaster in living memory occurred in 1966 with the Aberfan colliery spoil tip collapse, which engulfed a primary school and other buildings resulting in the loss of 144 lives. Since 2001, 10 fatalities have resulted from landslides. More recent impacts have included the collapse of buildings, rail derailments, road closures and commuter disruption.

2. Description of main phenomena

2.1 Seismicity

An earthquake occurs when two tectonic plates of the Earth's crust displace relative to each other. Generally, three types of displacement are possible: plates sliding past each other, plates running onto one another, plates moving away from one another. The focus of an earthquake is its origin point below the Earth's surface, and the location directly above it on the Earth's surface is the epicentre.

The level of shaking experienced during an earthquake is affected by the earthquake magnitude and the amount of energy released, the distance from the earthquake epicentre, and the ground conditions. Seismic waves are distinguished into two broad types: body waves and surface waves (*Figure 2*). Body waves consist of primary or P-waves, and secondary or S-waves; surface waves comprise Rayleigh waves and Love waves. Body waves propagate through the Earth, whereas surface waves propagate along the Earth's surface. P-waves are longitudinal and compressional in nature, whereas S-waves are transverse *shear waves**. P-waves are faster than S-waves and can propagate in any medium, whereas S-waves propagate in solids only. Rayleigh waves propagate with motions similar to those of water waves and are slower than S-waves. Love waves are polarised shear waves and exist only in a semi-infinite medium overlain by an upper finite layer. Another type of wave, the Stoneley wave, propagates along a solid-fluid boundary under specific circumstances.

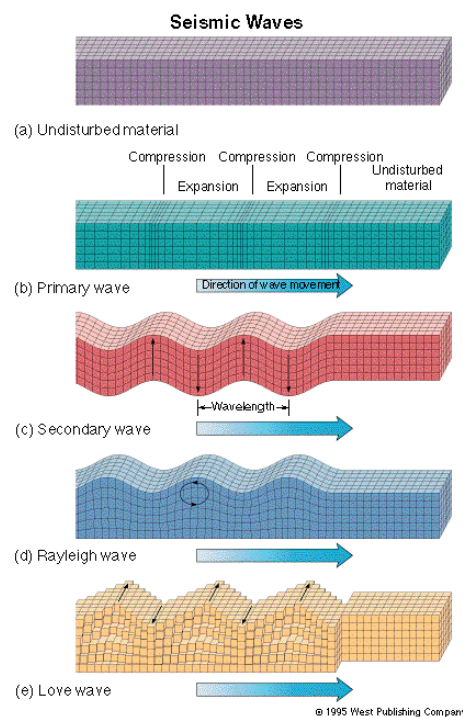


Figure 2. Schematic of different forms of seismic waves (USGS, 2018).

*All technical terms marked in blue can be found in the Glossary section.

2. Description of main phenomena

The UK is situated within the Eurasian tectonic plate; *Figure 3* shows a map of the tectonic plates around the world. However, earthquakes in the UK are not directly driven by plate boundary movement. In general, they occur at faults located either at the surface or several kilometres below the surface (*Figure 4*). *BGS (2018b)* suggests that earthquakes in the UK are driven by regional compression due to the motion of tectonic plates and uplift due to the melting of ice sheets that covered the UK many thousands of years ago. The intensity of earthquakes that occur due to movement of faults is typically lower than those that occur due to plate boundary movement, where more energy is released. As such, the intensity of earthquakes in the UK is often much lower than observed at other places on Earth.

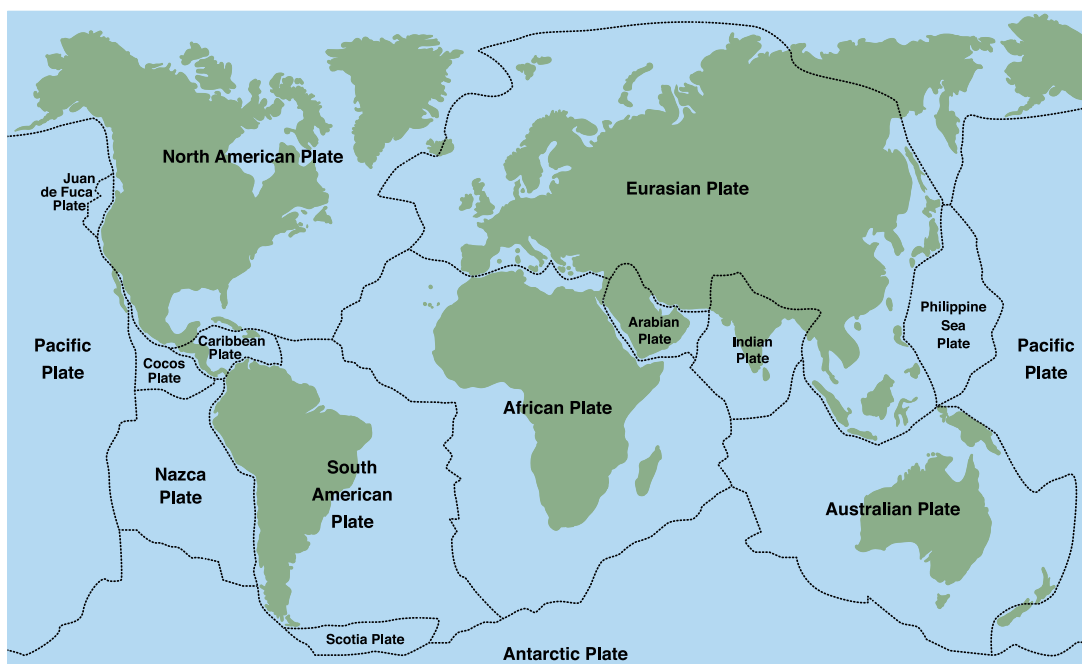


Figure 3. Map of Earth's tectonic plates (Source: Shutterstock).

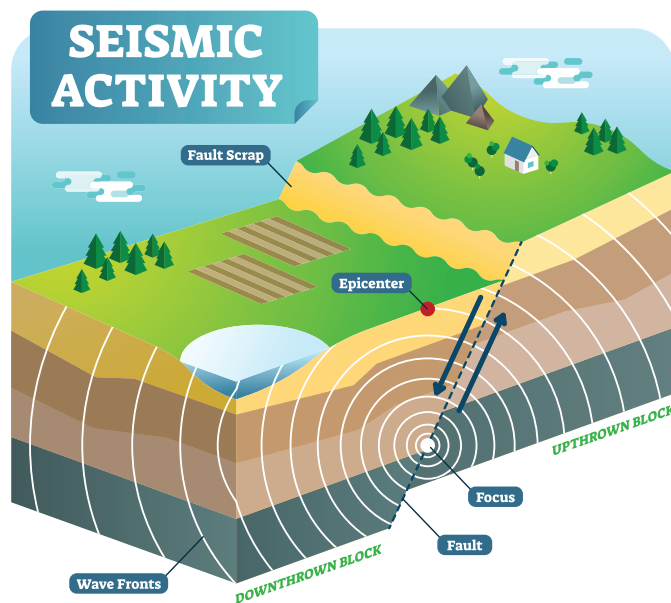


Figure 4. Illustration of the occurrence of an earthquake due to the movement of a fault between two plates (Source: Shutterstock).

2. Description of main phenomena

2.2 Volcanicity

Volcanic explosive eruptions can produce large quantities of fragmented pulverised rock, known as 'tephra'. The smallest fragments, from 2 mm down (with fine defined as <0.063 mm) are described as 'volcanic ash' and can be produced in huge volumes (*Figure 5*). The *fragmentation* of molten rock (magma) is controlled by several factors (*Durant et al., 2009*):

- internal: e.g. ascent rate, dissolved volatile content;
- external: e.g. subaerial, subaqueous, subglacial vent conditions.



Figure 5. Eyjafjallajökull eruption 2010. (Image: Árni Friðriksson.)

Silicic eruptions, comprising igneous rock rich in silica, produce more fine ash (<0.063 mm) than low silica content *basaltic eruptions* (often 30 to 50% fine ash in the former, compared to 1 to 4% in the latter) (*Durant et al., 2009*). Interaction with glacial meltwater during subglacial silicic eruptions can enhance fragmentation, leading to *phreatoplinian type eruptions* where magma interacts violently with water residing in caldera lakes, with more than 90% of ash finer than 1 mm (*Stevenson et al., 2015*). *Figure 6* shows an example of an ash particle.

2. Description of main phenomena

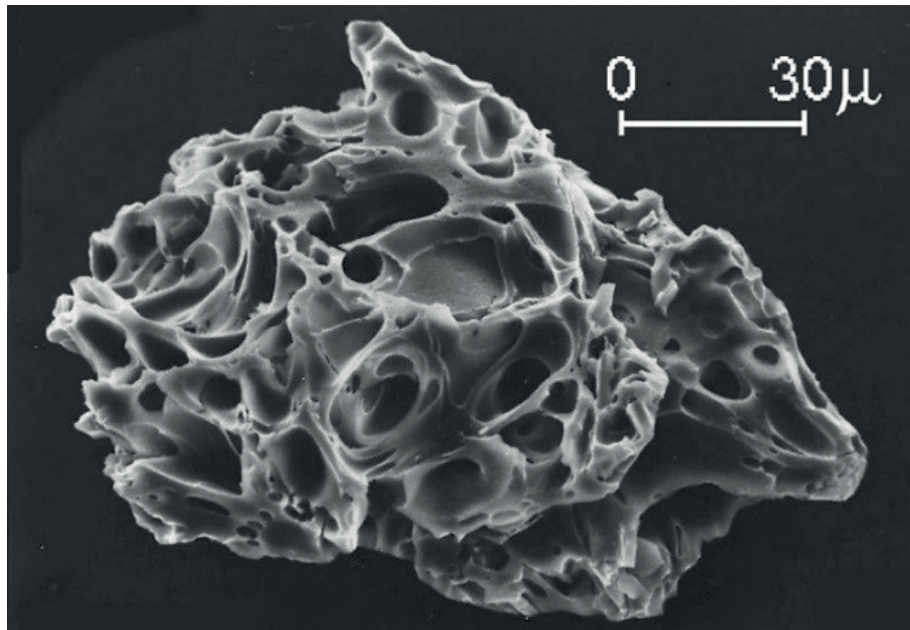


Figure 6. Microscopic image of an ash particle. (Image: A.M. Sarna-Wojcicki, USGS.)

Ash particles are incorporated into eruption columns which are convected up into the atmosphere. At a height where the bulk density of the column is the same as the surrounding atmosphere, the column will cease rising and start moving laterally and gradually dispersing.

Ash fallout occurs immediately after eruption and is primarily controlled by particle size, shape and density. The coarsest particles fall out close to the source, with a subsequent reduction of particle size as a function of the distance from the source. This results in an ash fall deposit which generally decreases in thickness and grain size exponentially with increasing distance from the volcano, as a function of eruption type and magnitude (Pyle, 1989).

Lateral dispersion of the ash component within the plume is controlled by high-altitude wind direction and speed, and atmospheric conditions (humidity). The ash may be deposited hundreds to thousands of kilometres from the volcano, depending on eruption column height, particle size of the ash and climatic conditions. A satellite image of the ash plume from the Eyjafjallajökull 2010 eruption is provided in Figure 7. Fine ash particles may remain in the atmosphere for days to weeks.

2. Description of main phenomena

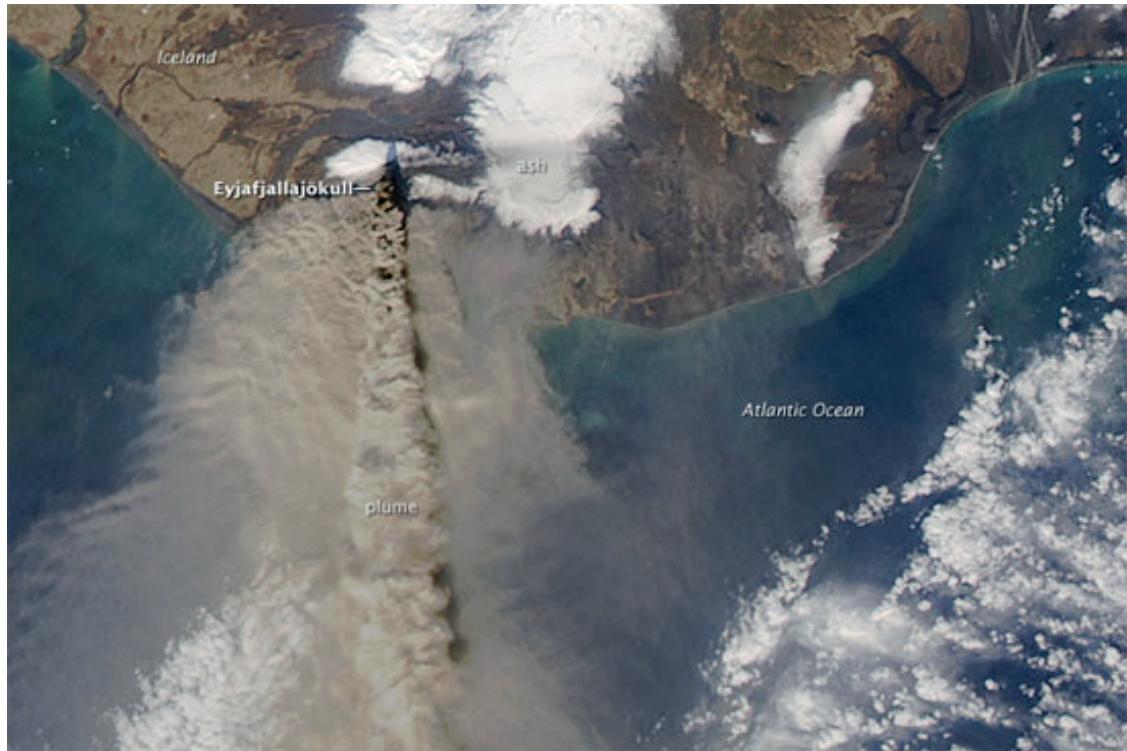


Figure 7. Ash plume from the Eyjafjallajökull eruption 2010. (NASA image courtesy Jeff Schmaltz, MODIS Rapid Response Team at NASA GSFC.)

The impact of ash is dependent upon the atmospheric concentration and particle size/chemistry, as well as thickness, speed and duration of deposition. At ground level, impacts have been historically classified with reference to ash deposition thickness. More recently, ash loading (in mass per unit area) has become a preferred measure of intensity as it is more informative when considering impacts to structures. It should be noted that a water-saturated ash deposit can be up to twice the load of a similar thickness of dry ash (Jenkins *et al.*, 2015; Loughlin *et al.*, 2015).

Potential impacts from thin (~ 1 to 10 mm) ash falls are presented in Table 2, with increasingly adverse impacts for thicker deposition.

2. Description of main phenomena

Table 2. Potential impacts from thin ash falls alongside the relevant ash characteristics (Jenkins et al., 2015).

	Potential consequences of (~ 1 to 10 mm) ash falls	Relevant ash characteristics
Public health	Casualties from fall deposits may occur, e.g. due to people falling from roofs during clean-up. However, the most commonly reported public health effects of ash exposure are irritation of the eyes and upper airways and exacerbation of pre-existing respiratory conditions, such as asthma. Individuals who may be exposed to ashy conditions will require protective clothing and masks.	Particle size; Mineral composition; Surface area; Morphology; Soluble salt burden; Thickness.
Infrastructure	Most road markings obscured; traction and visibility problems. Airports often closed and requiring clean-up. Increased wear of engine and brakes. Possible signal failure on railway lines.	Thickness; Particle size; Mechanical strength.
	Possible clogging of air- and water-handling and filtration systems, mechanical and electrical equipment and abrasion damage by waterborne ash to pump impellers and turbines. Minor short-term increases, particularly in streams and small reservoirs, in elements leached from ash. Blockage of water intake structures, particularly in streams. Suspended ash in water intakes and sewer lines a possible threat to water/wastewater treatment plants. 'Open' systems (e.g. with open air sand filters) are more vulnerable.	
	Potential flashover of power lines and transformers (particularly in light wet weather conditions). Corrosion and/or abrasion of, e.g. paintwork, windscreens, metallic elements, some air- and water-handling, mechanical, electrical equipment or engines. Possible damage to external telecommunication components or power cables.	Soluble salt burden; Conductivity; Abrasiveness; Particle size.
Buildings	No structural damage. Possible infiltration and internal contamination and corrosion of metallic components. Roofing materials may be abraded or damaged by human actions during ash removal.	Loading; Soluble salt burden; Abrasiveness.
Clean-up	Minor clean-up required: sweeping of roads, paved areas and roofs/gutters usually sufficient. Ash falls of only a few mm depth will generate large volumes of ash for collection and disposal and clean-up is a time-consuming, costly and resource-intensive operation. Water demand may remain high for months afterwards if wind-remobilised ash requires dampening.	Thickness; Density; Abrasiveness.
Economy	Some economic activities may increase, e.g. volcano tourism, but most will be disrupted. Disruption to work and travel. Clean-up cost. Increased maintenance costs (e.g. at water supply plants where sand filter beds may need to be cleaned more frequently). Increased labour and health and safety requirements.	Thickness; Presence.

2. Description of main phenomena

With regards to health impact, the penetration of ash particles into the respiratory tract is dependent on particle size. Larger particles ($>10\ \mu\text{m}$ diameter) lodge in the upper airways, while those in the 4 to $10\ \mu\text{m}$ size range deposit in the trachea and bronchial tubes. Very fine ($<4\ \mu\text{m}$ diameter) particles may penetrate deeper into the lungs (*Horwell and Baxter, 2006*).

The majority of *cryptotephra* layers in northern Europe are of Icelandic origin. The graphs in *Figure 8* show the size distributions of Icelandic ash grains from across the UK, including samples collected during the Eyjafjallajökull 2010 and Grímsvötn 2011 eruptions (*Stevenson, 2013*). Most of these deposits are found in Scotland, northern England and Ireland. *Figure 8(a)* has results obtained by measuring grains down a microscope; the results presented in *Figure 8(b)* were collected by a laser technique. The microscope method misses grains of $<10\ \mu\text{m}$ diameter, but both methods give similar peaks showing that the smallest grains are a minor component.

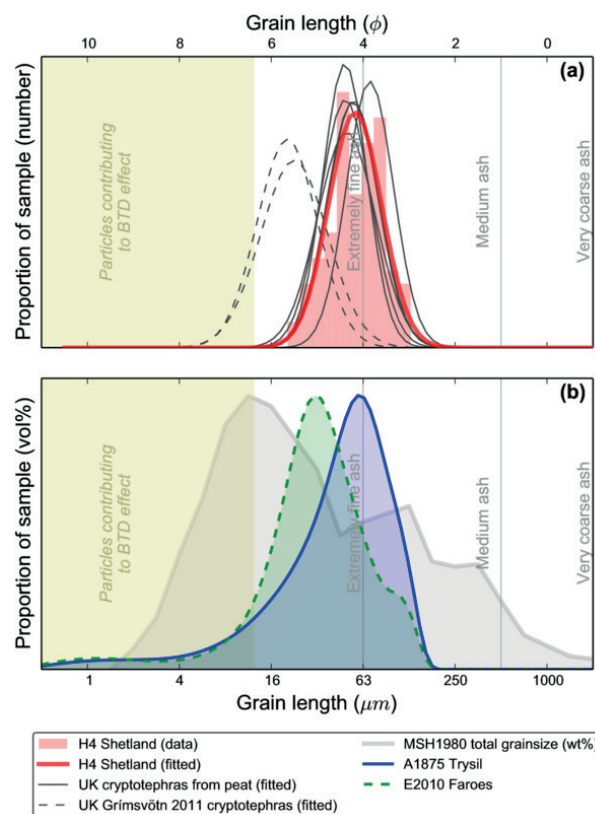


Figure 8. The size distribution of cryptotephra grains observed in soils from the UK and north-west Europe (a) Results obtained by measuring grains down a microscope and (b) Results were collected by a laser technique (Stevenson et al., 2015).

Although the UK has no active or credible volcanism, it lies within the influence of active or potentially active volcanoes which have been active within the last 10,000 years and are classified as a possible source of a hazard (*Figure 9*). The primary hazard source is from Iceland, with lower hazard risks associated with the remaining locations.

2. Description of main phenomena



Volcanic Sources around the UK

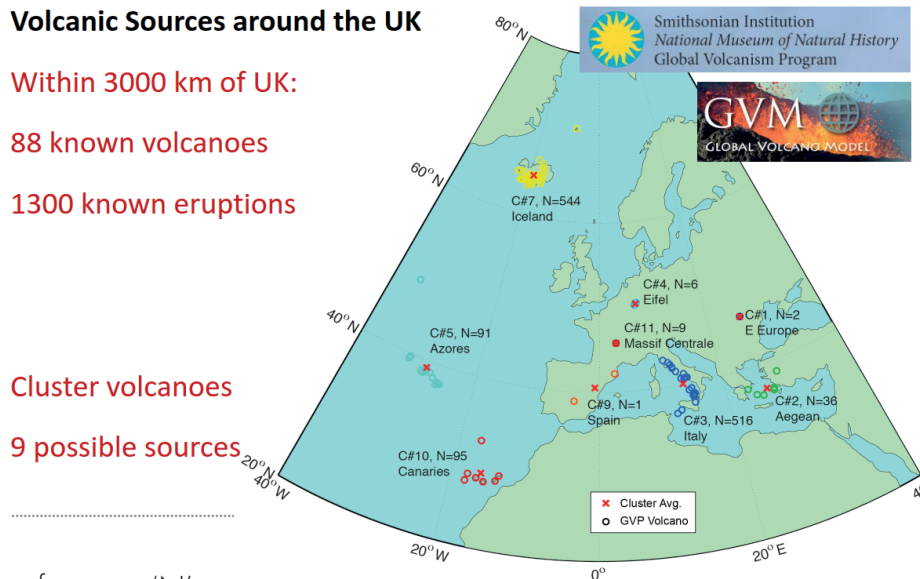
Within 3000 km of UK:

88 known volcanoes

1300 known eruptions

Cluster volcanoes

9 possible sources



'C' — cluster reference, 'N' — eruption occurrence count

Figure 9. Credible volcanic sources with the potential to impact the UK. (Work undertaken by the University of Bristol for NERC and funded by EDF, reference: NERC Environmental Risks to Infrastructure Innovation (NE-M008878-1).)

2.3 Geological instability

Ground instability, as defined by the BGS, refers to the propensity for upward, lateral or downward movement of the ground that can be caused by several natural geological or man-made hazards. Some movements associated with particular hazards may be gradual and of small scale (millimetres), whilst others may be sudden and larger in scale (metres or tens of metres).

The phenomenon can be broadly grouped within three categories: natural ground instability, natural ground movement, and man-made ground instability. The primary hazards within each of the three categories are identified below:

Natural ground instability:

- landslide;
- ground dissolution;
- soil creep;
- collapsible ground;
- running sand/liquefaction.

2. Description of main phenomena

Natural ground movement:

- shrink-swell clays.

Man-made ground instability:

- mining;
- ground water management — shallow compaction;
- ground water management — peat oxidation;
- ground water abstraction;
- underground construction;
- oil and gas production.

There is extensive literature and guidance on all aspects. For the purposes of this technical volume, the hazards associated with landslide, ground dissolution, shrink-swell clays and mining — which are of overall greater impact in the UK — are discussed in more detail in [Sections 2.3.1 to 2.3.4](#).

2.3.1 Landslides

The term 'landslide', as defined by [Cruden \(1991\)](#) for the Working Party on World Landslide Inventory, denotes 'the movement of a mass of rock, debris or earth down a slope' (under the force of gravity). The pre-requisite for landslide instability is the occurrence of conditions such that the force of gravity exceeds the strength of the material forming a slope. This is primarily a function of the morphological nature and the scale of the slope, as well as the material properties and groundwater characteristics of sloping material. Susceptibility of land to sliding is dependent upon these factors, and it will normally remain stable unless: (i) the landscape is altered by erosion or excavation; (ii) the land is loaded; (iii) groundwater pressure increases.

Landslide occurrence within the UK has been defined within the broad categories of:

- coastal landslides — predominantly associated with coastal erosion, with the east coast and parts of the south coast of England most notably being impacted due to the presence of soft erodible soil and/or rock deposits;
- inland landslides on natural slopes (natural causes) — often at sites where the base of the slope is being undercut by rivers, steep hillside slopes, or slopes with abrupt changes in gradient;
- inland landslides on natural slopes (human causes) — these are largely produced by the disturbance of pre-existing ancient landslides as a consequence of human intervention (e.g. construction of new roads);

2. Description of main phenomena

- landslides in cuttings, fills and waste dumps — these are produced wholly as a consequence of human activity (e.g. Aberfan colliery spoil tip collapse, 1966).

There have been numerous approaches to classifying the types of natural failure. However, there is no consensus within the international geotechnical community on which landslide classification system to use — all existing systems have shortcomings. The classification of landslides by the BGS currently follows the scheme based on *Varnes (1978)* and *Cruden and Varnes (1993)*. The scheme terminology is also that suggested by the UNESCO Working Party on the 'World Landslide Inventory'. The main classification criteria are:

- type of movement (falls, topples, slides, spreads, flows);
- type of material involved in the movement (rock, debris, earth).

The BGS has produced a graphic representation of the classification of landslides (*Figure 10*).

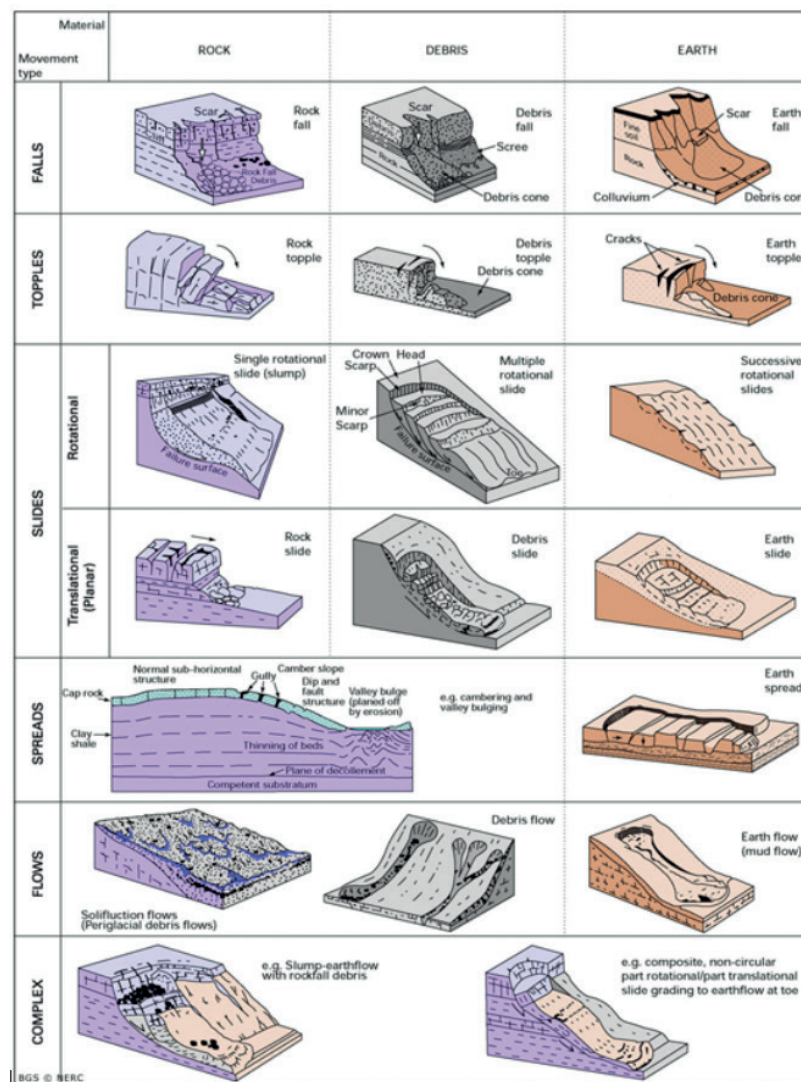


Figure 10. Graphic representation of the classification of landslides. (Reproduced with the permission of the British Geological Survey © NERC. All rights reserved.)

2. Description of main phenomena

The character of landslide failures has been further defined in terms of the velocity of the moving mass. **Table 3** shows the velocity scale proposed by *Cruden and Varnes (1993)*, which also includes an indication of *probable destructive significance*, the *actual destructive significance* being dependent upon the presence of sensitive receptors within the failure path, e.g. people, structures, and areas of environmental importance.

Table 3. Landslide velocity scale as proposed by Cruden and Varnes (1993).

Velocity class	Description	Velocity (mm/sec)	Typical velocity	Response	Probable destructive significance
7	Extremely rapid	5×10^3	5 m/s	Nil	Catastrophe of major violence; buildings destroyed by impact of displaced material; many deaths; escape unlikely
6	Very rapid	5×10^1	3 m/min	Nil	Some lives lost; velocity too great to permit all persons to escape
5	Rapid	5×10^{-1}	1.8 m/hr	Evacuation	Escape evacuation possible; structures, possessions and equipment destroyed
4	Moderate	5×10^{-3}	13 m/month	Evacuation	Some temporary and insensitive structures can be temporarily maintained
3	Slow	5×10^{-5}	1.6 m/yr	Maintenance	Remedial construction can be undertaken during movement; insensitive structures can be maintained with frequent maintenance work if total movement is not large during a particular acceleration phase
2	Very slow	5×10^{-7}	15 mm/yr	Maintenance	Some permanent structures undamaged by movement
1	Extremely slow			Nil	Imperceptible without instruments; construction possible with precautions

2. Description of main phenomena

2.3.2 Ground dissolution

The term dissolution describes the process of chemical weathering of bedrock in which the combination of water and acid slowly removes mineral compounds from solid bedrock and carries them away in liquid solution, producing underground cavities and cave systems.

The BGS defines the three common rocks that dissolve as rock-salt, gypsum and limestone (including chalk). The dissolution of these rocks produces caves, sinkholes, sinking streams and large springs, creating a landscape known as karst. These cavities can ultimately cause localised collapse of the overlying rocks and deposits, with consequential hazards comprising subsidence and sinkhole formation, uneven rockhead, reduced rock-mass strength, and rapid groundwater flow.

Rock-salt is extremely soluble and has usually been removed from the near-surface zone by natural dissolution. Gypsum is highly soluble and can cause problems if it dissolves. Limestone is moderately soluble and is removed over a longer timescale, but contains significant cavities.

The distribution of soluble rocks across the UK is presented in *Figure 11*.

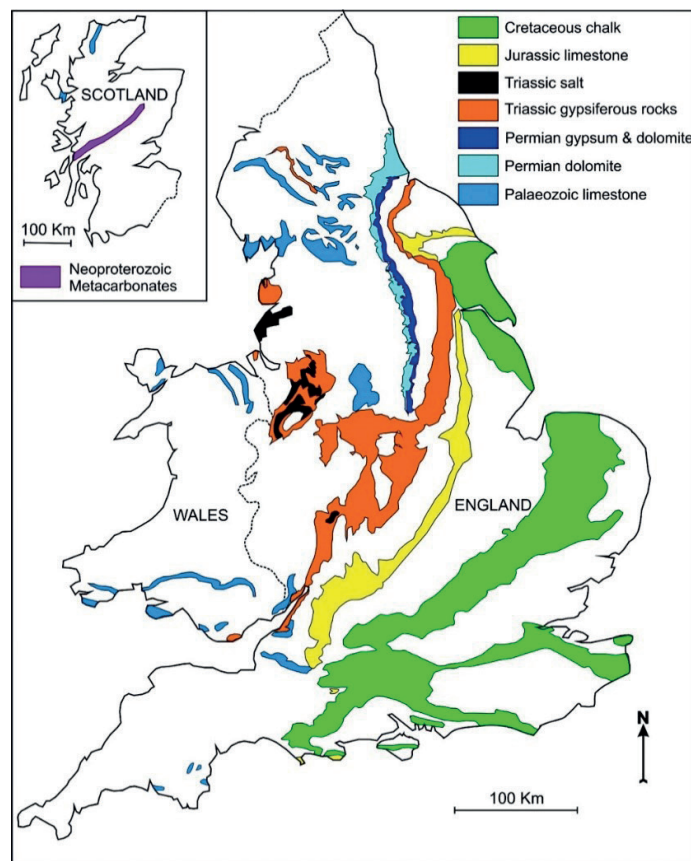


Figure 11. Distribution of soluble rocks across the UK. (Reproduced with the permission of the British Geological Survey © NERC. All rights reserved.)

2. Description of main phenomena

The impact of the collapse of karstic ground, although localised, can be significant as illustrated in [Figure 12](#) which shows the collapse of four garages into a subsidence hollow caused by the dissolution of gypsum at Ripon, North Yorkshire in 1997.



Figure 12. The impact of the collapse of karstic ground — collapse of four garages into a subsidence hollow caused by the dissolution of gypsum at Ripon, North Yorkshire in 1997. (Reproduced with the permission of the British Geological Survey © NERC. All rights reserved.)

2.3.3 Shrink-swell clays

This phenomenon describes the expansive behaviour of certain clay soils which exhibit a volume change due to natural climatic or human-induced moisture content variations. Swelling pressures can cause heaving, or lifting, of structures; shrinkage can cause variable settlement with potential consequent adverse effect on structures and infrastructure. Although the effect is generally confined to a shallow depth, it remains the geohazard with the singular greatest financial impact in the UK, costing an estimated £3 billion over the past ten years ([BGS, 2012](#)). The most vulnerable structures are lightly-loaded, shallow-founded buildings such as housing. Most energy infrastructure projects could be expected to be of a nature or designed such that the impact would not be significant.

The majority of geological soils susceptible to shrink-swell behaviour are located within the south-east of England, and are associated with particular geological formations as illustrated in [Figure 13](#). The combination of areas of high population and dense infrastructure with the presence of such soils has strongly contributed to the magnitude of the costs associated with this hazard.

2. Description of main phenomena

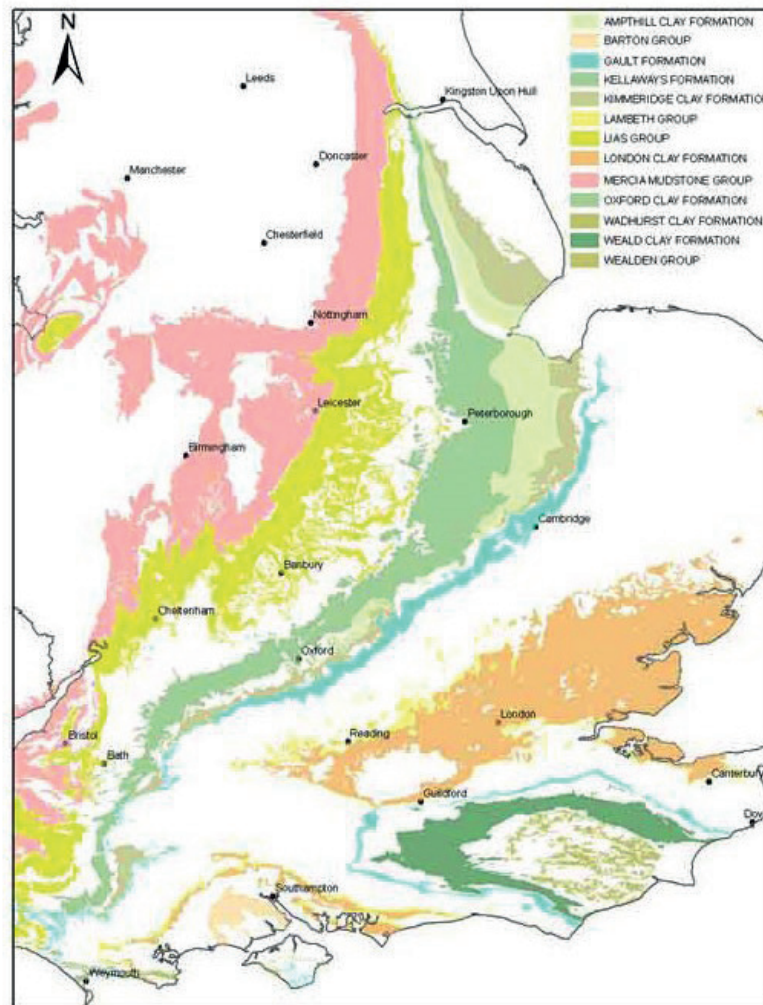


Figure 13. Locations of geological soils susceptible to shrink-swell behaviour in the UK. (Reproduced with the permission of the British Geological Survey © NERC. All rights reserved.)

2.3.4 Mining

The UK's long history of mining of non-ferrous minerals, particularly copper and tin, began in the Bronze Age. The Romans subsequently developed lead mines, from which they also extracted silver and gold. Although coal mining in the UK dates back to Roman times, with localised extraction of coal continuing into the Medieval period and increasing in the 18th century, the Industrial Revolution in the 19th century saw a dramatic increase in the exploitation of coal and iron within large areas of England, South Wales and Central Scotland.

Additionally, mining — both underground and surface extraction — of industrial minerals and construction materials (including potash, salt, brick clay, sandstone, slate, oil shales, china clay, sand and gravel, and hard rock) has been historically undertaken and, for a number of these materials, continues to be a significant industry.

2. Description of main phenomena

The BGS has been collecting locational and other information about operating and historical mineral workings in the UK since its formation in 1835, and has produced a digital dataset, BRITPIT, capturing this information. A visual representation of this is provided in [Figure 14](#) which includes both surface and underground mine workings.

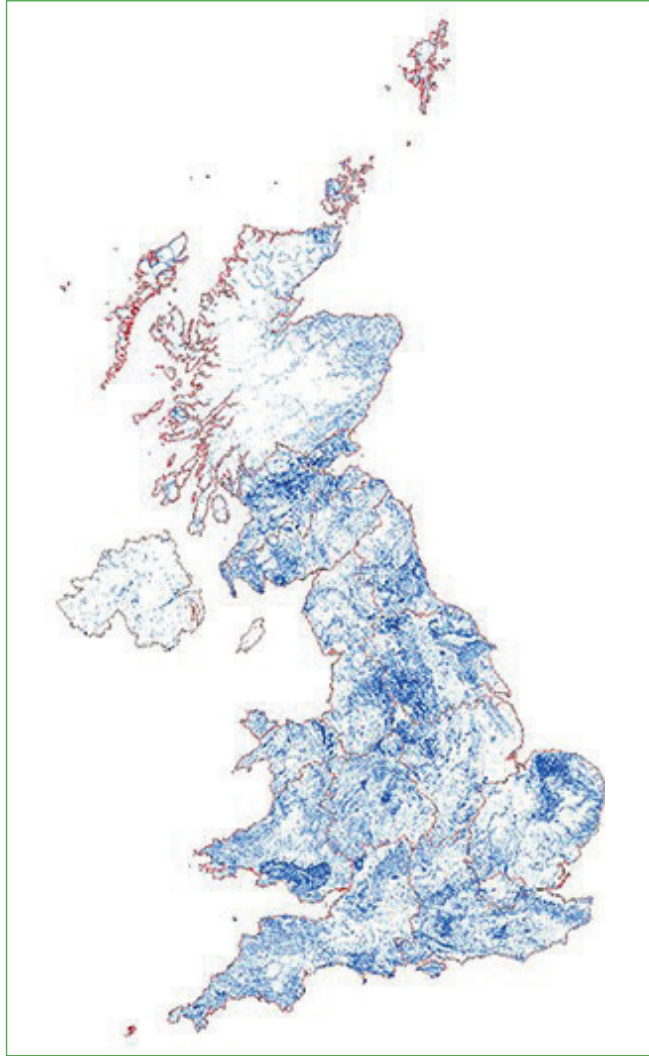


Figure 14. Map highlighting the locations of operating mineral workings in the UK. (Reproduced with the permission of the British Geological Survey © NERC. All rights reserved.)

Underground mining, which presents the most significant mining geohazard in terms of geological instability, may be broadly grouped within the following categories:

- coal and associated minerals;
- vein minerals including replacement deposits, e.g. lead;
- bedded (sedimentary) iron deposits (non-coalfield);
- rock mining, e.g. salt;
- evaporites, e.g. potash.

2. Description of main phenomena

Underground mining has been undertaken by the creation of *adits* or sinking of shallow to deep shafts and bell pits to allow the mineral deposits to be exploited, with the subsequent development of areas of extraction, including secondary shafts and underground roadways. The underground cavities, including shafts and adits, were either left open or partially or fully backfilled with unwanted spoil from the mining. Shafts and adits were often capped, but with material which was likely to deteriorate, e.g. timber.

The collapse of overlying strata into the zones of extraction potentially results in subsidence of the ground surface, the amount of which is dependent upon several factors, including the size and spatial extent of the cavities, whether they are open or filled, the depth from the surface and the nature of the overlying geology.

Subsidence at the surface can manifest itself in many ways ranging from insignificant and gradual movement through to sudden significant movement, and from very localised to extensive ground movement, including the opening of holes at the surface. In many areas of historical coal mining, subsidence has already occurred; however, there are significant areas where the potential for future subsidence remains.

Extraction of minerals other than coal has potentially created larger cavities within more competent strata. These may remain open and effectively stable for significant periods into the future and beyond the life span of construction developments, but remain a potential hazard to be addressed in terms of risk.

Surface extraction has left residual footprints in the shape of former pits, which may be: open; partially or fully infilled with water and/or fill materials. Fill materials, which may comprise unwanted waste residues from the original excavation or imported material of variable origin, are mostly uncompacted. Their composition presents behavioural characteristics (e.g. low bearing capacity and high settlement) that are generally unfavourable to developments.

An associated hazard to subsidence is the presence of noxious and explosive mine gases including combustible gases (methane, hydrogen and carbon monoxide) and excess inert gases (nitrogen and carbon dioxide). The migration of these to the surface in sufficient concentration primarily represents a gas poisoning safety risk to occupants of enclosed structures, notwithstanding the risk of explosion.

3.1 Seismicity

Earthquakes are recorded by seismometers (or seismographs). Seismometers are instruments that use electronic sensors, amplifiers and recording devices to measure acceleration or velocity of ground movement and facilitate real-time processing and analysis. Since the amplitude of seismic waves decays with distance, a network of monitoring stations is used to record earthquake signals.

The data recorded by seismometers are used to measure many different characteristics of earthquakes, such as magnitude (a measure of the size of the earthquake, independent of a location relative to the source) and intensity (a measure of the strength of the earthquake, at a location relative to the source).

For structural design, seismic hazards are typically defined by a single parameter, e.g. the value of the peak ground acceleration (PGA). PGA is a measurement of how much the ground moves during an earthquake and has a standard unit of measurement of m/s^2 .

Eurocode 8 requires that 'national territories shall be subdivided by the National Authorities into seismic zones, depending on the local hazard. By definition, the hazard within each zone is assumed to be constant. National Authorities are the relevant regulatory authorities of each European member state'. Maps have been produced for the UK National Annex to Eurocode 8 (BS EN 1998-1) with the purpose of displaying average values of PGA for areas across the UK. The modelling, performed by the BGS, was undertaken as a supporting document for the UK National Annex to BS EN 1998-1 and PD 6698; 2009. The model for these maps was generated using a combination of the Next Generation of Ground-Motion Attenuation models (NGA) following a seismic program run by the Pacific Earthquake Engineering Research Centre (PEER) and a slightly less complex model focused on the UK (*Musson and Sargeant, 2007*).

Ground-motion attenuation models are derived using empirical relationships that express the variation of ground motion with the magnitude and distance from the source (*Acun et al., 2011*). For each zone a mean value of the horizontal components of PGA was taken from the model and input in the map (see *Figure 15*).

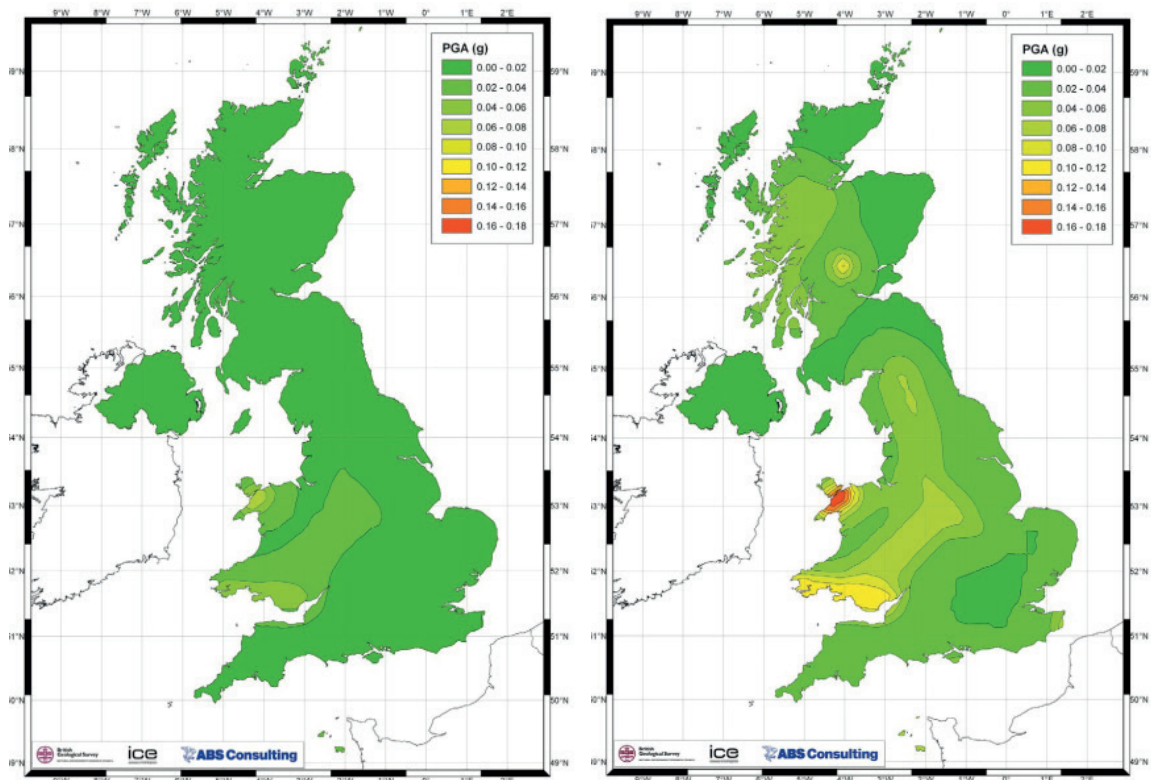


Figure 15. UK peak ground acceleration values for 475-year return period (left) and 2500-year return period (right) (Musson and Sargeant, 2007).

3.2 Volcanicity

The occurrence and scale of an ash fall within the UK is dependent on several pre-disposition factors which include:

- a volcanic explosive event of sufficient magnitude, duration and type to produce a large volume of fine ash that is projected high into the atmosphere;
- production of sufficiently fine ash that can be transported within the atmosphere over the significant distance to the UK;
- a sustained weather pattern that entrains the ash and transports it to the UK in sufficient concentration.

The most widely used measure of explosive volcanic intensity is the Volcanic Explosivity Index (VEI), ranging between 0 and 8 (Figure 16). Volcanoes can display variable VEI in different eruptions. In Figure 16, it can be seen that there is a requirement for a minimum intensity of VEI 2 for the injection of moderate substantial amounts of fine ash into the atmosphere.

3. Observations, measurement techniques and modelling tools

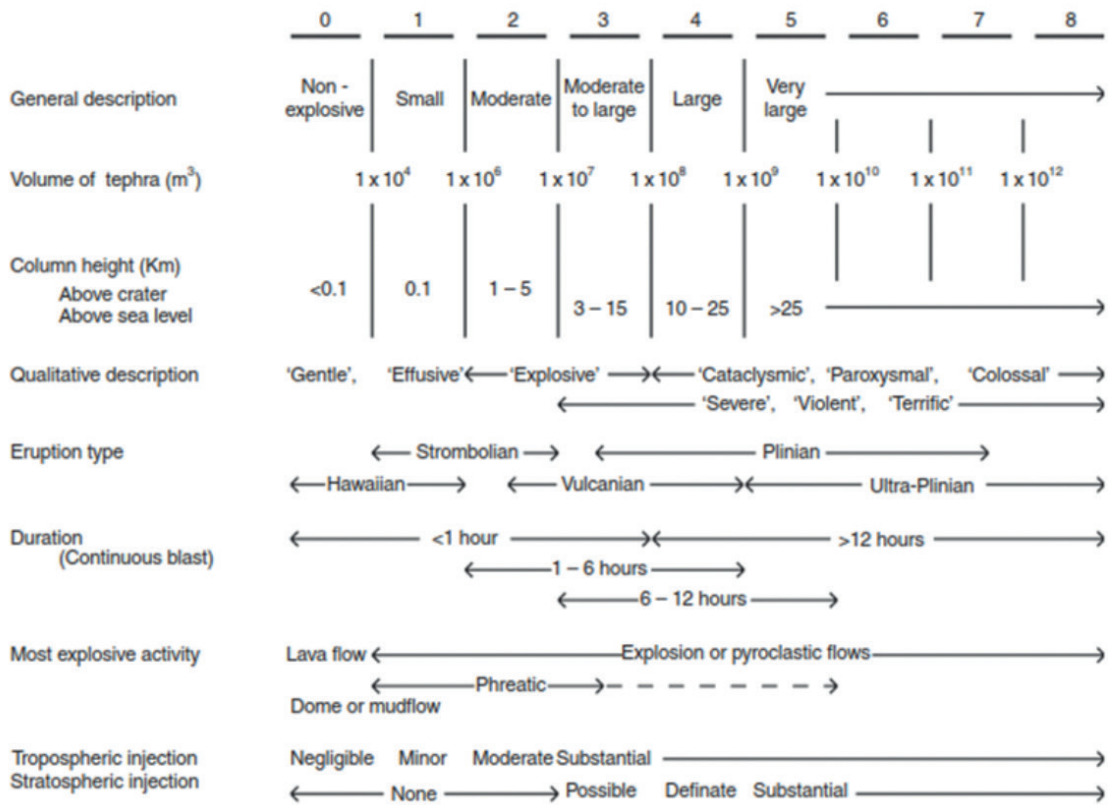


Figure 16. Scheme to illustrate the assessment of VEI (Sparks et al., 2013).

Volcanic events are monitored both at national and global levels with collaboration between the monitoring organisations. For example, volcanism in Iceland is monitored by the Icelandic Meteorological Office (IMO), a governmental institution. The IMO participates in international weather and aviation alert systems, which include the London Volcanic Ash Advisory Centre (VAAC), and the Icelandic Aviation Oceanic Area Control Center (OACC).

The London VAAC is one of nine International Civil Aviation Organization (ICAO) designated centres, responsible for issuing advisories for volcanic eruptions originating in Iceland and affecting the north-eastern corner of the North Atlantic, including Scandinavia. Ash events from and affecting mainland Europe, western Russia, Central and Southern Asia, and Africa are covered by the Toulouse VAAC.

London VAAC monitors ash within the atmosphere through several methods (Met Office, 2018). These are outlined in more detail in Sections 3.2.1 to 3.2.7.

3. Observations, measurement techniques and modelling tools

3.2.1 Satellite-based instruments

Satellite imagery products are the starting point for data collection after receiving news of an eruption. Data from different meteorological satellites are exchanged worldwide. Visible and infrared images are used to monitor the location of volcanic ash over large geographical areas. Multi-spectral sensors on both types of satellite platforms facilitate the production of derived imagery that can be used to identify ash-contaminated areas. Some multi-spectral data (e.g. over Europe and Africa) can be used to provide estimations of ash particle size, ash height and ash column mass loading (i.e. how much ash is in a vertical atmospheric column).

3.2.2 Radar

When an eruption takes place in Iceland, the near vent plume height is monitored by the IMO in near real-time using their ground-based radars.

3.2.3 LIDAR

A Light Detection and Ranging (LIDAR) device is an optical remote-sensing instrument, which can be located on the ground, mounted on an aircraft, or be satellite-based, and can be used to observe the location and vertical profile of aerosols such as volcanic ash. LIDARNET is a UK network operated by the Met Office, of approximately 40 ground-based Laser Cloud Based Recorders (LCBRs) — commonly known as *ceilometers*. LCBRs and LIDAR devices can offer near real-time height information to VAAC forecasters, but are not currently able to offer concentration (i.e. of ash in the volcanic cloud) measurements in near real-time. LIDAR devices are used to validate satellite imagery and other observations; distinguish, by use of expert interpretation, between clouds and aerosols; determine geometrical properties (height/base) and movement of the aerosol/ash cloud, the latter by using observations from the whole network and ideally observations from other instruments.

3.2.4 Sun photometers

A sun photometer is used to provide a measurement of the direct solar radiation at a point on the ground. Under cloud-free and broken-cloud conditions, sun photometers can also be used to detect the presence of atmospheric aerosols. This is because the aerosol layer, e.g. volcanic ash, causes a reduction in the direct solar radiation. A sudden and consistent increase in the observed aerosol optical depth (AOD) over the natural background level can indicate the arrival of an aerosol layer.

3.2.5 Arrival Time Difference Network

The Arrival Time Difference Network (ATDNet) is the Met Office's long distance lightning detection network. It covers large areas of the globe. Lightning detection instruments use the time taken for the lightning to be detected at different locations to triangulate the signal and determine where it originated. During volcanic eruptions, volcanic lightning is often generated by the erupting ash cloud. Detection of this lightning can be used to identify that an eruption is occurring and may be able to reveal information about the height of the eruption.

3.2.6 Met Office Civil Contingencies Aircraft

The Met Office Civil Contingencies Aircraft (MOCCA) is the dedicated aircraft for UK civil contingency incidents, including volcanic ash clouds and other atmospheric hazards, e.g. industrial fires. It is a small aircraft with two piston engines and capacity for two people on board. It is equipped to make a range of measurements of gases and aerosols in the atmosphere using instruments mounted on the aircraft and remote sensing techniques, including a LIDAR device. Data is sent to the Met Office in near real-time using a satellite communications link. MOCCA is on call for UK use 365 days per year.

3.2.7 Meteorological conditions

Suitable meteorological conditions are required to transport the ash to the UK, with forecast meteorological data utilised from the Met Office's numerical weather prediction models, addressing global, regional, and local short-term and extended period forecasts.

3.3 Geological instability

The phenomena associated with geological instability are recognised as geohazards to existing and future development within the UK. Many organisations (e.g. the BGS and the Coal Authority) have developed datasets to capture the most significant of these geohazards, and these are available on a number of platforms including provision of commercial reports specific to project sites.

3.3.1 BGS datasets

Using historical and concurrent records, the BGS has developed the BGS Geosure dataset, which comprises four principal elements:

BGS GeoSure dataset — 1:50,000 high-resolution dataset, providing information about six natural ground subsidence hazards in Great Britain, as follows:

- collapsible deposits;

3. Observations, measurement techniques and modelling tools

- collapsible deposits;
- compressible ground;
- landslides;
- running sands;
- shrink-swell;
- soluble rocks.

BGS GeoSure shrink-swell 3D London — 1:50,000 regional hazard susceptibility map that identifies areas of potential shrink-swell hazard, in three-dimensional space, at intervals down to 20 m in the London and Thames Valley area.

BGS GeoSure debris flow — 1:50,000 national landslide hazard susceptibility map, identifying areas of potential debris flow hazard for Great Britain.

BGS GeoSure 5 km hex grid — A geographic information system (GIS) model of interlocking hexagon cells (side length 5 km) summarising information about six natural ground-subsidence hazards in Great Britain.

Additional relevant datasets are held by the BGS and include:

BRITPITS — the BGS has developed a dataset known as BRITPITS ([BGS, 2018c](#)) (an abbreviation of British Pits, and the word 'pits' used to include both surface and underground mineral workings) which holds information on:

- names of mines, quarries, oil wells, gas wells, ash and desulphogypsum plants;
- geographic location;
- address;
- operator;
- mineral planning authority;
- geology;
- mineral commodities produced;
- end-uses where known.

Mining Instability in Great Britain — the dataset shows the extent of mining within Great Britain; it was captured in 1990 by Ove Arup on behalf of the Department of Environment as a series of paper maps and no updates have been carried out.

3. Observations, measurement techniques and modelling tools

BGS collection of mine plans — the dataset comprises plans of various types relating to mining activity, including abandonment plans, gathered since the 1800s.

3.3.2 The Coal Authority

The Coal Authority holds a large quantity of data, including historical information, relating to coal mining in the UK. This includes records of mines and the mapped extent of their workings, including shafts and adits. The BGS hosts some of these spatial data with open access map searches (*The Coal Authority, 2018*).

The map searching facility allows the interrogation of several datasets, including attributes of both coal and oil shale workings, the latter found in Scotland.

3.3.3 Land Information System

The Land Information System (LandIS) is an environmental information system operated by Cranfield University, UK. The database includes mapping of clay soils susceptible to shrink-swell.

3.3.4 PanGeo

PanGeo provides free access to ground instability geohazard information for many of Europe's largest cities, but with limited coverage in the UK. The dataset includes landslide, ground dissolution, shrink-swell clays and mining; information is mostly sourced from existing datasets hosted by agencies such as the BGS.

In addition to the data sources, areas of concern may be monitored for movement utilising a wide range of techniques varying between remote satellite and aerial monitoring through to in-situ surveying techniques.

4.1 Seismicity

To characterise the site-specific seismic hazard there are two approaches. For conventional buildings, the use of Eurocode 8 would be appropriate. For nuclear sites and other essential safety related parts of UK infrastructure (e.g. dams), the appropriate approach would be to carry out a site-specific PSHA using the appropriate zonal areas, capable faults and ground motion prediction equations conforming to industry-wide relevant good practice. This technical volume, targeted at general UK energy infrastructure, focuses on the former.

4.1.1 Eurocode 8

The reference PGA, chosen by National Authorities for each seismic zone, relates to the reference return period of the seismic action for a code requirement that the structure will not collapse. An importance factor (see [Equation 1](#)) is used to define the design value of PGA from the reference PGA. For the reference return period the importance factor is equal to 1.

The UK National Annex to Eurocode 8, Table NA.1, states that in the absence of a project-specific assessment a return period of 2500 years should be employed, for the no-collapse requirement. PD 6698-2009 recommends using a mapped PGA value for a return period of 2500 years (a_{gR}) to find a design value of PGA (a_g), where:

$$a_g = \gamma_I^x a_{gR} \quad \text{Equation 1}$$

where a_g is the design value of PGA, γ_I is the importance factor calculated based on various factors regarding building type, severity of failure, etc. and a_{gR} is the PGA from maps such as in [Figure 15](#).

These maps are not site-specific and are not recommended for sites where previous large-magnitude earthquakes have occurred; in this case the design PGA value should be selected by performing a site-specific hazard analysis ([Musson and Sargeant, 2007](#)).

Site-specific analysis is also recommended for structures and facilities where failure would present very significant regional or national consequences for the population and/or the environment. Values for the design PGA will be taken from the analysis, with a specific return period chosen based on the function and consequence of failure of the facility ([BSI, 2009](#)).

For structures where the return period differs from the 475-year reference return period given in the BGS maps and [Figure 17](#), Eurocode 8 (BS EN 1998-2) recommends using [Equation 2](#) where the value of peak ground acceleration for a 475-year return period is used as a reference:

$$\frac{a_g}{a_{gR}} = \left(\frac{T}{T_{NCR}} \right)^k \quad \text{Equation 2}$$

where T is the return period, T_{NCR} is the reference return period of seismic action for the no-collapse requirement, and k is a value which depends on the seismicity of the region, and normally takes values between 0.3 and 0.4.

This equation can be particularly effective when used for structures where the design considers 1 in 10,000-year events, such as nuclear facilities and large dams.

4.1.2 Seismic Hazard Harmonisation in Europe (SHARE)

An alternative set of PGA values for consideration alongside those of Eurocode 8 are provided by Seismic Hazard Harmonisation in Europe (SHARE). The main objective of SHARE, a collaborative project run as part of the Cooperation programme for the Seventh Framework Programme of the European Commission, is to provide the Euro-Mediterranean region with a seismic hazard model ([Giardini et al., 2013](#)). The PSHA method was used to develop these maps. The European Seismic Hazard Map presents the PGA that is expected to be reached or exceeded with a 10% probability in 50 years.

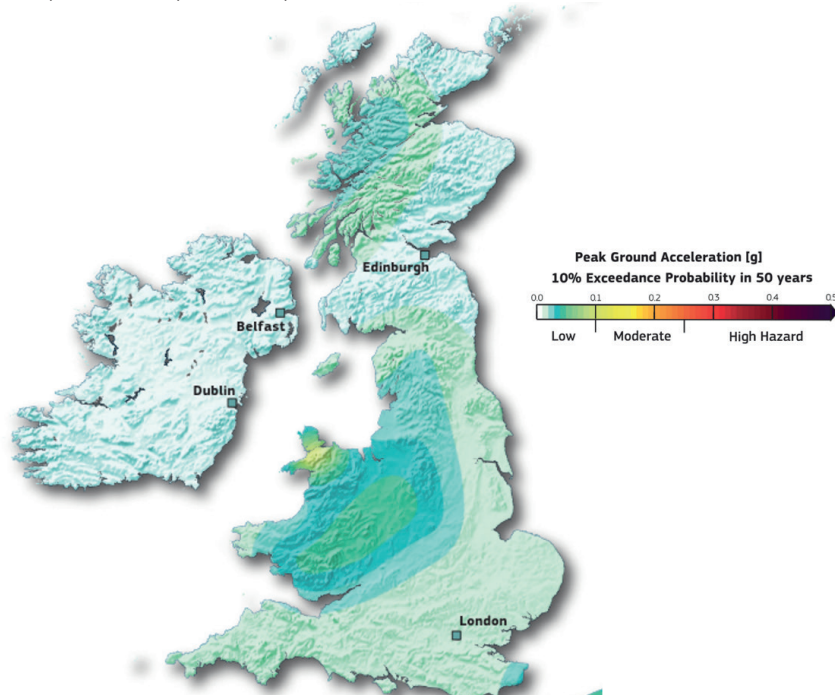


Figure 17. SHARE seismic hazard map for a mean return period of 475 years considering rock conditions ([Giardini et al., 2013](#)).

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4.1.3 European Utilities Requirements

The European Utility Requirements (EUR) for light water reactor nuclear power plants uses acceleration vs frequency response spectra to characterise the PGA for a site, depending on site class and building frequency. Site classes are defined by several parameters including shear wave velocity (propagation velocity of seismic shear waves) as follows: Soft 200 to 500 m/s (metres per second); Medium 600 to 1000 m/s; Hard 1200 to 2500 m/s. The relevant EUR information has access restrictions and is not available in the public domain.

4.1.4 Additional studies

Studies have investigated the consistency of PSHAs for the UK by investigating the sensitivity of analysis results to spatial seismicity and ground motion modelling. In 2013, a study was undertaken to compare a conventional source-zone model with two seismicity smoothing approaches, *Kernel Smoothing* (KS), and *geometrical Epicentral Cell* (EC) (Goda et al., 2013). The results from this study (see Figure 18) indicated similar results for different approaches.

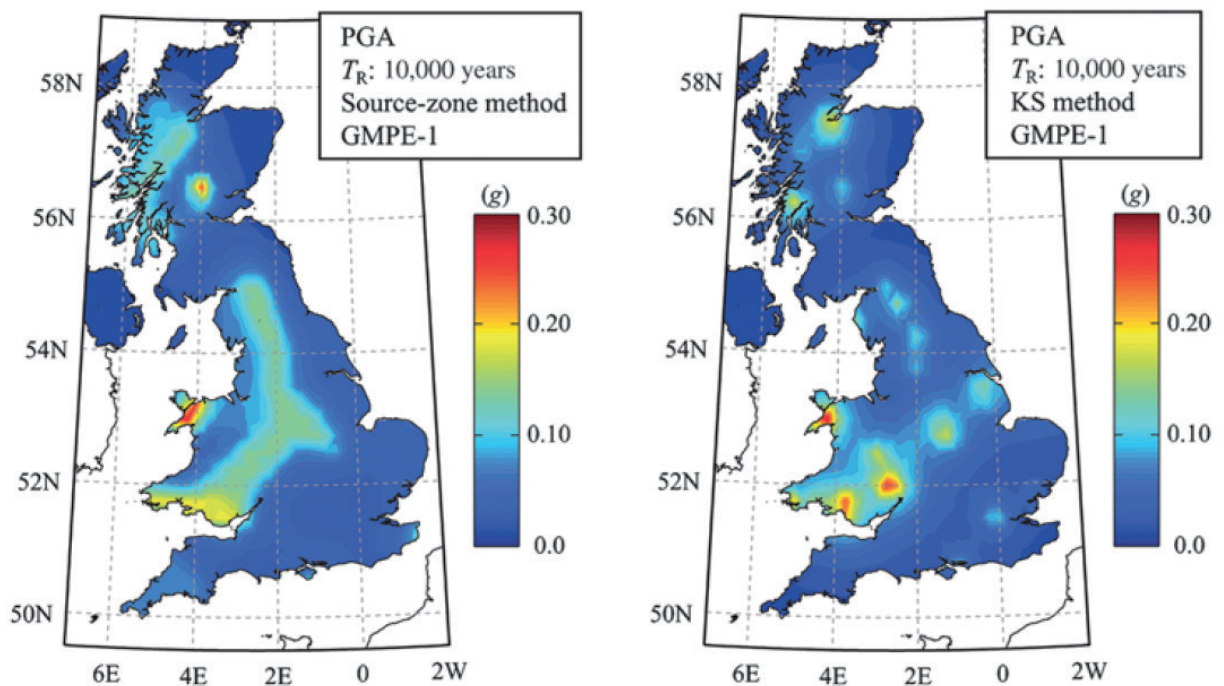


Figure 18. PGA contour map for source-zone model (left) and KS model (right) with return period of 10,000 years (Goda et al. (2013); © Seismological Society of America).

Further information can be found within the Health and Safety Executive (HSE) report produced in 2003 (Mallard et al., 2003) in which a detailed analysis of the existing seismic hazard estimation methods was undertaken.

4.2 Volcanicity

4.2.1 Factors and probability

The UK can be affected by ash from relatively small regional eruptions. However, the likelihood of an ash event affecting the UK is subject to a series of dependent and interdependent circumstances and factors with their own probabilities of occurrence; the prediction of each factor has variable levels of confidence. As an example, for the UK and an Icelandic event, the input factors required would include:

- probability of an eruption in a given period;
- probability that the event is of an explosive type and intensity to produce fine ash projected high into the atmosphere;
- probability of persistence of the ash event to provide a large volume/density of ash feeding into the atmosphere;
- probability of a suitable and persistent weather pattern with a flow from Iceland to the UK without significant diffusion and consequent reduction in concentration.

The derivation probability of any contributory factor is primarily dependent upon historical information. This can be obtained from direct measurements and records or inference from geologically dated markers, e.g. buried ash layers within soils, as well as the technical understanding of the processes occurring at the source of the event. The historical record of volcanic events, particularly the smaller events, is incomplete, which impacts upon the ability to predict future events. The combination of probability uncertainties associated with contributory factors will influence the overall uncertainty of the prediction of an ash event of significance.

University of Bristol (2016) estimated the probability of VEI events for the UK credible source clusters, as presented in *Figure 19*.

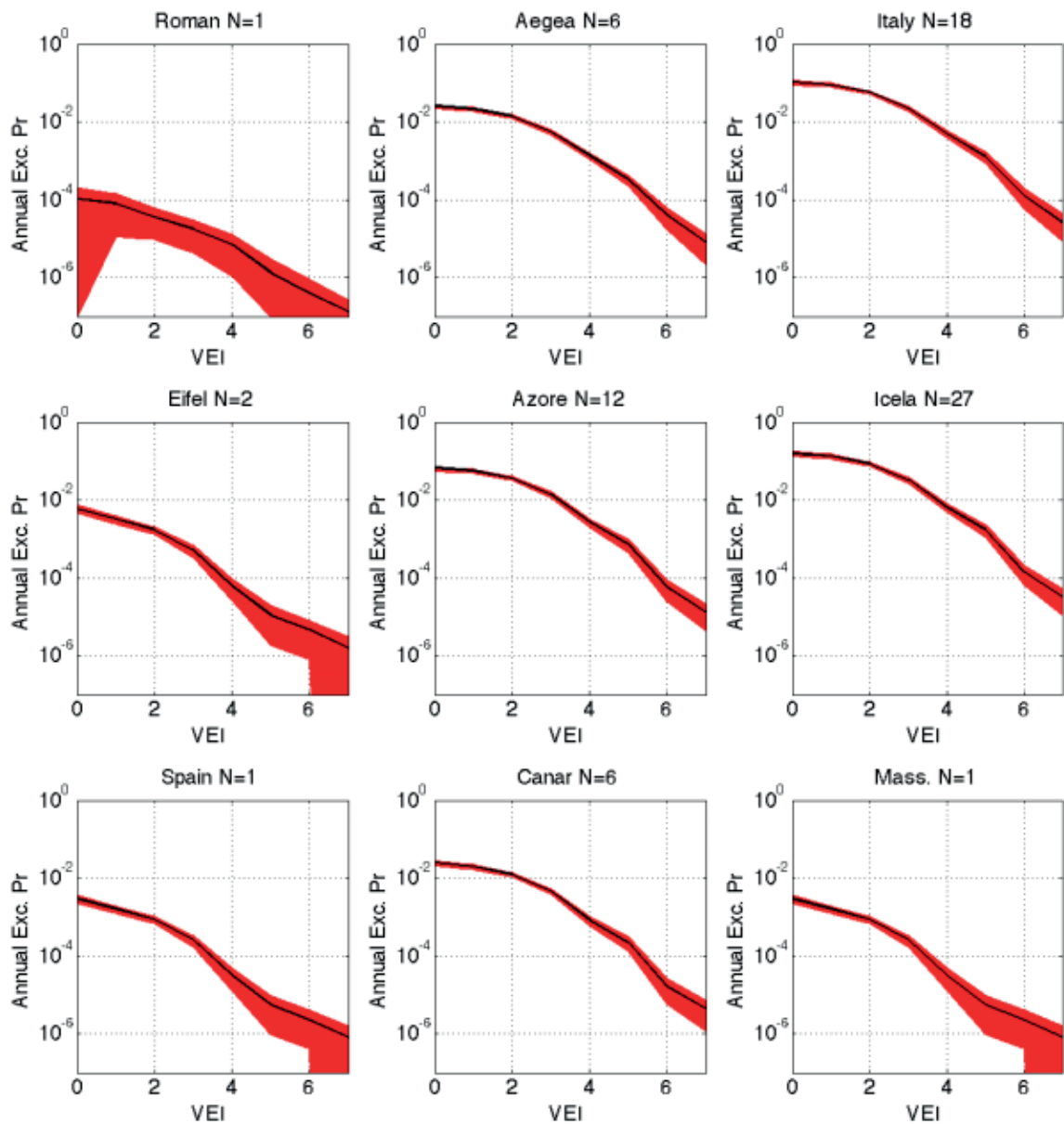


Figure 19. Weighted average annual exceedance probability of eruption per volcano cluster (see Figure 9 for the definition of the different clusters). The red area shows one standard deviation (clipped at $10^{-7}/\text{yr}$), the black curve shows weighted mean annual exceedance rate and N is defined as the number of eruptive vents. (Work undertaken by the University of Bristol for NERC and funded by EDF, reference: NERC Environmental Risks to Infrastructure Innovation (NE-M008878-1))

4.2.2 Modelling

Initial attempts to model ash hazards commenced in the 1980s. However, it was not until within the last ten years (as of 2018) that a more holistic approach was adopted addressing both event and meteorological factors, with detailed statistical analysis using improved datasets. In combination with this has been the development of more sophisticated digital modelling.

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At present, in terms of 'predicted ash loads', the only suitable data that exist for the UK are those used in [University of Bristol \(2016\)](#). This study of event occurrence and transportation of ash to the UK has derived an annual probability of ash from a volcanic eruption exceeding a ground level concentration of 0.5 mg/m^3 at a UK location as 1 in 300, with the duration of ashfall between 20 and 45 hours.

Although work has been undertaken in regions much closer to volcanoes, it is expected that this information is not relevant for the UK due to the different magnitudes of deposition that are considered. Therefore, the rest of this section focuses on aviation industry modelling approaches. However, it should be noted that this may not be the most suitable approach for analysis of other UK infrastructure.

For the UK, 75 to 80% of ash particles will be smaller than 10 microns (the respirable range, termed PM10), and the most likely source is a Moderate size Icelandic eruption. This ash ground level concentration will potentially impact filtration systems on a wide range of infrastructure, and human health (daily guideline threshold for good air quality is 0.05 mg/m^3 as stated in [HM Government \(2010\)](#)), leading to increased maintenance and possible workforce disruption. Higher ash concentrations (1 in 1000 annual probability) may disrupt air transportation and affect supply chains. At the 1 in 10,000 annual probability of occurrence, ash thicknesses are still approximately two orders of magnitude smaller than those required to cause ground transportation issues.

Following an event producing fine ash in the atmosphere within the north-eastern part of the North Atlantic Ocean including Iceland, it is the role of the London VAAC to monitor and forecast the movement and dispersion of volcanic ash for aviation; aviation being sensitive to very low concentrations of ash. The London VAAC and the Met Office's capability to forecast the transport and spread of volcanic ash is delivered by the Numerical Atmospheric-dispersion Modelling Environment (NAME) computer model. The model uses meteorological parameters derived from the main Met Office weather forecast model, i.e. the Met Office Unified Model (MetUM). For volcanic ash forecasting, NAME uses meteorological data from the global MetUM.

The NAME particle model calculates the dispersion of pollutants by tracking model 'particles' through a simulated atmosphere. The process is initiated by the release of model particles into the atmosphere from a user-defined source. The rate of fall-out of volcanic ash due to gravity (sedimentation) depends on the size, density and shape of the ash. Volcanic ash in NAME can

4. Methodologies

be removed from the model atmosphere by several processes:

- fall-out due to gravity (sedimentation);
- turbulent flux to the surface followed by impaction on roughness elements (dry deposition);
- washout where the pollutant is 'swept out' by falling precipitation (wet deposition);
- rainout where the pollutant is absorbed directly into cloud droplets as they form, prior to falling as precipitation.

Additionally, the following Eruption Source Parameters (ESPs) are input into NAME, where known:

- volcano location;
- date, time and duration of each eruptive phase;
- source geometry;
- upper and lower height of the eruption plume;
- mass eruption rate;
- vertical ash distribution;
- particle size distribution;
- ash density;
- ash shape.

The NAME VAAC outputs are produced by forecasters contained within the official ICAO Volcanic Ash Advisory (VAA) and Volcanic Ash Graphic (VAG) products. Calculated travel distances for ash particle sizes are illustrated in [Figure 20](#).

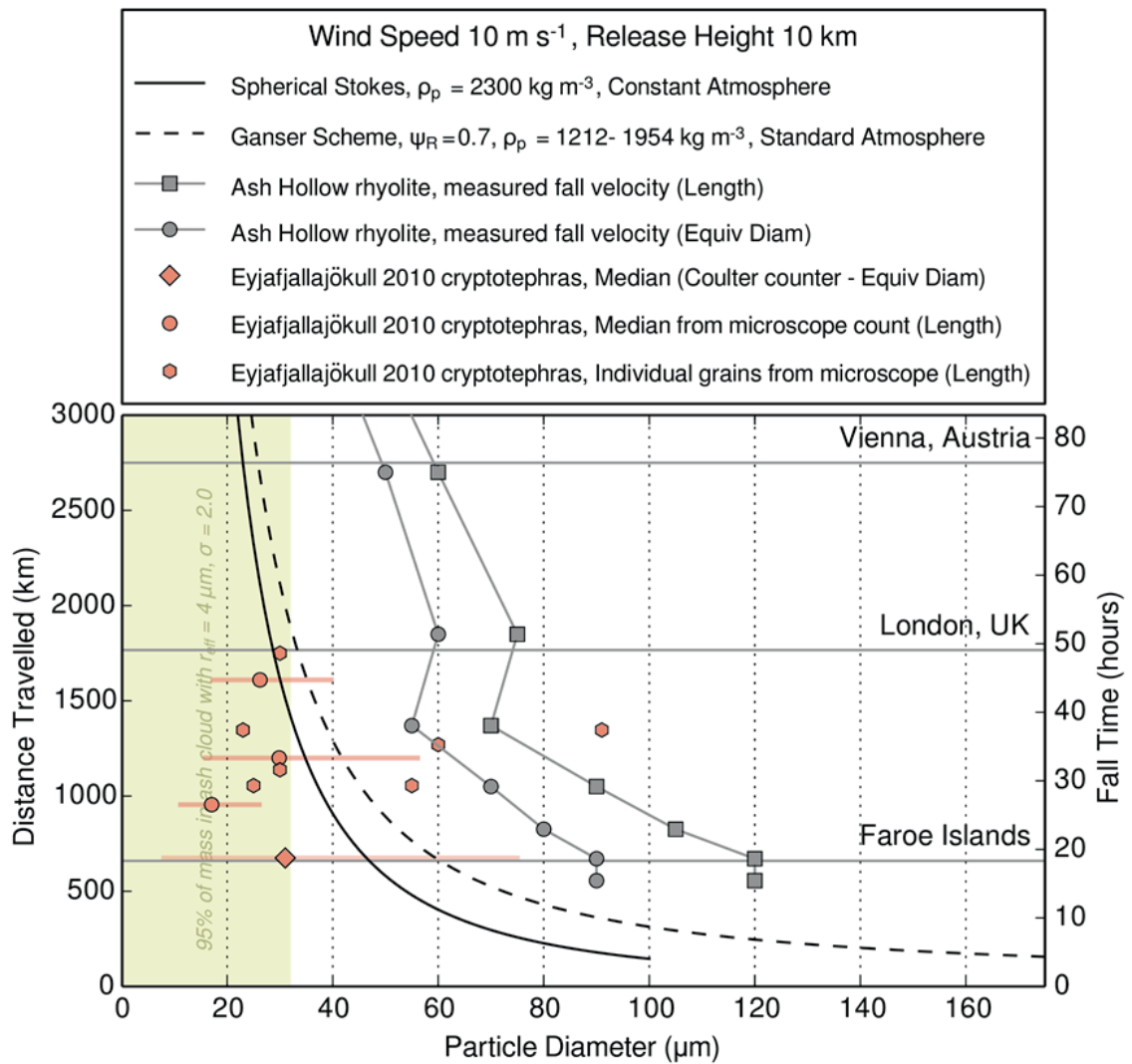


Figure 20. Calculated and measured travel distances for ash grains of different sizes and shapes (Stevenson et al., 2015).

Despite the effort placed in modelling and prediction, it is recognised that the principal uncertainty in these predictions arises from the variable duration of the eruptions and the persistence of weather patterns. The prediction of volcanic ash is subject to ongoing research and development.

4.3 Geological instability

4.3.1 Spatial analysis

The occurrence of potential geological instability within the UK has been captured by several organisations, as described in [Section 3.3](#), within datasets utilising records such as historical occurrence and contributory factors. Spatial analysis techniques are used to apply deterministic or probabilistic methods for identifying and mapping areas susceptible to instability. This is dependent on the topography, geology, geotechnical properties, climate, vegetation and anthropogenic factors.

4. Methodologies

This information may be managed through a GIS, whereby 'layers' of spatial distribution information are overlain and assessed in terms of the potential for instability. This information can be provided in several formats, including:

- open source or purchased GIS files which may be viewed within a commercial software package;
- open source internet-based searches;
- commercial formal reporting; either direct from the organisation concerned or from a second-tier supplier with licensed access to the information.

The outputs are often summarised on the organisation's websites as hazard potential or impact maps for the UK. Individual areas may be assessed in greater detail, depending upon the data definition; this should be undertaken by appropriate ground specialists who are experienced in determining hazards and risks.

As an example, for landslides spatial analysis is based on a combination of digital geological, hydrogeological and topographic data, as well as historical records of failures. The BGS has developed two national datasets that define the susceptibility of an area to undergo landsliding; these being 'Geosure landslides' and 'Geosure debris flow'. The aim of a susceptibility map is to show where a landslide may occur in the future due to favourable conditions.

BGS GeoSure landslides provides a 1:50,000 national hazard susceptibility map, identifying areas of potential landslide hazard for Great Britain. This susceptibility map is most suited to translational and rotational landslides. Additionally, the BGS has produced a map characterising the types of failures that may occur (see [Figure 21](#)).

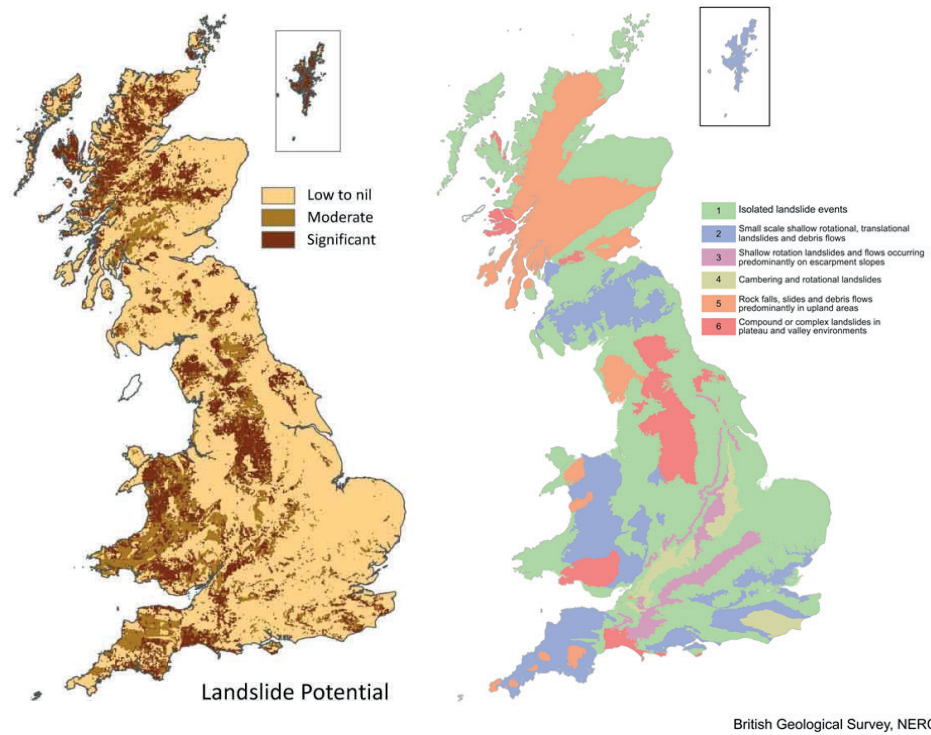


Figure 21. National hazard susceptibility maps defining the potential (left) and predominant landslide type (right). (Reproduced with the permission of the British Geological Survey © NERC. All rights reserved.)

Similarly, for ground dissolution subsidence, the approach is able to define *solution potential* and hence enable risk assessment for developments. The output from this is the definition of the solution potential with the following classifications; Low to Nil, Moderate, and Significant; see [Figure 22](#).

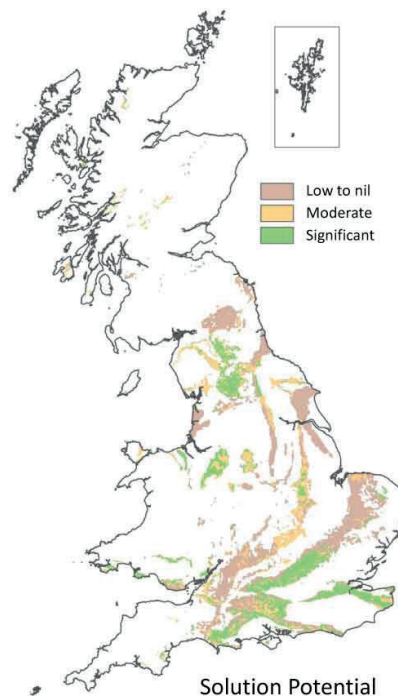


Figure 22. Potential for solution to be a hazard with the following classifications; Low to nil, Moderate, and Significant. (Reproduced with the permission of the British Geological Survey © NERC. All rights reserved.)

4. Methodologies

The Coal Authority provides both commercial reporting and a free interactive online viewer. Both will provide a summary of historical, existing and potential coal reserves, as well as the potential impact of subsidence at ground level taking account several factors including the thickness and depth of the coal seams, the method of extraction, and geology.

The Coal Authority has used its extensive mining records to divide UK coalfields into two spatial areas: 'high risk' and 'low risk'. A definition is provided in *The Coal Authority (2017)*. **Figure 23** shows an example of development high risk areas.

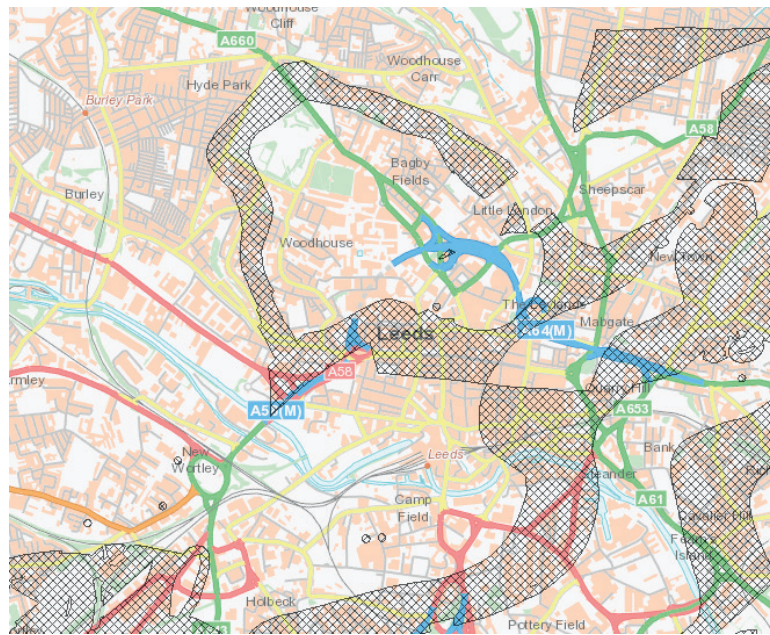


Figure 23. Development high risk areas (shaded) with regards to shallow coal mining. (Reproduced with the permission of © The Coal Authority. All rights reserved. Contains OS data © Crown Copyright and database right 2017.)

Although the datasets described are useful tools in a preliminary assessment of a location, they generally require supplemental site-specific information, including field surveys and intrusive ground investigation. The subsequent determination of the probability of a geological instability hazard impacting a development requires the input of appropriate specialists experienced in the interpretation of the data, assessment of risk, and the provision of advice with regards any further site-specific studies required.

5. Related phenomena

5.1 Seismicity

Earthquakes occurring under large volumes of water such as oceans or large lakes can be a cause of tsunamis (tidal or seismic sea waves). The disruption of the earth under the water sets in motion a series of waves which, should the earthquake have sufficient energy, can induce large waves with the potential to cause destruction.

The largest tsunami ever recorded was created following the 1958 earthquake along the Fairweather fault, Alaska. Water ejected up to a height of up to 524 m (1720 feet) above sea level and the waves generated destroyed large areas of land (*Geology.com, 2018*). It is important to note that there are two known recorded tsunamis in the UK, due to a landslide off the coast of Norway 8200 years ago and due to a Lisbon earthquake that occurred on 1st November 1755 (*Defra, 2005*).

Following a tsunami in the Indian Ocean in 2004, a study was undertaken by the Department for Environment, Food and Rural Affairs (Defra) to determine the likelihood of a tsunami affecting the UK. This study concluded that the threat to the UK is minimal and current defence systems should be sufficient to resist any tsunamis (*Defra, 2005*). The uncertainties surrounding the impact of a tsunami for a specific site can be reduced by undertaking a short-term study using existing models and techniques.

Furthermore, there is another phenomenon — liquefaction — where partial or fully saturated soils lose a substantial proportion of strength and stiffness under the applied force of earthquake vibrations. The soil begins to act like a liquid and has the potential to cause failure in the foundations. Guidance on liquefaction can be found in Eurocode 8 Part 5 with further guidance recommended by a report published by the Institution of Civil Engineers (*Booth at al., 2008*).

5.2 Volcanicity

For the UK, the main related phenomenon associated with an eruption is the production of volcanic gases, predominantly water vapour. However, significant amounts of carbon dioxide, sulphur dioxide, hydrogen sulphide and hydrogen halides can also be produced. Specifically, sulphur dioxide may be emitted in large quantities and potentially has significant health effects, both as a gas and once converted to sulphate aerosol. Additionally, where the gas combines with atmospheric water a potentially acidic aerosol is formed. A volcanic gas plume will not necessarily coincide with volcanic ash production.

In 2014, emissions from the non-explosive effusive eruption of the Icelandic Bárðarbunga-Holuhraun eruption were detected 2000 km downwind by satellites and sensors in Europe. In the UK, sulphur dioxide and sulphate aerosol were detected at the ground by existing monitoring networks. Peaks in concentrations were short-lived (hours) and did not exceed Moderate on Defra's Daily Air Quality Index scale.

Modelling by the Natural Hazards Partnership ([NHP, 2018](#)) to inform the National Risk Register has shown that even in larger gas eruptions the most likely outcome in the UK is short (hours to days) pollution episodes with surface concentrations at Moderate and High Air Quality Index levels.

However, research work undertaken on the impact of the fissure eruption of Iceland's Laki volcano in 1783, which produced huge volumes of gas over a prolonged period, concluded that the resulting exposure of the population to increased volcanic air pollution similar to the Laki eruption could potentially cause significant premature deaths. The UK, due to its proximity to Iceland, would be one of the worst affected areas in Europe with an estimated 20,000 extra deaths from heart and lung diseases ([Schmidt et al., 2011](#)).

5.3 Geological instability

The occurrence of a geological instability hazard event can theoretically trigger a secondary event of a different instability type. For example, the occurrence of a karstic dissolution collapse could trigger a landslide event, depending upon the characteristics of the ground and whether the change created a scenario where the strength of the ground was insufficient to counter the disturbance effect of gravity. Such conditions are rare or the occurrence is very localised and of insignificant impact.

Of most significance to natural geological instability is the impact of weather and seismic events. For the UK environment, weather is the dominant related phenomenon. With respect to weather events, most shallow landslides initiate during rainfall, with the magnitude of rainfall being closely related to the frequency of landslides, as illustrated in [Figure 24](#).

5. Related phenomena

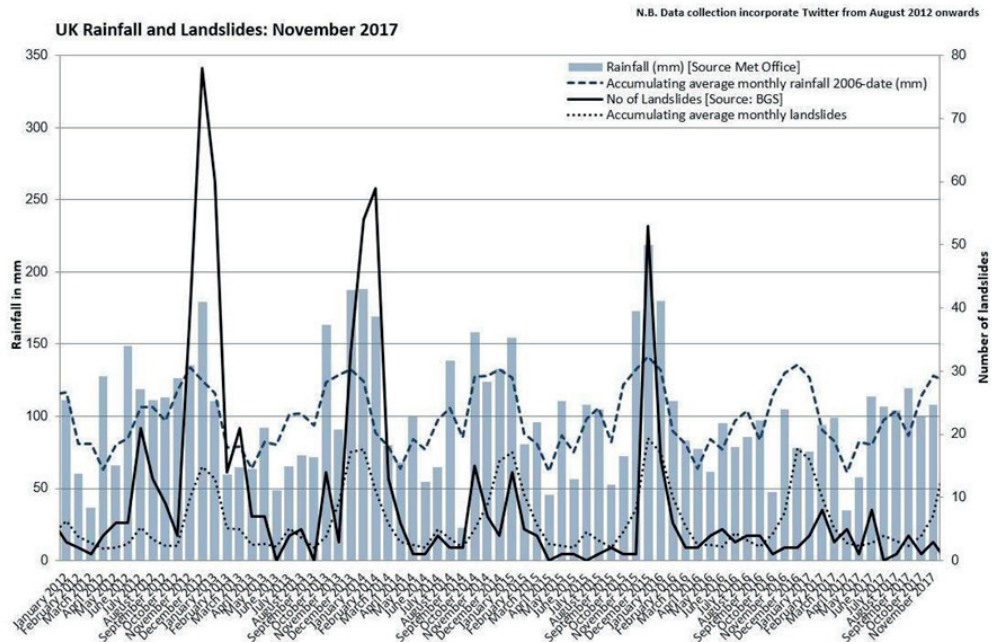


Figure 24. Rainfall and landslide data in the UK. (Source: the British Geological Survey.)

Coastal erosion and associated landslides have a correlation with storm events where a combination of storm surge, elevated sea levels and wave height leads to erosion of the toe of coastal slope leading to instability.

Regulation associated with hazard protection of industrial infrastructure in the UK is governed primarily under the Health and Safety at Work etc. Act 1974. This Act is the overarching statutory mechanism with which organisations must comply. Under this primary legislation there is a framework of supporting legislation, including Acts and Statutory Instruments, which provides secondary regulation relating to specific hazards and industries. These regulations are enforced by the HSE. The exact legislation applicable to any particular infrastructure project will depend on the nature of the project. The nuclear industry specifically is regulated by the Office for Nuclear Regulation (ONR), established by the Energy Act 2014. ONR was formed by the merger of the HSE Nuclear Directorate, the Office for Civil Nuclear Security, the UK Safeguards Office and the Department for Transport Radioactive Materials team.

Although specific requirements are sometimes stipulated in legislation, health and safety regulation in the UK is usually governed by the principle that risk must be tolerable and reduced to As Low as Reasonably Practicable (ALARP). It is a legal requirement that potential hazards must be identified and that the risks associated with these hazards must be assessed. This includes risks associated with natural hazards.

In this section, specific guidance is provided on regulatory instruments, codes and standards applicable to seismic, geological and volcanic hazards. For more information on general regulatory considerations, please see Volume 1 — Introduction to the Technical Volumes and Case Studies.

6.1 Seismicity

For most power infrastructure projects there is no specific seismic regulation, other than referral to the design codes and guidance documents discussed within [Section 4.1](#).

6.2 Volcanicity

Specific legislation relating to ash is restricted to aviation and falls under the Civil Aviation Authority. There is no legislation with respect to ash deposition.

When the Eyjafjallajökull volcano in Iceland erupted, the guidance used worldwide from the International Civil Aviation Organization was to avoid any amount of ash.

The eruption of Eyjafjallajökull in spring 2010 affected some of the most congested airspace in the world and, as the ash covered much of Europe, flying round it was not an option. Subsequent to the event and the eight-day closure of airspace, international and European

regulators, manufacturers and aviation experts co-ordinated their expertise and agreed a new zoning system for airspace affected by volcanic ash. However, this guidance is of minimal use when addressing energy infrastructure.

6.3 Geological instability

Specific legislation relating to geological instability is addressed by the planning system, alongside many other regimes, including:

- building regulations, which seek to ensure that any development is structurally sound;
- the Coal Authority's responsibility for public safety risks arising from past coal mining activities and dealing with proven claims for subsidence under the Coal Mining Subsidence Act 1991 (*HM Government, 1991*) and the Coal Industry Act 1994 (*HM Government, 1994*);
- consultation with the Cheshire Brine Subsidence Compensation Board, where land is subsiding or liable to subside owing to past brine pumping within a defined planning area;
- the safeguarding of mine entries once they are abandoned to protect health and safety as required under the Mines and Quarries Act 1954 (*HM Government, 1954*).

Local authorities, in the context of planning, are required to consider land stability in local plans, which will vary between areas and the types of issues that the plan covers, but planning authorities may need to consider:

- identifying specific areas where particular consideration of landslides, mining hazards or subsidence will be needed;
- including policies that ensure unstable land is appropriately remediated, prohibit development in specific areas, or only allow specific types of development in those areas;
- circumstances where additional procedures or information, such as a land stability or slope stability risk assessment report, would be required to ensure that adequate and environmentally acceptable mitigation measures are in place; and
- removing permitted development rights in specific circumstances.

For the specific case of subsidence, planning authorities have a range of mechanisms, through both local plan policies and in determining planning applications, available to mitigate and minimise risks to development proceeding. These include:

- establishing the principle and layout of new development, e.g. designing a layout to avoid mine entries and other hazards;

6. Regulation

- ensuring proper design of buildings and their structures to cope with any movement expected, and other hazards such as mine and/or ground gases; or
- requiring ground improvement techniques, usually involving the removal of poor material and its replacement with suitable inert and stable material. For development on land previously affected by mining activity, this may mean prior extraction of any remaining mineral resource.

UK Government planning guidance on procedures and process that a local authority would expect with respect to land development is provided in *Figure 25*.

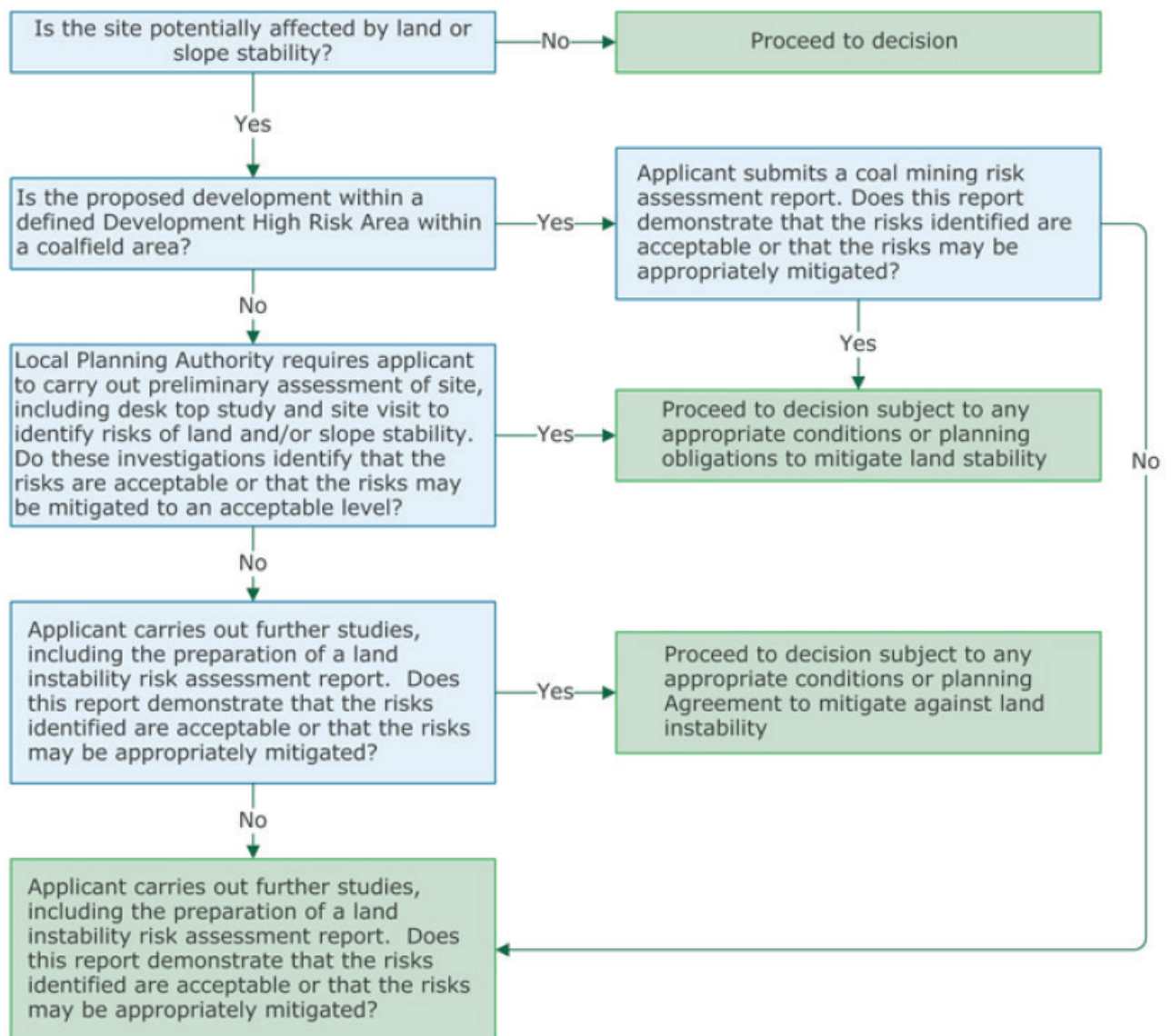


Figure 25. Ground instability: UK Government planning guidance 2014 (HM Government, 2014).

6. Regulation

For the submission of a planning application in the Coal Authority Development Low Risk Area, there is no statutory requirement to submit a Coal Mining Risk Assessment. However, if the site is in a Development High Risk Area there is a requirement to submit a Coal Mining Risk Assessment to the local planning authority, to support a planning application. The Coal Authority considers that some types of development do not need to be supported by a Coal Mining Risk Assessment and these are published on an exemptions list. Guidance is provided in *The Coal Authority (2017)*.

With regard to best practice, there is significant published literature and guidance on geological instability assessment, including *BSI (1990)*, *BSI (1999)* and *BSI (2007)*.

7. Emerging trends

7.1 Seismicity

The prediction of seismic events and their effects is subject to ongoing research at national and international level, with increased sophistication of monitoring, and probability modelling being undertaken. It is not expected that climate change will have an impact on seismic activity.

7.2 Volcanicity

The prediction of volcanic events and their effects is subject to ongoing research at national and international level, with increased sophistication of monitoring, and probability modelling being undertaken. In Europe, the eruption of Eyjafjallajökull in 2010 was a wake-up call with regards to aviation impact. Refinement of modelling and impact remains ongoing ([Loughlin et al., 2015](#); [Chai et al., 2017](#); [Zidikheri et al., 2017](#)).

7.3 Geological instability

The effects of climate change on the frequency of geological instability events remain unclear. Intuitively, it may be expected that the predicted increase in rainfall as a consequence of climate change would result in an increase in landslide events. However, this topic is complex as numerous other factors come into play (e.g. higher evapotranspiration rates in the summer months will also influence groundwater levels). An example of recent findings from research by Cardiff University ([Parker et al., 2016](#)) would indicate that the frequency of common landslides in the UK is not likely to increase as a result of more rainstorms brought about by future climate change. Research by other parties is ongoing, with no current overall consensus of opinion.

For circumstances associated with erosion of the toe of slopes due to fluvial flows and coastal events, this may not be the case, as material available for failure would not necessarily be constrained by the same processes.

- Acun B, Athanasopoulou A, Pinto A, Carvalho E, Fardis M. 2011. *Eurocode 8: Seismic Design of Buildings, Worked examples*. JRC Scientific and Technical Reports. Available at: http://eurocodes.jrc.ec.europa.eu/doc/WS_335/report/EC8_Seismic_Design_of_Buildings-Worked_examples.pdf (accessed on 4th May 2018).
- BGS. 2012. Ground shrinking and swelling. *UK Geohazard Note*. <https://www.bgs.ac.uk/downloads/start.cfm?id=2499> (accessed on 4th May 2018).
- BGS. 2018a. UK historical earthquake database. http://quakes.bgs.ac.uk/historical/query_eq/ (accessed on 4th May 2018).
- BGS. 2018b. Earthquakes in the UK. <http://www.bgs.ac.uk/discoveringGeology/hazards/earthquakes/UK.html> (accessed on 4th May 2018).
- BGS. 2018c. BRITPITS. <http://www.bgs.ac.uk/products/minerals/britpits.html> (accessed on 4th May 2018).
- Booth E, Skipp B, Watt P. 2008. *Establishing the Need for Seismic Design in the UK*. Institution of Civil Engineers, London, UK.
- BSI. 1990. *Methods of Test for Soils for Civil Engineering Purposes, Parts 1 to 9: BS 1377*. British Standards Institution, London, UK.
- BSI. 1999. *Code of Practice for Site Investigation: BS5930 + A2, Incorporating 2010 Amendment*. British Standards Institution, London, UK.
- BSI. 2007. *Eurocode 7 — Geotechnical Design, Part 2: Geotechnical Investigation and Testing: BS EN 1997-2:2007*. British Standards Institution, London, UK.
- BSI. 2009. *PD 6698; Recommendations for the Design of Structures for Earthquake Resistance to BS EN 1998*. British Standards Institution, London, UK.
- Chai T, Crawford A, Stunder B, Pavlonis MJ, Draxler R, Stein A. 2017. Improving volcanic ash predictions with the HYSPLIT dispersion model by assimilating MODIS satellite retrievals. *Atmospheric Chemistry and Physics*, 17, 2865–2879. doi: [10.5194/acp-17-2865-2017](https://doi.org/10.5194/acp-17-2865-2017)

- Cruden DM. 1991. A simple definition of a landslide. *Bulletin International Association for Engineering Geology*, 43, 27–29. doi: [10.1007/BF02590167](https://doi.org/10.1007/BF02590167)
- Cruden DM, Varnes DJ. 1993. Landslide types and processes. In *Landslides investigation and mitigation*. Transportation Research Board, National Academy of Sciences, USA.
- Defra. 2005. *The Threat Posed by Tsunami to the UK*. Available at: <http://webarchive.nationalarchives.gov.uk/20080520220503/http://www.defra.gov.uk/enviro/fcd/studies/tsunami/tsurpes.pdf> (accessed on 4th May 2018).
- Durant AJ, Rose WI, Sarna-Wojcicki AM, Carey S, Volentik ACM. 2009. Hydrometeor-enhanced tephra sedimentation: Constraints from the 18 May 1980 eruption of Mount St. Helens. *Journal of Geophysical Research: Solid Earth*, 114, B03204. doi: [10.1029/2008JB005756](https://doi.org/10.1029/2008JB005756)
- Geology.com. 2018. World's Tallest Tsunami. <https://geology.com/records/biggest-tsunami.shtml> (accessed on 4th May 2018).
- Giardini D, Woessner J, Danciu L, Crowley H, Cotton F, Grünthal G, Pinho R, Valensise L, and the SHARE consortium. 2013. SHARE European Seismic Hazard Map for Peak Ground Acceleration, 10% Exceedance Probabilities in 50 Years. doi: [10.12686/SED-00000001-SHARE](https://doi.org/10.12686/SED-00000001-SHARE)
- Goda K, Aspinall W, Taylor C. 2013. Seismic hazard analysis for the U.K.: Sensitivity to spatial seismicity modelling and ground motion prediction equations. *Seismological Research Letters*, 84, 112–129. doi: [10.1785/0220120064](https://doi.org/10.1785/0220120064)
- HM Government. 1954. Mines and Quarries Act 1954. Available at: <http://www.legislation.gov.uk/ukpga/Eliz2/2-3/70/contents> (accessed on 4th May 2018).
- HM Government. 1991. Coal Mining Subsidence Act 1991. Available at: <http://www.legislation.gov.uk/ukpga/1991/45/contents> (accessed on 4th May 2018).
- HM Government. 1994. Coal Industry Act 1994. Available at: <http://www.legislation.gov.uk/ukpga/1994/21/contents> (accessed on 4th May 2018).

- HM Government. 2010. UK Air Quality Standards Regulations 2010. Available at: <http://www.legislation.gov.uk/uksi/2010/1001/contents/made> (accessed on 4th May 2018).
- HM Government. 2014. Guidance — Land stability. <https://www.gov.uk/guidance/land-stability> (accessed on 4th May 2018).
- Horwell CJ, Baxter PJ. 2006. The respiratory health hazards of volcanic ash: a review for volcanic risk mitigation. *Bulletin of Volcanology*, 69, 1–24.
doi: 10.1007/s00445-006-0052-y
- Jenkins SF, Wilson TM, Magill CR, Miller V, Stewart C, Marzocchi W, Boulton M. 2015. *Volcanic Ash Fall Hazard and Risk: Technical Background Paper for the UNISDR 2015 Global Assessment Report on Disaster Risk Reduction*. Available at: <https://ir.canterbury.ac.nz/handle/10092/10551> (accessed on 4th May 2018).
- Loughlin SC, Sparks S, Brown SK, Vye-Brown C. 2015. *Global Volcanic Hazards and Risk*. Cambridge University Press, UK.
- Mallard DJ, Skipp BO, Aspinall WP. 2003. *An Appraisal of Existing Seismic Hazard Estimates for the UK Continental Shelf*. Available at: <http://www.hse.gov.uk/research/rrpdf/rr166.pdf> (accessed on 4th May 2018).
- Met Office. 2018. The London VAAC Process. <https://www.metoffice.gov.uk/aviation/vaac/process> (accessed on 4th May 2018).
- Musson R, Sargeant S. 2007. *Eurocode 8 Seismic Hazard Zoning Maps for the UK*. British Geological Survey Technical Report CR/07/125. Available at: http://www.earthquakes.bgs.ac.uk/hazard/UK_seismic_hazard_report.pdf (accessed on 4th May 2018).
- NHP. 2018. *Volcanic Gases*. Available at http://www.naturalhazardspartnership.org.uk/wp-content/uploads/Volcanic_Gases_Hazard_Overview.pdf (accessed on 4th May 2018).
- Oxford Economics. 2010. *The Economic Impacts of Air Travel Restrictions Due to Volcanic Ash*. Available at: <https://www.oxfordeconomics.com/publication/open/240242> (accessed on 4th May 2018).

- Parker RN, Hales TC, Mudd SM, Grieve SWD, Constantine JA. 2016. Colluvium supply in humid regions limits the frequency of storm-triggered landslides. *Scientific Reports*, 6, 34438. doi: [10.1038/srep34438](https://doi.org/10.1038/srep34438)
- Pyle DM. 1989. The thickness, volume and grainsize of tephra fall deposits. *Bulletin of Volcanology*, 51, 1–15. doi: [10.1007/BF01086757](https://doi.org/10.1007/BF01086757)
- Schmidt A, Ostro B, Carslaw KS, Wilson M, Thordarson T, Mann GW, Simmons AJ. 2011. Excess mortality in Europe following a future Laki-style Icelandic eruption. *Proceedings of the National Academy of Sciences*, 108, 15710–15715. doi: [10.1073/pnas.1108569108](https://doi.org/10.1073/pnas.1108569108)
- Sparks RSJ, Aspinall WP, Crosweller HS, Hincks TK. 2013. Risk and uncertainty assessment of volcanic hazards. In *Risk and Uncertainty Assessment for Natural Hazards*. Cambridge University Press, UK.
- Stevenson JA. 2013. Grímsvötn 2011 (Part 1): UK ash deposition from the biggest Icelandic eruption since Katla 1918. <http://all-geo.org/volcan01010/2013/07/grimsvotn-2011-in-uk-part-1-where/> (accessed on 4th May 2018).
- Stevenson JA, Millington SC, Beckett FM, Swindles GT, Thordarson T. 2015. Big grains go far: understanding the discrepancy between tephrochronology and satellite infrared measurements of volcanic ash. *Atmospheric Measurement Techniques*, 8, 2069–2091. doi: [10.5194/amt-8-2069-2015](https://doi.org/10.5194/amt-8-2069-2015)
- The Coal Authority. 2017. *Risk Based Approach to Development Management: Guidance for Developers*. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/588157/Resources_for_Developers_Risk-Based_Approach_to_Development_Management_Version_4.pdf (accessed on 4th May 2018).
- The Coal Authority. 2018. Interactive Map Viewer. <http://mapapps2.bgs.ac.uk/coalauthority/home.html> (accessed on 4th May 2018).
- University of Bristol. 2016. *Volcanic Ash Hazard Assessment for UK Nuclear Sites*. NERC Environmental Risks to Infrastructure Innovation Programme (NE-M008878-1).

USGS. 2018. USGS Earthquake Hazards Program. <https://earthquake.usgs.gov/> (accessed on 4th May 2018).

Varnes DJ. 1978. Slope movement types and processes. In *TRB Special Report 176, Landslides: Analysis and Control*. Transportation Research Board, Washington DC, USA. Available at: <http://onlinepubs.trb.org/Onlinepubs/sr/sr176/176-002.pdf> (accessed on 4th May 2018).

Zidikheri MJ, Lucas C, Potts RJ. 2017. Estimation of optimal dispersion model source parameters using satellite detections of volcanic ash. *Journal of Geophysical Research: Atmospheres*, 122, 8207–8232. doi: [10.1002/2017JD026676](https://doi.org/10.1002/2017JD026676)

Adits

Horizontal passages leading into a mine for the purposes of access or drainage.

Basaltic eruptions

Eruptions of low silica content magma of low viscosity that potentially covers large stretches of land or the ocean floor with basalt lava.

Ceilometers

Used to measure the aerosol concentration within the atmosphere.

Cryptotephra

Historical ash that is invisible to the naked eye.

Fragmentation

In this context, the breaking up of magma into other products, e.g. ash.

Geometrical Epicentral Cell

A method employed to develop seismic hazard maps.

Kernel Smoothing

A statistical technique to estimate a real valued function as the weighted average of neighbouring observed data.

Phreatoplinian type eruptions

Eruptions characterised by large explosive eruptions as a result of contact with water.

Probable/actual destructive significance

Potential or actual adverse effect to infrastructure or human life.

Shear wave

A type of elastic wave, which propagates transversely through the body of an object, unlike surface waves.

Silicic eruptions

Eruptions that contain silica-rich magma, more viscous than basaltic lavas.

Solution potential

Potential for chemical subterranean erosion of rock.

ALARP	As Low as Reasonably Practicable
AOD	Aerosol optical depth
ATDNet	Arrival Time Difference Network
BGS	British Geological Survey
BRITPITS	British Pits
BSI	British Standards Institute
Defra	Department for Environment, Food and Rural Affairs
EC	Epicentral Cell
ESP	Eruption Source Parameter
EUR	European Utility Requirements
GIS	Geographic information system
HSE	Health and Safety Executive
ICAO	International Civil Aviation Organization
IMO	Icelandic Meteorological Office
KS	Kernel Smoothing
LandIS	Land Information System
LCBR	Laser Cloud Based Recorder
LIDAR	Light Detection and Ranging
MetUM	Met Office Unified Model
MOCCA	Met Office Civil Contingencies Aircraft
NAME	Numerical Atmospheric-dispersion Modelling Environment
NERC	Natural Environment Research Council
NGA	Next Generation of Ground-Motion Attenuation models
NHP	Natural Hazards Partnership
OACC	Oceanic Area Control Center
ONR	Office for Nuclear Regulation
PEER	Pacific Earthquake Engineering Research Centre
PGA	Peak ground acceleration
PSHA	Probabilistic Seismic Hazard Assessment
SHARE	Seismic Hazard Harmonisation in Europe
VAA	Volcanic Ash Advisory
VAAC	Volcanic Ash Advisory Centre
VAG	Volcanic Ash Graphic
VEI	Volcanic Explosivity Index



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