Engineering geological and geotechnical aspects of the Soufriere Hills volcanic eruption, Montserrat

LAURANCE DONNELLY[1], LEE JONES[2], MIKE PALMER[3] & CONRAD DILKES[4]

[1] Halcrow Group, Deanway Technology Centre, Wilmslow Road, Handforth, Cheshire, SK9 3FB, United Kingdom., (DonnellLJj@Halcrow.com)
[2] British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK. (ldjon@bgs.ac.uk)
Halcrow Group, Deanway Technology Centre, Wilmslow Road, Handforth, Cheshire, SK9 3FB, United Kingdom. (DonnellyLJ@Halcrow.com)
[3]Halcrow Group, Burderop Park, Swindon, Wiltshire, SN4 0QD, United Kingdom. (PalmerMJj@Halcrow.com)
[4]Public Works Department, Government of Montserrat, Montserrat, West Indies. (dilkesc@gov.ms)

Abstract: The Soufrière Hills volcano on the British dependant Caribbean island of Montserrat began to erupt in July 1995, after about 400 years of remaining dormant. Phreatomagmatic explosions were followed by the extrusion of an andesitic lava dome within English crater. Its periodic collapse resulted in the generation of pyroclastic and explosive events, from 1996 onwards. Engineering geologists and geotechnical engineers have been involved in the various stages of the volcanic crises. These have included hazard identification, evaluation and zonation, risk assessments, monitoring, evacuation, exploration, redevelopment and construction. Various ground deformation features were observed, monitored and investigated on the crater walls and expanding lava dome. These included rock falls, pyroclastic flows, explosions, lahars, landslides and distinct, steep-sided subsidence depressions. Secondary geological hazards were also investigated on the island, beyond the area of primary volcanic activity. These had a significant impact on transportation, utilities and residential areas. Mineral exploration surveys, undertaken to locate suitable engineering raw materials, identified hard rock andesite-dacite intrusions in the northern part of the island for the construction of an evacuation jetty in Little Bay. Potential aggregate sources were also found throughout the island as a possible material source for the construction of a replacement airport. Geotechnical input was also required for the construction of a new airport to replace the island original airport, located in the 'danger zone' and now completely destroyed by series of pyroclastic flows and lahars. The objectives of this paper are to document and draw attention to the engineering geological and geotechnical input provided during the monitoring of this volcanic eruption and to demonstrate how geotechnical expertise has assisted in the subsequent redevelopment of the island.

Résumé: Le volcan la Soufrière sur les monts de l'île Caraïbes (dépendance britannique) du Montserrat erupta en 1995, après environ 400 ans de silence. Des explosions phréatomagmatiques suivirent l'extrusion d'un dôme, d'une coulée andésite à l'intérieur du cratère anglais. Depuis 1996, cette activité périodique a engendré des événements pyroclastiques et explosifs. Les diverses étapes des crises volcaniques ont été suivies et étudiées par des ingénieurs géologues et géotechniciens. Cela inclut l'identification, l'évaluation, la classification et l'estimation du risque, la surveillance, la mise en place de l'évacuation, l'exploration, la rénovation et la construction. Diverses données de déformation du sol ont été observées, surveillées et enquêtées dans les parois du cratère et dans le dôme de lave étendue. L'observation a révélé des chutes de roche, des coulées pyroclastiques, des explosions, des lahars, des glissements et des dépressions de subsidence avec pente a pic. Des risques géologiques secondaires ont été également étudiés sur à l'île, au delà de la zone primaire de l'activité volcanique. La répercussion de cet événement volcanique était ressentie dans le domaine du transport, et des commodités de la vie quotidienne. Les études d'exploration minérale, entreprises pour localiser les matières premières d'ingénierie ont permis d'identifier une intrusion de roche dure andesite-dacite dans la partie nord de l'île pour la construction d'un appontement d'évacuation dans Little Bay. Des sources potentielles d'aggrégats ont été identifiées partout dans l'île, comme source matérielle pour la réalisation d'un aéroport de substitution. Une étude géotechnique fut nécessaire pour la construction d'une zone de protection contre l'ouragan (cyclone tropical). Le but de cet exposé est de présenter le bilan de recherche et d'étude d'ingénierie géologique et géotechnique préparé pendant la surveillance de l'éruption de ce volcan. Cet exposé présente également la façon dont la compétence géotechnique a aidé au réaménagement de l'île.

Keywords: engineering geology, geological hazards, geotechnical engineering, landslides, site investigation, volcanic risk

INTRODUCTION

The Soufrière Hills volcano, located on the British dependant territory of Montserrat, began to erupt in 1995 after at least 400 years of dormancy, generating primary and secondary volcanic hazards, including pyroclastic flows, lahars, ash falls, landslides and earthquakes. The capital town, Plymouth, the 'Old Towne', several other smaller villages, the golf course, the main port, the island's only airport, bridges and other key infrastructure were destroyed and are almost entirely covered by volcanic and volcano-sedimentary deposits. Many of the 10,500 population relocated to the north of Montserrat or overseas; the population is now about 5000. As members of the Montserrat Volcano Observatory (MVO) team, currently managed by the British Geological Survey (BGS), engineering geologists have played an important contributory role in both the monitoring of volcanic hazards and the subsequent redevelopment of the islands infrastructure. They have assisted with volcano monitoring, geohazards identification, assessment, evaluation and zonation, ground deformation monitoring and mitigation. Engineering geologists have also provided expertise in mineral exploration and post-disaster redevelopment of the island. Ground investigations have been undertaken for the construction of a new airport and a proposed replacement bridge together with geological and geotechnical advice for landslide mitigation and improved road schemes.

PHYSIOGEOGRAPHY AND GEOMORPHOLOGY

Montserrat is approximately 17 km long (north-south) and 10 km wide covering an area of approximately 102 km^2. The island is dominated by the Soufrière Hills-South Soufrière Hills volcanic centres, which is surrounded by aprons of associated pyroclastic flow, lahar and air fall deposits. Chances Peak, an ancient lava dome forms the highest point on the island and is part of the Soufrière Hills volcano. On occasions the growing lava dome has been higher than Chance's Peak before collapsing. The other main massifs are Silver Hills in the north and Centre Hills in the middle of the island. Two smaller topographic highs also exist, Garibaldi and St. Georges Hills. The topography has been incised by river and stream erosion, forming steep sided gullies (known locally as ghauts). Radial, ephemeral drainage patterns have developed around the main massifs that only flow following prolonged heavy rainfall. Some valley bottoms are flat and filled with substantial thicknesses of recent volcanic deposits and deltas have developed since 1996 at the mouths of the larger valleys such around the volcano at Tar River and Belham River. At times regular, thick ash has been deposited in Plymouth by the prevailing low level winds to the west. Winds to the northwest have resulted in ash fall in the vicinity of St Georges and Garibaldi Hills, on Old Towne and other villages farther to the north. Montserrat has a maritime humid subtropical to semi-arid climate with annual precipitation ranging from 1000 mm in the north and southeast to more than 2000 mm at 365 m altitude. Daily temperatures range between 15°C and 34°C. Montserrat lies within the hurricane zone and Hurricane Hugo devastated the island in 1989; the previous recorded hurricane to cause widespread damage occurred in 1928. Vegetation in the valleys around the Soufrière Hills volcano has been impacted by pyroclastic flows, lahar and ash deposits. To the northwest of the volcano some vegetation has become stressed due to pyroclastic surges, lahar deposition and gas emissions or choked and buried by repeated ash fall (Figure 1).

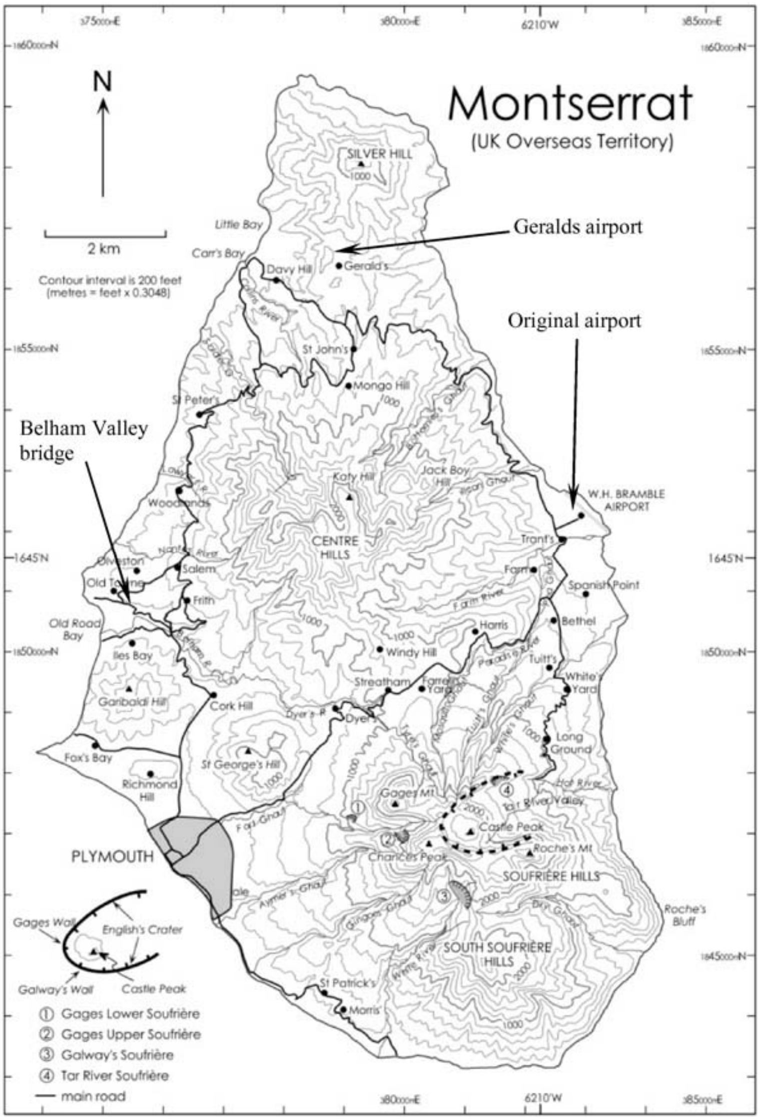

Figure 1. Topographic map of Montserrat (source: Montserrat Volcano Observatory & British Geological Survey).

TECTONIC SETTING AND GEOLOGY

Montserrat is located in the northern part of the Lesser Antilles in the Caribbean. This is a volcanic arc formed along the junction where the Atlantic (North America) plate is subducted westwards beneath the Caribbean Plate. The majority of the islands in this arc have evolved as a result of subduction-related volcanism. These are characterised by stratovolcanoes, produced by a combination of explosive and effusive eruptions and are mainly composed of andesite lavas and volcaniclastic rocks, although some basaltic rocks also occur. The geology of Montserrat is dominated by andesite lavas and breccias with basaltic andesites in the South Soufrière Hills. These are Pleistocene to Recent in age, the oldest rocks on the island (in the Silver Hills) being about 2.6 million years old (Rea 1974). Andesite dome lavas and breccias form the central part of long extinct volcanoes and are well-exposed in the Silver Hills. Around the andesite dome lavas are peripheral breccias, pyroclastic (block and ash) flow deposits, ash-fall, lahar and reworked deposits. These are exposed in the Centre Hills, Silver Hills and on numerous roadside exposures throughout the island. The youngest part of the island, the Soufrière Hills volcano has been in a state of eruption since 1995. There is a substantial scientific literature that has documented the eruption of the Soufrière Hills volcano since 1995 (Druitt & Kokelaar 2002 and references therein, Aspinall *et al.* 1998, Carn *et al.* 2003 and numerous MVO and BGS reports and publications). Lava is extruded as a viscous andesitic lava dome. Partial collapse of parts of the lava dome may generate rock falls (rock avalanches), which if they extend more than 1 km from the dome are termed 'dome collapse pyroclastic flows'. When the andesite magma is ejected explosively, the collapsing eruption column may generate 'fountain collapse pyroclastic flows' containing pumice. Thick pyroclastic deposits fill valleys and partially cover some slopes around the volcano, including the upper reaches of the Belham Valley. Lava dome collapses have on occasions bene triggered by prolonged torrential heavy rains, tropical storms and hurricanes (Matthews *et al.* 2002). Heavy rain can cause mudflows (lahars) that flow seawards along the incised ghauts radiating from the volcano such as the Belham Valley and Gages Valley (Figure 2).

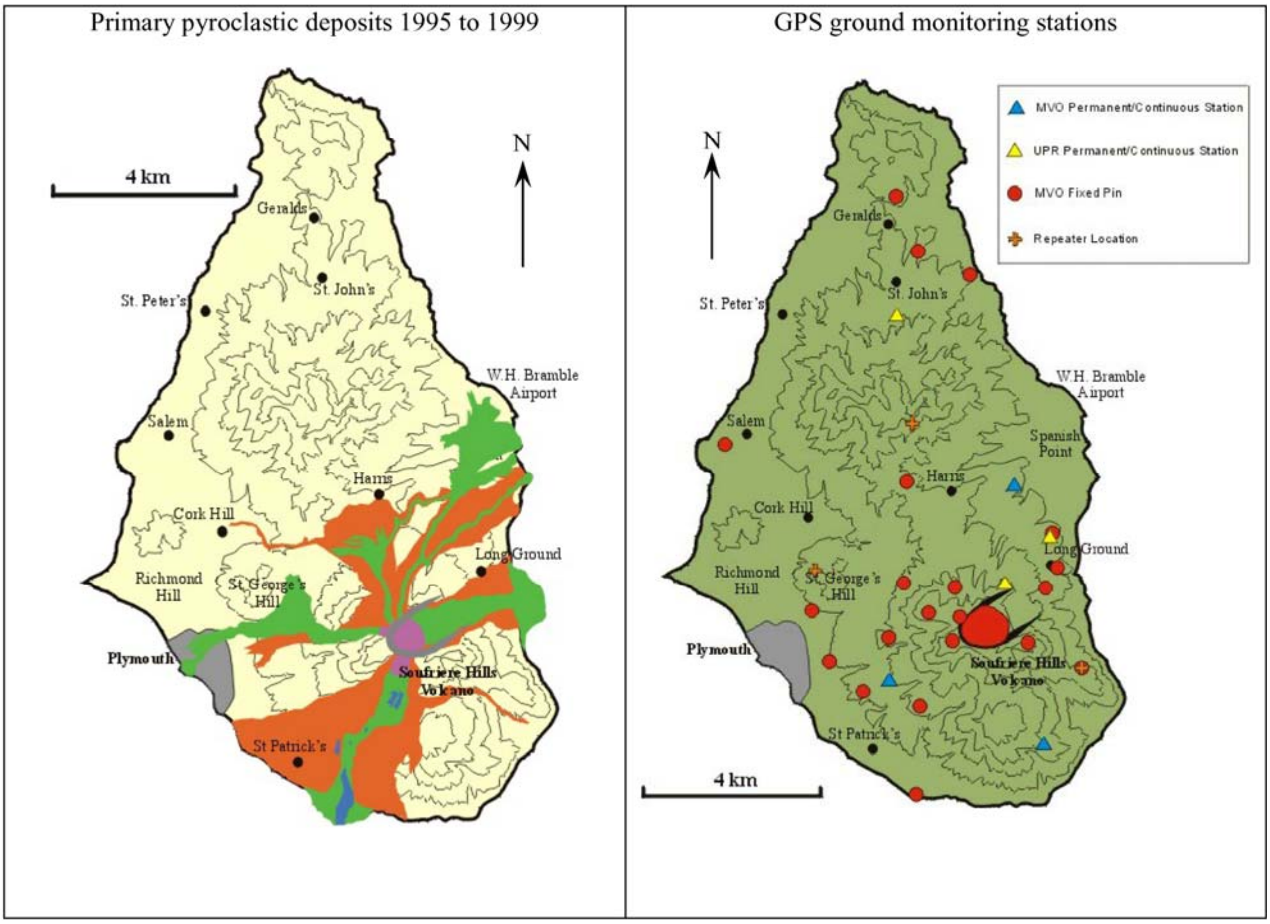

Figure 2. (Left) Montserrat volcanic and volcaniclastic deposits map (green, pyroclastic flow deposits; brown, pyroclastic surge deposits; blue, debris avalanche deposits; purple, lava dome. (source: Montserrat Volcano Observatory & British Geological Survey. (Right) Location of one of the GPS networks on Montserrat (source: Montserrat Volcano Observatory & British Geological Survey).

VOLCANIC HAZARDS AND RISK

Hazard zoning relies on the identification of volcanic hazards (such as lava flows, pyroclastic flows and surges, earthquakes, explosions & blasts resulting in tephra, ash & bombs, gases, debris avalanches, landslides, tsunamis, flash floods & lahars). These are mapped into deposits that have formed during particular phases of volcanic activity. Their extrapolation identifies areas around the volcano that would likely suffer a similar fate at some future time. This however, often assumes that volcanic activity will be consistent with past events, but this is not always the case and therefore a degree of judgement is required.

Volcanic hazard maps define a range of ‘danger zones’ that are usually forbidden, or have restricted entry. These also identify ‘safe zones’ where volcanic events are forecasted to have a low or negligible impact of lives, land, property or infrastructure. Volcanic risk maps provide information on the predicted extent of a particular volcanic hazard, such as a pyroclastic flow, lahar and lithic missile fall-out. These may also be of use for national government, land use, building codes, civil engineering, civil defence, evacuation response, economic and social planning. The overall aim of volcanic hazards maps and volcanic risks maps are to reduce losses caused by volcanic eruptions by a combination of prediction, land-use control and preparedness (Bell 1999).

Ground deformation monitoring

Ground deformation studies have been used by Montserrat Volcano Observatory (MVO) to detect both long-term ground movement, and short-term rapid movements that could act as pre-cursors to failures in the flanks of the volcano, or the dome. Engineering geologists, employed by the British Geological Survey, have on several occasions joined the MVO ground deformation monitoring team.

Ground deformation monitoring on Montserrat is carried out using several different methods, including Global Positioning System (GPS), Electronic Distance Measurement (EDM), tilt and fissure measurements (Aspinall *et al.* 2002). GPS is a worldwide, space-based, navigation system consisting of a constellation of satellites orbiting the earth. The MVO currently collects GPS data from a network of 6 permanently installed stations and from temporarily occupied sites, using mobile GPS units (Figure 2). The present system was set-up in early 1999 and has been continuously logging since. Data from the permanently installed stations is telemetered to the MVO where it is processed and analysed, on a daily basis, to provide the positions of these stations with accuracies of better than 1 cm.

EDM uses an infra-red laser in order to measure the distance between survey stations, located several kilometres from the volcano, and reflective targets placed high on the flanks. Electronic tilt measurements have been used to detect cyclic patterns of conduit and dome pressurisation. Fissure widths on the crater rim have been made using an extensometer (Young *et al.* 2002).

Risk management

Following the onset of the eruption in July 1995 an Emergency Operations Centre was activated in Plymouth. August 1995 saw the first major evacuation of the population from southern and eastern Montserrat. November 1995 saw Long Ground and White's yard evacuated and on December 1 1995 the second major evacuation took place, displacing all residents from Plymouth across to Trants (Kokelaar 2002). The residents of Plymouth and southern areas were allowed back into their homes by mid January 1996 but were evacuated finally in early April 1996, following small pyroclastic flows in the Tar River valley.

The Volcano Risk Map was introduced in May 1996, this was based on hazard assessments made by the Montserrat Volcano Observatory (MVO) and initially relied on a combination of the map and an alert scheme that changed the advice and access status depending on the alert level. In July 1997, following many map iterations and the movement of the population to the north of the island, the system was simplified (Aspinall *et al,* 2002). By September 1998 the Exclusion Zone ran from the bottom of the Belham River and all areas south across the Centre Hills to Pelican Ghaut. A Daytime Entry Zone (DTEZ) was established in April 1999 allowing access between 6.00 am and 6.00 pm. This stayed in place until early 2004 when the Exclusion Zone boundary was changed to its present position, allowing full access to Richmond Hill in the West and daytime entry to St Georges Hill (Figure 3 and Figure 4).

Volcanic hazards

Pyroclastic flows are the most serious hazard associated with the volcano and affect all the valleys adjacent to it. Pyroclastic flows are formed by explosions and also from partial lava dome collapse. The main avalanche of hot blocks and ash destroys most structures and kills people; the expanding turbulent hot-ash cloud (surge), which travels above the main avalanche, is also lethal and is less constrained by topography, travelling at over 100 kph with temperatures between 250 and 700 °C. The buoyant plumes of fine ash drift in the wind to be deposited across the island. Tephra fall, from large explosive events, can include rocks, pumice and volcanic ash. Large quantities can cause roofs to collapse. The ash can pose a serious aviation hazard and the fine ash can cause long-term health problems through inhalation and ingestion. The intensity and magnitude of the explosion, combined with the prevailing wind conditions, will determine where and how much tephra falls.

Volcanic mudflows, or lahars, are flows of volcanic debris and water that usually occur after heavy rainfall. These can be very destructive and life threatening in the valleys around the volcano. On Montserrat the risk is highest around the volcano and in the Belham Valley. After a large ash-fall followed by a heavy downpour problems can also occur elsewhere on the island. Volcanic landslides (debris avalanche) can occur when part of the edifice becomes unstable and fails. These can be triggered by weakening of the volcano edifice (Sparks *et al.* 2002), or by localised earthquakes. Tsunamis have occurred as a secondary hazard as a large volume of material suddenly enters the sea (Sparks et al., 2002). Other hazards include lightning and volcanic gasses which although unpleasant in odour do not pose a serious health risk, other than to the volcanologists working in close proximity to them or to people with breathing problems (e.g. asthmatics).

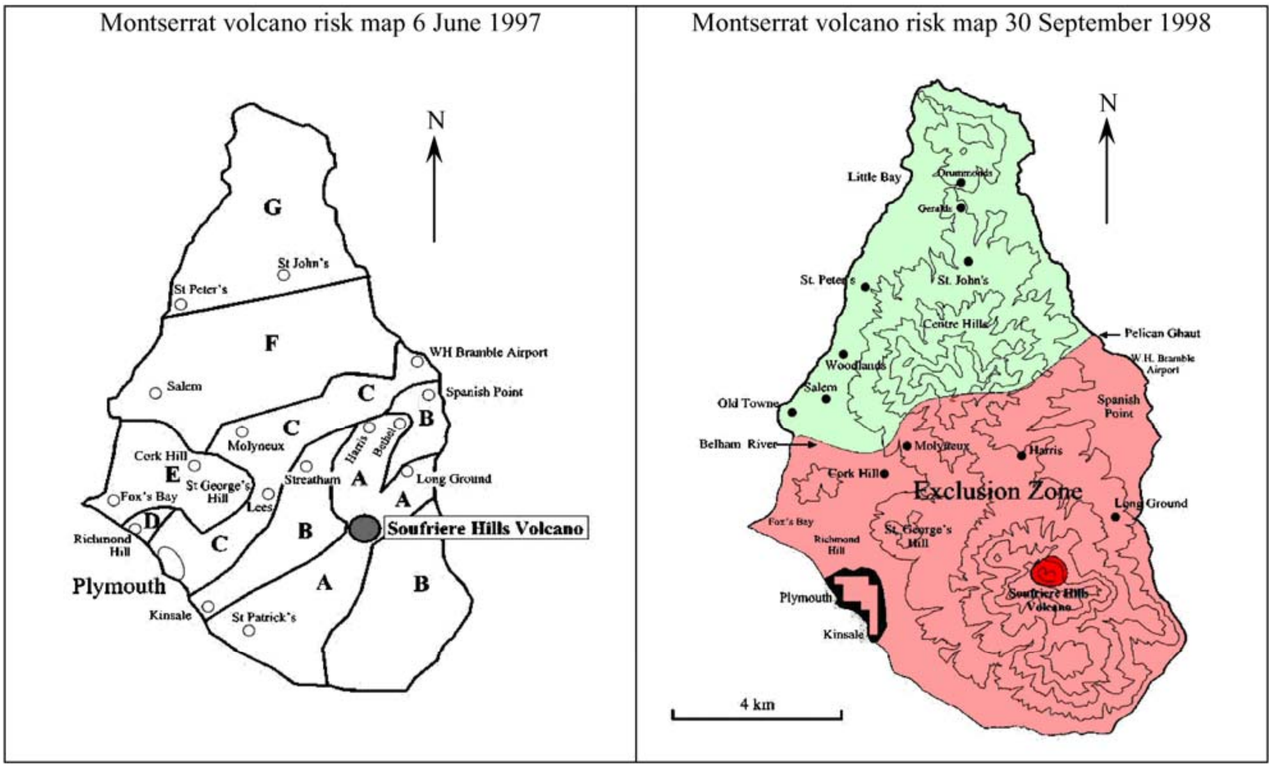

Figure 3. Evolution of volcanic risk maps from 1997 to 1998. The simplification in zones can be attributed to the removal of most of the population from dangerous areas, therefore after June 1997 the microzonation was no longer necessary (see Aspinall *et a.,* 2002). Zone A represents the highest risk and zone G the lowest. Engineering geologists, working at Montserrat Volcano Observatory, contributed to the compilation of these by assisting with the acquisition of ground deformation data and predicting geohazards (source: Montserrat Volcano Observatory).

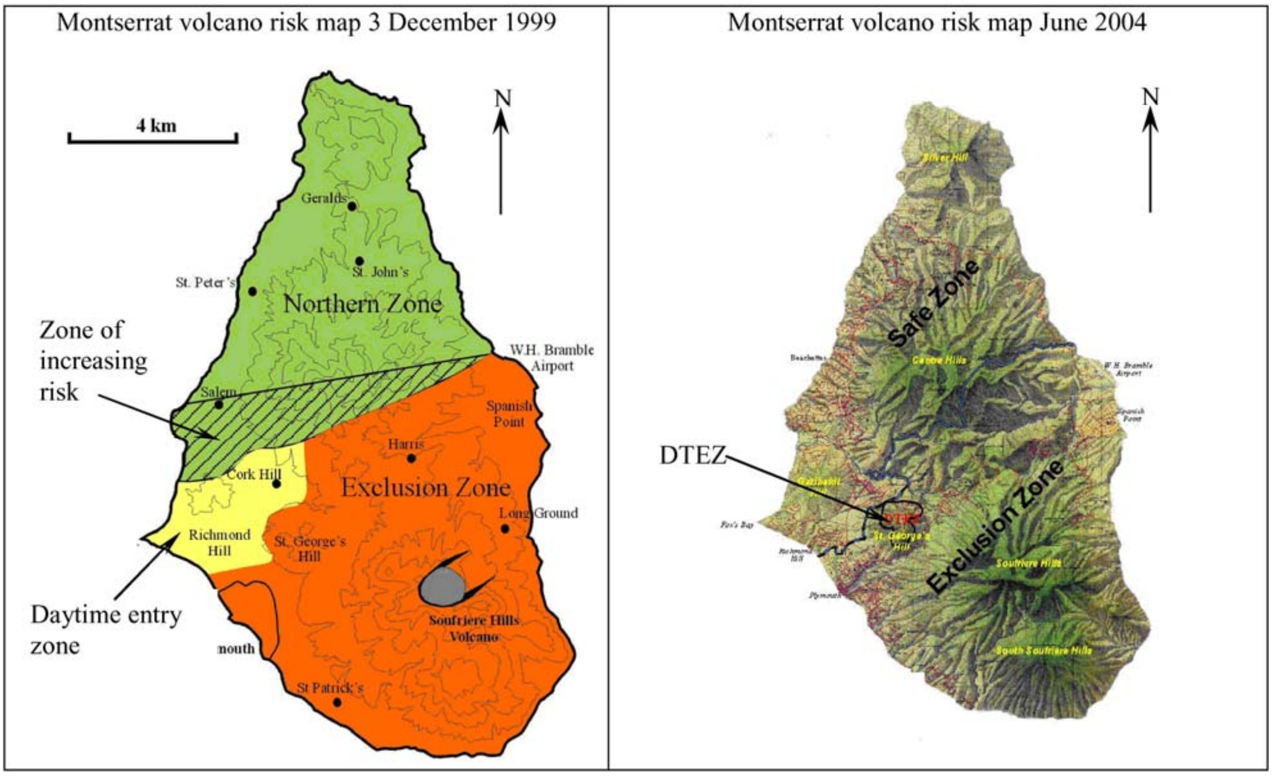

Figure 4. Evolution of the volcanic risks hazards maps from 1999 to 2004, showing the day time entry zone (DTEZ) and area of restricted entry (source: Physical Planning Unit, Government of Montserrat).

Seismcity and earthquakes

Seismcity and earthquakes are common on Montserrat due to its tectonic setting, situated in close proximity to the Caribbean plate boundary subduction zone. Earthquakes on Montserrat are currently generated by plate motions, the upwards movement of rising magma beneath the volcano, failures of the dome (rock failures, pyroclastic flows) and gas emissions; all of which have a characteristic seismic behaviour (detected on a network of seismographs across the island and throughout the Caribbean). Numerous moderately strong earthquakes have been felt in Montserrat since it was colonised in 1632, but none have been highly destructive, although there was structural damage in the 1930s. Major events were recorded in 1690, 1787, 1831, 1843 (largest recorded in Leeward Islands) 1867, 1888, 1897, 1918, 1943, 1946, 1969 and 1974 (Ambeh 1997). Volcanic seismcity, before the current eruption, has occurred in four distinct phases (seismic crisis) which were; 1897-1898, 1933-1937, 1966-1967 and 1992-1995 (Aspinall *et al.* 1998). Only the last phase was followed by volcanic activity (Ambeh 1997). The seismic hazard in Montserrat may be expressed in terms of maximum peak ground acceleration (PGA, measured in cm^2/sec), or as a proportion of acceleration due to gravity (g). Alternatively, seismic hazard, at a given location may be expressed in terms of a probability of occurrence in a certain time period. Estimates of seismcity prepared for the Caribbean indicates that the maximum PGA with a probability of non-exceedence in 50 years of 90% is >0.35g (Shepard *et al.* 1997). It is suggested that a corresponding Modified Mercalli Index (MMI) value of VIII is used as the maximum design intensity. This is equivalent to a ground acceleration with a return period of 475 years (Smith Warner International 2003).

GROUND INVESTIGATIONS

Ground investigation equipment available on the island was limited and restricted to trial pitting and walkover surveys. Consequently the use of qualitative observations and geohazard zonation maps were important additions to routine ground investigation methods. Rock, soil and groundwater samples were sent to Trinidad for geotechnical and chemical laboratory testing. Some in situ geotechnical tests were possible in trial pits (such as California Bearing Ratio and shear vane).

Lahars in the Belham Valley

The term lahar is used to describe volcanic mudflows involving mixtures of water and debris, or sediment-laden flow, in and around volcanoes. In the Belham Valley lahar deposits have accumulated resulting from the removal of pyroclastic debris on higher slopes during prolonged rainstorms, tropical storms and hurricanes. These have remobilised the huge volumes of volcanic debris, which have been redeposited on the middle and lower flanks of the volcano. From January 1999 to July 2004 there have been at least 41 days when lahars have been observed in the Belham Valley, or detected instrumentally using short-period seismic records (Barclay *et al.* 2004). The generation of lahars coincide with increased rainfall rates usually between the months of May to November. Of the 41 reported lahars, 63% were associated with rainfall of greater than 20 mm in a 3 hour period and 87% occurred after greater than 10 mm in 3 hours (Barclay *et al.* 2004). The Belham Valley Bridge was located on the northwestern flank of the volcano, in the lower portion of the Belham Valley. This forms one of the main river valleys which drains the volcano and enters the Caribbean Sea at the Old Towne, on the west side of the island. Numerous lahars have been generated along this valley depositing substantial quantities of sediments (Bouquet *et al.* 2003; Matthews *et al.* 2002). This has caused widespread damage to infrastructure and loss of land, including the island's golf course. The lower reaches of the Belham River Valley have been infilled by at least 15 m of lahar sediments. The original Belham Valley Bridge, has been completely inundated.

Belham Valley Bridge

A ground investigation and feasibility study was undertaken in the Belham Valley, in March 2005, for the design and construction of a replacement bridge. A qualitative assessment of the ease of excavation for the 30 trial pits gave some measure to the degree of consolidation for the deposits. The relative stability of the trial pit walls was recorded based on a qualitative classification, to give an indication of the relatively stability (Table 1). This table provides an initial assessment of the groundwater conditions, which influence the engineering behaviour and properties of the lahar deposits. This information may assist structural engineers to make an initial judgement to the type of possible foundations. These observations provide a useful indication of ground conditions and 'soil' types ahead of more detailed ground investigations. Engineering geological and geotechnical ground investigations, conducted in March 2005, shown the Belham Valley bridge currently lies under at least 3.8 m of 'recent' lahar sediments (Figure 5).

Description of material types

The lahar deposits consist of granular, variable, well-rounded, highly spherical, cobbles & boulders (mainly andesite and dacite) and sub-rounded, elongate cobbles and boulders with preferential alignment and cross laminations. The deposits were loosely packed, highly permeable, porous, saturated, with occasional clay and silt, some rootlets and tree stumps. Parts of the deposit consisted of a boulder-strewn field with individual boulders in exceeding of 3 m in diameter. In some of the trial pits palaeo-weathered surfaces, fossil soils and flow contacts of successive pyroclastic flow and lahar deposits were observed. These were characterised by red-brown weathered clay secondary minerals and an uneven flow stratigraphic interfaces. In other trial pits curvilinear, slickensided, orange-yellow and green clay smears were observed in the upper 2-3 m of pyroclastics. These were interpreted to represent slip surfaces caused by the landsliding and mass wasting of the weathered bedrock. These may reduce the strength of the rock mass and could have implications for the position and design of engineered foundations. In general the lahar deposits were weak, with low strength, low to negligible bearing capacity and probably incapable of carrying the loads necessary to support a bridge on spread foundations.

Figure 5. The Belham Valley Bridge with lahar deposits up to deck level. The lahar deposits consist of granular, variable, well-rounded, highly spherical, cobbles & boulders (mainly andesite and dacite) and sub-rounded, elongate cobbles and boulders with preferential alignment and cross laminations. The deposits were loosely packed, highly permeable, porous, saturated, with occasional clay and silt, some rootlets and tree stumps. The bridge deck currently lies at least 3.8 m below existing ground level.

Table 1. Qualitative classification for relative stability of trial pits.

Excavation Stability	Description
Extremely unstable	No strength in the walls on the excavation, side walls collapse, slump, or flow immediate upon excavation. The trial pit is likely to become immediately flooded by water ingress. Final shape of trial pit is circular.
Very unstable	Some strength in the walls of the excavation, side walls collapse after five minutes of standing, water ingress is high, flooding of the trial pit is likely. Final shape of trial pit is circular.
Unstable	Walls of the excavation remain vertical for greater than 10 minutes, but less than 30 minutes. Frequent falls, topples, slides and slumps. Water ingress moderate to high. Final shape of trial pit is oval.
Moderately stable	Walls of the excavation remain vertical for greater than 30 minutes. Occasional falls, topples, slides and slumps, from one or more face. Water ingress moderate.
Stable	Walls of the excavation remain vertical for greater than 30 minutes. Small, isolated falls, topples, slides and slumps, from one or more face. Water ingress moderate. Final shape of trial pit is coffin shaped.
Very stable	Walls of the excavation remain vertical for greater than 30 minutes. Small, isolated falls, topples, slides and slumps, from one or more face. Water ingress moderate. Final shape of trial pit is rectangular.
Extremely stable	Walls of excavation are vertical for greater than 60 minutes. No falls, topples, slides and slumps. Water ingress low to negligible. Final shape of trial pit is rectangular.

Montserrat Airport

The original airport, located at Brambles, on the eastern (Atlantic Ocean) coastline of the island was damaged by a pyroclastic flow and runways blocked due to lahars. The airport provided an important part of the infrastructure for residents and the tourist industry. A replacement airport was commissioned on the north side of the island at Geralds Park. The purpose of a ground investigation at Geralds Park was to determine the quantities and properties of the materials in the airport earthworks. The general sequence of materials encountered across the site comprised: topsoil, firm clay and poorly to moderately consolidated pyroclastics. This part of the island is dominated by pyroclastics from the Central Hills volcanic centre. In the many road cuttings around the island the materials can be observed and are very variable both vertically and laterally and range from fine to coarse pyroclastics with large boulders of andesite (ash and block flow deposits). Lahar deposits are probably also present. The pyroclastics encountered at the airport site were classified into two types; a tuff (fine) and an agglomeritic (coarse) tuff. A third pyroclastic unit was also encountered to the south of the airport site near the hospital. A qualitative assessment of the excavation ease for the materials encountered on site was established and this gives some measure to the degree of consolidation and used to assess excavation and the quantities of ‘hard’ and ‘soft’ excavation (Table 2). The tuffs are poorly consolidated which upon excavation become a silty sand, locally this material is clayey in particular at shallow depths. Particle size distribution tests indicated that this material breaks down further to predominantly silt (and clayey silt). Atterberg limits indicate that the excavated material is non-plastic. As the degree of consolidation increased some larger cobble sized fragments remain intact upon excavation. This material was moderately easy to excavate. In some areas the tuffs included andesite gravel and cobbles.

Table 2. Ease of excavation in pyroclastic rocks.

Ease of Excavation	Description
Easy	Excavator bucket penetrates soil with no significant resistance.
Moderately Easy	Excavator bucket penetrates soil/weak rock with only slight resistance, excavation progress not hindered.
Moderately Hard	Excavator bucket penetrates weak rock with some resistance, locally teeth on excavator bucket used to break up material, excavation progress reduced slightly.
Hard	Teeth on excavator bucket penetrate rock breaking up the material and allowing excavation, some scrapping, some boulders may be present to cause obstructions. Some reduction in rate of excavation.
Very Hard	Teeth on excavator bucket partially penetrate rock, much scrapping and some boulders present. Excavation possible but rate of progress is reduced.
Extremely Hard	Excavation rate very slow, much scraping, ripping required to progress excavation.

The agglomeritic tuffs comprised a similar matrix to the tuffs, however, they were generally more consolidated and comprised a significant percentage of andesite gravel, cobbles and occasional boulders. The agglomeritic tuffs were moderately hard to very hard to excavate. At some locations the tuff and agglomeritc tuff displayed weathering resulting in a slightly clayey to clayey silt matrix. In a few trial pits, thin buried soil horizons were also present in the upper metre and were mixed with subsequent ash deposits. South of the site adjacent to the hospital a purple brown coloured tuff was present. This tuff was distinctive from the other tuffs encountered on site by its colour. At the north end of the site an andesite layer was encountered. From nearby cuttings and exposures it would appear that this horizon is not extensive (or thick) and that agglomeritic tuffs are present below this layer. A more significant andesite outcrop is present further north of the prison camp, which is probably associated with the andesite plug that makes up most of Gerald's Hill. This andesite outcrop is attributed to the Silver Hills massif. The firm high plasticity clay overlying the pyroclastics was typically up to 0.5 m thick but was not present across the whole site. A number of ponds occur across the site. In other areas the surface appears wet and wallowing cattle have created small pools. It would appear that these ponds and pools represent the local accumulation of surface groundwater. The clay horizon above the pyroclastic deposits forming an impermeable barrier. A summary of the geotechnical parameters of the clays and pyroclastic deposits at Geralds Park are provided in Table 3.

Table 3. Summary of laboratory testing at Geralds Park Airport (Note; Although the terms 'agglomerate' 'tuff' and 'agglomeritic tuff' may no longer be used in volcanology, these terms are still commonly used in geotechnical descriptions). NMC (natural moisture content); LL (liquid Limit); PL (plastic limit); OMC (optimum moisture content); MDD (maximum dry density); NP (non plastic).

Lithology	NMC (%)	LL (%)	PL (%)	OMC(%)	MDD (Mg/m^3)
Clay	39-46	62-67	29-31	-	-
Tuff	8-25	mainly NP	mainly NP	18-26	1.56-1.77
Agglomeritic Tuff	19-21	mainly NP	mainly NP	22-23	1.64

In situ shear strengths were assessed from index tests and site observations and are summarised in Table 4. Laboratory tests were later undertaken on the tuffs, for use in a reinforced embankment, that confirmed the friction angles recommended.

Table 4. Effective shear strength of pyroclastic deposits at Geralds Park Airport.

Material	Effective Shear Strength
Agglomeritic Tuff, in situ	$c' = 5$kPa, $\phi' = 35°$
Tuff, in situ	$c' = 3$kPa, $\phi' = 30°$
Tuff, compacted fill	$c' = 1$kPa, $\phi' = 28°$

The new runway at Geralds Park sits across a topographic ridge. The length of the runway required to allow the desired aircraft types to land was longer than the width of the ridge. It was therefore necessary to extend to the runaway at each end, notably the west end. Due to the steep sides of the ridge any embankment constructed, effectively ended up chasing the natural slope downwards. Steep reinforced walls, gabion walls and reinforced embankments were considered. The preferred solution was to construct a 45^0 reinforced slope embankment. Due to the additional length of runway required the steeply dipping ground surface the vertical height of the embankment was some 30 m. The design of the embankment had to include seismic acceleration and required significant lengths and reduced spacing of the geotextile reinforcement. One problem encountered with the tuffs used the embankments was their high susceptibility to erosion during heavy rainfall and measures were necessary to protect the slopes which included the re-establishment of topsoil and native vetiver grass, *Vetiveria zizanoides* (Figure 6).

Figure 6. Photograph showing Geralds Airport and the reinforced earth slope at the west end of the airport runway.

MINERAL EXPLORATION AND MINERAL RESOURCES

The original quarry on Montserrat, Trants Quarry, is located in the exclusion zone and the use of this quarry is difficult and hazardous. Coarse aggregate for the island is currently imported by barge from Dominique. Reconnaissance studies have been undertaken to locate alternative sources. Surveys for aggregates have been undertaken at various times, initially to identify resources for an evacuation jetty and later for construction and economic development.

Rock aggregate

Rock aggregates, sand and gravel resources are necessary for the rehabilitation of Montserrat and in particular for the construction of homes, public buildings, other structures, for the maintenance of the island road network and the construction of new roads. Reconnaissance mineral exploration surveys have been undertaken which indicate the possibility that aggregate and other industrial mineral resource may be quarried on the island (Donnelly 1996*a*). Further surveys have been undertaken for the construction of Geralds Airport and in investigating the use and development of natural volcanic resources.

Scavenging of andesite boulder

Andesite boulders are present in ghauts and on the surface around the island; these have been scavenged in the past to provide material for small scale aggregate requirements. Some boulders are too large and heavy to move by hand or machine and the boulders are often variably weathered.

Geralds Hill

A possible site for a quarry, or borrow pit, was identified at the back of Gerald’s Hill. Exposures in the hillside revealed very strong massive porphyrictic andesite, with about 30% devitfried glass. Indications suggested that this would be a good material for use as an aggregate. However, this material had a high water absorption, which would fail to meet many specifications and would not be acceptable for concrete. The Sulphate Soundness values are also marginal. Samples were taken from surface outcrops and so could be reflecting weathering, although the samples appeared fresh in hand and thin section specimen. Some reports have suggested that the rock mass in this region may be unstable in alkali silica reactions (concrete cancer) in structural concrete mixes (personal communications, Government of Montserrat) although no long term testing has been undertaken on any aggregate sources on Montserrat.

The Silver Hills

The Silver Hills form the northern most part of the island, where intrusive, andesite-dacite rocks were observed. These are also potentially suitable as rock aggregate for construction and road building on Montserrat. Possible sites for the quarrying of this material are in the vicinity of Rendezvous and Drummonds villages.

Little Bay Quarry

Little Bay Quarry has been opened up in an outcrop of andesite. Rock from this quarry has low sulphate soundness but the water absorption value is high. Most of the quarry comprises disintegrated and weak material and although suitable for bulk fill the material is considered too weathered and altered for use as a concrete aggregate. The operators do not intend to use explosives and will rely on the abundance of rocks and boulders at or near the surface. The operators only plan the quarry life for 10 years, after which the site will be turned into a villa development. The site is in a narrow valley and has little storage area for processed material and even less for the stripped overburden. Exports of aggregates to Antigua have commenced for ready mix concrete, however no physical or mechanical test results have yet been taken.

Sand aggregate

Belham River

The main supply of sand on the island is obtained by abstraction from the river sediment and lahar deposits at Belham River near Old Road Bay. The material is excavated from areas that are replenished during floods. Coarse aggregate is also available at this site, however, the aggregate contains a very high proportion of pumice. The material has been used for all road construction materials except for the asphaltic concrete layer for which imported aggregates are still used. A screening plant supplies sand for block making, concrete and asphalt production throughout the island. There is a market in the Caribbean for this type of sand and there are plans to export this material. Early attempts at using the existing jetty at the mouth of the Belham Valley were unsuccessful due the lahar deposits confounding dredging of the area. Due to the high haulage costs transporting material to the north of the island, permission to use Plymouth Jetty in the south was given. The jetty is also partially inundated by lahar flows, again the build up of more deposits could occur from continuing lahar flows. On the end of the jetty and on the western side there is sufficient water for a 10,000 tonne barge and the operator plans to utilise a high volume conveyor for loading.

Trant's farm

Excavation of sand also takes place in the exclusion zone in the east near the old airport site. This sand is screened on site then transported to Little Bay and used in the production of concrete building blocks.

Volcanic ash

Coventry University carried out an evaluation of the volcaniclastic resource and its potential for exploitation. The report indicated that ceramic tiles could be manufactured using a mixture of ground pumice and or ash with a binder, pressing in a mould and then firing. This proposal is now close to fruition, with a factory shell being earmarked for a new factory, and production expected to start in 2007.

Pumice

Coventry University also identified that Montserrat pumice could be used successfully to create ceramic products, in particular ceramic tiles, although currently local entrepreneurs have not taken up the opportunities proposed.

Pozzolans

Pozzolans have latent cementitious properties, in concrete they can act as a cement replacement without loss of strength, can increase durability, be used to resist alkali-silica reaction, can increase resistance to chloride attack, increase resistance to sulphate attack, reduce heat of hydration and reduce cracking. Results of tests on materials from Montserrat have been mixed. However firm interest has recently been shown by a manufacturer of pozzalanic cement in Puerto Rico. Exports of pumice for the manufacture of pozzalanic cement are likely to start as soon as barge loading facilities at Plymouth jetty are installed.

ENGINEERING GEOLOGY DESIGN CONSIDERATIONS

Stability of excavated slopes

The pre 1995 pyroclastic deposits (mainly block and ash flows) are moderately consolidated and are effectively a weak to moderately strong rock. They are not too strong to prevent excavation by mechanical methods. The material breaks down upon excavation, to a granular material with cobbles and boulders. This may allow transportation and recompaction. Large boulders, up to 2m, are scattered throughout the pyroclastic deposits. Temporary cuttings in consolidated pyroclastic deposits may remain stable at steep angles (70^0 to vertical). However these may unravel over the longer term. Excavations in 'recent' lahar deposits may result in the failure due to the presence of groundwater, unravelling, heavy rain or during tectonic and volcanic seismcity. In weathered and more weakly consolidated pyroclastics and for high slopes benching is required. Flatter angled slopes of between 1:3 and 1:5 (vertical: horizontal) are recommended. These may be further protected by vegetation and from being grassed to reduce surface water erosion (Anderson and Kneale 1985).

Foundations & settlement

Pyroclastic rock forming bedrock may contain palaeo-weathered surfaces, palaeo-soils, slickensided surfaces and a thick laterite in the weathered zone. In lahar deposits the over riding factor in bearing capacity and settlement considerations and in foundation design is likely to be the presence of loose, saturated, sand and gravel. Alluvium and lahar deposits on Montserrat generally have low bearing capacities, high compressibility, and are often associated with high groundwater tables. Foundations placed in these materials may suffer excessive total and differential settlements.

Groundwaters encountered in the lahar deposits may have a sufficiently high sulphate content to attack concrete foundations. Trees stumps, rootlets (peat and organic soils) offer poor foundation conditions due to low bearing capacities and high, uneven settlements.

Excavations and cuttings

Method of excavation will depend upon the degree of weathering, the presence, type and density of discontinuities and strength of the deposit. Fresh or slightly weathered pyroclastics and acid igneous intrusions require ripping or pneumatic tools for excavation. Highly to completely weathered pyroclastics may be excavated by mechanical digging or scraping. Blasting is only likely to be required where massive, poorly jointed igneous intrusion occurs, such as in the Silver Hills area. Although the well jointed nature of the rock mass may allow mechanical excavation. Lahar deposits can be readily excavated by mechanical scraping or digging, but ripping or pneumatic breakers may be required. Hard digging is likely where cobbles and boulders are present in the lahar deposits. The accumulation of surface water in low permeability superficial deposits may cause problems during working. The inflow of groundwater may be a problem when excavating through perched water tables. Ideally these slopes should be protected with re-establishment of topsoil and native vegetation such as vetiver grass. Water needs to be controlled, kept off slopes by ditches at the top of cuttings and proper road drainage dealing with water and training it into ghauts (streams or rivers) at the first available point.

MONTSERRAT LANDSLIDES

Landslide events on Montserrat have been over shaddowed by the more spectacular, destructive and widespread damage associated with the eruption of the Soufrière Hills volcano. There is however, evidence for past and recent landslides through the Caribbean including Montserrat (Degraff *et al. 1989*). Exposed roadside rock, soil and debris cuttings are particularly susceptible to ravelling, sheet wash and gullying during rainfall or after tropical storms and hurricanes (for example several landslides were induced in 1989 when Montserrat was hit by Hurricane Hugo). Steeply dipping and vertical slopes appear to be less affected than more gently inclined cuttings that allow the accumulation and drainage of rainwater. Landslides, instability, subsidence and ground deformation were observed on Gages Wall, the flanks of the English Crater and around geothermal springs (known as soufrières) (Figure 7).

Figure 7. The Monterrat Volcano Observatory landslide; a complex debris slide earthflow with a component of rotational slip (source: Montserrat Volcano Observatory & British Geological Survey).

Instability of the lava dome

Rock falls, rock avalanches, debris slides and debris flows on the lava dome have been generated during the extrusion and growth of lava domes (facilitated by the escape of rapidly expanding volcanic gases), followed by gravitational collapse and the generation of pyroclastic surges, (accompanied by ash clouds and explosions) (Figure 8). Dome collapse pyroclastic flows were first observed, to travel from the volcano into the ocean, in 1996 (Donnelly 1996*b*). Since then numerous pyroclastic flows have been observed and documented (Calder *et al.* 2002) (Figure 9).

Changes in groundwater regime

Meteorological events, such as prolonged rainfall are often associated with the volcanic eruptions and lead to increased water content and porewater pressures of the slope; this can induce landslides.

Land use changes

Changes in land use, including the removal of vegetation (such as destruction by volcanic gas and ash emissions, or deforestation) and the subsequent loss of root strength, can result in less water being extracted from slopes. The reduced interception of groundwater will increase surface run-off, contributing to erosion and debris flows.

Figure 8. Failure of the flanks of the expanding lava dome and extrusive 'spines' generating a series of rock falls, topples, slides and flows. Instability is influenced by the density, geometry and type of rock mass discontinuities in the dome.

Figure 9. Large rocks falls and rock avalanches may develop into dome collapse pyroclastic flows. These tend to be controlled by topography, flowing along valleys (ghauts). Some pyroclastic flows have sufficient energy to reach the ocean (source: Montserrat Volcano Observatory & British Geological Survey).

ROAD & INFRASTRUCTURE

Following the volcanic eruptions 10 years ago the best roads in Montserrat were lost in the exclusion zone. The infrastructure network now consists of the roads described in Table 5. The dominant factor in the road condition rating is the condition of the wearing course. The condition indicator is assessed from a group of indicators carrying different weightings including potholes, cracking, edge break, side drainage and shoulders. Many roads in Montserrat were originally built by hand, placing boulders and cobbles and filling the intercies with smaller material and hand compacting the matrix. A variety of surfacings were used which included asphalt, reinforced concrete, stabilised material and surface dressing. After the volcanic eruptions the population was relocated from the south to the north of the island where infrastructure was less developed. To exacerbate the poor road condition many new large trucks have been introduced. These trucks are causing extensive damage to the highways, many sections have become badly potholed and rutted. All new road constructions are designed in accordance with Transport Research Laboratory's

ORN 31 (Overseas Road Note 31, a guide to the structural design of bitumen-surfaced roads in tropical and subtropical countries). Traffic counts have been carried out which show the heaviest to be in the order $1x10^6$ Equivalent Standard Axels (ESA) which is low. The subgrades are generally good and usually exhibit California Bearing Ration (CBR) above 20%. With these parameters the standard road construction is: 50mm of flexible bituminous surface, 150mm of granular roadbase and 100mm of granular sub-base.

Table 5. Summary of roads in Montserrat.

Class of road	Length (km)	Definition	Condition rated
'A' class roads	23	Main routes on the island, providing primary access between communities, commercial and other areas.	Fair to poor
'B' class roads	6.4	Secondary roads providing important routes between communities and other areas.	Poor to bad
'C' class roads	73.4	Roads serving the communities providing access to local services and the main road network.	Bad

With the relocation of the population from the south of the island a chronic housing shortage arose and immediately after the eruptions large numbers of people were accommodated in tents. As a result of this population shift the Government and private individuals developed new residential areas. Whereas the Government housing developments had satisfactory road infrastructure, many of the privately developed areas are serviced by rough-cut roads. New home homeowners have purchased lots in privately developed areas and have built homes. However these pioneers have had great difficulty in negotiating access to their homes because of poor road infrastructure. Not only is it a problem for the home owners but also to the Public Works Department (PWD), as during times of rain the roads become rivers and sediment, cobbles and small boulders get washed down, often ending up on the public roads causing driving hazards and additional highway maintenance. In these private developments scant regard has been paid to the stability of slopes and drainage. Some of the roads are so narrow and on such steep slopes there is little chance to stabilise the slopes or install effective drainage. It is not just in the new developments that unstable slopes have been formed. Some of the new road cuttings and embankments, constructed to improve the road network in the north of the island have been made with a 60^o to near vertical slope, including cohesive strata. Rock falls are frequent, varying from pieces measuring a few millimetres to small boulders. Fortunately, to date, there are rarely reports of injury to persons or vehicles.

CONCLUSIONS

The Soufrière Hills volcano, on Montserrat, in the Caribbean, has been in a state of eruption for 10 years. Volcanic activity has been dominated by the extrusion and subsequent collapse of a lava dome resulting in the generation of pyroclastic flows and ash clouds. The resulting deposits have engulfed parts of the upper and lower flanks of the volcano in the southern part of the island. Prolonged heavy rainfall and hurricanes have remobilised these deposits to generate lahars. These geological hazards have caused additional widespread destruction and damage to property, land, utilities and infrastructure. Teams of international scientists, working with the Montserrat Volcano Observatory (now managed by the British Geological Survey) including engineering geologists and geotechnical engineers, have monitored the Soufrière Hills volcano and assessed volcanic hazards. Engineering geologists have been involved with both the monitoring and investigation of primary geohazards associated with volcanic activity and secondary hazards (elsewhere on the island). Engineering geologists and geotechnical engineers have also played an important role in the post-disaster rehabilitation of the island. A new airport has been constructed to the north of the island, well beyond the affects of volcanic activity, involving the design and construction of a 45^0, 30m high, reinforced slope embankment. A ground investigation and geohazards feasibility study has been carried out in the Lower Belham Valley to consider the possibility for the construction of a new bridge. This is considered to be necessary to reconnect the southern part of the island. The original Belham Valley bridge was engulfed by huge volumes of volcaniclastic sediments deposited from lahars, it currently lies buried 3.8 metres below ground level. Reconnaissance mineral exploration surveys have located possible hard rock and aggregate raw materials. These still require more detailed exploration and their engineering properties need to be determined. These may enable the extraction of the islands natural resources and reduce mineral import costs. If proven to be suitable they may provide raw materials for building, civil-engineering construction, road repairs and new road construction schemes. Volcanic hazards still remain as a risks on Montserrat (in additional to other hazards such as hurricanes). However, it is also important to appreciate secondary geological hazards, well away from the volcano, throughout the island (such as landslides). These may have a detrimental impact on existing, new and planned infrastructure. It is recommended that all building and construction on Montserrat be subject to appropriate ground investigation and geohazards assessments to reduce the likelihood of unforeseen ground conditions. Engineering geologists do not traditionally form part of volcanic hazards monitoring teams. The contributions made by engineering geologists in Montserrat, has added value to this natural disaster investigation.

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Corresponding author: Dr Laurance Donnelly, Halcrow, Deanway Technology Centre, Wilmslow Road, Handforth, Cheshire, SK9 3FB, United Kingdom. Tel: +44 (0) 1625 540 456. Email: DonnellyLJ@Halcrow.com.

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