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EARTHQUAKE AND VOLCANIC HAZARDS IN THE CARIBBEAN AND THEIR MITIGATION

by

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Prepared for the "Caribbean Meeting on Mitigation of Natural Disasters" organized by the PAN AMERICAN HEALTH ORGANIZATION (PAHO) in Kingston, Jamaica.

May 26-29, 1992.

Introduction

Earthquakes and volcanic eruptions are just two of several natural hazards which include windstorms and floods. Windstorms and floods are seasonal and occur fairly frequently while volcanic eruptions and earthquakes are less frequent, non seasonal and generally more devastating. Furthermore, earthquakes and volcanic eruptions often produce secondary effects which greatly compound those of the initial effects. However, the greater frequency of occurrence of windstorms in the Caribbean has probably resulted in a higher level of awareness and better preparedness to cope with this hazard compared to earthquakes and volcanic eruptions.

Major earthquakes and volcanic eruptions in the Caribbean have caused thousands of deaths and millions of dollars of loss of property. For example, more than 5000 people reportedly died in Hispaniola (Haiti & the Dominican Republic) as a result of the devastating earthquake of 07 May 1842, while the town of St. Pierre in Martinique was completely destroyed, with the loss of approximately 30,000 lives, during the 1902 eruption of Montagne Pelee. Although local losses, in terms of economic damage, loss of life and injuries, may fluctuate from time to time, the vulnerability of people and their property to damage during earthquakes or volcanic eruptions increases with rapid population growth, increased urbanization and the dependence on sophisticated infrastructure. Although only some of the eastern Caribbean islands are directly threatened by volcanic eruption related hazards, all the Caribbean islands are vulnerable to earthquakes.

The occurrence of large earthquakes and/or volcanic eruptions in certain regions of the world is inevitable. However, losses from them can be reduced substantially by the adoption of certain mitigating actions. Adoption of measures to mitigate the effects of earthquakes and/or volcanic eruptions requires a clear understanding of where and why these phenomena occur, the recurrence rates for the large ones and the possible locations and severity of hazardous effects that they can generate.

In general, the pattern of earthquake occurrence and the distribution of volcanoes worldwide is explained to a first order by the theory of Plate Tectonics. This theory suggests that the uppermost 100 km of the Earth is made up of a jigsaw of large, rigid blocks called plates which are in constant motion relative to one another. The great majority of earthquakes and volcanoes are concentrated at the plate boundaries.

Regional Tectonic Setting of the Caribbean

The Caribbean islands are situated close to the boundaries of the Caribbean plate (Fig. 1), a small plate surrounded by the Cocos and Nazca plates to the west, and the North American and South American plates to the north and south respectively, whose margins have been defined mainly by the distribution of earthquake epicentres (Molnar & Sykes, 1969). Geological and seismological studies suggest that the Caribbean plate is moving eastward relative to the Americas at a rate of 2-4 cm/yr (Molnar & Sykes, 1969; Jordan, 1975; Sykes et al., 1982). It is generally accepted that this eastward motion is accomodated along the northern margin by left-lateral faults. At the eastern margin, Atlantic oceanic lithosphere attached to the North and South American plate is being consumed beneath the Caribbean plate. The volcanic islands and active volcanoes in the eastern Caribbean are a direct manifestation of this subduction process. The nature of the southern boundary, in the northeastern Venezuela and Trinidad and Tobago area, is not clear and is still the source of much controversy. The concept that motion along the Caribbean - South American plate boundary is accomodated along right lateral faults (e.g. Molnar & Sykes, 1969; Tomblin, 1972), is disputed by Bell (1972), Jordan (1975) and Perez & Aggarwal (1981) who propose that the plate boundary is a broad zone of deformation (up to 200 km north to south) characterised by a number of fault bounded blocks engaged in a complex pattern of relative motion. Along the western edge at the Middle America arc, oceanic lithosphere of the Cocos plate is being consumed. The relatively slow rate of relative motion along the Caribbean plate boundaries has resulted in longer return periods between large magnitude earthquakes for the region compared to the larger circum-Pacific arc (Molnar & Sykes, 1969; Kelleher et al., 1973).

Earthquake damage from the historical records

Almost all Caribbean islands have a long history of felt earthquakes as evidenced from the detailed catalogues of Robson (1964) and Tomblin & Robson (1977). The number of earthquakes felt in the various islands at Modified Mercalli (MM) intensities greater than or equal to VI is summarized in Table 1 for the period 1800 to present. This is the period for which the felt intensities of MM VI and greater are considered complete. It must, however, be noted that the historic damage record refers to the most earthquake-sensitive structures which existed at the time, and hence inferences drawn would not be directly applicable to modern structures.

Table 1: Numbers of earthquake intensities (MM) in the Caribbean, 1800-present.

	VI	VII	VIII	IX
Trinidad	23	4	3	
Tobago	5			
Grenada	2	3	2	
St. Vincent	2	3	2	
Barbados	2	4		
St. Lucia	3	4	2	
Martinique	6	5		1
Dominica	5		1	1
Guadeloupe	4	1		2
Montserrat	2	1	4	1
St. Kitts	3	4	1	1
Nevis	2	2	1	1
Antiqua	6	2	1	1
Barbuda		2		
Statia, St. Bartholomew, St. Martin	1		1	
Tortola			1	
St. Thomas	1		2	
Puerto Rico	2	2	3	1
Dominican Republic	1	1	4	1
Haiti	1	3	2	1
Jamaica	24	2	2	1
Cuba	5	3	4	1

Instrumental Seismicity

The seismicity of the Caribbean region was, in general, poorly observed during the first part of this century because of the paucity of seismograph stations. The creation of the Volcanological Research Department (now the Seismic Research Unit - SRU) in 1953, with headquarters in Trinidad, resulted in the start of a program of establishing a network of seismic stations in the British Caribbean islands. With the completion of the World Wide Standardized Seismograph Network by the United States Geological Survey in 1964, the number and quality of Caribbean earthquake data has increased considerably. The SRU, UWI, St. Augustine, currently operates a radio telemetered network of up to 30 seismic stations in the English-speaking Eastern Caribbean Islands for the purpose of earthquake and volcano monitoring. Local seismic networks are also operated by other agencies in Jamaica, Cuba, Puerto Rico, Guadeloupe and Martinique. Consequently, the quality of the available earthquake data for the Caribbean area is not spatially and temporally uniform, but has improved progressively with time, with some areas exhibiting higher resolution than others.

Fig. 2 shows epicentres of earthquakes of magnitude greater than or equal to mb 4.0 that have occurred in the Caribbean during the period 1900-1990. The distribution of epicentres shows clearly that all the Caribbean islands are close to major earthquake source zones. The activity rate appears to be greatest in the area from the Dominican Republic to Martinique and close to Trinidad.

Earthquake Hazards

The terms "earthquake hazard" and "earthquake risk" are often used interchangeably by many individuals. However, the application of restricted definitions to each of them can be very helpful. Seismic Risk is the expected or probable loss of life, of damage to property or of disruption to economic activity, given the probabilities that specified levels of, for example, ground shaking occur. Seismic risk depends on Seismic Hazard and Vulnerability of elements at risk. Seismic Hazard is defined as the probability of occurrence of a certain level of a ground motion parameter at a site within a specified time period while vulnerability is the degree of loss to a given element at risk resulting from the occurrence of a specified level of ground motion.

The assessment of earthquake hazards involves the delineation and characterization of potential effects from seismically induced processes at or near the ground surface. This procedure is often termed 'Seismic Zoning' and the main product is a seismic zoning map displaying a quantity (or quantities) related to the expected frequency and intensity of shaking that may be caused by future earthquakes in the vicinity of the site. Most existing zoning maps were compiled on a basis of assuming that the past pattern of earthquake activity will be valid in the future. Since these maps neglect completely the possibility that source regions may exist which have been quiescent during the observation period, future activity in these areas would cause surprises and may result in serious economic consequencies. A better way of zoning, which is more difficult, involves extrapolation from regions of past earthquake activity to potential earthquake source regions.

The principal hazards from earthquakes include surface faulting, ground shaking and ground failure while secondary effects are fire and tsunamis in coastal areas. The primary hazard for most Caribbean islands is the shaking hazard.

Shaking hazard

Ground shaking caused by earth waves travelling from the earthquake source is usually the primary cause of damage from earthquakes. Three major factors affect the severity of ground shaking at a particular site: the magnitude of the earthquake, the distance to the earthquake focus and the geologic conditions at the site. In general, larger earthquakes produce more vigorous ground shaking that occurs over wider areas than for a smaller event. For example, strong ground shaking for a magnitude 7 earthquake might typically last 15 seconds while shaking for a magnitude 8 earthquake may last a minute.

Using available data on earthquake source zones, rates of earthquake occurrence and curves depicting the rate of attenuation of seismic waves, the geographic variation in the shaking hazard in an area can be evaluated. Although the shaking hazard can be depicted as an iso-intensity map, engineers often prefer to see a map of contoured ground acceleration or particle velocity in firm ground which has 90% probability of not being exceeded within any 50-year period. Maximum accelerations recommended in CUBIC for some of the Caribbean islands are listed in Table 2, although some preliminary work done by the author seems to indicate that many of these values will have to be revised downward.

Table 2: CUBIC recommended design accelerations and zonal factors for some Caibbean islands (After Faccioli et al., 1983)

Island	Design Acceleration (cm/s/s)	Z-factor	UBC Zone
Antigua	300	0.75	3
Barbuda	300	0.75	3
St. Kitts	180	0.45	3
Nevis	210	0.53	3
Montserrat	200	0.50	3
Dominica	140	0.35	3
St. Lucia	110	0.28	3
St. Vincent	70	0.18	2
Grenada	90	0.23	2
Barbados	50	0.13	1
Trinidad	150-300	0.4-0.75	2-3
Tobago	200	0.50	2

Influence of near-surface site geology

Site geology is a major element affecting the likely intensity of ground shaking. Thick soils, such as alluvium, overlying solid rock tend to amplify the level of ground shaking and prolong its duration. The degree to which this effect takes place is dependent on certain physical properties of the soil such as its velocity, density and thickness relative to the underlying rock.

Many major Caribbean towns are located by the sea and have many structures which have been built on reclaimed land. The vulnerability of these structures to earthquake damage is greater than that of structures constructed on firm ground.

Vulnerability and Risk

As a result of strong ground motion generated by an earthquake, different elements at risk such as buildings, people, public utilities, industry, etc are damaged to various degrees and people are injured or killed. Every element is vulnerable to a different extent according to its sensitivity to vibrations or to secondary effects. The vulnerability of an element can be expressed by the percentage of its functional deterioration due to a certain level of seismic hazard.

Excluding region-specific instances such as landslides and dam failures, life loss and monetary loss come from the failure of man made structures such as buildings. Although Chin (1991) has carried out a vulnerability assessment for certain critical structures in Trinidad and Tobago, detailed inventories of buildings, structures and populations at risk, suitable for seismic risk assessment, have not yet been compiled for most of the Caribbean islands. It is, therefore, impossible for us to quantitatively evaluate seismic risk at the moment with any degree of objectivity.

Eastern Caribbean volcanoes and volcanic hazards

In the Eastern Caribbean, approximately 30 potentially active volcanic centres have been identified (Fig. 3). They are to be found in the island of Grenada in the south to Saba in the north, with Dominica having the largest number of potentially active sites. Many of these volcanoes have been dormant for very long periods of time and their only manifestations of volcanic activity are hot springs, solfataras and volcanic earthquakes. However, it is possible for a volcano to be inactive for centuries and then spring to life with devastating power. For the period 1600 - 1982, it has been estimated that about 30,761 people were killed in the Caribbean by volcanic eruptions. This is second only to Indonesia

(160,783 people) for the same period. However, most of the deaths in the Caribbean are due to the 1902 eruption of Montagne Pelee, Martinique, with the Soufriere of St. Vincent accounting for approximately 2,000.

The most famous Caribbean volcanoes which have erupted in historic times and are, therefore, better known for their activity, are the Soufrieres of St. Vincent and Guadeloupe, and Montagne Pelee in Martinique. Volcanism of the type commonly associated with the Eastern Caribbean islands (subduction zone type) is usually of the violently explosive type. Eruptions this century include Soufriere, St. Vincent (1902, 1971, 1979), Montagne Pelee (1902, 1929) and Soufriere, Guadeloupe (1903, 1956, 1976).

Descriptions of volcanoes as active, dormant or extinct, are unsatisfactory because the historic period varies from region to region and some so-called extinct volcanoes can become active. For example, the 1973 eruption of Heimay in Iceland was the first at this volcano for over 5,000 years and the devastating eruption of Mt. Lamington in Papua New Guinea in 1951 was probably the first for at least several thousand years. Some volcanoes clearly have periods of dormancy which are much longer than the historic record for the local area, and in general, it seems longer intervals commonly precede very explosive eruptions. This observation is of particular concern to us in the Caribbean since the vast majority of the volcanoes have been quiet for a very long time.

Given the tremendous amount of destruction that volcanic eruptions can cause, a question is often asked as to why people are willing to live with such dangers. An answer to such a question is not easy since many variables such as culture, economics, and the individual willingness to take risks are involved. More importantly, to those persons born in these areas, this is home and their bond to the area causes them to accept the risks of being there and most will have it no other way. Furthermore, in most tropical regions where fertile top soils are easily degraded by heavy rains, the most fertile land is usually located around volcanoes. So it is, in most situations, a matter of reaping the benefits today whilst hoping for the best some time in the future when nature changes the scene.

In the Caribbean, an estimated 250,000 persons live within close proximity of possible major volcanic hazards. This includes at least three capital towns and thousands of farmers who grow the best sugarcane, bananas and pineapples in high quality volcanic soils in St. Vincent, Dominica and the French Antilles. The level of danger of a volcanic eruption depends on several factors including the point from which it issues and the weather conditions.

The main hazards associated with volcanic activity include pyroclastic flows, which often follow topographic lows but have the ability to spread out over wide areas. This phenomenon, also called a glowing avalanche represents a density flow composed of gases, ash and glowing rock fragments, which roll down the sides of a volcano, buoyed up by the super-heated gases within and by the air trapped below. These flows may attain speeds in excess of 100 km/hr and have temperatures of over 600 C. The destruction of St. Pierre, Martinique, was due to pyroclastic flows during the 1902 eruption. Other hazards include lava flows, volcanic mudflows, airfall bombs and ash, ground deformation and toxic gases.

If human casualties are accepted as a measure of the degree of hazard associated with volcanic eruptions, then pyroclastic flows and tsunamis have been by far the most hazardous volcanic agents. However, volcanogenic tsunamis have been unimportant causes of human death in the twentieth century. More recently, since the eruption of Mt. St. Helens in the U.S.A. in 1980 when the top of the mountain was blown away in a gigantic explosion, the phenomenon of directed blast which devastates many square kilometres in seconds, has been listed as one of the most frightening volcanic developments. Evidence of this type of activity has been identified at the volcanoes in St, Vincent, St. Lucia and Guadeloupe from studies of ancient deposits.

Although massive in bulk, lava flows generally do not pose a significant threat to humans because of the low speeds at which they travel. This usually permits timely evacuation. Destruction to structures and laying waste of agricultural lands are the main concerns here.

Volcanic mudflows (lahars) are avalanche-type mass movements usually consisting of a mixture of both old and new, wet volcanic ash and angular rock fragments, whose high water content could have been derived from rains, rapidly melting snow near the crater, ground water or even the bursting of a crater lake, such as the one which existed in the Soufriere, St. Vincent, during the 1979 eruption. Areas that are likely to be at risk from mudflows can readily be predicted since they mostly flow down valleys. These flows usually wipe out roads and bridges thereby hampering the evacuation of populations who might then be trapped to face more deadly eruptive hazards. This was one of the main reasons for so many lives lost in St. Vincent in 1902.

Volcanic bombs (solid hot lava fragments thrown high up into the air) and tephra (volcanic ash) ejected from a volcano present another hazard capable of doing great damage. The bombs may smash through roofs and set buildings on fire, while tephra may bury entire towns, cause roofs to collapse and choke agricultural lands. Although Barbados has no volcanoes of its own, it is frequently inundated with ash from the eruptions in St. Vincent.

Ground deformation frequently occurs before and after eruptions as a result of inflation and deflation of the magma chamber. Deformation is often minor and highly localized, and although it is of great scientific interest as a monitoring tool, it is of no serious consequence from the hazard standpoint.

Tsunamis are fast moving sea waves generated by certain types of earthquakes or submarine volcanic eruptions which can propagate for hundreds or even thousands of miles from their source and may surge to damaging heights in coastal areas. The only known submarine volcano in the Caribbean is Kick-em-Jenny, located just off the north coast of Grenada. It erupts every 2-3 years and so far has not been known to have produced a tsunami, but since it lies only 150m below the surface, the threat is very real indeed. A substantial displacement of water is required to produce a tsunami. A large tsunami generated from Kick-em Jenny could have serious effects as far away as the Virgin islands or Jamaica.

Earthquake Risk Mitigation

It is a fact that it is easier for any sector of the economy to recover after a disaster if the effects of the disaster, be it man-made or natural, are relatively small. Consequently, actions which can be undertaken to mitigate or reduce the potential effect of an earthuake disaster must be considered as the first steps in any earthquake disaster recovery plan.

The occurrence of large earthquakes in certain areas of the world is inevitable. However, losses from them, in the form of deaths, injuries, property damage and socioeconomic disruption, can be substantially reduced through careful consideration of earthquake hazards information when making decisions regarding land use, structure design and building construction. Mitigating the impact of an earthquake disaster requires social, economic and political actions from both local and national governments. Individuals and community groups can also play a significant part in this process.

Five basic strategies that can be undertaken to mitigate the effects of earthquakes include:

a) Preparedness

It is generally accepted that the successful management of any risk depends on the degree of preparation which is associated with the hazard potential. The first step in this process is obviously an awareness of the likelihood of its development. Preparedness includes having plans for warning (before the event) if possible, response (during and immediately after the event, i.e. the emergency services), and post-event recovery (economic reinvestments, repairs to damaged infrastructure, counselling of victims, etc).

The study of earthquakes has not yet reached the stage where we can make a prediction in terms of location, time and magnitude. The best we can do at the moment is to use large scale seismicity patterns to make a forecast which, at best, only emphasizes the broad extent of the hazard and the uncertainties involved. To illustrate this point further, let us look at the Parkfield Earthquake Prediction Experiment in the USA. In April 1985, the United States Geological Survey forecasted that an earthquake of about magnitude 6 would occur before 1993 (1988+5.2 years) on the segment of the San Andreas fault near Parkfield, California. This forecast is the first officially recognized scientific earthquake forecast in the USA. Consequently, the Parkfield segment of the San Andreas fault has become the most densely and comprehensively instrumented earthquake source region in the world and the primary goal of the experiment is a detailed understanding of geologic processes that precede the anticipated earthquake. However, it must be emphasized that even if short-term premonitory effects are detected at Parkfield, the feasibility of earthquake prediction in other areas is not assured.

b) Land use

Information available on earthquake hazards, such as expected ground accelerations, liquefaction susceptibility, etc, can be used in amending land use policies to reflect the seismic and geologic hazards. New developments in hazardous areas should obviously be discouraged.

This, however, is often not the case. We are aware that because of limited land space, population pressures often lead to the widespread use of sites which may be hazardous. Furthermore, this is usually by people with relatively low incomes who cannot afford to incorporate recommended earthquake-resistant design parameters in their structures. It must also be pointed out that many individuals from higher income groupings often choose to build in 'fashionable' areas close to the seafront which may have been reclaimed and are thus prone to liquefaction.

c) Building Codes, Standards and Design Practices

A code of practice for the design of earthquake resistant structures and the retrofitting of older structures in the

Caribbean is given in Part 2, Section 3, of the Caribbean Uniform Building Code (CUBIC) published by the CARICOM Secretariat (CARICOM Secretariat, 1985). Structures constructed to meet seismic resistance code requirements generally fare better in earthquakes than those that do not meet the standards.

Although the standards recommended in CUBIC seem to be adhered to for certain types of constructions, cultural preference in design for specific purposes as well as traditional choices and the utilization of some indigenous materials often results in structures which are of an inferior standard with regard to earthquake resistance. For example, there is a prevalence of residential houses of the 'top-heavy' design in Trinidad. In the present economic climate, it will also be difficult to convince either individuals or the government to retrofit older structures.

d) Insurance and Relief

The provision of financial incentives in the form of tax credits for the construction or rehabilitation of buildings to meet standards set for earthquake resistance is a possible step for the government. Insurance companies could also play a role in mitigation by loading premiums in favour of earthquake resistant structures.

e) Information and Education

The availability of information about earthquake risk does not necessarily ensure its use. In the formulation of any policy to mitigate the effects of earthquakes, it is important to ask ourselves how well informed citizens are with regard to hazards and their mitigation. This is very important since the acceptance and effectiveness of any mitigation measures, many of which require an economic commitment, will depend critically on the public's perception of the necessity and utility of the measures, as well as on the reliability of the technological information on which they are based. To date, the dissemination of information about seismic hazards to the public has been primarily in response to inquiries by individuals (very few), companies (insurance and construction) or the mass media. Little or no effort has been made to educate the public in a systematic manner about the causes and effects of earthquakes and what they can do to moderate its impact.

Volcanic Risk Mitigation

Given the nature of a volcanic phenomenon and its potential to do untold damage to life and property over very wide areas in relatively short periods of time, it follows that one of the imperatives in any volcanic environment is to understand the local hazard potential and to prepare for the eventuality which is sure to occur in the future. Investigation and preparation are costly undertakings, but the cost of ignoring it or being ill-prepared can be very high indeed.

Many volcanoes give early warning signs before their eruptions. Precursory phenomena to more serious activity include earthquake swarms, minor steam or ash eruptions, and changes in the temperature and composition of volcanic gases. No single currently available method is adequate to predict volcanic eruptions. Methods employed in monitoring potentially dangerous volcanoes include the monitoring of changes in shape by the reflection of laser beams off targets placed in critical spots on volcanoes, periodic sampling and analysis of the temperature and composition of gases, and, most importantly, the monitoring of earthquake activity with seismic instruments.

After the avoidable calamities at Soufriere, St. Vincent, and Montagne Pelee, Martinique, at the turn of the century, the colonial governments of those islands took steps to mitigate the circumstances under which populations coexist with their volcanoes. In the commonwealth islands, the governments, through the Seismic Research Unit of the University of the West Indies, St. Augustine, provide the necessary round-the-clock monitoring service with sensitive seismographs whose signals are continuously transmitted directly to St. Augustine, Trinidad.

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effective legislation to deter residents from constructing in these hazardous areas or to force developers to adhere to maximum safety standards when constructing in difficult areas. Landslide prone areas are along Ridge Road, Ballast Bay/Cane Garden Bay, West End Road, and the Windy Hill road.

EARTHQUAKES

The British Virgin Islands lying at the eastern edge of the Greater Antilles chain and at the north eastern corner of the Caribbean plate, is prone to seismicity occurring along the margin of the Caribbean plate. This is due to either interplate motion, in this case subduction resulting from convergences between the Caribbean and North America plate, or intraplate motion, i.e. motion between blocks within one plate (See Appendix III, IV, V). Regardless of their origin strong earthquakes near Puerto Rico and the Virgin Islands pose a hazard to local populations. Moreso, the islands are in close proximity to the Puerto Rican Trench some 50-100 km north of the BVI, which is the seismically active northern boundary of the Caribbean plate margin (See Appendix VI). The historic record of earthquakes affecting Puerto Rico and the Virgin Islands span some 400 years describing strong damaging earthquakes that have periodically stricken the islands. A severe earthquake occurred in 1785 which was reported to have formed a "small island" off Tortola. No additional details are known.

In 1787 another major quake was recorded which resulted in major destruction in Puerto Rico and the Virgin Islands. Of noteworthy importance is the earthquake of 1867 accompanied by a destructive seismic sea waves (tsunami) which ravaged the coast of south eastern Puerto Rico and various parts of the Virgin Islands (Anon, 1972; Reid and Taber, 1920). Local records in Tortola indicated that a multiple trauma earthquake measuring 7.8 on the Richter

Scale and lasting fifteen minutes (fairly questionable) was felt throughout the islands. A severe tidal wave associated with this earthquake caused extensive damage. Anegada was particularly affected by this tidal wave. More recently in the first quarter of 1992, three tremors were felt in the islands of the BVI. Their magnitudes ranged from 3.9 4.1 on the Richter Scale. Their hypocentral coordinates ranged between 18.847N-18.94N latitude and 64.075W 65.011W longitude. They were shallow in depth and did not cause any damage.

Seismic activity is definitely high along limited segments of the Puerto Rican Trench. These active segments are separated by zones of relatively little seismic activity. The relatively long period of time over which this consistent distribution of seismicity is observed (up to 80 years) and the ability to correlate the level of seismic activity with features on the inner wall of the trench, strongly suggests that the distribution of seismicity is not random, but rather is associated with long term tectonic processes occurring near the plate boundary. Mc Cann (1984) on Earthquake hazards of Puerto Rico and the Virgin Islands estimate a seismic potential of 2 for Puerto Rico and the Virgin Islands which is a moderately high potential for a large earthquake in the future. (See appendix VIII)

In addition to the Puerto Rican Trench, there are other structural features in the vicinity of the Virgin Islands which encourage susceptibility to earthquake hazard. Regions to the east, west and south of Puerto Rico and the Virgin Islands (structurally the same i.e. they lie on the Puerto Rico Virgin Islands Platform) (See Appendix VII) include many complex geologic structure that increase the seismicity of this region. Down dropped blocks (grabben) striking north or north westerly are the most prominent features in this region. The most prominent of these grabbens is the Mona Canyon which forms the Mona Passage and is bathymetrically clearly defined with a significant vertical displacement of the sea floor. This feature is a likely source for strong earthquakes since active faults are observed in the seismic reflection records near this feature. (Mc Cann 1984) See Appendix VII.

The Muertos Trough which lies to the South (Appendix VII) like the Puerto Rico Trench, it accommodates the convergence between two blocks. Along much of this trough the floor of the Caribbean Sea moves underneath the massif of Puerto Rico. So the "rigid" block, upon which Puerto Rico and the Virgin Islands lie, (300 km wide in the north-south direction) overrides converging seafloor from both north and south directions, significantly increasing seismicity. (Mc Cann 1984)

In addition, steep scarps characterize the margins of the deep Virgin Islands Basin and micro earthquakes are found in association with these features. (See Appendix VII).

The relatively simple structure of the Virgin Islands basin, being bounded by long fault segments is a more likely source of strong shocks (M. 7-8) than the more complex structures (grabben) to the west.

In addition complex features separate the Virgin Islands Basin from the smaller Saint Croix Basin. At this region the north-easterly trending faults extending from the Puerto Rico Trench intersect the westerly trending structures.

This complex junction of faults is structurally similar to the region west of the Virgin Islands Basin and therefore is likely to pose a similar earthquake hazard.

Some researchers like W.R. Mc Cann (of the Lamont Doheryt Geological Observatory in Palisades, New York), recognised that while the earthquake of 1787 originating in the Trench resulted in major destruction in Puerto Rico and the Virgin Islands with a probable magnitude of 8-8.25 making this shock the largest in our historic record, he strongly felt that more damaging quakes of somewhat smaller magnitude (7-8) occurred much closer to land (10-50km). A major shock on one of the many faults nearer to the Islands may, on average, occur just as frequently as the great earthquakes in the Puerto Rico Trench. This means that the main earthquake hazard for us in the Virgin Islands may not come from great earthquakes to the north but rather from major ones occurring closer to land.

The observations presented above are largely the work of William R. Mc Cann from his paper Earthquake Hazard of Puerto Rico and the Virgin Islands. These observations provide a tectonic framework in which to estimate the likely sources of strong earthquakes. The conclusions should not be taken as definitive since more research is needed to further define the hazard.

PHYSICAL EFFECTS OF EARTHQUAKES

For the Virgin Islands the types of physical effects that can be expected in MMI VIII earthquake (Modified Mercalli Index - 8) are:

(1) Vibratory ground motion
(2) Tsunami
(3) Landsliding
(4) Liquefaction

On the basis of the available scientific data, planners have to consider the likelihood of the occurrence of a number of relatively large aftershocks. These aftershocks, which could impact overall planning concepts, could have a significant effect on human response to the emergency as well as causing further weakening of slopes and structure.

The information collected in the last decade has clarified our understanding of the nature of the seismic zone near Puerto Rico and the Virgin Islands. Numerous active faults are located in the offshore region; some may extend onshore. Identification and detailed mapping of active faults, focal mechanisms, a more precise location of small earthquakes, together with more detailed investigation of the historic record and collection of geometric data are few areas deserving of more research before comprehensive and more realistic evaluation of the earthquake hazard can be derived for these islands.

HAZARDOUS MATERIAL SPILLS

On the man-made side the possibility of being impacted by a major oil spill is cause for serious concern in the BVI. The Anegada Passage located 18-38'W latitude and 63-39'W longitude (sometimes referred to as the Sombrero Passage) situated between Anegada and Sombrero Island is a major shipping transit route, with a high annual frequency of transit, for cargo ships carrying petroleum, petroleum products and other types of hazardous materials. Within recent years the BVI have had to respond to small spills and mount clean ups as a result spill accidents.

These spills resulted in damage to our coastal areas as well as marine areas like coral reefs and the lifeforms that these natural areas support. The economy is heavily based on tourism, especially yachting. This sector is therefore highly vulnerable to oil spills and other hazardous material spills occurring in the marine areas.

In addition the islands are flanked by a well developed reef system which not only provides attractive snorkelling sites for tourism but protection to coastal areas from high energy wave action, and breeding grounds for fish and other marine lifeforms which sustain our small local fishing industry. Ecological disruptions resulting from any major spill could have serious economic implications resulting in undesirable development setbacks. Very recently, there was serious concern about the possibility of a plutonium shipment passing in close proximity to our Territorial Waters. The destructive potential of such a spill due to the physical and chemical properties of the material itself was cause for alarm.

Although this shipment did not traverse our waters, it does not make the BVI any less vulnerable to spills generating from marine accidents involving hazardous materials of a similar nature or to the deliberate dumping of toxic waste, by carriers in search of third world dumping sites.

VULNERABILITY FOR THE POPULATION AND ECONOMY

The major sector of economic activity within the BVI is related to tourism which accounts for approximately 70% of the GDP with yacht chartering accounting for approximately 50% of the direct earnings from tourism. The Offshore Banking and Financial sector accounts for approximately 20% with fishing and construction activities making up the major portion of the remaining 10%. Approximately 85% of the hotel rooms in the BVI are concentrated directly on the coast.

It can therefore be seen quite clearly that the coastal zone holds the key to the major economic activity as well as being hosts to all major settlements, government infrastructure and local business activity. Over the past two decades major expansion of the capital, Road Town has been concentrated seaward with the reclamation of a considerable portion of coastal area, sites upon which large scale construction is occurring at a rapid pace. These reclaimed areas now house the multi-million dollar Government Administration building, and many other types of business, directly related to either Tourism or the Financial Sector.

The Tourism sector with its coastal concentration of hotels, beaches, yacht charter and marina properties and major population centers is by far the most vulnerable element of the economy to tropical storms and hurricanes.

The hurricanes of 1916, 1924, 1928, Donna in 1960, David in 1979, Frederick in 1979, Klaus in 1984 and Hugo in 1989 all did considerable damage to the coastal zone and severely disrupted economic activity. The major consequence of the storm surges from these tropical disturbances in the past has been flooding. This flooding was normally as a result of the accompanying precipitation, the rise in the sea level of the receiving waters and the gully type flows that can be expected from the short steep catchments.

The vulnerability of some sections of the coastline to the Atlantic disturbances are far more noticeable since almost all of the disturbances that have impacted the BVI in the past have resulted in severe damage to the coastal highways. Seasonal weather phenomenon, have resulted in the flooding of sections of the coastal highway. Consequent coastal erosion is also noticeable at these sites and in particular on the south coast where the erosion has been exacerbated by the destruction of the mangrove and by unplanned reclamation.

The Queen Elizabeth bridge constitutes the only vehicular access to the airport and is particularly vulnerable to the surges which are expected to run in the narrow Beef Island channel during a storm.

The Wickhams Cay area, the reclaimed portions of Road Town and its rapidly growing concentration of business activities is also quite vulnerable to the earthquake hazards with the obvious liquefication that could affect the entire area if impacted by a strong enough earthquake. This possibility is further emphasized by the fact that the poor engineering design during reclamation and construction have created inadequate drainage facilities for the Cay development, resulting in the area being water logged even after low precipitation events.