CHAPTER 5 SEISMIC HAZARDS

5.1 INTRODUCTION

This chapter outlines the nature of seismic hazards in the BVI and represents a summary of a report produced by Dr. William Ambeh of the Seismic Research Unit at the University of the West Indies (Trinidad). No attempts have previously been made to evaluate seismic hazard for the BVI in a detailed quantitative manner although qualitative assessments have been made for the northeastern Caribbean using available data on seismicity and neotectonics.

This detailed seismic study was carried out because the BVI is located close to a tectonic plate boundary zone and other possible seismogenic structures such as the Anegada Trough which have the potential to generate moderate to large earthquakes.

The scope of the seismic study included:-

(1) a probabilistic seismic hazard assessment of the BVI area based on information available about the geology, neotectonics and seismicity of the area. Although three major physical phenomena (strong ground shaking, surface fault rupture and ground failure) can cause damage to structures during an earthquake, the greatest economic losses usually result from strong ground shaking because of its relatively large areal effect.

In most situations, dwellings which are the most numerous and geographically dispersed of all building types and are not designed to site-specific standards, sustain the largest losses. The dominant contribution to the earthquake hazard of the BVI is expected to be from ground shaking, with hazards from surface fault rupture being minimal to non-existent and those from liquefaction being highly localised. Hence, the main focus of this study is on ground shaking and this hazard is expressed as the peak horizontal ground acceleration (PHGA) with 90% probability of not being exceeded in 50 years. A probabilistic seismic hazard assessment usually utilises a model which consists of three main elements:

X The seismic source zones

X Characteristics and statistics of the seismicity within each zone (activity rate, recurrence interval, maximum magnitude)

X An earthquake energy dissipation model or strong ground motion attenuation relationship.

Probabilistic ground motion hazard data have become the standard basis for earthquake resistant design requirements, and have found widespread application in regional land-use planning, emergency preparedness and insurance analyses.

(2) A microzonation of Road Town and East End in Tortola, and Spanish Town in Virgin Gorda using micro tremor data given that certain areas of some of these communities have a relatively unconsolidated near-surface geology and hence the potential for earthquake ground motion amplification.

(3) An evaluation of the liquefaction potential for a reclaimed site in Road Town.

(4) A review of the tsunami hazard to the BVI.

5.2 SEISMIC SETTING OF THE BVI

The Caribbean islands are situated close to the boundaries of the Caribbean plate (**Figure 5.1**), 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.

Geological and seismological studies suggest that the Caribbean plate is moving eastward relative to the Americas at a rate of about 2 cm/yr or about 4 cm/yr. At the eastern margin of the Caribbean plate, Atlantic oceanic lithosphere attached to the North and/or South American plate and about 80-100 Ma old is being subducted beneath the Caribbean plate at the Lesser Antilles subduction zone at a rate of about 2-4 cm/yr. The volcanic islands and active volcanoes in the eastern Caribbean are a direct manifestation of this subduction process.

The basis for all seismic hazard assessments is the space and time distribution of earthquakes, i.e., seismicity, in the area. The geologic record, primarily through the presence of faults, may

FIGURE 5.1 Caribbean Plate

contain within it the traces of earthquakes which occurred during the billions of years of geologic time. The historic record may contain reports of earthquakes that occurred during the hundreds and, in some cases, thousands of years of recorded human history. The instrumental record, which is just about 100 years old, yields information about those earthquakes for which actual instrumental evidence exists.

Since earthquakes range broadly in size from extremely small ones which involve the fracture of only a few centimeters of rock to, for example, the Rat Island earthquake of 1964 in the Aleutian arc which involved the rupture of a 650 km length of the Earth's crust, it is convenient to introduce a parameter which would serve as a measure of earthquake size. Such a fundamental parameter used to describe an earthquake is its magnitude.

The concept of an instrumentally determined earthquake magnitude was first introduced by the American seismologist Charles Richter and his original scale is called the Richter or local magnitude scale (Ml). Subsequently, other magnitude scales have been developed of which the most common ones are the body wave magnitude scale (mb), the surface wave magnitude scale (Ms) and the moment magnitude scale (Mw).

However, before the introduction of instrumental measures of earthquake size, earthquakes were rated on highly subjective intensity scales which are based on observations of the direct effects of the earthquake on structures, the ground, people, objects, etc. Several intensity scales have evolved since the end of the 19th century and most of them are divided into 12 levels, with the highest level representing the most destructive effects. Of these intensity scales, the one most commonly used in the Caribbean and North America is the Modified Mercalli (MM) scale.

5.3 HISTORICAL SEISMICITY OF THE BVI (1700-1960)

Historical seismicity is seismicity for which evidence can be found in the written record of human kind but which predates the availability of instrumental recordings. In the evaluation of seismic hazard, the record of historical earthquake activity, although less accurate, is very important, especially in areas with low rates of seismic activity. Historical records usually differ greatly in the length, completeness and quality of the earthquake histories they portray and, in most cases, only those events which led to catastrophic consequences are mentioned in ancient records.

Several large damaging earthquakes have occurred along various parts of the northeastern Caribbean. The largest earthquake that has occurred in the northeastern Caribbean during the historical period is the Leewards earthquake of 08 February 1843. Other significant earthquakes in the region took place in 1690, 1787, 1831, 1839, 1867, 1888, 1897, 1918, 1943, 1946, 1969 and 1974. The historic distribution of earthquakes in the region with M>1 is shown in **Figure 5.2.**

The record of reported felt earthquakes for the British Virgin Islands is relatively poor although European settlement of the islands dates as far back as 1648. Unlike the BVI, the record of reported felt earthquakes in the neighboring US Virgin Island of St. Thomas appears to be more impressive.

Since these two islands are less than 30 km apart, most of the earthquakes felt in St. Thomas at intensities V and greater must also have been felt in Tortola, although written reports may not be available for Tortola. It must also be noted that the difference is mainly in the lower intensities which are not necessarily significant when it comes to seismic hazard assessment.

Table 5.1 is a listing of earthquakes known to have been felt in either Tortola and/or St. Thomas at Modified Mercalli intensities IV and greater.

An earthquake which is thought to have produced effects in Tortola consistent with Modified Mercalli intensity VIII occurred on 11 July 1785. It was reported that "In Tortola, the earthquake made great clefts in the rocks, and separated completely a part of the island, forming a new island; also felt in Antigua and St. Kitts, and on ships in the neighborhood of all three islands". Should this be correct, then this earthquake must have been very close to Tortola, if not directly beneath it, and could have been of magnitude Ms 6-7 or greater.

However, some doubts have been cast as to whether this event really occurred and without further detailed studies of any available original reports of the earthquake, extreme caution has to be exercised in the interpretation of the reported phenomena in terms of surface rupture and/or subsidence effects.

Another historical earthquake of interest is that of 18 November 1867 whose effects on St. Thomas were more damaging and probably consistent with MMI VIII. The following was written: "In St. Thomas, a violent earthquake; several shops collapsed, nearly all houses were severely

FIGURE 5.2 Seismicity of the Northwestern Caribbean 1900-1963; Ms>=4

TABLE 5.1: Earthquakes reported felt on Tortola and/or St. Thomas at MMI IV or greater (1700-1960).

Date	Island and intensity	Comments
02 Sep. 1777	St. Thomas (V)	
03 Sep. 1777	St. Thomas (IV)	
26 Feb. 1785	St. Thomas (V)	
11 Jul. 1785	Tortola (VIII)	see text
16 May 1818	St. Thomas (V)	series of shocks
20 Aug. 1821	St. Thomas (IV)	
20 Apr. 1824	St. Thomas (VII)	
07 May 1842	St. Thomas (V)	
08 Feb. 1843	Tortola (V), St. Thomas (IV)	no damage
05 Mar. 1843	St. Thomas (V)	
16 Apr. 1844	St. Thomas (V)	
28 Aug. 1856	St. Thomas (VI)	
18 Nov. 1867	St. Thomas (VIII), Tortola (VII),St. Croix, (VIII), St. John (VIII)	see text
17 Feb. 1868	St. Thomas (V)	
08 Aug. 1882	St. Thomas (IV)	
19 Sep. 1886	St. Thomas (V)	
04 Jan. 1888	St. Thomas (V)	
21 May 1888	St. Thomas (V)	
27 Nov. 1889	St. Thomas (V)	
22 Feb. 1892	St. Thomas (V)	
02 Aug. 1896	St. Thomas (V)	
22 Oct. 1901	St. Thomas (V)	
22 Jun. 1906	St. Thomas (V)	
13 Sep. 1906	St. Thomas (V)	
26 Sep. 1906	St. Thomas (V)	
17 Feb. 1909	St. Thomas (V)	
24 Jul. 1913	St. Thomas (V), St. Croix (V)	
11 Oct. 1918	St. Thomas (V)	
27 Nov. 1923	St. Thomas (V)	
23 oct. 1957	St. Thomas (IV)	

damaged; fifteen minutes after the first shock, a tidal wave invaded shops in the lower part of the town to a depth of several feet; aftershocks were felt approximately every five minutes for the first 24 hours". This earthquake, which produced effects in Tortola consistent with MMI VII, has been assigned an approximate magnitude of Ms 7.7 and may have been associated with the Anegada Trough.

It must be mentioned that the historic damage record refers to the most earthquake-sensitive structures which existed at the time, i.e., unreinforced masonry structures of rarely more than one story. Consequently, the historical results only define in the broadest terms the future hazard to buildings of this type but not, for example, to more modern, relatively well-constructed structures.

As has already been mentioned, a probabilistic seismic hazard analysis involves four fundamental stages:

X delineation of seismic source zones (linear, areal, volume);

X statistical characterization of the seismicity in each fault zone;

X definition of an appropriate ground motion attenuation function;

X calculation of the relevant hazard parameter using an appropriate model.

5.3.1 SOURCES OF SEISMIC ACTIVITY

Historical seismicity records provide an important contribution to our understanding of the seismic behavior of a region. Modern techniques of quantitative seismic hazard assessment necessitate the use of instrumental data that is as accurate, homogeneous and complete as possible. However, significant improvements in both the quality and quantity of seismological stations worldwide have generally occurred with time, especially since the 1960s, making it impossible to prepare an earthquake catalogue that is complete and accurate for the period under consideration, 1900 - 1995.

The data used in this study are from an earthquake catalogue prepared for the area bounded by latitudes 15°N and 22° N and longitudes 61° W and 68° W. The catalogue, which contains estimates of origin time, epicentral coordinates, focal depth and magnitude, mainly relies on a systematic procedure of selecting and combining earthquake parameters from several agencies rather than on a re-determination of these parameters.

Magnitude estimates for the earthquakes are required for the seismic hazard analysis and are necessary if any completeness analysis of the data is to be undertaken. The surface wave magnitude scale, Ms, was selected as the standard magnitude for the earthquake data. Only earthquakes with a magnitude of at least Ms 4.0 were included in the catalogue since this is about the smallest size for which damage could result to structures. The resultant earthquake catalogue is attached as Appendix 1 of the original seismic report.

5.4 SEISMIC SOURCE ZONES

Although no standard method has been adopted for delineating seismic source zones, each seismic source zone is usually chosen so that it encloses an area of related seismicity and tectonism. In the specification of seismic source zones for a region for probabilistic seismic hazard analysis, it is commonly assumed that earthquakes:

(i) Are equally likely to occur within a source zone.
(ii) Have an average rate of occurrence that is constant in time.
(iii) Follow a poisson distribution of recurrence (hence the elimination of foreshocks and aftershocks from the earthquake catalogue; although this leads to an underestimation of the hazard for small events, it gives a more accurate estimate for large damaging earthquakes).

In this study, the seismic source zones (**Figure 5.3 - 5.5**) have been defined mainly on the basis of the spatial distribution of instrumental seismicity although some of them can be associated with certain neotectonic features.

5.4.4.1 SHALLOW SEISMIC SOURCES: 0 - 50 km.

ZONE 1: Encompasses areas of the Puerto Rico trench and the Mona Canyon. An

Mmax of 8.5 was assigned to this zone.

ZONE 2: Encompasses parts of the Puerto Rico Trench and is underlain by the Main Ridge.

FIGURE 5.3

FIGURE 5.4

FIGURE 5.5

For conservativeness, an Mmax of 8.5 was assigned to this zone.

ZONE 3: Encompasses the area of transition from westerly to southerly under thrusting of Atlantic oceanic lithosphere beneath the Caribbean plate, incorporating the region interacting with the Barracuda Ridge in the southeast to near the intersection of the Anegada Trough with the Puerto Rico Trench near 19.5oN and 63oW. Again for conservativeness, an Mmax of 8.0 was assigned to this zone.

ZONE 4: The northern Leewards. Probably underlain by segments of the Barracuda and Tiburon Ridges. An Mmax of Ms 8.5 was assigned to this zone.

ZONE 5: This zone was defined to take care of activity associated with the Anegada Trough which, from the historical record, seems to be active although slip rates of the faults associated with the Trough are not known. Contemporary small to large-sized earthquake occurrence seems relatively low. An Mmax of Ms 7.5 was adopted for this zone.

ZONE 6: This zone has been drawn to encompass the little seismicity in southern Puerto Rico and part of the Mona Passage. An Mmax of Ms 8.0 was assumed for this zone.

5.4.4.2 INTERMEDIATE DEPTH SEISMIC SOURCES: 51 - 100 km.

These zones are quite similar to those for shallow depth earthquakes and the seismicity is obviously a reflection of the subduction process at these depths. A uniform Mmax of Ms 8.0 was assigned to all the source zones in this depth range and the hazard was modeled at a depth of 75 km. This Mmax is again considered to be relatively conservative.

ZONE 7: The largest instrumentally located earthquake in this zone occurred on 24 April 1916 at 04:26 UTC. Assume Mmax of Ms 8.0.

ZONE 8: The largest instrumentally located earthquake in this zone occurred at 04:25 UTC on 22 January 1979 at 19.1^{o}N and 64.7^{o}W. It's focal depth was 51 km and the assigned magnitude Ms 5.2. Assume Mmax of Ms 8.0.

ZONE 9: The largest instrumentally located earthquake in this zone occurred at 02:22 UTC on 09 February 1988 at 18.6°N and 62.9°W. It's focal depth was 52 km and the assigned magnitude Ms 5.2. Assume Mmax of Ms 8.0.

ZONE 10: The largest instrumentally located earthquake in this zone occurred on 03 October 1914 at 17:22 UTC. It's location was calculated as 16.0°N and 61.0°W, with a focal depth of 100 km. It was assigned a magnitude of Ms 7.4. Assume Mmax of Ms 8.0.

5.4.4.3 DEEP SEISMIC SOURCES: 101 - 200 km

The hazard for sources in this depth range was modeled at a depth of 125 km. A uniform maximum magnitude of Ms 7.5 was assigned to all zones within this depth range, mainly because an earthquake of magnitude Ms 7.0 did occur on 19 March 1953 at a depth of 130 km in the Lesser Antilles close to St. Lucia. This seismicity is also associated with the subducted lithospheric slab.

ZONE 11: The largest instrumentally located earthquake in this zone occurred at 04:49 UTC on 08 July 1970 at 18.0°N and 64.7°W. It had a focal depth of 148 km and was assigned a magnitude of Ms 5.6. Mmax assigned for this zone was Ms 7.5.

ZONE 12: The largest instrumentally located earthquake in this zone occurred on 08 January 1959 at 01:33 UTC at 15.25°N and 61.26°W. It had a focal depth of 140 km and was assigned a magnitude of Ms 6.4.

5.4.3 MAXIMUM MAGNITUDE EARTHQUAKES

For the northeastern Caribbean region as a whole, an Mmax of 8.5 is possible for certain areas based on the following evidence:

(i) an examination of the historical seismicity of the area since 1500 suggests that the following earthquakes may have had magnitudes in the range 7.5 - 8.5.

X 08 February 1843:A magnitude of Ms 8.0 - 8.5 was assigned to this Leewards area event. Re-evaluated the historical information associated with this earthquake suggests a lower magnitude of Ms 7.5 - 8.0.

X 02 May 1787: a violent earthquake which occurred north of Puerto Rico and was felt throughout the whole island, causing considerable damage and destruction on all but the southern part of the island. A magnitude of Ms 8.0 - 8.5 was assigned to this earthquake but there is significant uncertainty because of the offshore location and the inherent problems of accurately defining the area of maximum intensity.

(ii) the largest instrumentally recorded earthquakes include those of:

X 8 October 1974: Leewards, Ms 7.5

X 11 October 1918: Mona Passage, Ms 7.5

X 29 July 1943: NW of Puerto Rico, Ms 7.7

(iii) application of Gumbel's type III asymptotic distribution of extremes to data from the whole of the eastern Caribbean region (8°N - 20°N, 58°W - 66°W) yielded an upper bound magnitude of 7.97+-0.14.

(iv) the degree of coupling at subduction zones is influenced by the convergence rate and the age of the lithosphere being subducted.

5.5 SEISMIC HAZARD ASSESSMENT

A probabilistic seismic hazard analysis has been done using the computer program SEISRISK III. The version of the program adapted for use on Personal Computers.

As has already been mentioned, a probabilistic seismic hazard analysis involves four fundamental stages:

X delineation of seismic source zones (linear, areal, volume);

X statistical characterization of the seismicity in each fault zone;

X definition of an appropriate ground motion attenuation function;

X calculation of the relevant hazard parameter using an appropriate model.

The selected hazard output in this study is peak horizontal ground acceleration (PGA). All the hazard outputs calculated for this study are for a 90% probability of non-exceedence.

The determination of seismic hazard in terms of acceleration usually necessitates the use of an attenuation relationship linking this parameter to, for example, magnitude and distance from the source. The attenuation function estimates the effect of earthquake energy dissipation as the shock waves leave the source zone. The very few earthquake strong ground motion recordings available for the Caribbean are generally of poor quality and are not adequate for generalizing attenuation characteristics in the region. In fact, no earthquake strong ground motion recordings are available for the northeastern Caribbean region.

Consequently, recourse has to be made to using attenuation relationships determined for other environments considered to be tectonically similar to the northeastern Caribbean, i.e., subduction zone - island arc setting. For this hazard assessment, the preferred attenuation relationship. This relationship was derived using Alaskan and Japanese strong ground motion data and is of the form:

$$\ln(A)=5.347+0.5Ms-0.85\ln[R+0.864\exp(0.463Ms)]$$

where A is acceleration in cm/s/s, Ms is surface wave magnitude, R is the closest distance to the rupture area, and the one standard deviation in ln(A) is 0.5.

The Peak Horizontal Ground Acceleration with 90% probability of non-exceedence in 50 years for Road Town given zero attenuation variability is 0.20g (196 cm/s/s) and 0.5 attenuation variability is 0.36g (358 cm/s/s) where g is the acceleration due to gravity (~ 980 cm/s/s).

The contribution of each of the seismic source zones to the overall hazard of Road Town are listed in **Table 5.3**. The largest contributions originate from zones 2, 5 and 8. These, as expected to a certain extent, are in fact the closest sources to Road Town and the BVI.

TABLE 5.3: Individual source zone contributions to overall hazard for Road Town (18.46°N, 64.66°W)

SOURCE ZONE	AREA (Km2)	ACTIVITY RATE per sq.km for mags. 1.0 - 4.5	50 yrs 90% extreme prob. hazard sig= 0.0 (g)	50 yrs 90% extreme prob. hazard sig= 0.5 (g)
01	40083	.17713E-4	0.075	0.128
02	31496	.26639E-4	0.166	0.291
03	50828	.63351E-5	0.063	0.108
04	46298	.11145E-4	0.047	0.082
05	12823	.49910E-5	0.124	0.191
06	13283	.48182E-5	0.045	0.076
07	40902	.78235E-6	0.045	0.068
08	21368	.21153E-4	0.183	0.309
09	35862	.63019E-5	0.094	0.150
10	31744	.11183E-4	0.054	0.089
11	61247	.47350E-5	0.115	0.196
12	69546	.60248E-5	0.079	0.133

Figure 5.6. is a contour map of PHGA with 90% probability of non-accedence in 50 years for the Virgin Islands area. The values vary smoothly from a minimum of about 0.16g (157 cm/s/s) in the southeastern part to 0.25g (245 cm/s/s) in the northern part. The range of variation of PHGA=s within the BVI territory is from about 0.20g to about 0.25g.

FIGURE 5.6

5.6. ASSESSMENT OF SITE EFFECTS: MICROZONATION

Although ground motion amplification by near-surface sedimentary deposits has not yet been documented for the BVI area, because of its proximity to the Caribbean / North American plate boundary earthquake source zones and the fact that several communities within Road Town are founded on alluvial deposits and reclaimed land, there exists the potential for severe earthquake-related damage in some areas possibly associated with site amplification.

In general, the aim of microzonation is to go beyond a region's average hazard exposure by assessing the small- scale variations in expected ground motions. This serves to delineate and characterise the locations at risk to increased ground motion. In this section, we estimate the potential for soil-column amplification of seismic ground motions in Road Town (Tortola), East End (Tortola) and Spanish Town (Virgin Gorda) using the technique of Nakamura as applied mainly to micro tremors and to a lesser extent earthquake weak motions.

The response of a structure to an earthquake depends mainly on the dynamic frequency-dependent properties of the earthquake source, the wave propagation path, the soil-rock column underlying the structure and the physical characteristics of the building (dimensions, material, construction quality, etc.). The best dynamic representation of how the ground moves during an earthquake is provided by the ground motion records obtained on hard rock sites (free-field locations).

The response of the soil-rock column is mainly influenced by the strain-dependent properties of the soil and the contrast in physical properties of the soil and rock, and could either enhance or dissipate the incoming seismic energy. Therefore, anticipation of the magnitude of the influence of local soil conditions on the characteristics of earthquake ground motions and thereby on structure damage at the design stage, especially in terms of ensuring that the site and structure periods do not match, is of fundamental importance.

The influence of soil conditions on ground motions can be assessed by theoretical and/or empirical methods. Soil transfer functions have often been evaluated using empirical methods which utilise weak and/or strong ground motion data from micro tremor (ambient seismic noise) and earthquakes. The use of micro tremors as the ground motion source offers a very cost-effective approach in seismic microzonation in areas with low levels of background seismicity or for which a reference hard rock site is not readily available.

5.6.1 METHODOLOGY

The technique is a single-station method which involves the analysis of micro tremors in site-response investigation by comparing the amplitudes of spectra computed from the horizontal- and vertical-component records.

During the period 07 to 14 June 1996, we recorded micro tremors at 50 locations in Road Town (Tortola), 9 locations in East End (Tortola) and 8 locations in Spanish Town (Virgin Gorda) in order to evaluate empirical transfer functions for microzonation purposes.

5.6.3.2 RESULTS

The results for Road Town can be used to roughly divide the area into two broad zones as shown in **Figure 5.7**.

Zone 1: encompasses all stations which possess spectral ratios which exhibit a well-defined, relatively narrow, spectral peak within the frequency range 2 to 5 Hz. The width of this frequency range and the actual frequency value at maximum H/Z varies from site to site.

This zone includes all reclaimed land such as Wickhams's Cay, Wickhams's Cay 2, Prospect Reef Hotel and Port Purcell. Other stations with narrow-peaked spectra located in this zone are probably founded on relatively unconsolidated alluvial deposits. These spectral peaks can be interpreted as representing the fundamental resonant frequencies of the sites. It must be mentioned that for most of the stations for which a resonant peak is observed on H/Z spectral ratios, a peak at about the same frequency is also seen in the horizontal component spectrum alone.

Zone 2 : encompasses stations whose spectral ratios do not show a clear resonant peak but may

FIGURE 5.7: Separation of occupied sites in Road Town according to the shapes of spectral ratios (zone 1 is shaded)

be quite complex, flat or near-flat. It includes stations located on rock and others located on sites originally thought to be underlain by relatively unconsolidated sediments. The shape of the spectral ratio of the latter may be due to the sedimentary cover being either too thin or relatively well-consolidated. Some of the sites exhibit spectral ratio values significantly greater than 1 and this is interpreted here as not necessarily representing site amplification but may be due to the non-validity of the assumption of a laterally homogeneous layering beneath the site.

5.6.3.3 East End And Spanish Town

The spectral ratios for stations in East End and Spanish Town generally do not show a narrow peak and are either complex, flat or near-flat, similar to those in Zone 2 in Road Town. Although some of them show H/Z values much greater than 1, these are again interpreted to be due to a breakdown of the Nakamura formulation for these sites because of the absence of a laterally homogeneous layer rather than indicating site amplification.

5.6.3 HAZARD IMPLICATIONS

The results from this study indicate that ground motions in certain areas of Road Town, especially reclaimed lands and some areas underlain by alluvial deposits, are amplified by factors ranging from about 2.5 to 7 within a relatively narrow frequency band from 2 to 5 Hz. The relatively narrow frequency band peak probably represents the fundamental resonant frequency of the particular site. Spatial variations in these frequencies may be due to lateral variations in the near-surface geology.

The fundamental frequency of vibration, Fb, of a building depends on several factors, including its height and width, and the nature of the materials used in its construction. However it may be approximated by the equation,

Fb = 10/N

where N is the number of storeys in the building. For one and five-storey buildings, Fb is approximately 10 Hz and 2 Hz respectively.

Given the fact that most buildings in the BVI are one to three storeys high, some care should be exercised when constructing structures in the areas defined by Zone 1 of **Figure 5.7**. so that there is no matching of site and structure fundamental frequencies and, consequently, resonance during significant earthquakes.

5.7 LIQUEFACTION POTENTIAL

A soil consisting of water-saturated, loose granular materials subjected to ground vibration, such as during an earthquake, tends to compact and decrease in volume. If drainage is unable to occur, this tendency to decrease in volume result in an increase in pore water pressure which may build up to the point at which it is equal to the overburden pressure. Consequently, the effective stress becomes zero, the sand loses its strength completely, and thus develops a liquified state.

This may manifest by the development of quick sand-like conditions over substantial areas with the consequent result that buildings may sink substantially into the ground or tilt excessively, and foundations may displace laterally causing structural failures.

The liquefaction potential of any given soil deposit is determined by a combination of the soil properties (dynamic shear modulus, damping characteristics, unit weight, grain characteristics, relative density, soil structure), environmental factors (method of soil formation, seismic history, geologic history, lateral earth pressure coefficient, depth of water table, effective confining pressure) and characteristics of the earthquake to which it may be subjected (intensity of ground shaking, duration of ground shaking).

Several studies of the field performance of sands and silty sands during actual earthquakes have shown that a good correlation exists between soil liquefaction resistance to earthquake shaking and soil penetration resistance, soil properties which are both affected by the same fundamental factors influencing soil behavior. Since the standard penetration test (SPT) is the most commonly run test in soil exploration, methods using its results to estimate the liquefaction potential of a soil deposit are the most common.

Wickhams Cays are underlain by very loose to loose, cohesionless soils and hence it is important to examine whether these would liquefy during significant earthquakes. In this chapter, a semi-empirical approach is used to estimate the liquefaction potential of these soils from SPT results.

Empirical studies involving correlations of field performance data and observations of liquefaction during earthquakes have led to the formulation of a simple procedure for estimating the liquefaction potential of sands and silty sands using SPT or cone penetration test (CPT) data.

The results indicate that the soils beneath Wickhams Cays 1 and 2 **Figure 5.8**, have a high potential to liquefy, even during moderate-sized earthquakes of magnitude 6.0 - 6.5. Furthermore, the liquefaction potential also varies spatially (both laterally and with depth), even within relatively small areas. Generally, the low corrected standard penetration resistances seen in the reclaimed areas of Road Town may be considered as being indicative of high damage potential during liquefaction. A wide range of effects is possible depending on the earthquake magnitude.

5.8 TSUNAMI HAZARD OF THE BVI

Tsunamis (Japanese word meaning long wave in the harbour) are long water waves generated impulsively by mechanisms such as exploding volcanic islands, submarine and subaerial landslides, rockfalls into bays or the ocean, tectonic displacements associated with earthquakes and debris avalanches or flows from volcanoes which propagate in the open ocean with minimal heights at speeds up to 800 km/hr and may build up to devastating heights upon approaching land.

In general, the dominant generating mechanism for large tsunamis is submarine earthquakes having a significant vertical component (dip-slip) in their mechanisms so that the action can be simplistically compared to a huge paddle shoving a vast amount of water. Obviously, the larger the earthquake size and component of dip slip, the bigger the tsunami generated. Since the speed of the tsunami depends on the square root of the water depth, the nature of the ocean floor can sometimes lead to wave refraction in such a manner that there is either constructive interference (leading to waves that are higher than average) or destructive interference (leading to waves that

FIGURE 5.8: **Location of boreholes**

are lower than average).

When tsunami waves reach a coast, the water runs up onto the land. The elevation above the tide level at the time of the tsunami reached by this water is called the run-up elevation. As well as the run up onto the land, there is also a drawdown of the water level along the coast, with both the run-up elevations varying considerably from point to point along the coast and being extremely difficult to predict. These difficulties arise because in very shallow water near the shore, refraction is complicated by diffraction, trapping of waves and other poorly understood phenomena. However, in most cases, the water rises like a rapidly rising tide.

Thus, the size of a tsunami at a particular location depends not only on the size of the displaced ground (hence the size of the earthquake) but also on the shape and orientation of the displaced ground and the nature of the bathymetry close to the location.

For the BVI, the tsunami associated with the 18 November 1867 earthquake which has been considered to have occurred on the southern segment of the Anegada fault zone, is the most significant since historical times and is the only one for which a run-up height is available. It was reported that "At the British Virgin Islands the shock lasted 15 minutes and damaged all the buildings on Tortola. The sea receded, then rose 1.2 to 1.5 m above its usual level. It submerged the lowest part of the town (Road Town) and swept away most of the smaller houses. At Peter Island, 4.8 to 6.4 km farther south, the people were so alarmed by the earthquake and tsunami that they took to their boats and went to the larger and more populous Tortola".

5.8.3 POSSIBLE SOURCES OF TSUNAMIS WHICH COULD AFFECT THE BVI

The nature of sources capable of generating tsunamis which may affect the BVI can be divided into near, regional and far, depending on their distance from the BVI. For near sources, the most important tsunami genic source to the BVI is the Anegada fault zone. As has already been mentioned, an earthquake in 1867 in the southern part of this fault zone generated a tsunami which affected several areas in the northeastern Caribbean and the Lesser Antilles.

Although the nature of tectonic movement on the Anegada fault is still debatable, i.e., whether it is pure strike slip or oblique, the fact that the sea first receded almost everywhere before flooding land has been interpreted as being due the presence of a significant normal component in this earthquake's mechanism. If a maximum magnitude earthquake (Ms 7.5) did occur on the longest continuous segment of the Anegada fault zone, values of maximum run-up elevations of the order of 2-3 m are obtained. **For these near events, the tsunami travel times are just of the order of minutes**.

In the near- to regional-distance range, large, shallow thrust events associated with the Lesser Antilles subduction zone, and even the Puerto Rico trench, may be possible tsunami sources for the BVI but no significant historical precedents are known. Another possible regional source of tsunamis that could affect the BVI is Kick-'em-Jenny submarine volcano which is located approximately 8 km north of Grenada and 800 km south of Tortola.

Using computer modeling techniques and assuming a worst case eruption with magnitude as large as that of the 1883 eruption of Krakatau in Indonesia (Volcanic Explosivity Index (VEI) = 6), preliminary estimates suggests final wave runup values generally greater than 10 m throughout most of the Eastern Caribbean and travel times of about 90 minutes to the Virgin Islands. An assumed smaller and more reasonable eruption (VEI=3) obviously resulted in smaller wave runups of the order of about 2.5 m in the Virgin Islands.

Although the Lisbon, Portugal, earthquake of 01 November, 1755, generated a tsunami which substantially affected several Caribbean islands (effects on the BVI not known), the long distance earthquake and volcanic sources with direct access to the Caribbean and the BVI are not necessarily considered a major tsunami threat. Also, for Road Town, there are high prospects for wave attenuation by diffraction round the headlands and by refraction on the shelving bed.

Given the nature of the hazard as inferred above, maximum wave runup elevations will probably generally not exceed 2-3 m and the effects would not be expected to exceed those from a hurricane-related tidal inundation of similar size, i.e., flooding of shorefront and near-shore houses, destruction of some boats in harbour, damage and to vegetation.

5.9 CONCLUSIONS

The seismic study identified 12 zones of seismic activity that have the capacity to produce damaging earthquakes in the BVI. The zones which pose the greatest threat are the zones associated with the Anegada Trough and the Puerto Rican Trench. It has been estimated that earthquakes with a magnitude of Ms 8.5 can be produced in these zones.

Seismic hazard in the BVI was assessed in terms of the degree of ground shaking defined as the Peak Horizontal Ground Acceleration (PGA). The PGA calculated for Road Town was 0.2 - 0.36 with a return period of 50 years. This corresponds with a range of intensity of (MMI) VIII - IX.

The assessment of site amplification effects indicates that for Road Town, reclaimed land and areas underlain by thick alluvial deposits, might experience amplification factors of 2.5 - 7.

Study also indicates that a very high potential exists for liquefaction within the areas of reclaimed land in Road Town even from moderate-sized earthquakes of magnitude 6 - 6.5.

The most significant potential source of tsunami threat to the BVI is the Anegada Trough. It was estimated that an earthquake of magnitude 7.5 could produce run-up in Road Town of 2 - 3m (6 - 9ft). The kick-em-jenny volcano 8 km north of Grenada posed a minor threat. It was estimated that an eruption of this volcano of magnitude (VEI=3) could produce run-up of 2.5 meters in the BVI.