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Seismic Ground Motion Hazard Assessment at a Site near a Segmented Subduction Zone: the Roseau Dam, Saint Lucia, West Indies

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The seismic hazard at the site of a new dam in Saint Lucia, West Indies, is evaluated probabilistically for engineering design purposes. The assessment takes advantage of recent high quality regional seismological data, reappraised older instrumental catalogues and current tectonic interpretations. Saint Lucia stands at a position in the Lesser Antilles island arc where two distinct, seismically active, subduction zones appear to converge at different depths. As a result, the seismic hazard is critically dependent on site position relative to the boundaries of these major source zones, which each exhibit different activity rates. The ground motion hazard at the damsite is computed using the probabilistic logic-tree program PRISK, which accepts weighted input parameter distributions and is also able to model complex source geometries such as those needed to realistically represent a subduction zone. At an exceedance probability of $2x10^{-3}$ per annum, the expected peak ground acceleration on rock at the site is 0.27g, and the expected peak ground velocity is 12.9 cm/sec. At an exceedance probability of 10^{-4} per annum, the expected peak ground acceleration on rock at the site is 0.51g, and the expected peak ground velocity is 29.1 cm/sec. The major contributor to the seismic hazard is a large magnitude earthquake occurring in the northern segment of the Lesser Antilles subduction zone. Sensitivity tests show that the results are stable in the face of rational variations in the seismicity parameters but the hazard values are dependent on the choice of attenuation relationship which, in the absence of local information, has to be adopted from other subduction zone areas. The PGA obtained in this study is markedly higher than the value suggested in current regional code recommendations.

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INTRODUCTION

The Roseau Dam will be a 45m high concrete face rockfill dam, built on the upper reaches of the Roseau River in the central mountainous region of Saint Lucia, West Indies (see Figure 1). The reservoir will provide sufficient water storage to meet future demands for domestic and commercial water supply and irrigation. At the damsite, hard andesite bedrock is exposed at river level; this is thought to be underlain by older, basalt basement rock but none could be found in a 40m drill hole at the site. The andesite extends part way up the abutments where dacite and some agglomerate are found. The depth of weathering within the dam footprint reaches a maximum of 10m with an overall average

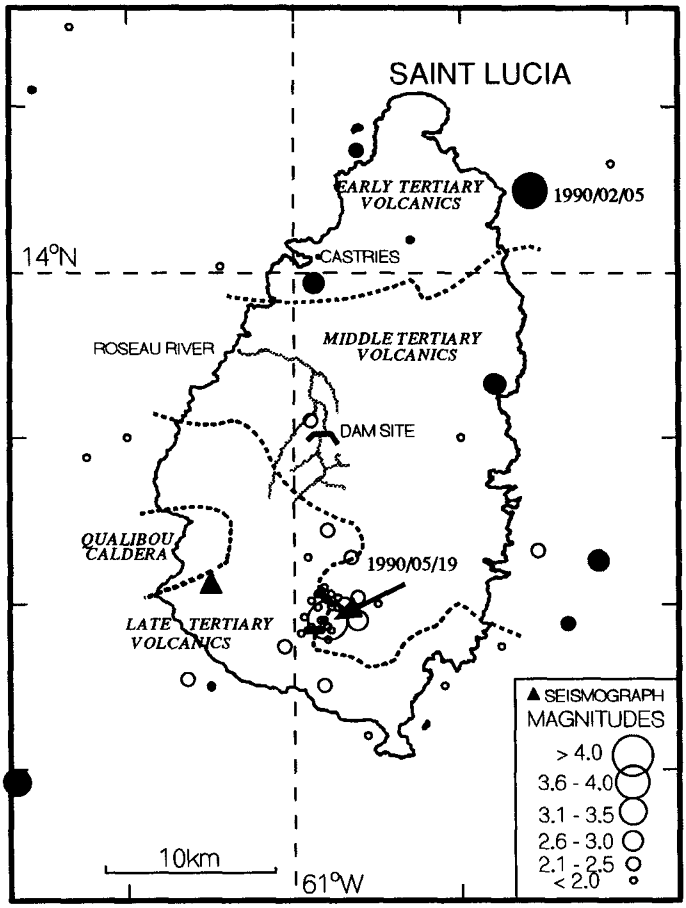

FIGURE 1 The island of Saint Lucia, showing the locations of the damsite, the Roseau River, Qualibou Caldera and permanent seismograph station. Instrumental epicentres are revised and relocated, filled circles indicating focal depths greater than 25km.

of about 6m. The weathered rock will be removed from areas beneath the concrete plinth and most of the foundations of the rockfill, so the response of natural overburden materials to bedrock motions is not a concern. As a consequence, bedrock ground motion has been specified for expressing the seismic hazard for this particular engineered structure, and the scope of the present assessment has been limited to providing reasoned and specific answers to the seismic design problem, using available information. A full-scale exploration of all conceivable seismological and tectonic scenarios has not been possible in this exercise.

TECTONIC SETTING AND GEOLOGY OF SAINT LUCIA

Saint Lucia is part of the Lesser Antilles island arc (Figure 2) which has formed as a result of the subduction of the western Atlantic seafloor beneath the Caribbean (Tomblin 1975). In the islands south from Anguilla to Grenada, the active volcanic ridge associated with the Lesser Antilles subduction zone has been in existence at least since Middle to Upper Eocene time, when large volumes of pyroclasts were erupted along the entire length of the arc. The oldest rocks in Saint Lucia date from this period. In the Lower Miocene there was a general submergence of the arc resulting in the growth of reefal limestones, which occur in northern Saint Lucia as lenticles in the older volcanics. The ridge was uplifted at the end of the Miocene and in the northern Lesser Antilles volcanic activity shifted from the east to the west side of the arc platform, resulting in the growth of a new branch of the volcanic chain from the western half of Guadeloupe northwestward to Saba, leaving the islands from the eastern half of Guadeloupe to Anguilla as extinct limestone-capped volcanoes. In the islands south of Guadeloupe (including Saint Lucia), volcanic activity has continued along the original ridge with the building of new volcanic centres adjacent to older ones.

Like other island arcs, the Lesser Antilles arc is marked by a dipping plane of earthquake hypocentres known as a Wadati-Benioff zone. The shallowest earthquakes occur on the eastern (Atlantic) side of the arc and are close to the surface at distances of between 100km and 150km east of the islands themselves. Depths increase progressively in a generally westward direction and beneath the islands themselves earthquakes typically occur at depths of 100km to 150km. The deepest earthquakes occur at depths of about 200km, at distances of about 50km to the west of the islands.

Two distinct segments to the arc can be recognized: one to the north of Martinique trends NNW and one to the south of Saint Lucia trends NNE (Wadge and Shepherd, 1984). The precise position and nature of the discontinuity is not known but it may represent the triple junction of the Caribbean and separate North and South American plates. As will be shown later in this paper, seismic activity in the northern segment of the arc is more intense than in the southern segment. The position of Saint Lucia close to the junction between the two segments means that it is potentially subject to the effects of earthquakes in both.

The youngest identified volcanic formations in Saint Lucia, and hence those most likely to generate significant shallow seismic activity, are associated with a depression in the

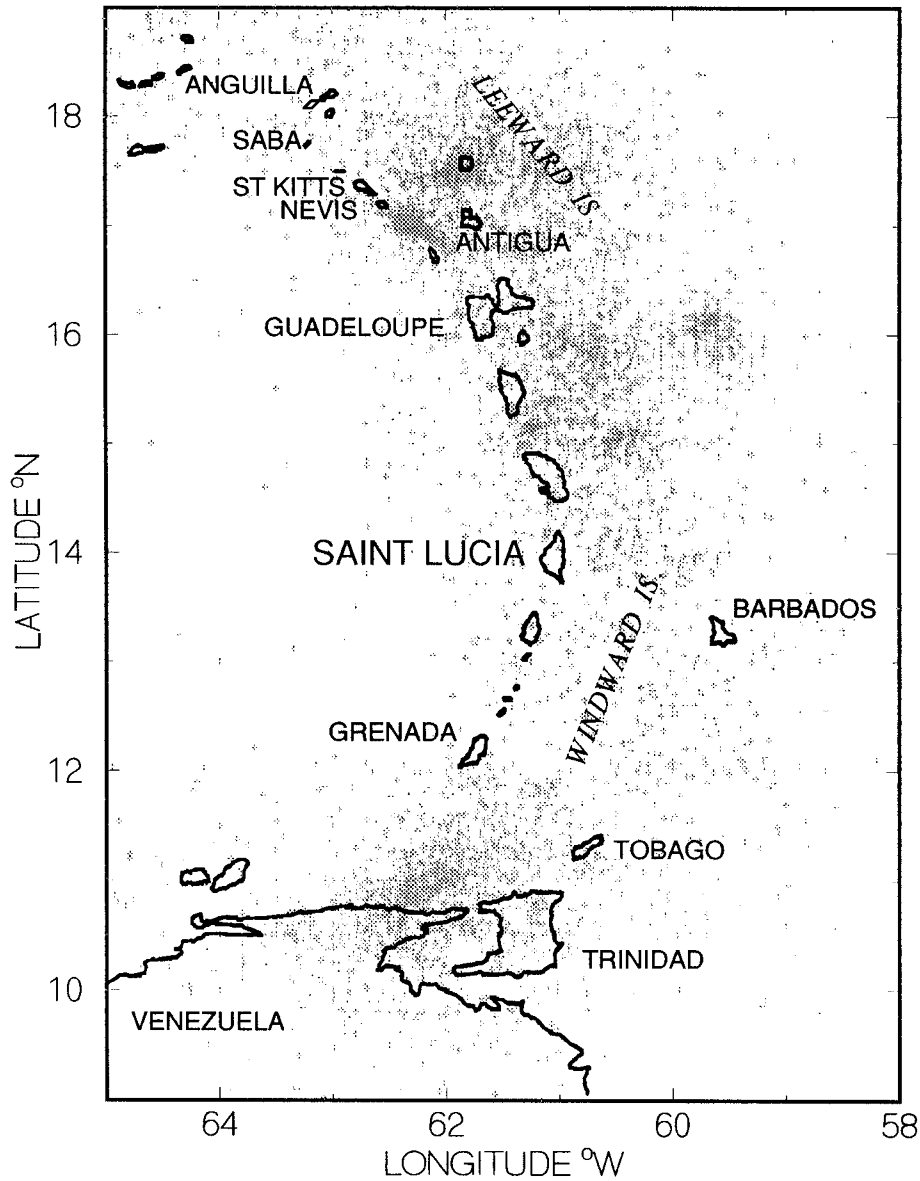

Figure 2 Epicentres of instrumental earthquakes in the Eastern Caribbean from 1906 to 1985, reported by the ISC. Many foreshocks and aftershocks are included on this plot.

southwestern part of the island, known locally as the Sulphur Springs region, but described by Tomblin (1964) as the Qualibou Caldera (Figure 1). This depression is located about 8 kilometres southwest of the proposed dam site. It is open to the Caribbean Sea on its western side and contains a number of volcanic domes and craters ranging in age from 21,000 to 200,000 years. The most recent major volcanic eruptions in this region, which are therefore the most recent anywhere in Saint Lucia, took place about 21,000 - 34,000 years ago (Wright et al. 1984), but activity of hot springs (known locally as soufrières) continues to the present day and a steam explosion or phreatic eruption occurred there in 1766 (Robson and Tomblin, 1965-67).

Tomblin's interpretation of the depression as a volcanic caldera - that is, a depression formed after a very large scale volcanic eruption by the collapse of the ground surface into the volume formerly occupied by the erupted material - has recently been called into question. Roobol et al. (1983) suggested that the depression is, in fact, a large-scale gravity slide in which the whole area slid on an arcuate fracture towards the Caribbean Sea. On the other hand, Wohletz et al. (1986) reaffirmed the view that the feature is a caldera but noted that it is bounded on the north and south by normal faults forming a graben-like structure and that the bounding faults continue across the width of the island. More recently, Bouysse et al. (1988) have suggested that the depression is neither a caldera nor a gravity slide; they suggest that it is part of a larger, complex graben-like structure which cuts completely across the island.

However, Saint Lucia is almost entirely overlain with Holocene volcanic deposits, much of it covered by dense tropical rainforest, so little is known in detail about local tectonics or structure.

LOCAL SEISMIC ACTIVITY

In the context of this study, the debate over the origin of the Qualibou depression is of more than simply academic interest. A short period seismograph station has been in operation on the rim of the depression (Figure 1) since 1981 and, up to early 1990, it recorded local microearthquakes at an average rate of one or two per month with occasional bursts of up to 10 events in a single day. Since no other stations recorded these events, determination of exact locations is impossible, but S-P intervals of less than 2 seconds indicate that they originated in southern Saint Lucia. In May 1990, the rate of occurrence of these events began to escalate and an event of magnitude $4.5m_b$ occurred on 1990 May 19. From arrival times at regional seismograph stations, the location of this event was estimated to be 6km ESE of the Qualibou depression (see Figure 1) - the epicentral uncertainty of the mainshock is approximately the same as the spread of its aftershocks, which were better constrained by additional local stations. These aftershocks, generally with magnitudes less than $2.5m_b$, were recorded for more than eighteen months.

The cause of these particular events remains unclear. One theory is that they result from the intrusion of a magma body at depth beneath southern Saint Lucia. If this is so then it is a unique occurrence in the Lesser Antilles: all previous volcano-seismic swarms in this region have been associated with specific surface features which have evinced very recent volcanic activity (Shepherd, 1989). A more likely explanation is that the seismic activity in this area results from active secondary faulting in the over-riding plate - that is, faulting which is not directly associated with the subduction zone. This type of faulting has been identified in the northern Lesser Antilles (Bernard and Lambert, 1988) but is much less common in the southern islands. The series of events better fits the pattern of a typical foreshock-mainshock-aftershock sequence, rather than the gradual build up of a volcano-seismic crisis, and there is no spatial correlation with any active volcanic centre in southern Saint Lucia.

The absence of a secure understanding of current causes of shallow seismicity in Saint Lucia precludes a detailed semi-deterministic modelling of the situation in this site-specific hazard assessment. Our revised catalogue of relocated instrumental seismicity, in and around Saint Lucia, is depicted on Figure 1, and can be compared with the regional instrumental seismicity, as reported by the ISC, on Figure 2. On Figure 1, shallow hypocentres (less than 25km depth) are drawn as open circles; other events can originate at significant depths below the island, such as that of 1990 February 5 near the northeast coast, which had a focal depth of 186km. The magnitude threshold of detection in this area has varied through time (and with depth) so that completeness is only assured for the largest events. As there are virtually no grounds for associating individual earthquakes with particular structures or sources at this scale, an extended area, which may have higher levels of observed activity in parts, needs to be considered for acquiring data with which to define the parameters of local shallow seismicity.

EARTHQUAKE HISTORY OF SAINT LUCIA

The main source of information about earthquakes felt in all the Lesser Antilles from 1530 to 1960 is the catalogue of Robson (1964). Because Saint Lucia was a French colonial territory for most of its early history, an additional valuable source is Feuillard (1984) who researched the earthquake history of the central islands. Since 1960, a comprehensive current catalogue of maximum earthquake Intensities has been maintained at the Seismic Research Unit of the University of the West Indies, in Trinidad.

Robson assigned an Intensity (or range of Intensities) to each earthquake of which he had knowledge using the restricted 1956 version of the Modified Mercalli scale. His sources of information were contemporary books, journals and newspapers. The published catalogue contains only brief accounts of each earthquake but his notes and sources survive in the Seismic Research Unit and we have consulted them in preparing this paper. Faccioli et al. (1983) noted that Robson's estimates for historical earthquake Intensities are often one to two degrees higher than modern appraisals would give, and that some accounts of major earthquakes in the early historical period were either spurious or grossly exaggerated.

Two examples of exaggeration are particularly relevant to Saint Lucia. The first is Robson's account of the Leeward Islands earthquake of 1690 April 5. This earthquake was felt at about Intensity IX in the northern Lesser Antilles and Robson's account gives the impression that the area of maximum Intensity extended as far south as Guadeloupe. This would imply that the earthquake was greater than magnitude $8M_s$, and would considerably reduce the estimated recurrence interval for earthquakes in this magnitude range in the northern Lesser Antilles. Feuillard (1984) asserts that the event was felt at no more than Intensity VI in Guadeloupe and was not felt in Martinique, which would reduce the inferred surface-wave magnitude by about one unit. But documentary evidence from Barbados (Calendar of State Papers: Colonial Document #839) suggests that the earthquake was felt in Martinique, Barbados and Saint Lucia; this signifies that the shaking was stronger than in the recent 7.4M_S event in 1974. It therefore seems likely that the 1690 earthquake was perhaps nearer 8M_S in magnitude than 7.5M_S

A second, more pertinent example concerns an alleged earthquake on 1788 October 12 which Robson suggests killed 900 people in Saint Lucia and was felt at Intensity IX. Although Robson himself states that this report may be false, the earthquake appears in his summary tables and has occasionally been carried over into earthquake hazard studies. However, Feuillard (1984) shows that there is no mention of this earthquake in contemporary French sources either for Saint Lucia or neighbouring Martinique. We have therefore disregarded this purported earthquake. With these events removed and many other, marginal events downgraded in Intensity, the list of earthquakes known to have been felt in Saint Lucia at potentially damaging Intensities is shown in Table 1.

TABLE 1. EARTHQUAKES WIDELY FELT ON SAINT LUCIA, MM INTENSITY VI OR GREATER.

DATE	EPICENTRE	ESTIMATED MAGNITUDE (from Dorel, 1981)	REMARKS
1839 JAN 11	-	7.5M_S	Intensity VIII in Martinique; VIII in northern Saint Lucia, VII in the south. Felt on ships at sea 300km east of Barbados. Wide felt area and intensity distribution suggest significant focal depth, and epicentre between Saint Lucia and Martinique.
1843 FEB 8	-	8.0 - 8.5M_S (see text)	Intensity VII in Saint Lucia; Intensity IX throughout the Leeward Islands.
1844 AUG 30	-	6.5 - 7.0M_S	Intensity VII in St. Vincent, VI in Saint Lucia. Probable deeper focus close to St. Vincent.
1906 FEB 16	14.2°N 60.8°W	?	Intensity VI-VII on Saint Lucia, VI in Martinique. Submarine cable break between Saint Lucia and St. Vincent.
1940 JUL 5	13.0°N 61.25°W	6.5M_S	Intensity VI on Saint Lucia. Focal depth 160km(?).
1946 MAY 21	14.5°N 60.5°W	7.0M_S	Intensity VI on Saint Lucia. Focal depth 50km(?).
1953 MAR 19	14.0°N 61.0°W	7.75M_S	Intensity VII on Saint Lucia. Focal depth 200km (USGS), 0.015R (≈135km, ISS).

Early interpretations of the earthquake of 1906 February 16, and some older catalogues, relied on the reported submarine cable break between Saint Lucia and St. Vincent to infer a shallow focus for this event. But, more recent studies (J. Grases, pers. comm.; Shepherd et al., 1993) indicate that, taken on the whole, Intensities in all the islands were more consistent with an earthquake further north, between Saint Lucia and Martinique, and were similar in nature to some confirmed deep focus, felt events of more recent vintage.

Seismic gaps ?

The current low level of activity in the southern Lesser Antilles was noted by Kelleher et al. (1973) who suggested that it might indicate the presence of a seismic gap - that is, a region where the contemporary seismicity is anomalously low and the immediate potential for a major earthquake is therefore high. In view of later developments in the seismic gap debate, this possibility is unlikely. Using the terminology of Habermann et al. (1983), the southern Lesser Antilles is a *Permanent Seismic Gap*; that is, there is no clear history of significant events in the area.

In fact, the southern end of the arc is a region of persisting low seismicity. From careful considerations of the seismotectonic evidence, it has been recognised that the southern Lesser Antilles subduction zone has a different orientation to and is physically separated from the northern zone (Wadge and Shepherd, 1984) and that, relatively, it involves lower strain rates (Russo et al., 1992). In this case, these conclusions remove the basic justification of the seismic gap hypothesis, which asserts that adjacent sections of the same plate boundary cannot move far ahead of each other without catching up in major earthquakes.

REGIONAL INSTRUMENTAL SEISMOMETRY

The Eastern Caribbean region was not well endowed with seismograph stations until the 1980's. Up to 1952, only three seismograph stations had been operated in the region: two continuously in Martinique (established 1927) and Guadeloupe (since 1938), and one for a limited time in Montserrat (1938 - 1946). These stations were primarily intended to detect local earthquakes, occurring close to the active volcanoes in these islands, which might indicate impending eruption. Because of their lack of accurate time control or reliable calibration, they contributed little to an understanding of the regional seismicity distribution. Starting in 1952, the volcanic monitoring was expanded considerably and served this purpose well, but the improvement in time control and calibration, necessary for reliable location and magnitude estimation of regional earthquakes, was not achieved until the mid-1970's.

Beginning in 1976, regional seismograph stations were integrated into four radio-linked networks and the number of stations greatly increased. One of these networks, based on Trinidad, covers the southern Lesser Antilles from Trinidad to Saint Lucia, and another monitors the northern Lesser Antilles from Montserrat to St. Kitts. Other networks, based on Guadeloupe and Martinique, cover the central Lesser Antilles. The networks achieved full regional effectiveness in 1980 and, as a result of international co-operation in sharing stations and data, now span about 1000km. The first permanent seismograph station in Saint Lucia was installed 1979 as part of the southern regional network.

There are, therefore, three different periods of time from which instrumental data are available:

1) Up to 1952: No more than two regional stations in operation at any time. Earthquake locations depend entirely on readings at distant seismograph stations. Epicentres and magnitudes are not reliable for earthquakes of magnitude less than about 5.5 to 6 (m_b). Focal depths are generally default depths - that is, earthquakes can be classified as deep, intermediate or shallow only.

2) 1952-1977: The number of regional seismograph stations increased from 2 to 9 but problems of poor time control, low serviceability and inadequate calibration meant that the regional effectiveness was not improved significantly. In addition, the use of inappropriate formulae for magnitude determination meant that the rate of occurrence of earthquakes of engineering significance was overestimated (Taylor et al. 1978).

3) 1977 - to date: The number of regional seismograph stations increased to more than 30. Uniform time control and adoption of more appropriate methods of magnitude determination have ensured that earthquakes down to about 3.8 are located routinely and accurately. The improvements were essentially completed in December 1977 for the southern Lesser Antilles and in July 1980 for the northern Lesser Antilles. For this period complete data are available for all earthquakes of magnitudes greater than or equal to about 4.0 (m_b).

Traditionally, earthquake magnitudes for the Eastern Caribbean have been reported by local agencies in terms of m_b body-wave estimates.

Early instrumental epicentres, recorded prior to the latest improvements in coverage, indicated that there are two regions of relatively high seismic energy release in the Eastern Caribbean: west of Trinidad where two nests are found, one shallow and one deep, and an extended area adjoining the northern half of the island arc. The same features are present in the ISC catalogue data (see Figure 2). Over the area of this map and through time, thresholds of magnitude detection have not been uniform and completeness at low magnitudes is not assured; also, many foreshocks and aftershocks are included in this dataset. The active seismic sources in the vicinity of Trinidad and Tobago are not considered further since they are too far from Saint Lucia to be of relevance to this study.

PREVIOUS EARTHQUAKE HAZARD ASSESSMENTS

Before 1950, earthquake hazard as an engineering concern was virtually ignored in the whole Eastern Caribbean region. Moderately serious earthquakes close to St. Kitts (1950), Saint Lucia (1953) and Trinidad (1954), followed later by others close to Dominica (1969) and Antigua (1974), forced a reappraisal of this attitude. The first quantitative estimates of seismic hazard were produced by the Trinidad and Tobago Association of Professional Engineers (Key et al., 1970; 1972); the thrust of these recommendations was that the entire Eastern Caribbean region (including Saint Lucia) should be treated as equivalent to the highest risk zone of the building code of the Structural Engineers Association of California (the SEAOC Code or Blue Book).

Many Caribbean professional engineers (e.g. Rothwell, 1978) refused to accept these high levels of hazard arguing that they were unrealistic and economically infeasible to accommodate. The situation was further complicated by four papers, dealing with earthquake hazard in the Lesser Antilles, which were presented at the first Caribbean Earthquake Engineering Conference held in Port-of-Spain, Trinidad in 1978 (Pereira and Gay, 1978; Rothwell, 1978 ; Taylor et al., 1978; and Tomblin, 1978). The level of hazard (expressed as the peak horizontal bedrock acceleration with 10% probability of exceedance in 50 years) varied markedly; for Saint Lucia, the recommended acceleration ranged from 0.1g to 0.3g. The Caribbean Council of Engineering Organisations (CCEO) subsequently requested a small group to examine the databases and methodologies used, to consult with the different authors, and to recommend levels of lateral force to be applied for earthquake resistant design in the Caribbean. This group reported to the Regional Conference on Earthquake and Wind Design in Port-of-Spain in 1983 (Faccioli et al., 1983), and recommended a simple approach to earthquake-resistant design based on the United States Uniform Building Code. For each island, a value of the recommended horizontal design acceleration and associated factors required by the UBC was specified: for Saint Lucia, the recommended value of peak ground acceleration was $110 cm/s^2$. Faccioli et al. (1983) drew attention to the limitations in the database, and advocated that the recommended accelerations and factors should be regarded as guidance for the practising engineer rather than hard-and-fast rules. They also recommended that projects of particular sensitivity or importance should always be accompanied by special site-specific seismic hazard studies which could take account of relevant results of ongoing research. The recommendations and the accompanying commentary were accepted by the CCEO and subsequently incorporated in the Caribbean Uniform Building Code, CUBiC (CARICOM Secretariat, 1985).

APPROACH TO THE HAZARD ASSESSMENT

Current practice for the design of water retention dams calls for a two level approach whereby:

1) a facility is required to remain in operation with only minor damage after being subjected to an earthquake that can reasonably be expected during the lifetime of the structure (termed the Operating or Design Basis Earthquake, OBE or DBE)

2) that, if subjected to the Maximum Design Earthquake (MDE), the facility may be damaged but there shall be no uncontrolled release of the reservoir; depending on the risk downstream, the MDE may equate to the Maximum Credible Earthquake (MCE) or, alternatively, to some fraction of it (typically 50% to 75%) if the risk to life is negligible or non-existent.

Prevailing recommendations (e.g. ICOLD, 1989) call for the OBE to be specified on a probabilistic basis, generally at an exceedance probability of 2.1×10^{-3} per annum. The MCE design ground motion values, on the other hand, may be estimated deterministically or using probabilistic analysis, or both approaches may be used as an aid to final design criteria selection. Annual exceedance probabilities in the range 2×10^{-5} to 10^{-4} are most often associated with probabilistic estimation of MCE ground motion values. The latter value was selected for the MCE for this probabilistic assessment.

The seismic hazard for the Roseau Dam site is here evaluated using the program PRISK (Probabilistic RISK), a state-of-the-art code which incorporates a number of features necessary to calculate annual exceedance probabilities of peak ground acceleration at this particular site (Prinicipia Mechanica, 1985). This program, which has been developed over the past decade from the original McGuire (1976) programs EQRISK and FRISK for seismic hazard computation, has been used extensively for critical industrial installations, including nuclear and petrochemical facilities, offshore platforms, dams and pipelines, in many parts of the world (e.g. Seismic Hazard Working Party, 1988).

PRISK allows seismic sources not only to be defined as area zones, representing diffuse seismicity over a general region, but also as specific geological structures, including arcuate subduction zones. Whether listric faults or great subduction zones, structures may be modelled as having curvature in both strike and dip directions. The contribution of a specific geological structure to the site hazard is computed by summing the contributions from a large number of individual segments, which are assumed to be equally likely as nucleation centres. The size of the rupture area around a nucleation centre is calculated from a specified magnitude-rupture area relation; the direction of rupturing can be specified if information is available to support focusing. The shortest distance from the rupture area to the site is the critical attenuation distance measure for peak acceleration, and a specific subroutine exists to determine this distance for each nucleation centre.

For a standard area zone, where seismicity is assumed to be homogeneous, the contributions of individual point sources within the zone are summed, with the hypocentral distance from the point source at depth to the site being the defining attenuation distance. A seismic source model may include any combination of area zones, planar faults, listric faults, subduction zones, and so on.

The treatment of uncertainty is one of the pillars of modern seismic hazard analysis: no observational parameters are measured with sufficient precision to warrant their input as single best estimate values. Seismic hazard computations undertaken with input limited in this way are beyond attribution of confidence levels. In order to adequately account for the range of data uncertainty and error, and to recognize the variability in expert judgement, more detailed input is required. PRISK implements the logic-tree formalism, which allows multiple values and their corresponding weights to be input for each parameter. These weights reflect the parametric uncertainty over the choice of suitable attenuation relations, activity rates, maximum magnitudes and the other seismological variables. The equivalence in the representation of uncertainty in empirical data and expert judgement is consistent with the modern Bayesian paradigm, in which probabilities are assigned as degrees of belief, rather than calculated as frequencies.

For this application, the seismic source model is defined and input information for the PRISK evaluation is derived in the following way:

1) The geometries of the source zones are defined by the locations of well-constrained earthquakes from the period January 1980 to July 1990. This period corresponds to the period of most efficient operation of the entire Lesser Antilles seismograph network. Demarcation of the source zone boundaries is reinforced by discernible differences in activity rates and b-values.

2) Older earthquakes, for which precise locations are not available, are assigned to one or other of the identified source zones on the grounds of expert opinion. Magnitudes for these events come from several sources and are reported against different magnitude scales. Surface wave magnitudes (M_S) are accepted at face value, but body wave magnitudes are converted to M_S equivalents by means of the conventional relation:

$$m_b = 2.5 + 0.63 * M_S$$

It must be noted that this particular relationship, which is extensively quoted in the seismological literature (see, for example, Richter, 1958), has not been verified as to its suitability for converting Eastern Caribbean instrumental magnitudes; it may be overconservative. In addition, all m_b magnitude values reported by the Trinidad seismological agency TRN prior to 1977 are adjusted downwards by 0.5 magnitude unit before conversion, in line with the findings of Taylor et al. (1978) that such values are generally overstated. These older data are taken to comprise incomplete catalogues, containing the magnitudes of only the larger events.

3) The reliable recent magnitude data form the basis of complete catalogues of earthquake occurrence for each zone. Because the only appropriate attenuation relationships available are expressed in terms of surface wave magnitudes (see below), these data have to be converted to equivalent M_S values for conflation with the incomplete catalogues and input to PRISK.

4) The incomplete and complete earthquake catalogues are combined and analysed in a maximum likelihood sense to give distribution estimates of

activity rate, b-value and maximum magnitude for each source zone, using the method developed by Kijko and Sellevoll (1989, 1992). This method incorporates magnitude uncertainties and is therefore suitable for providing parameter distributions for input to the PRISK analysis. The results obtained from this maximum likelihood analysis, which represent the optimum use of all the available seismological information, are examined for harmony with the more reliable but limited quantity recent data.

SOURCE ZONES DEFINED BY RELOCATED HYPOCENTRES

Until the time in the late 1970's when significant improvements in instrumentation were made, the discerning of any variation in activity levels in the Eastern Caribbean had to depend on the distribution of larger instrumental earthquakes (i.e. greater than about 4.0m_b). But, because of gross uncertainties in many of their published locations, these data are not suitable for defining seismic source zones. On the other hand, locations of all earthquakes since the start of 1980 are well-constrained and these have been re-estimated by the method of Joint Hypocentral Determination using the solutions published in the regular quarterly bulletins of the Seismic Research Unit as start points. Arrival times for P and S waves at regional stations only have been used in the recomputations together with travel-time tables locally derived from large-scale refraction studies (Boynton et al., 1979; LADLE, 1983). Teleseismic observations have been used only to fix focal depths from intervals of pP - P, wherever possible. Magnitudes are estimated from the duration-magnitude formula derived by Shepherd and Aspinall (1983) specifically for this region. In all cases where comparison is possible these magnitudes agree with teleseismic determinations to within 0.2 units.

After preliminary examination, the locations were jointly recomputed in two groups, north and south. Event locations were recomputed relative to the location of a single master event in each group. Master events were chosen on the following grounds:

1) the event was recorded both by a large number of regional stations and a large number of stations at teleseismic distances;

2) the focal depth was well-determined from teleseismic depth phases;

3) global and regional epicentral determinations agreed closely;

4) the event was close to the centroid of the relevant group of events.

The three-dimensional spatial distribution of relocated hypocentres (see, for example, Figures 3 and 4) confirms the conclusion of Wadge and Shepherd (1984) that the subduction zone is distinctly segmented with the major break occurring between the islands of Saint Lucia and Martinique. A second, major difference is that there is widespread shallow seismicity in the northern zone, which is absent in the southern zone.

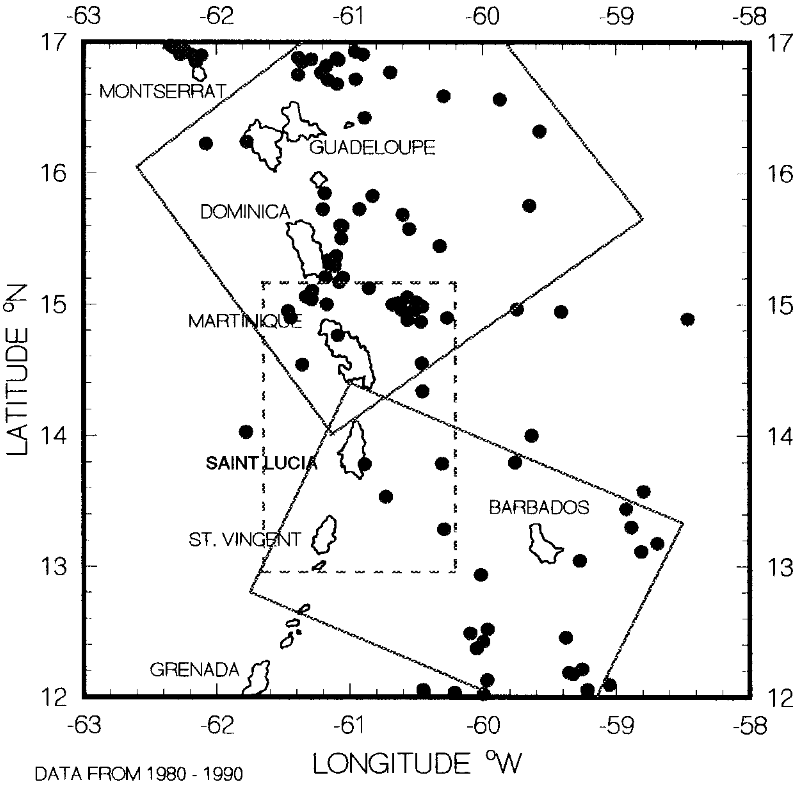

FIGURE 3 Epicentres relocated by the Joint Hypocentral Determination method, 1980 to 1990, with plan outlines of the northern and southern subduction zone sources and the overriding plate source (dashed).

Shallow events on the Atlantic side of the arc are probably directly related to the subduction process: that is, they probably result from downbending of the Atlantic lithosphere before it is thrust down into the mantle. By and large, their magnitudes are modest and they are sufficiently far from land that their contribution to the hazard can be neglected. Shallow events on the Caribbean side of the north end of the arc have been the subject of intensive study by McCann and Sykes (1984, 1986) who showed that they were related to the subduction of aseismic ridges (the Barracuda Ridge and the Tiburon Rise); strictly speaking, these events are near-boundary intraplate earthquakes. They occur mainly in a zone bounded by Guadeloupe, Antigua and Nevis but are not considered further because of their large distance from Saint Lucia.

The depths of events in the southern segment are fairly evenly spread down to about 100km. Here, the hypocentres delineate a volume with a planar surface striking in a NNE direction and an orthogonal dip at 45° to 50°. In the north, the relocated hypocentres depict a clear Wadati-Benioff zone striking NNW with an orthogonal dip of 50° to 60°, reaching down to 200km depth (see Figure 4).

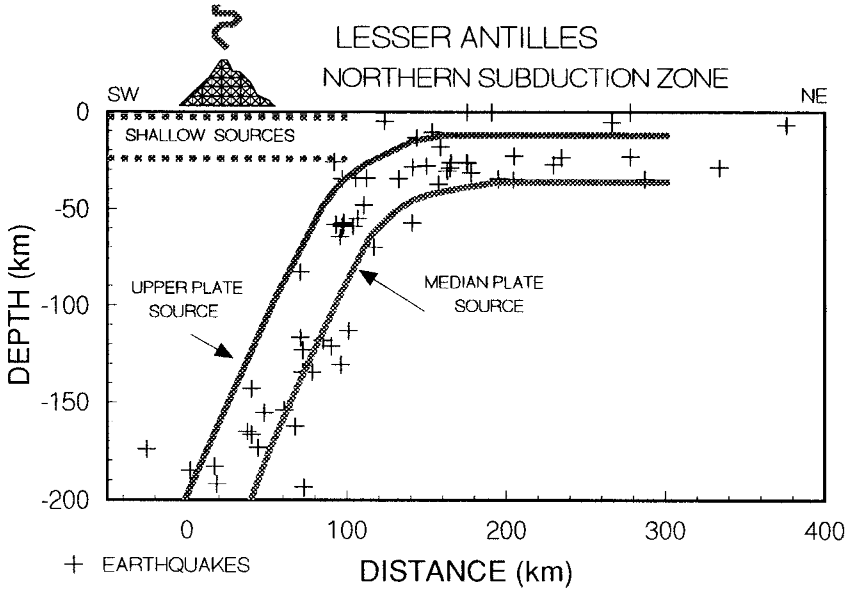

FIGURE 4 Cross-section of relocated hypocentres from 1980 to 1990 in the northern segment of the Lesser Antilles subduction zone, showing the geometries of the sources representing the Benioff-Wadati seismicity and the seismicity in the overriding plate margin.

The higher rate of seismic energy release in the northern segment of the island arc relative to the southern segment and, in turn, of the southern segment compared with the rest of the area of study, indicate that the "background" seismicity (other than that at shallow depths in the over-riding plate) can be reasonably treated as negligible in terms of its contribution to hazard at the damsite and it is not, therefore, modelled in this assessment.

For hazard assessment purposes, each source zone requires a maximum magnitude parameter and this can be inferred from historical observation, from an understanding of the seismotectonic processes in play in the region, or from the statistics of instrumental data where these are sufficient. The greatest observed magnitudes in the historical record are described in the next section, whilst maximum magnitudes derived from considerations of tectonics and seismicity statistics are discussed in subsequent paragraphs.

LARGEST HISTORICAL MAGNITUDES

If the period of observation is sufficiently long - that is, long in comparison with the return period for maximum events - then it may reasonably be assumed that examples of the largest magnitude earthquake, which can be generated in the prevailing seismotectonic regime, have already been observed. For the Eastern Caribbean as a whole, the earthquake catalogue extends back to 1530 A.D. (Robson, 1964) so the record is approximately of the same order as the return period corresponding to the event with a $2x10^{-3}$ probability of exceedance (500 years). It is, therefore, quite plausible that an event could occur, larger than any experienced in the historical period, and this possibility is recognized in the assignment of weights to the maximum magnitudes. However, it is more likely than not that the historical record does contain an event which corresponds closely in size to the value appropriate for defining the source zone maximum magnitude parameter.

Northern zone

For the Lesser Antilles, the largest historical earthquake is certainly the Leeward Islands event of 1843 February 8. Some dispute exists about the magnitude, as inferred from felt area, of this event (Shepherd, 1992; Bernard and Lambert, 1992). McCann and Sykes (1984, 1986) assigned magnitude 8.5M_S to this event while Bernard and Lambert (1988) assigned 7.5 to 8.0M_S. We have re-examined the historical data and agree with the higher assessment. What is not clear is whether this event was a major normal-faulting event within the subduction zone or an interplate thrust event between the subduction zone and the overriding plate. Without further research it seems safest to allow both possibilities, that is, a largest magnitude of at least 8.5M_S of either type. For the present, it has been assumed that such an earthquake could nucleate anywhere within the northern half of the area of study.

Southern zone

The largest historical earthquake which can be assigned unambiguously to the southern segment of the subduction zone is the earthquake of 1844 August 30, with estimated magnitude 6.5 to 7.0M_S. (The earthquakes of 1839 January 11, 1946 May 21 and 1953 March 19 all belong to the southern end of the northern subduction zone). This indicates 7.0M_S as the greatest historical magnitude for the southern segment of the island arc.

Local shallow zone

The largest earthquake for which an instrumental magnitude is available is that of 1990 May 19, reported at magnitude 4.5m_b by TRN, but only 3.7M_S by ISC. In this zone, a few events have produced magnitudes approaching but not exceeding this value in the instrumental era.

With respect to much earlier events, some interpretations of (exaggerated) meizoseismal Intensity reports of the earthquake of 1906 February 16, its long aftershock sequence, and a submarine cable break which was possibly related to this disturbance, have given the impression that this earthquake may have had a shallow origin. From the extent of its felt area, it is clear that the magnitude of this earthquake probably approached 6.0M_S. However, two recent independent reappraisals of the evidence strongly suggest that it had a much deeper origin, in the vicinity where the two subduction zones overlap, and that it should not be assigned to the shallow source zone. Nonetheless, the remote possibility that this earthquake was shallow is acknowledged in the present assessment by assigning a small weight to a source maximum magnitude of 6.0M_S ; it should be noted, however, that a gap of more than two units of magnitude exists between this estimate and the largest affirmed M_S value (3.7) for earthquakes in this source zone.

ZONAL MAXIMUM MAGNITUDES FROM TECTONIC CONSIDERATIONS

The maximum magnitude which can occur in a region may also be inferred from considerations of crustal structure and dynamics.

Northern zone

Two types of major earthquake appear to be possible in the northern subduction zone. One is a normal-faulting event in the downgoing plate, in which the lithosphere ruptures through its entire thickness along the whole length of the segment. Major earthquakes of this sort have occurred in similar tectonic settings in the present century in Indonesia in 1977 (Stewart, 1978) and off the Japanese coast in 1933 (Kanamori, 1971). The maximum magnitude for this type of event can be estimated from the expression for the seismic moment:

$$M_0 = \mu A\,\bar{u}$$

combined with Kanamori's (1977) moment-magnitude formula:

$$M_\omega = 0.667*\log(M_0) - 10.7$$

Here μ is the modulus of rigidity of the rocks which rupture, A is the total area of the rupture and $\bar{u}$ is the mean displacement during the rupture. The northern Lesser Antilles segment is approximately 450km in length and the thickness of the seismic lithosphere is about 35km so that a normal fault cutting through it at a dip angle of 45° would have a width of about 50km.

For crustal rocks, μ is about 3.3×10^{11} dynes cm^{-2} and the mean displacement is probably of order 500 cm (Molnar, 1979; p 122). Substituting these figures into the first equation, we have:

$$(M_0)_{max} = 3.7 \times 10^{28} \text{ dyne-cm}$$

which corresponds to:

$$(M_\omega)_{max} \approx 8.3$$

The second type of major earthquake which can occur is a thrust earthquake on the interface between the downgoing Atlantic plate and the overriding Caribbean plate. These earthquakes occur in the mantle where μ is higher by a factor of about two. The area of contact between the Atlantic plate and the thicker Caribbean plate is also greater by a factor of about two. The maximum moment is therefore greater by a factor of about four, say:

$$(M_0)_{max} \approx 10^{29} \text{ dyne-cm}$$

or:

$$(M_\omega)_{max} \approx 8.6$$

In this magnitude range, the moment magnitude M_ω is equivalent to the surface wave magnitude M_S and we assume that, if the entire plate boundary ruptures, the slip can initiate at any point on the boundary.

Southern zone

Similar calculations can be performed for the southern zone. Here the calculations are affected by two additional factors. One is the (probably) lower rate of convergence which reduces the recurrence rate of earthquakes of all magnitudes. The second is the presence of the very thick accretionary prism of the Barbados Ridge on the leading edge of the downgoing Atlantic Plate. The accretionary prism can affect the seismicity in a number of ways. Chen et al. (1982) have shown that earthquakes do not occur within an accretionary prism itself. This restricts the thickness within which normal faulting takes place to about the lowermost third of the seismic lithosphere. The length of the southern segment is about one half that of the northern segment so that, if displacements and rigidity moduli are about the same, $(M_0)_{max}$ is reduced to 6 x 10^{27} dyne-cm (i.e. by a factor of 6), and $(M_\omega)_{max}$ to about 7.8.

Deep seismic reflection profiles (Westbrook et al., 1982) show that the accreted sediment is carried down into the subduction zone. This will, in turn, have effects on the subduction process which are generally unpredictable without specialized studies. Certainly, one probable effect will be to lower the effective modulus of rigidity at the interplate boundary and thus reduce $(M_0)_{max}$. The effective area of contact is about one quarter of that in the northern zone. Combining these two, we estimate that the maximum magnitude would be reduced by about three-quarters of one unit, to M_S = 7.8.

MAXIMUM LIKELIHOOD ZONAL SEISMICITY PARAMETERS

In addition to the appraisals of maximum magnitudes given in the preceding sections, the statistics of incomplete and complete catalogues of earthquake occurrence in the three principal source zones can be analysed by the maximum likelihood method described by Kijko and Sellevoll (1989, 1992). The datasets comprise incomplete and complete catalogues for the northern subduction source zone (34 and 61 earthquakes, respectively), the southern subduction source zone (5 and 28 earthquakes), and the shallow overriding plate source zone (9 and 5 earthquakes). The respective magnitude thresholds for the two kinds of catalogue are $4M_S$ and $3M_S$, or equivalent m_b values.

The maximum likelihood seismicity parameters and their uncertainties (at the $\pm 1\sigma$ level) derived in this way for the source zones areas are as follows:

Northern subduction zone

$$\lambda_{(4.0)} = 0.92 \pm 0.11$$
$$b_{(Ms)} = 0.47 \pm 0.04$$
$$M_{MAX} = 8.9 \pm 0.5$$

Southern subduction zone

$$\lambda_{(4.0)} = 0.29 \pm 0.06$$
$$b_{(Ms)} = 0.53 \pm 0.07$$
$$M_{MAX} = 7.55 \pm 0.4$$

Shallow overriding plate zone

$$\lambda_{(4.0)} = 0.06 \pm 0.01$$
$$b_{(M_S)} = 0.45 \pm 0.26$$
$$M_{MAX} = 5.6 \pm 0.3$$

where $\lambda_{(4.0)}$ is the annual number of events in each zone equal to or exceeding $4.0M_S$, this being chosen as a suitable threshold for earthquakes of engineering significance. M_{MAX} is the estimated maximum magnitude earthquake (in M_S) assuming the data arise from a Poisson arrival process and can be represented by a doubly truncated exponential magnitude-frequency distribution. The maximum likelihood expected values for these parameters are summarised in graphical form on Figure 5.

In the case of the shallow overriding plate zone, it should be noted that the incomplete part of the catalogue includes entries which represent known swarms and volcano-seismic crises; for conservatism, these entries have been ascribed magnitudes which are 0.5 unit higher than the largest single event in the sequence.

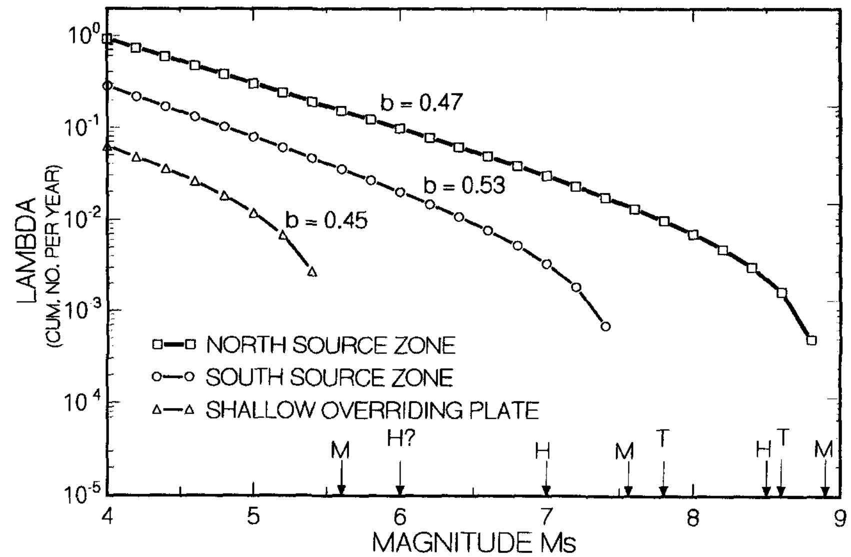

FIGURE 5 Magnitude-frequency plots for the three source zones, using the maximum likelihood method of Kijko and Sellevoll (1989, 1992) with M_S values. The arrows indicate zone maximum magnitudes inferred from historical observations (H), tectonics (T) and the maximum likelihood method (M).

The analysis makes optimum use of the whole dataset, including both complete and incomplete parts of the catalogue, and its results are the primary input parameter distributions for PRISK. The values obtained for M_{MAX} by this method show reasonable concurrence with those inferred from tectonic and historical considerations (see Figure 5). The greater M_{MAX} for the northern subduction zone produced by this maximum likelihood analysis is attended by large uncertainty. Without further substantiation it is probably overconservative and so the value of $8.6M_S$ is preferred here.

Estimated statistically, the central value of maximum likelihood M_{MAX} for the shallow overriding plate zone, $5.6M_S$, is greater than that recorded in the more reliable historical data but the spread on this estimate takes the input distribution up to $5.9M_S$. For conservatism, the distribution is extended further, to $6.0M_S$, to accommodate the remote possibility that the 1906 earthquake was shallow.

PARAMETERIZATION OF SEISMIC SOURCE MODEL

A primary seismotectonic model is constructed in the light of these appraisals of the seismological data and the regional geological interpretation. The following judgmental decisions are made on the values to attribute to the input parameter distributions and on the source geometries to use for the PRISK hazard computation.

SOURCE GEOMETRIES

Three source zones are designated: the first accommodates earthquakes in the northern subduction zone but excludes distant, shallow events in the Leeward Islands north of about 16.5°N; the second models seismic activity in the southern segment of the subduction zone, and the third has been configured to represent shallow tectonic earthquakes in the overriding plate, and swarms and volcano-seismic activity in the islands of St. Vincent, Saint Lucia and Martinique. The outline plan dimensions of these sources have been set from the distributions of relocated epicentres and are shown on Figure 3. Other, background seismicity is deemed either too low or too remote to influence the hazard at site.

Both subduction zone sources are modelled as two parallel fault sources striking along each segment with curvilinear geometries governed by the shapes of the Wadati-Benioff zones. One fault source is positioned conservatively on the upper surface of the descending plate and the other on an approximate median line (see, e.g., Figure 4). On the grounds of conservatism, seismic activity is assumed to be shared equally on these model fault sources although most of it clearly occurs close to and beneath the median line.

In the case of the overriding plate zone, the seismic source is modelled as two flat rectangular areas, one at a depth of 5km and the other at a depth of 25km. Activity is assumed to be equally divided between the two. The Cartesian co-ordinates of these source geometries, expressed in kilometres relative to the site, are input to the PRISK program.

SEISMICITY PARAMETER DISTRIBUTIONS

For PRISK, seismicity parameter distributions have to be set and weightings assigned to discrete values making up the distributions. Where the parameters are determined solely from the maximum likelihood analysis, weightings are attributed to the central value and the $\pm 1\sigma$ values to approximate a normal distribution. In other cases, expert judgement is used to weight alternative parameter values. For the northern subduction zone source, the following distributions are used:

$\lambda_{(4.0)}$:	0.81	0.92	1.03
Weights:	0.2	0.6	0.2
$b_{(Ms)}$:	0.43	0.47	0.51
Weights:	0.2	0.6	0.2
Max. magn:	8.3	8.6	8.9
Weights:	0.35	0.60	0.05

The weights for the maximum magnitude distribution have been adjusted to reflect the findings of the tectonic interpretation of local conditions rather than the higher values indicated by the maximum likelihood analysis, which are held to be probably overconservative.

For the southern subduction zone source, the following distributions are used:

$\lambda_{(4.0)}$:	0.228	0.285	0.342
Weights:	0.2	0.6	0.2
$b_{(Ms)}$:	0.46	0.53	0.60
Weights:	0.2	0.6	0.2
Max. magn:	7.1	7.5	7.9
Weights:	0.2	0.6	0.2

These distributions are not modified on any judgemental basis, although it may be noted that the upper maximum magnitude value ($7.9M_S$) implies some conservatism, encompassing the maximum credible earthquake inferred from tectonic considerations.

For the overriding plate zone source, the following distributions are used:

$\lambda_{(4.0)}$:	0.053	0.063	0.073	
Weights:	0.2	0.6	0.2	
$b_{(Ms)}$:	0.42	0.45	0.48	
Weights:	0.2	0.6	0.2	
Max. magn.	5.3	5.6	5.9	6.0
Weights:	0.2	0.5	0.2	0.1

Other than extending the distribution for maximum magnitude up to $6.0M_S$, as discussed above, no specific judgement is applied to the distributions for this zone.

ATTENUATION RELATIONSHIPS

Modelling the attenuation of seismic ground motion has traditionally been based on the regression analysis of recorded strong-motion data. With the intensive early deployment of accelerographs in California, most of the established ground motion attenuation relations are Californian in authorship as well as origin. Amongst the best known, and commonly cited, are the attenuation relations constructed by Joyner and Boore (1981) from a database of shallow western North American earthquakes. Although widely adopted for use in seismic hazard assessments, their application to subduction zone environments has been questioned by Jacob and Mori (1984), who have shown them not to be sufficiently conservative in the light of some limited data from deeper earthquakes in Alaska and Japan.

There is a marked paucity of information on attenuation in subduction zone areas and much recent published work has reflected a current interest in the seismic hazard of the Puget Sound, Washington region, (see, for example, Hays and Gori, 1986). Background on those features of seismicity and tectonics which are distinctive to this particular area are provided by Crosson (1986).

Crouse et al. (1988) provide relationships for peak ground velocity as function of period, but not peak ground acceleration; they used subduction zone earthquakes of any mechanism, recorded on mostly "stiff, shallow soil sites". They remarked the probable influence of local geology on the Mexico data used in their analysis, but reported no discernible differences in attenuation as a function of focal mechanism type. In their attenuation relationship, the distance variable is defined as the distance to centre of energy release.

The intention of Youngs et al. (1988) was to estimate peak ground acceleration (PGA) in the range 20 to 50km by extrapolating from a mixture of true records and numerical simulations (the latter needed especially for events above M>8) for "rock" sites, using sets of M_ω magnitudes and converted M_S and m_b values mixed in unstated proportions. Youngs et al. introduced a variable into their regression for faulting type but as they use focal depth as a discriminant between thrust and normal faulting in several cases this seems to invalidate it as an independent variable. Their distance variable is the closest distance to rupture.

A Dames & Moore study (Crouse, 1990), subsequently published as Crouse (1991), also has a particular Cascadia perspective, with an emphasis on "stiff soil sites". The data used are from subduction zones but several "unprocessed" Japanese strong motion records and two previously ignored recordings from the M6.5 1965 Puget Sound earthquake are introduced. For the latter event, one record is from Portland at a distance of about 210km; the second, from Tacoma (epicentral distance 20km), gives a peak horizontal acceleration of only 56 gals. Crouse introduced a focal depth variable into his regression which has a strong positive influence on estimated PGA for increasing depth, but there does not seem to be any explicit restriction on the depth range for which the relationship is deemed valid. His distance variable is the distance to centre of energy release.

Away from the Pacific Northwest, Kawashima et al., (1984) used Japanese data to obtain attenuation-distance relationships. However, their data came from limited response SMAC recorders, and only from earthquakes of shallow depth (less than 60km). Their derived relationships are further restricted in applicability as they are based on JMA magnitudes and on epicentral distances.

Houston and Kanamori (1990) compared actual strong-motion recordings of three magnitude 8 subduction zone earthquakes (from Chile, Mexico and Japan) with modelled far-field waveforms and found that the spectral decay with distance was much less marked in real records than their model predicted. They attributed the discrepancy to multi-pathing in the complex crustal structure of the subduction zone and to site response effects. Similar effects are reported from the Aleutians by Stephens et al. (1990). These findings suggest that attenuation laws such as that of Youngs et al. (1988), which rely on extrapolations, should be used with caution, especially at greater distances.

In summary, many recent published studies address predicted ground motions in subduction zone areas similar in nature to the Cascadia zone and not to an island arc environment (for example, data from the South Sandwich Islands is deliberately excluded in the analysis and review by Heaton and Hartzell, 1986). By implication, island arc areas probably differ from those specifically selected as analogues to the Cascadia region and a conservative position must be taken when adopting attenuation relationships for use in the Eastern Caribbean, where empirical data do not yet exist.

For an earthquake of magnitude $8M_S$, a comparison of the median PGA attenuation predictions of some applicable relationships is shown on Figure 6.

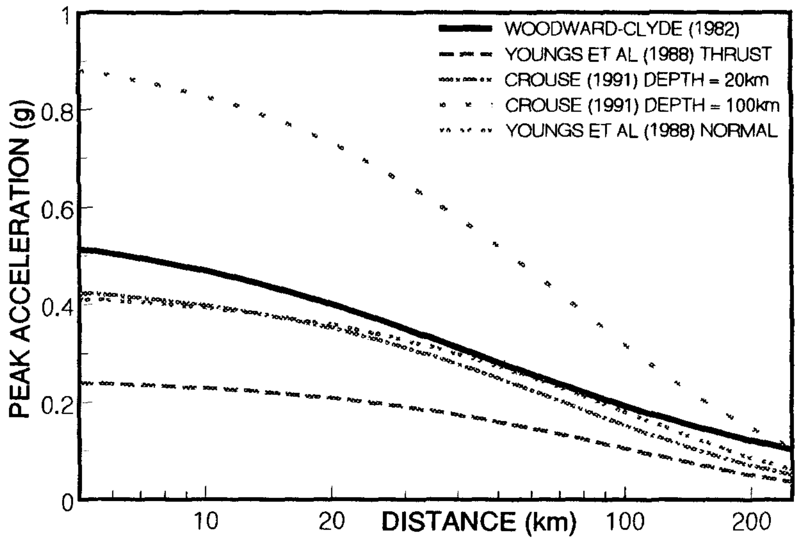

FIGURE 6 Comparison of median PGA predictions as a function of critical distance for an $8M_S$ earthquake, using selected subduction zone relationships.

There is close correspondence between the Woodward-Clyde, Youngs et al. (normal events) and Crouse (25km, i.e. shallow focus) curves. For thrust earthquakes, the Youngs et al. relation produces much lower PGA's, whilst increasing the assumed focal depth propels the Crouse predictions to increasingly high levels. Given the complex geometry of the sources in the Eastern Caribbean, it is not clear how best Crouse's depth factor should be applied in these circumstances.

For the present probabilistic hazard assessment, the attenuation relationships used are those proposed by Woodward-Clyde Consultants (1982), which appear to fit well some Alaskan and some Japanese data (see Figure 2 of Jacob and Mori, 1984). Over all distances, they are slightly more conservative than the others (if the Crouse depth effect is ignored). For Benioff zone earthquakes, such as occur in the Lesser Antilles arc, the chosen acceleration and velocity attenuation relationships have the following form:

$$\mathrm{Ln}\ (acc) = 5.347 + 0.5 * \mathrm{M} - 0.85 * \mathrm{Ln}(\ \mathrm{R} + 0.864 * \exp(0.463*\mathrm{M})\ )$$

$$\mathrm{Ln}\ (vel) = 1.673 + 0.72 * \mathrm{M} - 1.05 * \mathrm{Ln}(\ \mathrm{R} + 0.864 * \exp(0.463*\mathrm{M})\ )$$

where *acc* is acceleration in cm/sec^2; *vel* is velocity in cm/sec; M is surface wave magnitude and R is the closest distance to the rupture area. These attenuation relations are chosen with reduced sigma values of 0.5 and 0.55 respectively for the Eastern Caribbean, which are judged to fairly represent the likely spread of peak acceleration and velocity around the medians given by the above formulae.

MAGNITUDE - FAULT RUPTURE AREA RELATIONSHIP

In order to represent, as accurately as possible, the significant source extent of large magnitude earthquakes, PRISK allows events to nucleate at random on the modelled fault sources. The rupture area corresponding to the event's magnitude is extended radially from the initiation point according to a suitable relationship; that due to Wyss (1979) is as appropriate as any other and takes the form:

$$\mathrm{Log}_{10}(\mathrm{A}) = -\ 4.15 + \mathrm{M_S}$$

where A is the rupture area and M_S is the surface wave magnitude. With the exception of inferences from the shallow 1957 and 1986 Andreanof Islands earthquakes (Das and Kostrov, 1990), there is a lack of specific knowledge on typical source dimensions in subduction zones and for the purposes of this assessment, the Wyss relationship is considered to provide an adequate guide to rupture area as a function of magnitude. Other correlations, such as those reported by Singh et al. (1980) and Bonilla et al. (1984), would be expected to give similar results at the hazard levels being considered here.

RESULTS OF THE PROBABILISTIC HAZARD EVALUATION

The seismic hazard at the proposed Roseau Dam site in Saint Lucia has been calculated using the PRISK program in terms of peak ground acceleration and peak ground velocity, using the seismic sources and seismicity parameters prescribed above. The results for peak ground acceleration and velocity are summarised on Figure 7.

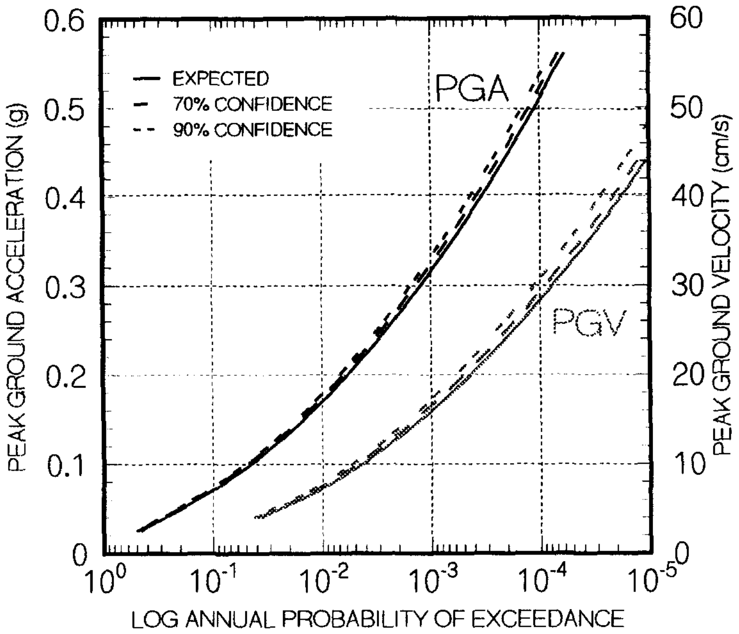

FIGURE 7 Results of the PGA and PGV hazard assessments for the damsite in Saint Lucia, showing annual probabilities of exceedance expressed as expected values with 70% and 90% confidence levels.

GROUND MOTION HAZARD

The expected peak acceleration at the $2x10^{-3}$ probability per annum exceedance level is 0.27g, with corresponding values of 0.28g and 0.29g at the 70% and 90% confidence levels (the issue of confidence levels, as used here, is addressed in more detail in the Discussion, below). At the 10^{-4} per annum exceedance level the expected value is 0.51g with corresponding values of 0.54g and 0.56g at the 70% and 90% confidence levels. Curves showing the probability of exceedance of the expected value, 70% and 90% confidence levels for a range of peak ground accelerations are shown on Figure 7; these have been calculated from the distribution spreads for the input seismicity parameters.

When only single best estimate values are assumed for the input parameters (rather than weighted distributions), the corresponding figures for the expected values are 0.27g and 0.52g respectively.

The results for peak velocity hazard are as follows: 12.9 cm/sec at the $2x10^{-3}$ probability per annum of exceedance with corresponding 70% and 90% confidence levels of 13.2 cm/sec and 13.7 cm/sec respectively. At the 10^{-4} per annum exceedance level, the expected, 70% and 90% confidence levels are: 28.3 cm/sec; 28.9 cm/sec and 30.4 cm/sec respectively. When single best estimate values are assumed for the input parameters, the corresponding return period figures are 13.2 cm/sec and 29.1 cm/sec respectively.

Curves showing the probability of exceedance of the expected, 70% and 90% confidence levels for a range of peak ground velocities are also shown in Figure 7.
The contributions of the six seismic sources to the total hazard have been determined as percentages at the $2x10^{-3}$ per annum hazard level and these are further divided by magnitude range on Table 2.

TABLE 2. HAZARD CONTRIBUTIONS FROM SOURCE ZONES

MAGNITUDE **OVERRIDING PLATE**	**M<5**	**5≤M<5.5**	**5.5≤M<6.0**	**≤6.0**	**TOTALS**
SOURCE (DEPTH 5km)	11.8%	3.2%	1.6%	<0.1%	16.6%
SOURCE (DEPTH 25km)	2.9%	1.6%	0.9%	<0.1%	5.5%
MAGNITUDE **NORTH SUBDUCTION ZONE**	**M<7**	**7≤M<7.5**	**7.5≤M<8**	**8≤M<8.7**	
UPPER PLATE SOURCE	3.6%	4.6%	8.6%	17.5%	34.3%
MEDIAN PLATE SOURCE	2.0%	3.0%	6.1%	13.4%	24.5%
MAGNITUDE **SOUTH SUBDUCTION ZONE**	**M<6**	**6≤M<6.5**	**6.5≤M<7**	**7≤M<7.6**	
UPPER PLATE SOURCE	1.8%	2.0%	3.4%	4.8%	12.0%
MEDIAN PLATE SOURCE	0.8%	1.1%	2.0%	3.2%	7.1%

At the $2x10^{-3}$ annual probability of exceedance level, the northern subduction zone source is the dominant contributor with 60% of the hazard, large magnitude events proving significant. The overriding plate zone contributes a quarter of the hazard at this exceedance level, which is greater than the contribution of the southern subduction zone. This local hazard is the result of relatively low magnitude earthquakes in close proximity to the site and has implications for the frequency content of ground motion shaking.

SENSITIVITY TESTS

Fifteen sensitivity studies have been carried out by successively adjusting single individual input parameters. The results are compared with the hazard value computed from best estimate input values and are given on Table 3. Values are quoted here to three decimal places for comparative purposes only.

TABLE 3. SENSITIVITY TESTS OF SEISMIC HAZARD ASSESSMENT

TEST	CONDITION	PGA @ $2x10^{-3}$ p.a. EXCEEDANCE	PGA @ 10^{-4} p.a. EXCEEDANCE
1	Single-value best estimate input parameters	0.271g	0.518g
2	Attenuation sigma = 0.606 (Alaska)	0.329g	0.679g
3	McGuire attenuation relation	0.184g	0.271g
4	Youngs et al. (1988) attenuation relation	0.247g	0.597g
5	Upper b-values used for all sources	0.255g	0.490g
6	Upper values of M_{MAX} used for all sources	0.295g	0.572g
7	Site moved 50km north	0.295g	0.571g
8	Site moved 100km north	0.329g	0.646g
9	Site moved 50km south	0.258g	0.485g
10	Site moved 100km south	0.234g	0.438g
11	Site moved 50km west	0.247g	0.473g
12	Site moved 100km west	0.210g	0.396g
13	Site moved 50km east	0.286g	0.546g
14	Site moved 100km east	0.284g	0.545g
15	All local source events at 5km depth	0.279g	0.535g
16	All subduction events on median planes	0.261g	0.494g

There is close correspondence between the peak acceleration found using the full set of input parameter distributions, 0.267g, and the acceleration given by single, best estimate input values, 0.271g. The scatter on the published Alaskan attenuation relationships was judged to be conservative and lower sigma values (0.50 for acceleration and 0.55 for velocity) were chosen; if the higher sigma value for acceleration (0.606) is invoked, then the peak acceleration is significantly increased from 0.267g to 0.329g. If a relationship from the Cascades region of northwest America is used (Youngs et al., 1988), then a slightly lower peak acceleration is obtained for the $2x10^{-3}$ probability per year (0.247g) whilst a higher 10^{-4} per year figure is indicated (0.597g); these values reflect respectively lower median behaviour and wider scatter in this particular relationship. The adoption of a Californian attenuation relation can be seen to be manifestly unconservative.

The sensitivity of the results to variations in b-value are marginal: using the upper b-values for all sources reduces the acceleration by less than 5%. Conservatively accepting upper range values for M_{MAX} in all sources increases the hazard by 10%. The same order of increase would result if all the local overriding plate source events were assumed to occur only at 5km depth. The degree of conservatism in taking half the activity in each subduction zone on the upper face of the down-going slab is illustrated by relaxing all events on to the median plane; it is moderate and acceptable: a difference of 0.006g in the peak acceleration.

A series of eight tests varying the position of the site relative to the source zones illustrates the well-known sensitivity of site-specific hazard assessments to distance from source boundaries. Saint Lucia stands on a saddle-point or inflexion in terms of regional seismic hazard: to the north, hazard increases markedly in response to the dominant northern segment of the subduction zone; to the south, there is a reduction to a plateau dictated by activity on the less active southern segment; to the west, the hazard is reduced below the previous cases as a result of an absence of source zones; moving east, the hazard at first increases as the closest distances to both subduction sources are reduced, and then diminishes in the apparent low seismicity wedge between the two converging plates.

DISCUSSION

The figure derived for PGA of 0.27g at the Roseau Dam site at the $2x10^{-3}$ probability per annum of exceedance is greater than that recommended by CUBiC for the island by a factor of about 2.4. The CUBiC figure, in fact, represents an interim compromise between the opinions of earthquake engineers and seismologists. The engineers favoured adoption of a lower figure which would persuade a typical building contractor to make some provision for protection against earthquake-induced lateral forces, which previously had been ignored entirely. The seismologists favoured a higher figure more in line with that required from seismological considerations. The CUBiC recommendation that projects of particular importance should be preceded by special studies of seismic hazard was intended to help ensure that structures such as the Roseau Dam were adequately designed to resist those forces generated by earthquakes which have a finite probability of occurring during the expected life of such a structure.

Analysis shows that the values of PGA and PGV are relatively insensitive to assumptions about the geometry and activity rates of the identified seismogenic sources in the Eastern Caribbean region. The major contributor to seismic hazard at the Saint Lucia site is clearly the northern Lesser Antilles subduction zone which contributes about 60% to the hazard at all probability levels; in the light of current knowledge, it has been taken to be a single, coherent source with a conservative distribution of values for its maximum magnitude.

The much lower activity rate and smaller maximum magnitude in the southern Lesser Antilles subduction zone make this source relatively much less important at all probability levels for a site on Saint Lucia. Although future seismological studies of both these features may engender minor adjustments to their activity figures, such adjustments are likely to be modest unless some new and fundamental discovery is made on the nature of regional seismogenicity.

The second most important contributor to seismic hazard at the site (contributing about one quarter of the hazard at all probability levels) is provided by close shallow, intraplate earthquakes in the leading edge of the overriding Caribbean plate. The significance of this source was emphasized during the course of this study by the continuation of aftershocks of the shallow 4.5m_b earthquake of 1990 May 19, whose epicentre was about 10km from the damsite. The precise cause of these earthquakes is still uncertain. One opinion is that they are caused by intrusion of magma beneath southern Saint Lucia. If this is so, then there is a serious threat of an explosive volcanic eruption from a vent somewhere in the south of Saint Lucia within the next few decades. The other view is that they are tectonic in nature. It is clearly desirable to ascertain the source mechanism of these local earthquakes in order to resolve this matter, for both scientific and hazard assessment purposes.

The main numerical uncertainty in the present hazard assessment arises from the lack of direct measurements of the way in which PGA and PGV depend on earthquake magnitude in the Eastern Caribbean region, and the rate at which these quantities are attenuated with distance from the causative fault plane. Here, we have used a conservative relationship, which helps to explain why our recommended figures are higher than the CUBiC figures.

A less important, but possibly overconservative assumption, which carries additional uncertainty into the assessment, concerns the relationship used to convert body wave magnitudes to surface wave magnitudes. For seismic hazard assessment in the Eastern Caribbean, this also is a proper subject for further analysis and quantification.

It should be noted that, under the logic-tree approach adopted here, and following Kulkarni et al. (1984), the intrinsic or *inherent* uncertainties in the earthquake process (including the dispersion on the attenuation relationship) affect the computation of the hazard level but not the confidence levels. Confidence bands reflect the *statistical* uncertainties on parameterized variables as represented by input probability distributions. The effect of this approach is to arrive at a probabilistic expected value of ground motion which will be higher than that given by the direct use of the median attenuation relationship alone (i.e. when sigma = 0), but the 90% confidence limit then falls well below the 84%ile value from a deterministic evaluation using worst case input values.

Interpretation of hazard confidence levels is rarely straightforward, due to the element of judgement implicit in any probabilistic assessment. In this study, the bands reflect parametric uncertainty for which there is some quantitative basis. Taking divergent expert judgements into account (e.g. with respect to attenuation models) would considerably broaden the confidence intervals, which would then reflect subjective differences in opinion, much more than objective data variability. For the present exercise, we were primarily concerned with providing a pragmatic assessment of the level of the PGA to use for an engineering design problem, based on available data. The sensitivity tests give the result a perspective against some other possible models and relationships. The introduction of a wide range of alternative seismological hypotheses into the logic-tree was outside the scope of the present work, but would be a very desirable research topic.

Finally, we recognise that other geological hazards, such as phenomena related to volcanic eruption, or secondary effects such as seiching in the impounded reservoir caused by long-period seismic waves from a distant great earthquake, have not been addressed in this study: comparable assessments, set in a similar probabilistic framework would be desirable.

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