

# A preliminary investigation of strong-motion data from the French Antilles

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## Abstract

Strong-motion networks have been operating in the Caribbean region since the 1970s, however, until the mid-1990s only a few analogue stations were operational and the quantity of data recorded was very low. Since the mid-1990s, digital accelerometric networks have been established on islands within the region. At present there are thought to be about 160 stations operating in this region with a handful on Cuba, 65 on the French Antilles (mainly Guadeloupe and Martinique), eight on Jamaica, 78 on Puerto Rico (plus others on adjacent islands) and four on Trinidad.

After briefly summarising the available data from the Caribbean islands, this article is mainly concerned with analysing the data that has been recorded by the networks operating on the French Antilles in terms of their distribution with respect to magnitude, source-to-site distance, focal depth and event type; site effects at certain stations; and also with respect to their predictability by ground motion estimation equations developed using data from different regions of the world. More than 300 good quality triaxial acceleration time-histories have been recorded on Guadeloupe and Martinique at a large number of stations from earthquakes with moment magnitudes larger than 4.8, however, most of the records are from considerable source-to-site distances. From the data available it is found that many of the commonly-used ground motion estimation equations for shallow crustal earthquakes poorly estimate the observed ground motions on the two islands; ground motions on Guadeloupe and Martinique have smaller amplitudes and are more variable than expected. This difference could be due to regional dependence of ground motions because of, for example, differing tectonics or crustal structures or because the ground motions so far recorded are, in general, from smaller earthquakes and greater distances than the range of applicability of the investigated equations.

## Introduction

The Caribbean region is an area of moderate to high seismic hazard [e.g. Bernard and Lambert, 1988, Tanner and Shedlock, 2004]. Feuillet et al. [2002] carried out a detailed study of the recent tectonics and related seismic and volcanic activity in the Lesser Antilles. In the northern part of the arc, a series of grabens dominate with normal faults oriented in the east-west direction, perpendicular to the trench. The leading edge of the arc near Guadeloupe appears to be the site of predominantly trench-parallel extension, which gives rise to prominent normal fault and fissure systems trending mostly east-west in the outer arc. They demonstrate that there is a hazard within the arc from seismicity located on shallow faults. The most active area is shown to be between Marie-Galante and Grande-Terre, and the length of these faults suggests that earthquake magnitudes could reach or exceed 6. This was demonstrated recently by the shallow crustal earthquake of 21st November 2004 that occurred near Guadeloupe ( $M_w$ 6.3) and was associated with macroseismic intensity up to EMS98 VIII on the islands of Les Saintes. The southern Caribbean arc south of Martinique shows a different structure. The current deformation of the upper plate south of  $15^\circ\text{N}$  is characterised by shortening and overthrusting, without signs of arc-parallel extension. Feuillet et al. [2002] interpreted such contrasting tectonic regimes in terms of variable slip partitioning. North of  $16^\circ\text{N}$  deformation along the arc is dominated by the interaction between the North American and Caribbean plates, which entails a trench parallel component of sinistral shear. Such slip vanishes south of Guadeloupe. The change in tectonic style and cessation of the parallel arc south of Dominica probably reflects the vanishing of sinistral slip partitioning.

In order to accurately assess the seismic risk in this region (and consequently derive appropriate and cost-effective strategies to mitigate this risk) it is important that the seismic hazard is well estimated. A central aspect of seismic hazard assessment is the estimation of strong ground motion expected during future earthquakes. This estimation is usually performed by assuming that future ground motions will be similar to those that have occurred during previous earthquakes. Therefore it is vital that any accelerometric data recorded within the region is carefully studied. The main purpose of this article is to summarize the accelerometric data that has been recorded by networks operating in the French Antilles (Guadeloupe and Martinique) and to present some preliminary analysis of this data in order to improve seismic hazard analysis within the region. In addition, brief descriptions of strong-motion networks operating on neighbouring Caribbean islands are given.

The geographical extent of networks in this region is quite limited because they are located on relatively small islands (there are thought to be no sea-bed strong-motion instruments operating in the area). In addition, the areas monitored by the different networks often overlap

therefore the same earthquakes can be recorded by stations of various networks. Hence it is important that all the data from this region are considered together.

## Strong-motion networks on Guadeloupe

There are currently three accelerometric networks operating on Guadeloupe. One of the networks is part of the Réseau Accélérométrique Permanent (RAP) of France and is operated by the Observatoire Volcanologique et Sismologique de Guadeloupe (Institut de Physique du Globe de Paris, IPGP), one is operated by the French Geological Survey (BRGM) and the third is operated by BRGM and IPGP under the direction of the Centre de Données Sismologiques des Antilles (CDSA).

In 1977, a small network of nine analogue (Kinematics SMA-1) stations was installed on Guadeloupe, however, only four usable accelerograms from one earthquake (16th March 1985,  $M_w = 6.4$  at epicentral distances of more than 100 km) were recorded by these stations [Bernard and Lambert, 1986, Martin, 1993]. From 1994, BRGM installed three SMACH SM-2 instruments in the Pointe-à-Pitre area to study site effects in this region. Samarcoq et al. [1998] provide a summary of the early years of this network and highlight the importance of site effects at a number of stations. This network was progressively extended between 1998 and 2001. At its greatest extent it comprised 16 instruments (eight SM-2s and eight Kinematics K2s) and it permitted the study of site effects at 24 different sites in the region (see Le Brun et al. [2001] and Lebrun et al. [2004] who study the data with respect to microzonation of the region). This network still operates but it has been reduced to five stations; the other instruments have been transferred to Martinique or elsewhere. In 2003 and 2004, two new stations were installed in the region of Basse Terre (a K2 at Saint Claude and a Geosig GSR-24 at Gourbeyre). Detailed descriptions of the BRGM network and analyses of some early data are provided by Samarcoq et al. [1999], Lebrun et al. [2000], Le Brun et al. [2001], Dominique et al. [2001] and Castro et al. [2003].

The Réseau Accélérométrique Permanent (RAP) is the national accelerometric network of France and is currently composed of about one hundred stations throughout the seismically-active parts of the country. The RAP was extended to the French Antilles in 2002. The network on Guadeloupe is managed by Observatoire Volcanologique et Sismologique de Guadeloupe (IPGP) and is composed of 12 stations with Kinematics Episensors. This network was developed between 2002 and 2004.

In the framework of a project to create a Centre of Seismological Data of the Antilles (CDSA), it is planned to install eight new stations in order to augment the RAP by using

identical instruments. By July 2005, five stations were operational, of which two are installed north of the subduction arc on Saint Martin and Saint Barthélemy. For details of this network see Bengoubou-Valerius et al. [2006].

In order to increase the quantity of data used for the comparisons with the ground motion estimation equations, data from a network of five stations with Güralp CMG40-T broadband seismometers (flat response between 0.016 and 100 Hz), which was set up in Bouillante on the west coast of Basse-Terre for a geothermal project [Jousset et al., 2004], are also used here even though this network was not installed for seismic hazard assessment purposes. For this study records from this network have been instrument corrected and then converted to acceleration from velocity through time-domain differentiation. Due to the sensitivity of the instruments, records are saturated when the ground motion velocity exceeds  $0.5 \text{ cm s}^{-1}$ , and hence cannot be used. However, smaller ground motions are successfully recorded by the network.

Table 1 summarizes the stations that have operated, or are still operating, on Guadeloupe and Figure 1 displays their locations. Most of the stations would be classified as ‘free-field’ using the commonly-used criteria summarised in Douglas [2003a] since they are mainly located within instrument shelters or the ground floors of small one- or two-storey buildings.

[Figure 1 about here.]

## Strong-motion networks on Martinique

Like Guadeloupe, three accelerometric networks are currently operating on Martinique. One of the networks is part of the RAP and is operated by Observatoire Volcanologique et Sismologique de la Martinique (IPGP), the Conseil Général de la Martinique (CGM) also operates a network and the third is run by BRGM.

In the mid-1980s a network comprising of two analogue stations was installed on Martinique but this did not produce any usable data [Martin, 1993]. As on Guadeloupe, in 1994, two digital instruments of type GeoSig SMACH SM-2 were installed by BRGM in order to update the analogue network. Martin [1993] describes the plan for this network. This network was complemented in November 2001 by instruments from the dense network at Pointe-à-Pitre on Guadeloupe [Dominique et al., 2001]. It is currently composed of six stations, of which five are at Fort-de-France and one is at La Trinité. The main research interest of this network is site effects.

The strong-motion network of the Conseil Général de la Martinique has been operating since 1995 (the first records were recorded on 11th January 1996). Currently the network consists of 29 stations (three of which are installed on upper stories of buildings). One station

was removed in 2003. A detailed description of this network and the data that it has recorded is provided by Douglas et al. [2005].

Observatoire Volcanologique et Sismologique de la Martinique (IPGP) operates eight stations with Kinematics Episensor on Martinique within the framework of the RAP. Table 1 summarizes the stations that have operated, or are still operating, on Martinique and Figure 1 displays their locations. Like the stations of Guadeloupe, most of the stations on Martinique are classified ‘free-field’ stations using commonly-used criteria.

## Networks on other Caribbean Islands

This section briefly outlines the accelerometric networks that are operating on other islands in the Caribbean area. Knudson [1975] provides a brief summary of the strong-motion instruments that were known to be operating in the region in December 1974.

### Trinidad

The Seismic Research Unit (SRU) of the University of West Indies (UWI) installed a six accelerograph network of Kinematics SMA-1s in Trinidad in 1974 [Knudson, 1975]. Since 2000, it operates a four station linear array at the north of Trinidad. The stations are equipped with Kinematics K2 instruments with a full-scale amplitude of 2 g. The Unit is currently conducting a preliminary analysis of the recorded data.

### Puerto Rico

In the early 1970s five SMA-1s were installed on Puerto Rico [Knudson, 1975]. Currently, the Puerto Rico Strong Motion Program (PRSM) (at the Civil Engineering Department, University of Puerto Rico) operates about 78 strong-motion instruments on Puerto Rico, with additional stations on the islands of Vieques, Culebra and Mona. Martinez-Cruzado [2003] provides a brief overview of the state of the network in 2003 but the network has recently grown significantly. PRSM plan to install additional sensors on the British Virgin Islands and in the Dominican Republic soon. All of the instruments are at least 18 bit (Etna and Episensors), most of which (about 75%) are dial-up instruments and ten have real-time connections. In addition, PRSM operate eight 19-bit K2 multi-channel structural arrays on critical infrastructure (high-rise buildings, bridges and dams). As yet no significant strong-motion records have been recorded.

## **Jamaica**

Since 1974 there has been an accelerometric network operating on Jamaica but only one earthquake (in 1978) produced a good-quality strong-motion record [Jackson, 1988]. Since roughly 2000, eight digital strong-motion instruments (seven Etnas and one K2) have been operating on Jamaica. The first significant earthquake recorded by this network was the 13th June 2005 ( $m_b5.1$ ) event, which was recorded at three stations [Stony Hill, Mona Campus (UWI) and Runaway Bay].

## **Other networks**

The USGS Albuquerque Seismological Laboratory has operated one strong-motion station (SJG) at San Juan on Puerto Rico since 1988 as part of the Global Seismographic Network of the Incorporated Research Institutions for Seismology (IRIS). The United States Geological Survey plan to install eight new broadband and strong-motion stations in this region as part of a tsunami warning system. There are also thought to be some strong-motion instruments operating on Cuba but little information is available. Knudson [1975] mentions a network of six SMA-1s that was installed on Barbados in 1974 by the SRU of the UWI but this is no longer operating.

## **Site effects at strong-motion stations**

It is now well known that site effects, due to local geology or topography, can strongly amplify the surface ground motion. One of the most dramatic examples of such a phenomenon is the Michoacán earthquake of 19th September 1985, which caused more than 10,000 casualties and large economic losses in Mexico City situated more than 350 km from the rupture zone. The damage was essentially due to the presence of a very soft superficial clay layer [Chávez-García and Bard, 1994]. Topographic effects can also cause large ground motions [e.g. Geli et al., 1988]. Due to their volcanic origin, the French Antilles are characterized by complex topography and geology with heterogeneous volcanic deposits. They are susceptible to site effects as shown by the variation in damage on Guadeloupe caused by the earthquakes of 16th May 1851 and 29th April 1897 [Bernard and Lambert, 1988]. Site effects assessment is thus a key aspect in the general understanding of earthquake ground motion and, in a more specific way, for the realisation of efficient earthquake risk mitigation plans. In this context, site effects on the French Antilles have been extensively studied during the past ten years by the realization of seismic microzonations of the districts of Jarry-Baie Mahault, Pointe-à-Pitre and Basse-Terre on Guadeloupe [Martin et al., 1994a, Monge, 1997, Monge et al., 1998, Mompelat et al., 2003]

and the districts of Schoelcher, Fort-de-France and Lamentin on Martinique [Martin et al., 1994b, Chassagneux et al., 1996].

Recent studies [Gagnepain-Beyneix et al., 1995, Castro et al., 2003] have demonstrated that in regions of complex geology and topography the use of local accelerometric networks can lead to a better estimation of site effects due to very local conditions and are a good complementary tool to classical microzonation [Lebrun et al., 2004]. In this framework, the strong-motion networks recently installed on Guadeloupe and Martinique are essential. For each station, it is important to know its site classification (Table 1) and the possible presence of site effects before analyzing the data. In this section, the method followed to detect the presence of site effects and to define the site class (rock or soil) for the stations of the Conseil Général de Martinique is described. The same method was used for the other networks.

Site effects evaluation is usually performed by computing spectral ratios using either earthquake records (spectral ratios relative to a reference station, or horizontal component to vertical component spectral ratios for the S-wave portion of the record) or ambient noise measurement. In this study, we use the so-called Nakamura's technique [Nakamura, 1989] based on the calculation of horizontal-to-vertical component spectral ratios (H/V) from ambient noise measurements. For a complete overview of the method, its assumptions and its limitations, the reader is referred to Lachet and Bard [1994] and Lermo and Chávez-García [1994]. It has been shown to be an efficient way to determine the dominant resonance frequency of a site [e.g. Lermo and Chávez-García, 1993, 1994, Bour et al., 1998]. However, it is important to keep in mind that H/V spectral ratio amplitudes do not provide a good estimation of the expected amplification factor [Lachet and Bard, 1994].

For each station, a series of noise measurements were undertaken using a triaxial 5 s Lennartz seismometer connected to a 24 bit GeoSig recorder. The resulting spectral ratios have been calculated following the procedure described in Bour et al. [1998]. For each site, the resonance frequency of the site was obtained and the shape of the resulting H/V spectral ratios gave important clues concerning the soil response (e.g. homogeneity of the site, importance of the site effect and possible topographic effects). The H/V results were combined with the available topographic, geological and geotechnical data to obtain the final interpretation given in Table 2. Site classification is divided into two main groups: rock and soil. For the soil class, a complementary characterisation (stiff/medium/soft/very soft) is also estimated, if possible. The following paragraphs summarise the main results, more information can be found in Douglas et al. [2005].

The results show that nine stations (CGVI, CGBP, CGSA, CGTR, CGSJ, CGPA, CGPB, CGAT and CGDB) located on weathered tuff, alluvium or colluvium, show large site amplifi-

cation (see Figure 2) although H/V spectral ratio amplitudes and frequencies for two of these stations (CGBP and CGVI) are lower than the rest. In addition, CGVA, CGLO and CGDT show a site effect (Figure 3) but the results are more uncertain. At CGVA and CGLO most of the measurements were conducted on concrete slabs adjacent to the buildings, which could have affected the results obtained. At station CGDT, which is located on a crest, probably from a massive basalt lava flow as indicated by the geological map of the region, the geology and the H/V spectral ratio are contradictory. Since the noise measurements were performed close together, it would be necessary to undertake additional measurements before final interpretation.

[Figure 2 about here.]

[Figure 3 about here.]

Eight stations are clearly located on rock (CGOB, CGDD, CGAB, CGCO, CGCA, CGDI, CGRA and CGAS). Station CGCA shows a low noise level and a very clear and flat H/V spectral ratio, hence it could be considered as a good reference station in future studies (Figure 4). The H/V results for CGAS show a small peak at 11.5 Hz due to the presence of a very thin layer of alluvium. However, despite this high-frequency site effect it has been considered as a rock station since massive andesites underlie this alluvium layer. At two rock stations (CGRA and CGOB), H/V ratios present a high mean level despite a clear geology characterised by firm soils (Figure 4). This could be due to topographic effects since these stations are located on hill crests. Topographic effects are also suspected for two other stations (CGRP and CGDT) that are also located on top of hills.

[Figure 4 about here.]

Finally, the results of the last five stations (CGMB, CGFR, CGRP, CGLR and CGCP, which is colocated with CGLR) could not be interpreted. CGMB (located at the base of a dam) is characterised by heterogeneous spectral ratios, probably due to the heterogeneity of the superficial geological formations. CGFR, CGCP and CGLR seem to be affected by weak site effects. This does not agree with the known geology since CGFR is located on alluvium and the other two stations are located on pumice and alluviums. The noise measurements were made very close to the buildings and therefore cannot be considered as free-field measurements. Hence, the results are not certain and must be confirmed by an additional study. Results for CGRP, located on conglomerates at the top of a hill, show small amplification of the horizontal ground motion between 1 and 7 Hz, which cannot be explained by the local geology. Again,

it could correspond to a topographic effect but additional study is required before concluding this.

This study shows that sites on Martinique, and in a more general way, the volcanic Antilles, display large site-specific amplifications mainly due to superficial geology (site classifications from very soft to medium soil). The influence of topography seems to be important but additional complementary studies are required to fully understand the amplifications at some stations situated on hill crests.

## Summary of recorded data

Table 3 summarises the largest earthquakes that have been recorded by the RAP, BRGM, CDSA and CGM networks on Guadeloupe and Martinique at ground response stations (records from the borehole station on Guadeloupe and from upper storeys of buildings have been excluded). This table also includes a classification of the earthquakes with respect to type (crustal, interface or intraslab). Interface earthquakes are produced at the interface of the subducting slab and generally have a reverse mechanism and intraslab earthquakes occur at depth within the subducting slab and generally have a normal mechanism [e.g. Atkinson and Boore, 2003]. Figure 5 displays the locations and focal mechanisms of these earthquakes.

In total, there are 336 high-quality records available from 24 earthquakes and 74 different stations. Figure 6 displays the distribution of data from these largest earthquakes from the strong-motion networks operating on Guadeloupe and Martinique plus the seven usable records from the Bouillante broadband network. This figure shows that all of the available data are from small and moderate-sized earthquakes ( $M_w \leq 6.6$ ) and the majority was recorded at large distances ( $d_h > 100$  km). Consequently the vast majority of the ground motions are of low amplitudes, however, the signal-to-noise ratios for the vast majority of these records is high. For each acceleration time-history, the signal-to-noise ratio was calculated using the pre-event portion of the record as an estimate of the noise and the rest of the record as an estimate of the signal. Most of the records are from interface subduction earthquakes (91 from eleven earthquakes) and crustal earthquakes (189 from ten earthquakes of which six occurred during the Les Saintes 2004–2005 sequence) with only 56 records from three intraslab earthquakes.

The distance between Guadeloupe and Martinique (about 100 km) and the relatively small size of the islands means that the distribution of data from a given earthquake with respect to distance always shows two well-separated tight distributions of records meaning that analysis of the decay of ground motions with distance is difficult due to a lack of constraint.

[Table 1 about here.]

[Figure 5 about here.]

[Figure 6 about here.]

## Comparison of recorded data to existing ground motion estimation equations

Equations for the estimation of the strong ground motion [e.g. Douglas, 2003a] are an important component of both probabilistic and deterministic seismic hazard assessment. At present, there are no published peer-reviewed equations for the estimation of strong ground motions based on data recorded in the Antilles [Douglas, 2004] and therefore seismic hazard assessments for this region [e.g. Tanner and Shedlock, 2004] are obliged to use equations based on data from other regions of the world. Although Motazedian and Atkinson [2005] have recently developed a ground-motion model through the stochastic simulation technique [e.g. Boore, 2003] for the prediction of motions in Puerto Rico based on data from seismological networks. In order that the seismic hazard in the Caribbean is accurately estimated it is important that the applicability of the equations developed from data from other parts of the world is assessed.

It is traditional to assess the applicability of ground motion estimation equations derived using data from one area to other regions through graphs comparing the estimated and predicted ground motions or through the use of residual plots [e.g. Boore, 2001]. Scherbaum et al. [2004] have recently developed a more quantitative method for ranking the applicability of existing ground motion estimation equations based on the values of a number of statistical quantities. They test their method on data recorded during an earthquake in eastern France (the St Dié earthquake on 22nd February 2003,  $M_w$ 5.0) and use only data from stations sited on rock (13 stations in total). In this article, the method is applied to data from both rock and soil sites from the earthquakes listed in Table 3.

### Shallow crustal earthquakes

Observed ground motions from the selected shallow crustal earthquakes (see Table 3) have been compared with ground motions estimated by these nine sets of recent well-constrained equations: Abrahamson and Silva [1997], Ambraseys et al. [2005], Berge-Thierry et al. [2003], Boore et al. [1997], Campbell and Bozorgnia [2003], Motazedian and Atkinson [2005]<sup>1</sup>, Lussou et al. [2001], Sadigh et al. [1997] and Spudich et al. [1999]. In total 189 accelerograms have been

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<sup>1</sup>This model was derived from a combination of event types, both crustal and subduction, but was shown by its authors to closely match predictions derived from crustal data from other regions hence we compare it here to data from shallow crustal earthquakes.

used for this comparison. All of these equations, except Berge-Thierry et al. [2003] and Lussou et al. [2001], use  $M_w$  therefore no magnitude scale conversion is required. For the model of Berge-Thierry et al. [2003]  $M_w$  has been converted to  $M_s$  by using Equation 5.3 of Ambraseys and Free [1997].  $M_w$  has been converted to  $M_{JMA}$  for use with the model of Lussou et al. [2001] by using Equation 24 of Fukushima [1996]. Ambraseys et al. [2005], Boore et al. [1997] and Spudich et al. [1999] use distance to the surface projection of the rupture ( $d_f$ ), Abrahamson and Silva [1997], Motazedian and Atkinson [2005] and Sadigh et al. [1997] use distance to the rupture ( $d_r$ ), Campbell and Bozorgnia [2003] use distance to the seismogenic zone ( $d_s$ ) and Berge-Thierry et al. [2003] and Lussou et al. [2001] use hypocentral distance ( $d_h$ ). The locations of the faults that ruptured during the chosen earthquakes have not been precisely determined therefore epicentral distance ( $d_e$ ) is used in place of  $d_f$  and  $d_h$  is used in place of  $d_r$  and  $d_s$ , because there are few records from close distances these assumptions will not have an important effect. The ground-motion models are evaluated for the same mechanism as the earthquakes; for normal faulting earthquakes all the equations except Ambraseys et al. [2005], which have a coefficient for normal earthquakes, are evaluated for strike-slip faulting. Berge-Thierry et al. [2003], Lussou et al. [2001] and Motazedian and Atkinson [2005] do not include rupture mechanism as an explanatory variable. All equations predict the geometric mean of the horizontal motions except those of Ambraseys et al. [2005], which predict the larger horizontal component, and those of Berge-Thierry et al. [2003] and Lussou et al. [2001], who used both horizontal components. Motazedian and Atkinson [2005] develop their relations for NEHRP C sites ( $360 \leq V_{s,30} < 760 \text{ ms}^{-1}$ , where  $V_{s,30}$  is the average shear-wave velocity to 30 m) therefore the relation is only compared to data from such sites. All stations have been classified into the site classes used within the ground-motion models, e.g. soft soil, stiff soil and rock for the model of Ambraseys et al. [2005]. The goodness-of-fit measures are computed using PGA and spectral accelerations at all periods between 0.1 and 2 s for which ground-motion estimates are given by the selected models, in accordance with the approach followed by Scherbaum et al. [2004].

The normalized residuals, i.e.  $\epsilon_{i,j} = (\log y_i - \log y'_{i,j}) / \sigma_{i,j}$  where  $y_i$  is the observed  $i$ th ground motion value,  $y'_{i,j}$  is the predicted  $i$ th ground motion from the  $j$ th model and  $\sigma_{i,j}$  is the predicted standard deviation of the  $i$ th ground motion from the  $j$ th model, of all the observed ground motions are computed with respect to each of the selected ground motion models. Following the method of ranking suggested by Scherbaum et al. [2004] the following goodness-of-fit measures are computed using these sets of normalized residuals: mean (MEANNR), median (MEDNR), standard deviation (STDNR) and median LH (MEDLH), where the LH of a value  $z_0$  is defined by:  $\text{LH}(|z_0|) = \text{Erf}(|z_0|/\sqrt{2}, \text{inf})$  where  $\text{Erf}(z)$  is the error function  $\frac{2}{\sqrt{\pi}} \int_0^z \exp(-t^2) dt$ . The

results for the nine selected ground motion models are given in Table 4. The same ranking criteria as used by Scherbaum et al. [2004] have been used here, i.e.: for a model to be ranked in the lowest accepted capability class (C) requires a MEDLH of at least 0.2, the absolute value of MEANNR and MEDNR and their standard deviations to be smaller than 0.75, and STDNR is required to be smaller than 1.5; for a model to be ranked in the intermediate capability class (B) requires a MEDLH value of at least 0.3, the absolute value of MEANNR and MEDNR and their standard deviations to be smaller than 0.5, and the STDNR to be smaller than 1.25 and; for a model to be ranked in the highest capability class (A), requires a MEDLH value of at least 0.4, the absolute value of both MEANNR and MEDNR and their standard deviations not to deviate more than 0.25 from zero and, in addition, the STDNR is required to be smaller than 1.125. Ground-motion models that do not meet these criteria are ranked in the lowest capability class (D).

Tables 4 shows that none of the chosen ground-motion models closely predicts the observed ground motions from shallow crustal earthquakes and all are ranked in class D using the criteria of Scherbaum et al. [2004], except the model of Ambraseys et al. [2005] which is ranked in class C. All models, except that of Lussou et al. [2001], overestimate the shaking (shown by negative mean and median normalized residuals) and in addition the observed grounds motions show larger variability than modelled (shown by values of the standard deviation of the normalized residuals being larger than unity). The median ground motions are well estimated by the model of Lussou et al. [2001] (shown by mean and median normalized residuals close to zero) but the observed motions are more variable than the model predicts. The model of Motazedian and Atkinson [2005] is the first that uses data from the Caribbean region (specifically Puerto Rico), however, it does not estimate well the observed ground motions on Guadeloupe and Martinique. This could be because the geology and tectonics of Puerto Rico are not comparable to those of the French Antilles, in particular Puerto Rico is not a volcanic island.

One reason that could explain these findings is that the data used for the validation procedure mainly comes from smaller events and from greater distances than the data used to derive the selected models. Ground motions from small and moderate events display faster decay with distance, higher dependence on magnitude and greater variability than ground motions from larger earthquakes [e.g. Douglas, 2003b]. In order to test this possible reason for the observed poor match between observations and predictions, a subset of data (45 records) was selected from earthquakes with  $M_w > 5.5$  and distances less than 100 km (i.e. data within the range of validity of most of the ground-motion models considered) and the analysis repeated. The results obtained show generally smaller absolute values (but still generally negative) of the median and mean normalized residuals, showing that the average ground motions are better

predicted, but the standard deviations of the normalized residuals remain high.

This preliminary analysis suggests that ground motions from earthquakes in the Antilles seem to be weaker than those in California and seismically active parts of Europe and the Middle East. One possible reason for lower average ground motions is that most of the data used here comes from normal faulting earthquakes, which generally show slightly weaker ground motions than those from strike-slip and reverse earthquakes [e.g. Bommer et al., 2003] and this difference is not explicitly modelled by any of the chosen ground-motion models except for Ambraseys et al. [2005]. However, this is unlikely to be a significant factor since the effect of style-of-faulting is generally quite small [Bommer et al., 2003].

Other possible reasons for the lower ground motions from earthquakes in the Antilles compared with those in other regions are differences in average focal depth between the regions, lower stress drops and faster attenuation. Castro et al. [2003] estimate that  $Q = 64.5f^{0.4}$  in the Antilles region, which they find is lower (i.e. attenuation is faster) than the  $Q$  obtained for other regions close to subduction zones (Oaxaca and Guerrero, Mexico). Atkinson and Silva [2000] find that  $Q = 180f^{0.45}$  in California, which again is higher (i.e. attenuation is slower) than in the Antilles. Castro et al. [2003] suggest that the fast attenuation in the Antilles is due to complex source-station paths that sample low-velocity and high-attenuation zones in the crust and mantle wedge associated with arc magmatic systems.

[Table 2 about here.]

Figure 7 shows the normalized residuals for PGA for the equation of Ambraseys et al. [2005] with respect to epicentral distance and  $M_w$ . It shows that the model of Ambraseys et al. [2005] predicts the median PGA reasonably well at all distances from 20 to 500 km (note that the model of Ambraseys et al. [2005] was derived using data from distances less than or equal to 100 km) and for all magnitudes greater than about 5.5. PGA values from earthquakes with  $M_w < 5.5$  are on average overestimated by the equation of Ambraseys et al. [2005]. For the rest of the article the model of Ambraseys et al. [2005] is used since it seems to be the most appropriate available model for ground-motion estimation for shallow crustal earthquakes in this region.

[Figure 7 about here.]

## Ground-motion variability due to source effects

An interesting example of the variability in ground motions is the differences between the accelerograms recorded during the Les Saintes aftershocks at 13:37 and 18:53 on 21st November

2004, which had similar magnitudes (5.3 and 5.4 respectively) and occurred at similar locations. Ground motions recorded during the event at 13:37 are, generally, much smaller than those observed during the 18:53 aftershock. This cannot be explained by repeatable site effects, which should be similar at the same stations during both earthquakes [ground-motion amplitudes are too small ( $< 0.15$  g) for nonlinear soil behaviour, which could cause inter-event site amplification variation, to be an issue]. In comparison with the ground-motion model of Ambraseys et al. [2005] the motions from the 13:37 aftershock are smaller than expected while those from the 18:53 event are larger than expected.

Figure 8(a) shows the ratios between the spectral accelerations recorded during the 13:37 event to those recorded during the 18:53 event for the ten common stations. To minimize the minor differences in distance and magnitude between records from the two events, the equations of Ambraseys et al. [2005] were used to adjust the observed spectral accelerations to a common distance and magnitude (the maximum correction factor is roughly 1.5). For the three closest stations (Belfond Saint-Claude, A rodrome Baillif and Ecole Pigeon) the difference between the earthquakes is a factor of about ten at all examined periods. As the source-to-site distance increases the difference between the ground motions in the two earthquakes decreases; this is expected since source effects are reduced in importance as waves propagate due to scattering and attenuation.

The eight common stations that recorded much higher ground motions during the 18:53 aftershock than during the 13:37 event are all located on Guadeloupe (to the north of the epicentre) whereas the two common stations on Martinique (to the south of the epicentre) recorded similar or lower ground motions during the 18:53 event. Therefore one possible explanation for the differences in ground motions in the two earthquakes is directivity [e.g. Somerville, 2003], i.e. the fault ruptured away from Guadeloupe (and towards Martinique) during the 13:37 event (explaining the lower than expected motions) and towards Guadeloupe (and away from Martinique) during the 18:53 earthquake (the published focal mechanisms of these two events show strikes roughly aligned in the directions of the two islands). Directivity effects, however, are believed to only affect a narrow band (roughly  $T_{\text{dir}}/1.5 < T < 1.5T_{\text{dir}}$ , where  $T_{\text{dir}}$  is a magnitude-dependent pulse period) of intermediate- and long-period response spectral ordinates for stations close to moderate and large earthquakes ( $M_w > 6$ ) [Somerville, 2003] rather than the whole period range at all distances from relatively small earthquakes. Therefore it is more probable that other source effects [e.g. differing stress drops, the slightly different focal mechanisms or directionality due to focussing of waves along the path aligned with the rupture propagation direction (J. J. Bommer, written communication, 2005)] are the cause of the observed differences in ground motions. It is possible that the  $M_w$  of the 13:37 event

is overestimated or the  $M_w$  of the 18:53 event is underestimated but this is thought unlikely since the  $M_w$  values given by Harvard CMT for these events are consistent with reported  $M_s$  and  $m_b$  values.

For comparison the same type of analysis was conducted for two other Les Saintes aftershocks with similar magnitudes: those of 27th November 2004 at 23:44 and 2nd December 2004 at 14:47 with  $M_w$  4.9 and 5.0 respectively. Again, differences in ground motions due to slightly differing magnitudes and distances were corrected using the ground-motion model of Ambraseys et al. [2005]. The results of this analysis are shown in Figure 8(b). This figure shows that, unlike for the aftershocks discussed above, the ground motions during these two events were generally similar (most of the spectral ratios vary between 0.5 and 2), suggesting that the two sources were also comparable.

[Figure 8 about here.]

## Subduction earthquakes

Recorded ground motions from the selected subduction earthquakes (see Table 3) have been compared with ground motions estimated by these three sets of equations: Atkinson and Boore [2003], Crouse [1991] and Youngs et al. [1997]. Atkinson and Boore [2003] have combined the datasets of Crouse [1991] and Youngs et al. [1997] and also have added much additional data therefore the equations of Atkinson and Boore [2003] could be thought to have superseded the equations of Crouse [1991] and Youngs et al. [1997]. The equations of Crouse [1991] and Youngs et al. [1997] have been included here since they have often been used for seismic hazard assessments of the Antilles and therefore it is important to check their validity. All three equations use  $M_w$ . Hypocentral distance has been used as the distance metric for all comparisons. Both horizontal components have been used by Crouse [1991], the geometric mean of the two horizontal components have been used by Youngs et al. [1997] and Atkinson and Boore [2003]. Crouse [1991] only uses data from stiff soil sites therefore comparison has been made here only for data from such sites. The equations of Atkinson and Boore [2003] and Youngs et al. [1997] model differences between ground motions from interface and intraslab earthquakes whereas the model of Crouse [1991] does not.

The same analysis procedure was followed for the ground motions from the subduction earthquakes as for the data of the shallow crustal earthquakes. The results for the three selected models are given in Table 5. The analysis shows that the model of Youngs et al. [1997] is quite successful at predicting the ground motions on Guadeloupe and Martinique although it slightly overestimates the shaking. Surprisingly, the recent model developed by Atkinson and Boore [2003] through sophisticated analysis of a much larger dataset, including all the data

of Crouse [1991] and Youngs et al. [1997] plus additional records, greatly underpredicts the observed ground motions and also the variability of motions. The reason for this difference is thought to be that Atkinson and Boore [2003] mainly concentrated on developing a ground-motion model for predicting the response spectra from earthquakes much larger than those in the dataset used here. In addition, Atkinson and Boore [2003] excluded data from large distances partly to avoid bias due to non-triggering instruments, whereas Crouse [1991] and Youngs et al. [1997] did not, which will lead to lower predicted motions at great distances than when such a truncation is not applied [e.g. Joyner and Boore, 1981].

[Table 3 about here.]

Figure 9 shows the normalized residuals for PGA for the equation of Youngs et al. [1997] with respect to hypocentral distance and  $M_w$  for the two types of subduction earthquake (intraslab and interface). It shows that the model of Youngs et al. [1997] slightly overpredicts the median PGA at all distances from 50 to 300 km and for all magnitudes from 4.8 to 5.8 for both types of event.

[Figure 9 about here.]

### **High-amplitude ground motions recorded at the station TDBA**

Since its installation in November 2004, the station TDBA on Guadeloupe has regularly experienced much higher than expected ground motions given the magnitudes and distances of the causative earthquakes. The station is located in the hamlet of Petites Anses, on Les Saintes, within the fire station, which is a small one-storey building. This area was the most affected by the Les Saintes earthquake of 21st November 2004.

On 12th December 2004, an earthquake of  $M_L$ 2.9 that occurred at a depth of 3 km at an epicentral distance of 3 km caused a horizontal PGA of nearly 0.3 g at TDBA. This large PGA is similar to the large PGA values from small earthquakes reported by Hanks and Johnson [1976] and can be attributed to the short source-to-site distance.

Another example of particular high ground motions recorded at TDBA is the record from the 14th February 2005  $M_w$ 5.8 normal-faulting earthquake that occurred at a focal depth of 12 km at an epicentral distance of 8 km (hypocentral distance of 14 km). This strong-motion record has been processed with a high-pass filter with a cut-off frequency of 0.125 Hz, which was chosen by an examination of the signal-to-noise Fourier spectral ratio. The horizontal PGA of this record is about 0.7 g, which is over four times that estimated by the ground-motion model of Ambraseys et al. [2005] for that distance from such a sized normal-faulting earthquake and it is thought to be the highest acceleration ever recorded in the Antilles (Figure 10). The elastic

response spectrum of this record is also up to a factor of seven times larger than the spectrum estimated by the model of Ambraseys et al. [2005], see Figure 11. The record is similarly underestimated by other ground-motion models for shallow crustal earthquakes. Table 6 lists a number of strong-motion parameters of this record and compares them with predicted values of recent ground-motion models for a rock site. This comparison shows that all the amplitude measures are much higher than expected whereas the relative significant duration is almost identical to that expected, thereby showing importance of the point raised by Bommer et al. [2004] that extreme records with respect to one characteristic (for this record, amplitude) are unlikely to be extreme in another respect (here, duration).

[Figure 10 about here.]

[Figure 11 about here.]

[Table 4 about here.]

Possible reasons for the large amplitude ground motions include directivity and site effects. Site effects are unlikely to be responsible since H/V spectral ratio measurements conducted by CETE Méditerranée for this station show low-frequency (2 Hz) amplification (E. Bertrand, personal communication, 2005) whereas as shown above high-frequency ground motions from this station are also much higher than expected. In fact, the record was significantly higher than expected over the entire period range of engineering interest. The high-amplitude motions recorded at this station are likely due to proximity to the causative fault, which is not fully accounted for here in the comparison with ground-motion models because of the use of point-source distance measures, and possibly rupture towards the site during the 14th February 2005 earthquake (directivity effects). Directivity effects could perhaps explain the large long-period spectral ordinates of the EW component (probably roughly the fault-perpendicular component) but not on the NS component. At present the causative fault of this earthquake has not been identified nor has any strong-motion modelling been attempted therefore it is not currently possible to confirm this suggestion.

## Conclusions

This article has summarised current strong-motion observation capabilities within the Caribbean and in particular it has summarised and presented a preliminary analysis of the available data from the French Antilles. The strong-motion networks on the French Antilles have been greatly developed in the last decade but the distribution of stations in the eastern Caribbean is highly

inhomogeneous. This inhomogeneity is a particular concern because of the complex geological and tectonic context in this region with transform zones in the north (close to Puerto Rico) and the south (close to Venezuela) and a long subduction arc in the east.

In total, 336 records from 24 moderate earthquakes ( $4.8 \leq M_w \leq 6.6$ ) that occurred in the past ten years are exploitable from the networks on Guadeloupe and Martinique (from 74 different stations). However, apart from those records from the Les Saintes sequence of late 2004 and early 2005, most of the available records are from hypocentral distances greater than 100 km. There are only 56 records from three intraslab earthquakes.

It is possible that ground motion estimation equations developed for other regions (California, Europe and the Middle East, Japan and Puerto Rico) may not be applicable for the estimation of ground motions for sites on the French Antilles. However, for shallow crustal earthquakes, the ground-motion model of Ambraseys et al. [2005] was shown to be the most appropriate of those tested and for subduction earthquakes, predictions from the model of Youngs et al. [1997] gave the closest match to observed ground motions. The ground-motion model of Motazedian and Atkinson [2005], which was developed for Puerto Rico, does not provide good estimates of ground motions on the French Antilles.

Because the strong-motion networks in this region have only been operating for about a decade there is insufficient data of engineering significance to develop region-specific empirical ground motion estimation equations. Therefore one possible way of improving the estimation of ground motion in the French Antilles is to use the hybrid empirical ground motion estimation method of Campbell [2003, 2004], which has been developed further by Scherbaum et al. [2005] and applied by Douglas et al. [2006] to southern Spain and southern Norway. The results of Castro et al. [2003] on site effects and crustal attenuation would be useful for this purpose.

Data from the Les Saintes sequence shows that source effects can be at least as important as site effects in explaining the variability in ground motions. Two aftershocks with similar magnitudes, focal mechanisms and locations caused ground motions at some stations on Guadeloupe that were more than ten times higher in one earthquake than in the other. The cause of this variability should be investigated further. In addition, some near-field records from this sequence are greatly underestimated by ground-motion models over a wide frequency band, probably due to the proximity to the source and, possibly, directivity.

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Name
Pointe-à-Pitre — Berg
Pointe-à-Pitre — Gen
Baie Mahault Jarry —
Saint François — Obs
Anse-Bertrand — DD
Sainte-Rose — Genda
Basse-Terre — Fort S
Route des Mamelles —
Marie-Galante — Obs
Houëlmont Gourbeyre
Saint Claude — Belfo
Gosier — Saint Felix
Gosier — Ecole Suzan
Gosier — Eucher
Jarry Baie Mahault —
Jarry Baie Mahault —
Jarry Baie Mahault —
Baie Mahault — Cent
Baie Mahault — L. C
Baie Mahault — Simé
Baie Mahault — Priso
Pointe-à-Pitre — Inst
Pointe-à-Pitre — AD
Pointe-à-Pitre — Sous
Pointe-à-Pitre — Ecol
Pointe-à-Pitre — CCI
Pointe-à-Pitre — Stac
Pointe-à-Pitre — Ecol
Abymes — Antea
Abymes — Collège Ra

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Name
Abymes — Glide Fond
Abymes — Glide Surf
Abymes — Aeroport 1
Abymes — Perrin
Terre de Haut — Mai
Terre de Haut — Fort
Belle Eau — Stade C
Sainte Anne — Lycée
Saint Barthélemy — C
Saint Martin — Mari
Terre de Bas — Petit
Marie Galante — Gra
Basse Terre — Prefec
Baillif — Aerodrome
Bouillante — Ecole P
Pointe-à-Pitre — Inst
Jarry Baie Mahault —
Saint François
Météo Le Moule — R
Sainte Rose — Lycée
Morne à l'Eau
Bertrand — Anse
Fort-de-France — BR
Fort-de-France — Eco
Fort-de-France — Pre
Fort-de-France — The
Fort-de-France — Exc
Fort-de-France — Eco
Trinité — Mairie
Caravelle — Presqu'il
Sainte Anne — Gare
Diamant — Collège d
Diamant — Radar M
Collège de Rivière Pil
Vauclin — Collège du
Ducos — Barrage de l
Ducos — Barrage de l

Name
Fort-de-France — Cer
Fort-de-France — Arc
Fort-de-France — Arc
Fort-de-France — Col
Fort-de-France — Col
Fort-de-France — Col
Fort-de-France — Imr
Lamentin — Collège o
Lamentin — Collège o
Lamentin — Collège I
François — Collège L
Saint Joseph — Collè
Absalon — Centre TH
Gros Morne — Réserv
Carbet — Piscine du
Fond Saint Denis — C
Trinité — Collège Ros
Saint Pierre — Local
Saint Pierre — Centre
Lorrain — Collège du
Lorrain — Station po
Basse Pointe — Collè
Collège des Trois-Ilets
Presbytère du Marin
Diamant — Morne Bl
Lamentin — Aéroport
Lamentin — Zone aér
Fort-de-France — For
Trinité — Centre Hos
Saint Pierre — Camp
Sainte Marie — Anse
Massieux
Muscade
Baltus
BO4
Morne Lézard

Table 2: Site descriptions for stations of the strong-motion network of Conseil Général de Martinique. For each station, a brief description of the geology [Westerkamp and Andreieff, 1989, BRGM, 2005], geophysical data (if available), the presence or not of soil effects, the resonance frequency, whether or not topographic effects are suspected, and the soil classification are given.

Station	Surface geology	Geophysical data	Soil effect?	Res. freq. (Hz)	Topo. effect?	Site class
CGBP	Weathered tuff (1.5 m deep)		Y	4.9		Med. soil
CGRA	Andesites				Y	Rock
CGMB	Weathered tuffites	$V_p = 300\text{--}700\text{ ms}^{-1}$ (clay), $V_p = 600\text{--}2500\text{ ms}^{-1}$ (weathered tuff), $V_p = 2500\text{ ms}^{-1}$ (sound tuff)				?
CGOB	Massive andesites				Y	Rock
CGDD	Conglomerates (7 m deep) on weathered tuffite					Rock
CGAS	Very thin layer of alluvium (1 m deep) on massive andesites		Y	11.5		Rock
CGAB	Thin layer of pumices (1–3 m deep) on altered andesites					Rock
CGCO	Conglomerates					Rock
CGAT	Modern alluvia (clays and sands, 10 m deep) on tuffites	$V_s = 150\text{--}200\text{ ms}^{-1}$	Y	2.2–2.7		Soft soil
CGDB	Colluvia (clays, 8–10 m) on clayey tuff (10 m thick) on sound tuff		Y	1.5–3.5		Soft soil
CGFR	Colluvia (soft clay, 1–3 m deep) on weathered tuff until 22 m	$V_s = 50\text{--}150\text{ ms}^{-1}$				?
CGDT	Clays (10 m deep) on massive basalt		Y	1.5–2.2	Y	Soft soil

*continued on next page*

Table 2: *continued*

Station	Surface geology	Geophysical data	Soil effect?	Res. freq. (Hz)	Topo. effect?	Site class
CGPB	Compact clay (3 m deep) on weathered tuff until 20 m		Y	2.5		Soft soil
CGPA	Clays (4 m deep) on breccias. Weathered conglomerate at 12 m		Y	1.9		Soft soil
CGVI	Sands and sandy clays		Y	0.9–2.1		Med. soil
CGLO	Clays on massive andesites		Y	4–6		Med./stiff soil
CGRP	Conglomerates				Y	?
CGSJ	Succession of compact clays and clayey tuffs		Y	2.2		Med. soil
CGTR	Soft sandy clays (15 m deep) on very weathered andesites		Y	1.6		V. soft soil
CGSA	Colluvia	$V_s = 150\text{--}400\text{ ms}^{-1}$	Y	3		V. soft soil
CGCA	Conglomerates					Rock
CGDI	Colluvia on pyroclastic breccias					Rock
CGVA	Modern alluvia (3 m deep) on soft rocky tuff	$V_s = 150\text{--}300\text{ ms}^{-1}$	Y	3–4		Soft soil
CGLR & CGCP	Pumices and modern alluvia	$V_s = 150\text{--}400\text{ ms}^{-1}$	?	1.5–1.7?		?

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Table 3: Earthquakes with  $M_w$  values from Harvard CMT recorded by the RAP, BRGM, CDSA and CGM strong-motion networks operating on Guadeloupe and Martinique.

Date	Time (UTC)	$M_w$	Depth (km)	Type and mechanism	Number of records	$d_h$ range (km)	PGA range ( $\text{ms}^{-2}$ )
24/09/1996	11:42	5.6	139	Intraslab	4	157–182	0.05–0.08
25/06/1998	21:03	5.6	30	Interface	4	149–154	0.02–0.03
08/06/1999	12:04	5.8	31	Interface	19	73–187	0.01–1.28
11/07/1999	11:51	5.2	31	Crustal (strike-slip)	7	188–193	0.02–0.04
28/08/1999	04:27	5.4	30	Interface	16	89–101	0.03–0.13
20/12/1999	10:43	5.3	29	Interface	15	112–120	0.03–0.16
16/02/2000	07:03	5.3	0	Interface	2	116–117	0.004–0.004
23/02/2000	19:20	5.4	34	Interface	3	153–156	0.01–0.01
27/10/2000	19:02	5.6	30	Interface	9	144–155	0.02–0.10
30/10/2000	03:07	5.8	33	Interface	9	129–140	0.03–0.19
05/01/2001	08:06	5.7	20	Crustal (strike-slip)	12	73–157	0.02–0.42
05/04/2001	13:54	5.1	47	Intraslab	17	89–168	0.02–0.20
25/09/2001	23:16	5.4	27	Interface	6	90–258	0.02–0.42
07/12/2001	15:59	5.1	22	Interface	3	103–251	0.01–0.08
14/05/2003	06:03	6.6	48	Crustal (strike-slip)	35	363–497	0.02–0.34
30/06/2003	00:07	5.7	30	Crustal (odd)	12	227–426	0.002–0.15
01/03/2004	06:12	4.8	43	Intraslab	35	67–180	0.01–0.88
30/03/2004	16:23	4.9	70	Interface	5	158–347	0.002–0.02
21/11/2004	11:41	6.3	13	Crustal (normal)	37	27–158	0.02–2.09
21/11/2004	13:37	5.3	19	Crustal (normal)	17	36–148	0.02–0.16
21/11/2004	18:53	5.4	13	Crustal (normal)	13	27–154	0.01–1.33
27/11/2004	23:44	4.9	13	Crustal (normal)	23	26–145	0.004–0.17
02/12/2004	14:47	5.0	14	Crustal (normal)	16	35–120	0.002–0.08
14/02/2005	18:06	5.8	12	Crustal (normal)	17	14–144	0.09–6.94

$M_w$  estimates have been taken from the Harvard CMT catalogue and times and locations from the IGP catalogues except for those earthquakes not in this catalogue, for which the ISC catalogue has been used. The mechanism classification scheme of Frohlich and Apperson [1992] based on the plunges of the moment tensor eigenvectors (T, B and P axes) has been used. In this classification scheme earthquakes with T-axis plunges greater than  $50^\circ$  are classified as thrust, earthquakes with B-axis plunges greater than  $60^\circ$  are classified as strike-slip, earthquakes with P-axis plunges greater than  $60^\circ$  are classified as normal and all other earthquakes are classified as odd (roughly corresponding to earthquakes classified as oblique by other classification procedures). Only data from ground response instruments are listed here. One record refers to three mutually perpendicular components.

Table 4: Ranking of different ground-motion estimation equations for modelling the entire Antilles shallow crustal earthquake ground motion dataset. MEDLH is the median LH value (see text), MEDNR is the median normalized residual, MEANNR is the mean normalized residual and STDNR is the standard deviation of the normalized residuals.

Model	Rank	MEDLH	MEDNR	MEANNR	STDNR
Abrahamson and Silva [1997]	D	0.037	-1.484	-1.471	1.610
Ambraseys et al. [2005]	C	0.217	-0.286	-0.341	1.304
Berge-Thierry et al. [2003]	D	0.098	-0.815	-0.877	1.546
Boore et al. [1997]	D	0.001	-2.323	-2.434	2.210
Campbell and Bozorgnia [2003]	D	0.004	-1.795	-1.868	2.341
Motazedian and Atkinson [2005]	D	0.002	-2.520	-1.981	2.495
Lussou et al. [2001]	D	0.151	0.092	0.177	1.556
Sadigh et al. [1997]	D	0.013	-0.557	-0.614	2.538
Spudich et al. [1999]	D	0.015	-1.114	-1.326	2.181

Table 5: Ranking of different ground-motion estimation equations for modelling the entire Antilles subduction earthquake ground motion dataset. MEDLH is the median LH value (see text), MEDNR is the median normalized residual, MEANNR is the mean normalized residual and STDNR is the standard deviation of the normalized residuals.

Model	Rank	MEDLH	MEDNR	MEANNR	STDNR
Atkinson and Boore [2003]	D	0.003	2.650	2.715	1.439
Crouse [1991]	D	0.007	-2.388	-2.360	1.406
Youngs et al. [1997]	B	0.362	-0.501	-0.508	0.881

Table 6: Observed and estimated strong-motion parameters of horizontal components of the record from TDBA of the 14th Feb. 2005 18:06 earthquake.

	PGA (g)	PGV ( $\text{cms}^{-1}$ )	PGD (cm)	AI ( $\text{ms}^{-1}$ )	RSD (s)
Observed	0.71	26.0	2.8	2.52	5.3
Estimated	0.16	7.1	1.1	0.10	5.5
Observed/estimated	4.44	3.7	2.5	25.20	1.0

where PGA is peak ground acceleration of the larger horizontal component, PGV is peak ground velocity (geometric mean), PGD is peak ground displacement (geometric mean), AI is Arias intensity (arithmetic mean) and RSD is relative significant duration (arithmetic mean), defined as the interval between the first exceedence of 5 and 95% of total Arias intensity [Trifunac and Brady, 1975]. Estimated PGA is from the model of Ambraseys et al. [2005], estimated PGV is from the model of Campbell [1997], estimated PGD is from the model of Sadigh and Egan [1998], estimated AI is from the model of Travararou et al. [2003] and estimated RSD is from the model of Abrahamson and Silva [1996].