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EARTHQUAKE MICROZONATION AND PREDICTION IN THE WEST INDIES

by

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ABSTRACT

Several different methods are being actively applied to the challenging and important problems of earthquake microzonation and prediction in the West Indies. For microzonation, these include the analysis of historical damage, the operation of strong motion accelerographs and conventional seismographs for the spectral analysis of site and building response in urban areas, the use of computer modelling techniques and of local refraction and resistivity surveys.

For prediction, substantial recent improvements have been made in the speed and accuracy of locating regional earthquakes. The distribution of events is being carefully watched for anomalous patterns of activity. In addition, seismic wave velocities are monitored routinely and geodetic studies have been carried out.

For both microzonation and prediction, emphasis is placed on the need for correlation of several different types of observation, in order to be confident that the results are significant.

1. Introduction

The subjects of earthquake microzonation and prediction are closely comparable. Both are important in that they are capable of considerably mitigating the human and property losses in major earthquakes. Both, however, have so far achieved only limited accuracy, and hence the confidence with which they can be applied at present remains distinctly low.

The purpose of this paper is to review the work carried out to date, and future plans aimed at the attainment of these objectives in the West Indies. For each subject in turn, a description will be given of the methods used and their limitations, of the results obtained, and future priorities. The seismicity of the region, and the location of the islands where particular studies have been made (Trinidad and Jamaica) are illustrated in Fig. 1.

2. Microzonation: methods and their limitations.

A considerable effort has been made in the Caribbean during the last few years to apply the more promising techniques of microzonation. These have included:

1) the analysis of damage distribution and liquefaction in large historical earthquakes;
2) the installation of strong-motion accelerographs and analysis of data collected;
3) the recording and analysis of the effects of moderate-sized regional earthquakes using conventional seismographs at important development sites;
4) the use of computer programmes for modelling the effects of alluvial profiles;
5) the use of shallow refraction and resistivity studies to establish the local dimensions and other properties of alluvial layers.

2:1. Historical records of earthquake damage

For numerous of the more destructive historical earthquakes in the Caribbean, reasonably detailed descriptions exist of the areas damaged and of the amount of damage done. Even though the damage is a function of the type of structures then existing, which may differ in earthquake response from numerous present-day (e.g. high rise) buildings, it remains an important record of local experience which can still be applied in general terms. The historical record is especially useful for the descriptions which it contains of liquefaction or ground failure, which remain directly applicable to modern situations. Earthquakes which have provided data of the above kinds include Port Royal (Jamaica) earthquake of 1692, the Cumana - Carupano - Port-of-Spain earthquake of 1766, the Caracas earthquake of 1812, the Guadeloupe event of 1843, the Kingston (Jamaica) earthquake of 1907, the Puerto Rico earthquake of 1918, the Caracas earthquake of 1967, and the Antigua earthquake of 1974. For several of these events, maps have been drawn indicating the areas of different types of damage, [illegible]

The obvious advantage of the historical damage reports is that they provide empirical data on the structures which then existed and on the areas then populated. The main disadvantages of the historical observations are that they are not directly applicable to many types of modern structure, and do not refer to areas which have only recently undergone major development.

2:2. Strong acceleration records from recent large earthquakes.

Records of the time-history of ground or building acceleration during strong earthquakes are the most important and directly applicable of all data for microzonation and also for structural design purposes. The main disadvantage is the rarity of such data. Even in active seismic belts, the acquisition of a good-quality strong-motion accelerogram with large-amplitude motions is an occurrence which takes place typically only once every few years. Experience in the Caribbean is that we waited four years (1973-1977) in Trinidad for the first strong motion accelogram with reasonably large amplitudes, and four years (1974-1978) for the first useful record in Jamaica. The Seismic Unit has direct responsibility for 23 accelerographs in three West Indian countries. 14 of these instruments were bought under an OAS supporting action for Trinidad and Tobago, Barbados and Jamaica. The other 9 instruments have been bought using local funds, mostly by the owners of large buildings at the instigation and encouragement of the Seismic Research Unit. In addition to the above accelerographs, 6 similar instruments have been installed in Guadeloupe and 9 in Puerto Rico.

A paper has been written on the accelerograms obtained in August 14, 1977 earthquake in Trinidad (Aspinall, 1978), and a preliminary account has been given of the 26 February 1978 event in Jamaica (Pereira, 1978), although the final spectra for the latter event are not yet available. The Trinidad event was of body wave magnitude 4.9, at a hypocentral distance of about 150 km from the accelerographs. Maximum accelerations in bedrock were $4\%_g$ and at the top of a 9 storey building $6.5\%_g$.

The Jamaican event of 26 February 1976 with body wave magnitude 4.5 (USGS) and 5.2 (U.W.I. Caribbean Network) was of special interest in that it originated at shallow depth (less than 10 km) and very close to Port Anti

Port Antonio in north-eastern Jamaica, where one strong motion accelerograph was installed. This instrument recorded a maximum acceleration of 17% g (Fig. 2) whilst in Kingston at a range of about 40 km from the source of the maximum acceleration was 5%g.

Neither of the two sets of accelerograms obtained recently in the West Indies has yet been used as input to computer modelling studies, although this application is planned for the future. A limitation over both sets of local accelerograms is that although they yielded interesting spectra, the magnitudes of both events were only moderate and there will remain uncertainty regarding the linearity of the accelerations when scaled to larger magnitudes.

2:3 Spectral analysis of records from high-gain seismographs.

To augment the slow rate of data collection from strong motion accelerographs, the Seismic Research Unit has deployed conventional, high-sensitivity seismographs in order to satisfy the urgent need for some kind of local measurements of predominant period and amplification of ground motion at the sites of important future development for high-rise buildings, water resevoirs, port facilities, steel mills, etc..

The measurement of moderate-sized earthquakes using conventional velocity transducers with high-gain electronic amplifiers for the prediction of spectral amplitudes in major earthquakes has met with criticism relating to the question of linearity between the small amplitudes actually measured, and the extrapolation of these measurements to predict ground response in major earthquakes. For example, Petrovski (1975) writes:

> "The use of microtremors and small earthquakes is probably a valid topic for scientific research, but does not yet appear to be a reliable method for the evaluation of characteristics of strong ground motions".

The opposite view has recently been expressed by Tezcan, Seed, Whitman et al. (1977), in their study of resonant period effects at one distant site during the Gediz (Turkey) earthquake of 1970.

Having used ordinary high-gain seismographs to collect their data these authors state that:

> "Analysis of soil response and damage at the Tofas factory site provides an example of the usefulness of aftershock motion records in predicting the probable characteristics of ground response during strong earthquakes."

The above authors estimate, however, that the rock to soil amplification factor was about 6 during larger aftershocks of Richter magnitude up to 5, but this factor was only about 3 during the main schock, of magnitude 7. It is pertinent also to note, in the context of realistic microzonation, that the effects of soil-structure quasi-resonance in this case were estimated equivalent to a further factor of three in amplification.

Experience to date in the Antilles with the spectral analysis of records from moderate magnitude earthquakes, has been obtained from recordings made at 5 different alluvial sites in areas of major urban or industrial development in Trinidad, over time intervals of between 3 and 6 months each. These studies were conducted as experiments to examine the differences in amplitude (representing ground velocity) between bedrock sites and sites with poorly consolidated near-surface layers. Two sites were in downtown Port-of-Spain, two at a new industrial complex close to the west coast of the island, and one at a large water treatment plant situated inland within a large area of thick alluvium. In 3 to 6 months of recording at each site, good quality magnetic tape records were obtained for 10 to 20 events with Richter magnitude between 4 and 5½ and with sources not more than 160 km distant. Frequency spectra were obtained either by manually digitizing the analogue seismograms followed by computer-based Fourier analysis, or by the much quicker but less precise technique of replaying the magnetic tape repeatedly through a sequence of narrow pass bands using suitable electronic filters. Automated techniques for digitizing the analogue magnetic tape records were unfortunately not available.

The results of one of these studies, at the Piarco Water Treatment Plant, are illustrated in Fig. 3, expressed as the ratio of spectral amplitudes at a bedrock site with similar distance from the earthquake sources. In this case, the thick alluvium (depth, layering and dynamic properties poorly known), gave a ratio of vertical ground displacement amplitudes which for the mean of all earthquakes analysed was greater than bedrock by a factor of 4.5, (this factor being 7.5 for the most extreme event), whilst the dominant period of ground motion (1.3 sec) was lengthened by a factor of three. In a similar study made at a site in downtown Port-of-Spain, the spectral ratio increased by a mean factor of 1.5 and a maximum of 3.5 over bedrock, with a dominant period of 0.8 sec for the alluvial site (Fig. 4). For comparison, computer-based modelling using the programme SHAKE produced acceleration and velocity spectra for large magnitude earthquakes, which in most cases peaked between 0.65 and 1.0 sec, with computed maximum ground accelerations equivalent to an amplification factor of 3.1 over bedrock, for the Port-of-Spain site.

We conclude from the close similarity of the results obtained by us using the above two methods that the empirical method of making local site measurements on moderate-sized earthquakes is an applicable technique and provides an important means of checking the computer-based modelling studies.

A series of measurements using high-gain seismographs at important development sites, similar to those made in Trinidad, will shortly be initiated in Jamaica.

2:4 Computer-based modelling studies

The application of computer modelling for microzonation is almost synonymous with the programme SHAKE, first developed at Berkeley (Schnabel et al.

1972). A copy of this programme was brought to Trinidad in the same year by the present writer and was eventually converted for use on the small computer at the University of the West Indies in Trinidad (Aspinall, 1976).

The programme SHAKE solves a one-dimensional wave equation describing the vertical propagation of shear waves through a linear viscoelastic system, i.e. a soil and alluvial profile. It requires as input a time-history of acceleration in bedrock, and values for the linear dynamic properties of the different soil types under strong shaking. It solves for response at the surface of the soil profile to the input bedrock motion. The results are in the form of acceleration, velocity and displacement spectra as a function of period of shaking.

The advantages of SHAKE are that, once established, it can be run for a great variety of input conditions, and it generates sepcific solutions which are directly applicable by engineers. The disadvantages of this or similar programmes are that it is often necessary to use strong motion accelerograms obtained in different geological and tectonic settings, using fixed scaling factors which may not be valid locally and making various assumptions about the dynamic properties, thicknesses and lateral continuity of soil layers which may not have been well established by means of local measurements. Finally, it solves the wave equation in one dimension only, taking no account of focusing, edge, or wave interference effects which in an alluvial basin may modify responses locally by up to an order of magnitude.

In the Caribbean, studies have been carried out using a slightly modified local version of SHAKE on various profiles obtained or estimated to exist at important development sites in Trinidad and in Jamaica. An example of a recent study for the Kingston area in Jamaica is that by Aspinall and Shepherd (1977). In this analysis, they considered three different earthquake sources, of Richter magnitude 7.5 at 160 km distance, magnitude 7.0 at 80 km, and magnitude 6.0 at 60 km. Uncertainties over the soil profiles within the broad alluvial fan upon which Kingston is built, led the authors to consider a profile which, for each earthquake, is stripped off from the bottom upward to give a series of 10 soil sections each of which is assumed to overlie bedrock. Aspinall and Shepherd state that "It must be stressed that this simple scheme represents no specific profile in the Liguanea Basin and that it is adopted only for the purposes of modelling earthquake response".

An example of the results of the above analysis for spectral acceleration classified into three period ranges of shaking, is reproduced in Fig. 5, in which it can be seen that a dramatic peak occurs, involving an acceleration of 0.95 g, in soils about 30 m thick for periods between 0.35 and 1 sec in the magnitude 7.0 earthquake at 80 km range.

Whilst the above analysis is valuable in that it establishes the range of probable accelerations for the different thicknesses and soil types which may be present beneath the Kingston area, it has not been established how the soil thicknesses or properties in reality vary across the deposit. These uncertainties exemplify the difficulties in applying theoretical modelling to areas where the actual soil profiles are only poorly known.

2:5 Use of local refraction, reflection and resistivity surveys

The main purpose of seismic refraction and similar surveys is to provide continuous profiles between specific, well-established vertical sections such as those obtained from boreholes. Refraction measurements will also give shear wave velocities and layer thicknesses for use as input to modelling studies such as SHAKE and similar computer programmes. The limitations of refraction seismology, however, are that the results are difficult to interpret in the many situations where non-uniform layer thicknesses, gradational changes in velocity from layer to layer, or velocity inversions are present. Also, without explosives, the maximum penetration of available signal sources such as weight dropping is about 30 metres. The firing of even small explosive charges at the surface in urban areas is complicated, although the possibility exists of firing small charges in any disused boreholes which are accessible.

Field investigations have been carried out by personnel of the Seismic Research Unit in Trinidad, Barbados and the Grenadines, using a signal-enhancement refraction seismograph with a hammer or weight-drop signal source, and also using an electrical resistivity meter, to determine the thickness and characteristics of near-surface alluvial material.

3. Earthquake Prediction

Studies in earthquake prediction are still in their infancy in the Caribbean, as in most other parts of the world. However, within the limitations of the funds and staff available, a considerable effort has been made to establish the main prerequisites for prediction, which include:

1. The rapid location of earthquake hypocentres and search for foreshock patterns.
2. The establishment of geodetic surveys across youthful faults on land.
3. The automated analysis of seismic wave velocity (V_p/V_s) ratios.

Experiments with other possible techniques for medium- or short-term earthquake prediction have not been carried out to date in the Antilles, although studies in long-term prediction such as the identification of seismicity gaps and analysis of their significance have been made.

3:1. Rapid location of hypocentres and search for foreshock patterns

Major improvements have been made in the last few years to the data collection systems in the Antilles. The installation of new telemetry networks with the continuous relay of signals to observatories in Trinidad, in the French West Indies, in the U.S. Virgin Islands, in Puerto Rico and in Jamaica has made possible the almost immediate location of hypocentres. With the recognition in numerous parts of the world of swarms of low-magnitude earthquakes as precursors to some devastating major events, it is important that a seismic observatory has the ability to detect such swarms. Several precursor sequences of this type have been recognized in the Caribbean, one example being a north-south alignment of 18 earthquakes north of the Virgin Islands between 6 April and 30 June 1969, leading to a main shock of Richter magnitude 5½, and followed by aftershocks over the next three months. Because of the long delay (of weeks to months) which then existed in data processing, this sequence and other comparable ones were only identified after the main event. The recent occurrence of 3 precursors within 20 hours before a modest-sized (Richter magnitude 5) earthquake on 26 February 1978 in eastern Jamaica, suggests that a larger main shock could be preceded by a longer and larger precursory sequence, and again illustrates the practical need for a rapid event location capability.

The recently installed U.W.I. Eastern Caribbean network is illustrated in Fig. 6 and has been described by Tomblin (1978). This consisted in October 1978 of 10 stations covering a zone 600 km long, all stations linked by continuous telemetry to a multi-channel magnetic tape recorder, backed up by visual (ink-pen) recorders and an audible event alarm. The network will soon be extended to cover the entire Eastern Caribbean and the adjacent part of Venezuela, and will eventually include at least 19 seismograph stations monitoring a zone 900 km long.

3:2. Geodetic measurements

Experiments were made in 1975 and 1976 in south-west Trinidad with measurements by theodolite across a well-exposed, large fault (the Los Bajos fault - see Fig. 7) which has shown significant seismic activity in recent years. This fault is one of the very few major faults which are well-exposed on land in the West Indies. Because of this and because most earthquakes in the Caribbean originate appreciably deeper than for example, in California (where precursory surface displacements are probably more common), the prospects for successful prediction by geodetic methods in the Caribbean are correspondingly less promising. The possibility that earth dilatancy prior to major earthquakes may be detectable through changes in flow at oil wells in Trinidad is currently being examined. The Seismic Unit has also recently established a programme of optical levelling to measure inflation or deflation of the flanks of Lesser Antillean volcanoes (Fiske et al., 1978). This technique could be applied in any area where tectonic inflation or tilting were suspected, e.g. in the area of a local earthquake swarm.

3:3 Seismic wave velocity ratios

Although the use of seismic wave velocity ratios (V_p/V_s) showed great promise as a technique for prediction when it was first described (e.g. Semonov, 1969), this early promise has not led to conclusive results, mainly because of the difficulty of identifying the S-phase onset on many seismograms. In the Caribbean, with the recent advent of magnetic tape recording which has brought not only more precise event location but also the possibility of clarifying the S-wave onset by filtering, the prospects are greatly improved for identifying meaningful variations in V_p/V_s ratio. Accordingly, a routine analysis and printout is made by computer, for every regional hypocentre processed, of the individual station and mean (event) velocity ratios. These data are recoverable on command for specific regions and time intervals. So far, no significant changes of velocity ratio have been noticed.

3:4 Future policy for action and research on prediction

We do not believe that we have at present more than a remote chance of making a successful prediction of a major tectonic earthquake. However, if we were to recognize a sequence of anomalous signs, we would not hesitate to advise the highest government authorities and to make numerical estimates of the probability of occurrence of the event within specific time, space and magnitude "windows". It is virtually certain that in the West Indies as in most other parts of the western world, civil authorities would have extreme difficulty in determining what increase in earthquake probability remained within the limits of acceptable risk.

Our policy on prediction research will continue to be to keep a close eye on the success and potential applicability in the West Indies of experiments being conducted at the best-endowed institutions, and to adapt and apply in our region those techniques which show the best promise.

4. Conclusions

The main conclusions of this paper are that:

1) The most reliable criteria for microzoning will be those obtained by a combination of the best direct field measurements and theoretical modelling techniques.

2) In the West Indies, we have generally obtained good correlation between the results from different methods, and we therefore have confidence in measurements and interpretations which have been made at the localities in question.

3) We have not yet made detailed measurements at sufficient different localities, and we do not have adequate confirmation of the existence of lateral continuity in soil and alluvial layers, to produce maps of entire urban areas. It is likely to be 5 years, at the present rate of progress, before we can begin to produce maps on a city scale which contain useful and reliable details.

4) Microzonation seeks to predict the intensity of damage from ground shaking, but this in turn is frequency-dependent in that the hazard to any structure at a particular site will be a function of the degree of matching between the natural periods of the site and the structure. Microzonation maps will therefore need to indicate a hazard level which reflects not simply the probability of a certain peak acceleration, but also the probability of that acceleration being reached in each of the different segments of the frequency spectrum which are of interest to engineers.

5) Microzonation and prediction are among the projects selected for our priority attention in the future. This reflects at the same time our awareness of the importance of producing local measurements for local application, and our confidence that these measurements are meaningful.

6) Future efforts aimed at microzonation will entail on the one hand increasing the rate of data collection by deploying more instruments such as accelerographs, and on the other hand diversifying methods so that those which

result in the faster collection of data can be employed judiciously to accelerate the rate and cost-effectiveness of research.

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