20. SHORT PRESENTATION ON SOME RESEARCHES ACTIVITIES ABOUT NEAR FIELD EARTHQUAKES

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IS THERE A NEAR-FIELD FOR SMALL-TO-MODERATE MAGNITUDE EARTHQUAKES?

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The major hazard posed by earthquakes is often thought to be due to moderate to large magnitude events. However, there have been many cases where earthquakes of moderate and even small magnitude have caused very significant destruction when they have coincided with population centres. Even though the area of intense ground shaking caused by such events is generally small, the epicentral motions can be severe enough to cause damage even in well-engineered structures. Two issues are addressed here, the first being the identification of the minimum earthquake magnitude likely to cause damage to engineered structures and the limits of the near-field for small-to-moderate magnitude earthquakes. The second issue addressed is whether features of near-field ground motions such as directivity, which can significantly enhance the destructive potential, occur in small-to-moderate magnitude events. The accelerograms from the 1986 San Salvador (El Salvador) earthquake indicate that it may be unconservative to assume that near-field directivity effects only need to be considered for earthquakes of moment magnitude M 6.5 and greater.

Keywords: Near-field, small earthquakes, moderate magnitude earthquakes, strong ground-motion.

1. Introduction

On 29 February 1960, an earthquake of magnitude 5.8 destroyed more than half of the modern buildings in the Moroccan town of Agadir, leaving a death toll of 12 000. The epicentral intensity was estimated as X on the Modified Mercalli scale [Reiter, 1989]. On 26 July 1963, the city of Skopje in Yugoslavia was hit by an earthquake of magnitude 6.0 M_s. The shaking was severe and reached VIII–IX on the MSK scale, resulting in the loss of more than 1000 lives and leaving up to 85% of the population homeless. The damage was mainly concentrated in the newer part of the city, an area of not more than 5 km^2, where more than 40% of houses were destroyed or damaged beyond repair [Ambraseys, 1965]. On 23 December 1972, an earthquake of magnitude 6.1 M_s struck Managua, capital city of Nicaragua,

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65 kilometers should be considered 'near' for exposure to a major earthquake". A number of researchers have proposed upper limits for the source-to-site distance that defines the near-field for large earthquakes that approximately coincide with the values proposed by Blume [1965]. For example, Campbell [1981] defined near-field as less than 50 km for earthquakes of magnitude greater than 6.25, and Krinitzsky and Chang [1977] proposed upper limits of 25, 35, 40 and 45 km for earthquakes of magnitude 6, 6.5, 7 and 7.5 respectively. More recently, Zhang and Kezhong [1997] proposed a limit of 40 km for earthquakes of magnitude 7 or greater and 35 km for earthquakes of magnitude 6 or greater. Damaging earthquake motions can be encountered at greater source-to-site distances but will generally be attributable to amplification by soft soil deposits or topographical features, or else to Moho bounce [e.g. Somerville and Yoshimura, 1990].

Figure 1 shows two different definitions for the engineering near-field in terms of the magnitude-distance space within which damaging ground are expected. The first curve was presented by Vanmarcke [1979] based on Chang and Krinitzsky [1978]. The other curves were developed by Martínez-Pereira [1999] using a much larger database of strong-motion accelerograms and a detailed procedure. The first step was to plot various strong-motion parameters against the corresponding values of MM intensity. Taking an intensity of VIII to be the threshold for motion that is potentially damaging to well-engineered structures, a lower bound was established for each strong-motion parameter [Martínez-Pereira and Bommer, 1998]. Passing any one threshold is not necessarily indicative of damaging motion, as for example many records have PGA values higher than the $0.2g$ threshold and yet correspond to

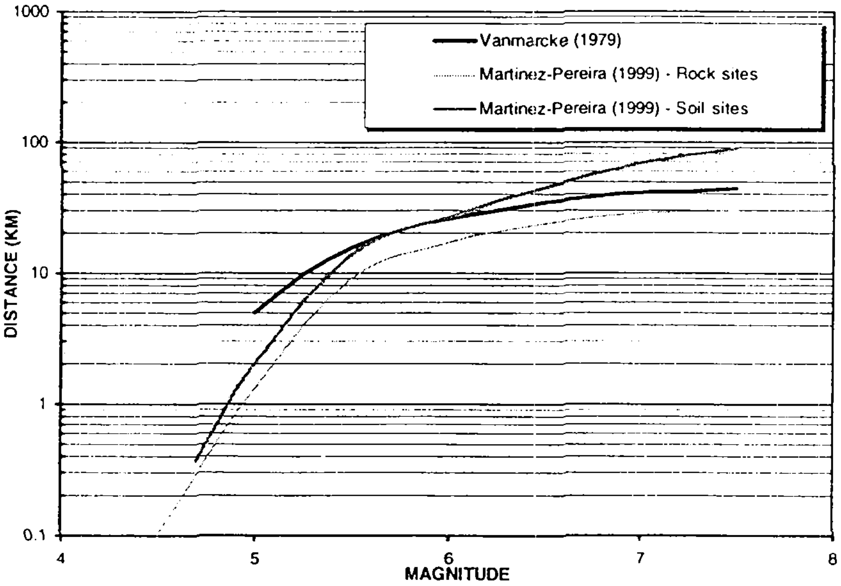


Fig. 1. Definitions of magnitude-distance space comprising the earthquake "near-field".

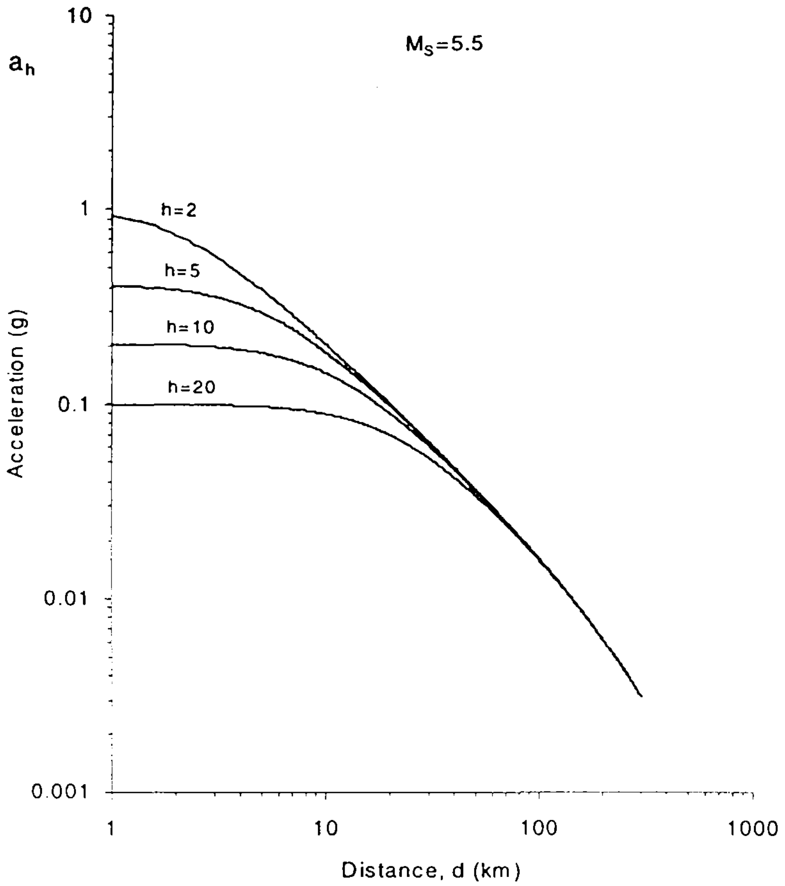


Fig. 2. Predicted values of horizontal peak acceleration (a_h) for earthquakes of M_s 5.5 and different focal depths from the relationship of Ambraseys and Bommer [1991].

of Ambraseys and Bommer [1991] — that includes implicitly the focal depth of the earthquake — for a moderate magnitude earthquake. It can be seen that for source-to-site distances of less than 5 km, the predicted levels of ground motion are very strongly dependent on the focal depth of the earthquake. Recalling the threshold of 0.2g for damaging motions, it can be seen from Fig. 2 that for M_s 5.5 events, only those with focal depths at less than 10 km from the surface would be expected to generate potentially damaging motion. Ambraseys [1985] showed similar results for intensities of northwest European earthquakes; the average magnitude for which intensity VI (MSK) shaking would be generated over a 5 km radius ranges from about 4.8 for a focal depth of 20 km to 4.3 for a focal depth of 10 km and just 3.7 if the earthquake is superficial. Ambraseys [1985] derived an empirical relationship between epicentral intensity and magnitude in northwest Europe, which suggests that the magnitude required to generate intensity VIII shaking is 5.4 although it is noted that very shallow earthquakes were excluded from the regression.

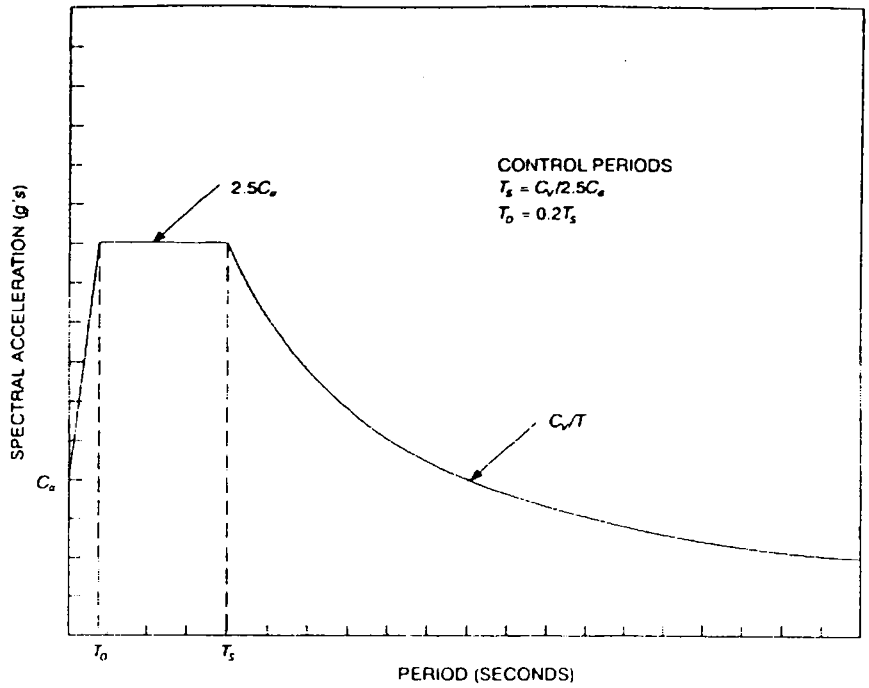


Fig. 3. Elastic acceleration response spectrum from UBC97.

UBC97 requires the application of near-source factors, termed N_a and N_v, to amplify the short- and intermediate-period spectral ordinates respectively, for sites in Zone 4 (highest hazard) that are potentially situated within the near field of an earthquake, determined by the proximity and activity of geological faults in the vicinity. The definitions of N_a and N_v imply that for earthquakes of M 7 and greater, the near field is limited to 15 km from the fault, and that the near field does not exist for earthquakes smaller than M 6.5.

Figure 3 shows the form of the elastic response from UBC97, controlled by the factors C_a and C_v in the short- and intermediate-period ranges. In Zone 4, the zone of highest seismic hazard, the near-source factors N_a and N_v, applied to the short- and intermediate-period ordinates respectively (i.e. multiplied by C_a and C_v respectively), need to be applied if the site is within 15 km of a known geological fault capable of producing an earthquake of magnitude M 6.5 or greater. Figure 4 shows the values of the near-source factors with distance from the closest fault, for the three different classes of fault defined according to the criteria given in Table 1.

Another important feature of ground motion exclusive to sites near to the causative fault are high vertical accelerations. The vertical motion can contribute significantly to the level of damage both directly and through interaction with the horizontal shaking [Papazoglou and Elnashai, 1996]. Few seismic codes consider the earthquake loading in the vertical direction and these usually assume that

3. Damage Due to Small Magnitude Earthquakes

There are now many detailed accounts of the effects, both observed and recorded, of small-to-moderate magnitude earthquakes around the world, which provide very useful insight into the possible lower limits for the near-field. The 1960 Agadir, 1963 Skopje and 1972 Managua earthquakes were cited in the introduction as well known examples of moderate magnitude events that resulted in severe damages and loss of lives. The earliest of these may well be an example of where the very high level of damage could have owed at least as much to the density and high vulnerability of the exposed building stock as it did to severe ground shaking although the reported maximum intensity was indeed high. Reiter [1989] lists several other important examples of damaging small-to-moderate magnitude earthquakes, including several earthquakes in Central Asia, such as an event in 1943 near Fiazabad (Tadjikistan, USSR), of magnitude 4.7, that resulted in damage corresponding to intensities of VIII to IX. Another event, of magnitude 5.5 and very shallow focal depth, occurred in Khulum (Afghanistan) in 1976 and destroyed over 1000 houses, leaving 29 dead. Significantly, this earthquake also caused irreparable damage to a power station, which presumably would have been built to much higher engineering standards than the affected houses.

It is possible for small earthquakes to cause considerable damage, at least in brittle houses built from rubble masonry or adobe, when these occur in extended swarms. Reiter [1989] again reports such a series of small events in Tashkent (Uzbekistan, USSR) in 1966; the largest single event had a magnitude of just 5.1 yet some 300 000 people were left homeless by the damage and much of the city needed to be repaired. Such swarms are also common in volcanic regions such as Central America: in the area of San Vicente in El Salvador, for example, a swarm of small earthquakes in March and April 1999, none of which reached even magnitude 5, resulted in damage to many adobe houses, ranging from minor to some cases of collapse. Also in El Salvador, during two days in May 1951, three earthquakes of magnitude 6 or lower caused the almost complete destruction of four towns in the east of the country, leaving 400 dead [Ambraseys *et al.*, 2001]. Earthquake series are also common in Italy, where the cumulative effect of several earthquakes over a period of days or weeks results in much more extensive damage than would be expected, or indeed caused, by a single event. Examples of such series are those of Ancona in 1972, Friuli in 1976 and Umbria-Marche in 1997, the largest magnitude in the first series no larger than about 4.5. It is, however, important to point out that the assigned intensities for such series, such as the value of IX for the Ancona earthquake, may be overestimated as a result of the superimposition of the effects of several events.

Many factors can be identified that contribute in different cases to the seemingly disproportionate damage caused by some small-to-moderate magnitude earthquakes. Apart from close proximity to important centres of population or industry, defined by the epicentre being within at most a few kilometres of the city none of the accelerograms recorded during the Athens earthquake were located close to the source [Elnashai and Ambraseys, 2000]. Nonetheless, Tselentis and Zahradnik [2000] have identified rupture directivity effects, resulting in short duration of motion, as well as a very short rupture rise-time, as contributing to the high accelerations recorded outside the near-field and the destructive near-field motions.

Another interesting case has been the **M** 5.0 Napa (California) earthquake of 3 September 2000 that caused disruption to lifelines, in particular to the water distribution system, and damage estimated at as much as US$ 100 million [EERI, 2000b].

4. The San Salvador (El Salvador) Earthquake of October 1986

Another earthquake that stands out as deserving of particular attention in this context is the San Salvador (El Salvador) earthquake of 10 October 1986, which left 1500 dead and caused economic damage estimated as being equal to 31% of the GNP of El Salvador in the same year [Olson, 1987; Bommer and Ledbetter, 1987; Coburn and Spence, 1992]. This moderate magnitude earthquake caused severe destruction in San Salvador, including the collapse of many large engineered structures. The earthquake was also very well recorded by a number of accelerographs in the city, providing a suite of records obtained very close to the source of this small but highly destructive earthquake, providing unique insight into the nature of destructive near-field motions from small-to-moderate magnitude earthquakes [Shakal *et al.*, 1987]. In addition to strong-motion recordings, excellent soil profile characterisations are available from the microzonation project carried out for a large part of the city following the earthquake [Faccioli *et al.*, 1988]. All of this data provides a unique opportunity to examine the presence of near-field effects in the destructive ground-motions produced by this earthquake, which was of a size that would be considered by many to be the threshold to cause damage with a magnitude of just M_s 5.4 (m_b 5.0, **M** 5.7).

There are many factors that may have contributed to the disproportionately high damage from this earthquake, including a great number of landslides in ravines and road cuttings, which despite their relatively small size, caused damage to many houses located near the susceptible and near-vertical slopes [Rymer, 1987]. A very significant proportion of the damage, particularly in larger engineered structures, can be attributed to damage caused by a similar earthquake in May 1965 [Lomnitz and Schulz, 1966; Rosenblueth and Prince, 1966], which was not followed by adequate repair and strengthening. Several of the multi-storey buildings that collapsed in the 1986 earthquake, including the Rubén Darío building where 300 perished, had been clearly identified as having been severely weakened in the 1965 earthquake. Many buildings may have been further weakened by the low-amplitude, long-duration ground motions caused in San Salvador by a large (M_s 7.3) earthquake off the coast in June 1982 [Alvarez, 1982; Lara, 1983]. Furthermore, the building stock was generally vulnerable, since the seismic design code introduced

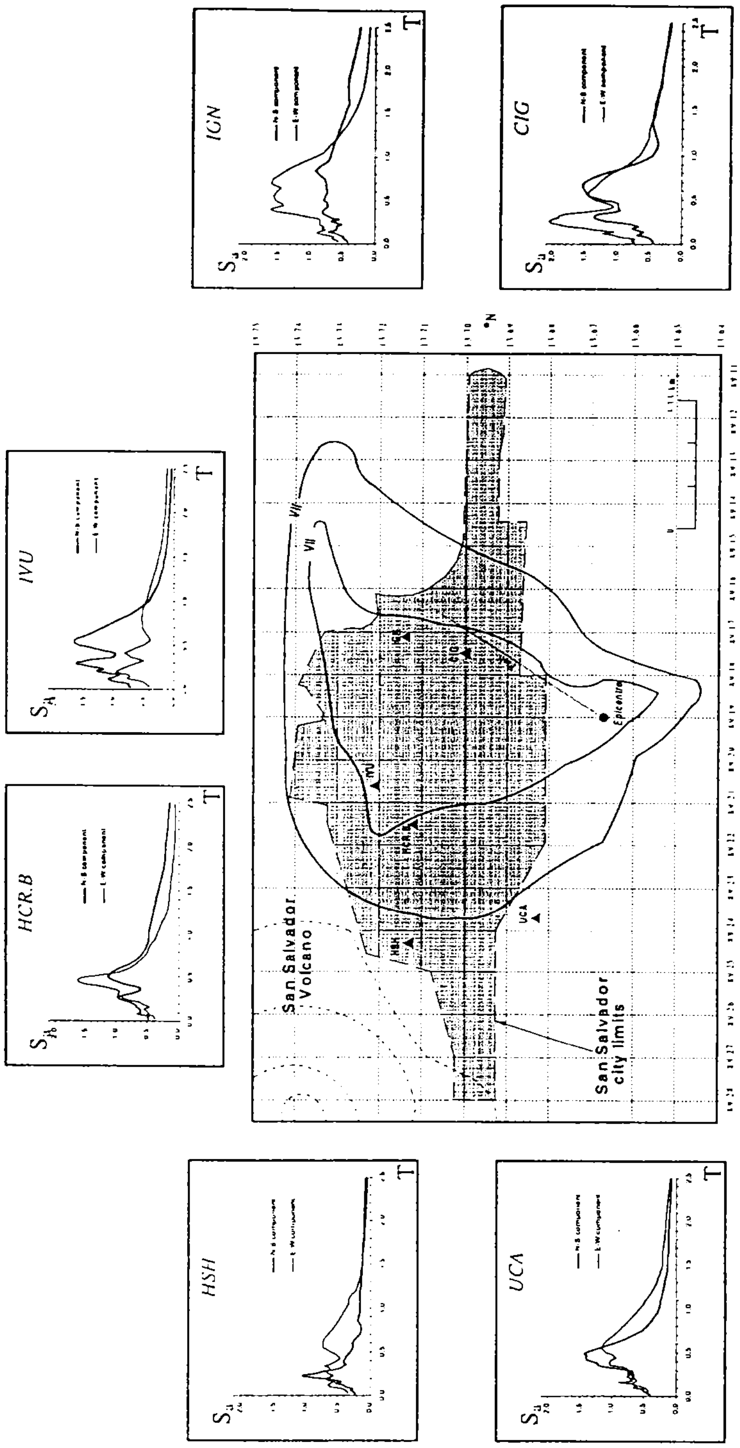


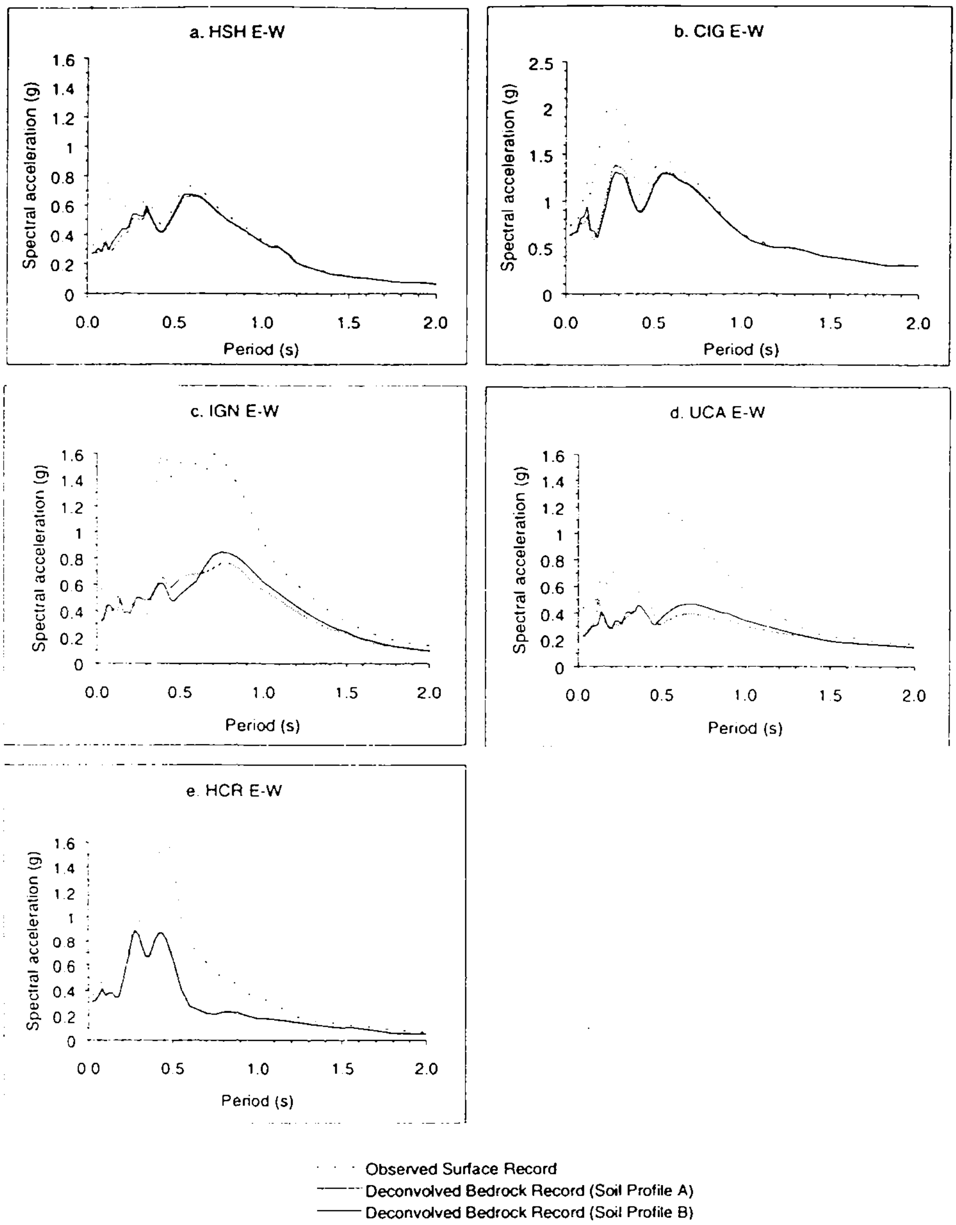
Fig. 5. Location of accelerograph stations that recorded the 1986 San Salvador earthquake and their 5% damped acceleration response spectra.

predictions from attenuation equations carried out by Bommer *et al.* [1996] found that the observed spectral ordinates exceeded the predictions by factors as high as 4 or more. It must be acknowledged that this degree of underestimation could be considered within the range of the scatter associated with the attenuation equations. Nonetheless, it is clear that the application of the Somerville *et al.* [1997] factors — notwithstanding their authors' suggestion that they be reserved for earthquakes of $M > 6.5$ — would not significantly reduce the underestimation of the spectral ordinates by the attenuation relationships.

The thickness of the layers of volcanic ash overlying bedrock in San Salvador decreases from east to west, with increasing distance from Lake Ilopango (located to the east of San Salvador, just outside the limits of Fig. 5), the volcanic centre that was the source of the most recent deposit, the *tierra blanca*, identified as the main culprit in the amplification of the ground shaking. Examination of Fig. 5 would then suggest that the high spectral ordinates at both short and intermediate periods observed in some of the spectra, and particularly those at CIG and IGN, could be explained entirely by their proximity to the fault and the amplifying effect of the dynamic soil response. However, deconvolution of the records to bedrock suggests that the soil response alone, although significant, does not account for the level of the spectral ordinates.

The first source of geotechnical data is the seismic microzonation study carried out by an Italian team, Italtekna-Italconsult, referred to previously [Faccioli *et al.*, 1988]. The second source of data is the report of Atakan and Figueroa [1993] on local seismic site response in San Salvador as part of a broader study on natural disaster reduction in Central America. These investigators had access to unpublished geotechnical and geological information from the Soil Mechanics Department of El Salvador's Centro de Investigaciones Geotécnicas, as well as the Italian data. The Italian data is of particular relevance to the current study, the laboratory and *in situ* tests having been carried out with a seismic response study in mind. The inclusion of extensive background information in the Italtekna-Italconsult reports is useful in allowing a third-party study such as this one to evaluate the stated soil parameters [Italtekna-Italconsult, 1987a,b,c]. A lack of background information for the other main source of data makes a critical analysis of the uncertainty associated with stated soil parameter values difficult. In the following soil profile descriptions, all "A-profiles" are based on data from the Italian investigation, whereas the "B-profiles" are from Atakan and Figueroa [1993]. For sites CIG and HCR, Atakan and Figueroa [1993] quote Italtekna-Italconsult as their source, so the profiles are almost identical.

In order to obtain bedrock motions, the observed surface records were deconvolved using a one-dimensional pseudo-linear ground response model, ProShake [EduPro Civil Systems Inc, 1998]. ProShake is an updated version of the widely used SHAKE [Schnabel *et al.*, 1972]. The analysis required the soil at each strong-motion recording site to be discretised into horizontal layers from the surface down



(a)

Fig. 6. (a) Response spectra (5% damped) of the surface and bedrock (deconvoluted) records from the 1986 San Salvador earthquake: E–W components. (b) Response spectra (5% damped) of the surface and bedrock (deconvoluted) records from the 1986 San Salvador earthquake: N–S components.

there is evidence to suggest that fault ruptures that do not reach the ground surface, but are somehow contained within the crust, produce stronger ground motions.

It is also important to note that no claim is being made to have newly identified directivity effects from this or other small and moderate magnitude earthquakes. Faccioli *et al.* [1988] identified directivity effects in the 1986 San Salvador earthquake from two-dimensional displacement plots. Boatwright and Boore [1982] found clear directivity effects, resulting in variations of PGA values by up to a factor of 10, from the Livermore Valley (California) earthquakes of 24 and 27 January 1980, which had magnitudes of M_s 5.8 and 5.0 respectively. They also pointed out that Bakun *et al.* [1978] had previously identified directivity effects in the high-frequency motions from central Californian earthquakes of magnitude as small as 2.0 and 3.0. Liu and Helmberger [1985] also identified forward directivity affects producing high-amplitude high-frequency ground motions in the M_L 5.0 Imperial Valley aftershock of 15 October 1979. They also point to high stress drop as a possible cause for the high levels of the recorded motions. On this point it is interesting to note the studies of Haddon [1995] and Haddon and Adams [1997], which considered the high levels of acceleration recorded in the 25 November 1988 Saguenay (M_s 6.0) and 19 October 1990 Mont-Laurier (M_s 4.2) earthquakes in Canada. In both cases, the accelerations had previously been attributed to exceptionally high stress drops, but they found that this was not the case, more likely explanations being related to fault rupture history, including the effects of directivity.

There is a potential danger in attributing all high-amplitude near-field motions to directivity effects, since many factors, including path effects due to lateral variations as well as spatial and temporal variations in the fault rupture propagation, can also exert a very significant influence [e.g. Panza and Suhadolc, 1987]. Nonetheless, there is a considerable body of evidence to support the presence of directivity effects producing amplified ground motions in the near-field of even small earthquakes. The point herein, however, is not primarily to show that directivity effects can exist for small-to-moderate magnitude earthquakes but rather to explore their possible implications for seismic hazard and seismic risk.

5. Implications for Seismic Hazard Assessment and Seismic Design

Following the 1986 earthquake, a new seismic design code was drafted that came into effect in 1989, although like its predecessor from 1966 there is little evidence of its having been enforced. In 1994 a third seismic design code was adopted in El Salvador [Bommer *et al.*, 1996]. None of these codes has considered near-field effects, although the 1989 code adopted a response spectrum based on the recordings of the 1986 earthquake. Indeed, the only codes to consider explicitly the effect of near-field directivity on seismic actions to be used in design are the 1997 edition of the US Uniform Building Code, UBC97 and its successor the International Building Code, IBC-2000 [ICC, 2000].

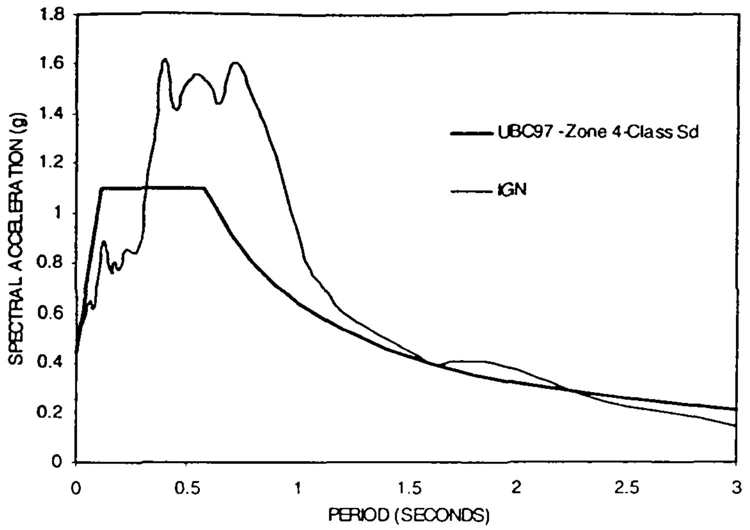


Fig. 9. Comparison of the envelope spectrum of the IGN record with the UBC97 Zone 4 spectrum.

The envelope spectra from the other stations, UCA and HSH, lie below the UBC97 spectrum across nearly the entire period range, the former exceeding the code spectrum slightly in the same period range as the HCR spectrum in Fig. 8. The most striking observation is the very large exceedance of the UBC97 spectrum by the spectra from CIG and IGN over a significant range of periods. Comparison of Figs. 7 and 9 with Fig. 4 shows that the application of the near-source factors for a Class B fault would produce code spectra that matched much more closely the observed spectra from these two near-field records. However, it is important to note that the application of the UBC97 factors for such small magnitude earthquakes would be made difficult by the fact that it would be necessary to identify and characterise geological faults of no more than a few kilometres in length.

Polarisation, another characteristic of near-field motion, is also observed in the recorded ground motions from San Salvador, the E–W components (which are closer to the fault-normal components) showing higher values of PGA and PGV than the N–S components, especially at IGN and CIG. This is also clear in the spectral ordinates, particularly at IGN, up to about 1.1 s; again, this is not accounted for by the Somerville *et al.* [1997] factors, which only predict polarisation effects at periods greater than 0.5 s and for magnitudes greater than or equal to M 6.0.

6. Discussion and Conclusions

It appears that rupture directivity effects could have played an important role in generating the very high ground motions recorded in the 1986 San Salvador earthquake. Recent re-evaluation of the empirical factors for the effects of rupture noting here that methods have recently been developed to include the effects of rupture directivity in PSHA, adopting the factors of Somerville *et al.* [1997] together with taper functions that introduce both magnitude and distance dependence not present in the original formulation [Abrahamson, 2000]. Rather than have an abrupt cut-off at **M** 6.5, the taper function interpolates between a value of unity at **M** 6.5 and zero at **M** 6.0, acknowledging the possibility of some directivity effects in events smaller than **M** 6.5 but still excluding the possibility of their presence in earthquakes smaller than **M** 6.

Regardless of how near-field directivity effects are modelled in the attenuation relationships employed, it is questionable whether the potentially destructive motions from small, shallow focus earthquakes can really be captured by PSHA. Only those events postulated to occur very close to the site of interest are likely to generate damaging motions, and these high amplitudes will generally be lost by the "smoothing" process that results from considering all possible earthquakes within each source zone, most of which will be too far away to produce near-field effects at the site. It is worth noting that the near-field factors in UBC97, although applied to an elastic response spectrum that is constructed from the output of a probabilistic seismic hazard assessment, are deterministic: the application of N_a and N_v implicitly assumes that an earthquake will occur on the closest adjacent fault to the site and that it will rupture in such a fashion as to produce forward directivity effects at the site. For the case of San Salvador, the recordings from the October 1986 suggest that the factors would be applicable for earthquakes of magnitude smaller than **M** 6.5.

It is not proposed, on the basis of the recordings from the 1986 San Salvador earthquake alone, that the near-field factors should be changed nor that the lower magnitude limit for their applicability should be altered. Nonetheless, it is abundantly clear that small-to-moderate magnitude earthquakes can, under certain conditions that include shallow focal depths, generate ground motions that are potentially destructive even to engineered structures. The evidence presented in this paper suggests that near-field directivity effects may be encountered in some small earthquakes and these may be the cause of the significant seismic hazard posed by these events. Since the ground shaking from these earthquakes is of short duration by virtue of their small magnitude, and the duration is further reduced by the forward directivity, it may not necessarily result in great destruction. However, because smaller earthquakes occur more frequently, there is always the danger that buildings will be weakened by the enhanced shaking and then caused to collapse by subsequent earthquakes. In those areas of the world where small-to-moderate magnitude earthquakes frequently occur in series over short periods of time, such as Italy and Central America [White and Harlow, 1993], the cumulative effect can be catastrophic.

It is clear that greater study of this topic is required, particularly the compilation of a database of observed effects from damaging — and, equally important, not damaging — small-to-moderate magnitude earthquakes. This database could help

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