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THE EL SALVADOR EARTHQUAKES OF 2001: IMPLICATION FOR SEISMIC RISK FROM CRUSTAL AND SUBDUCTION SEISMICITY

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ABSTRACT
On 13 January 2001 the Central American republic of El Salvador was struck by a magnitude **M** 7.6 earthquake that left more than 800 dead. Exactly one month later a second earthquake of **M** 6.6 occurred, adding to the death toll and the destruction. The two earthquakes had different tectonic origins: the former was located in the subducted Cocos plate, the latter in the overriding Caribbean plate. The two earthquakes correspond to the two principal sources of seismic hazard in El Salvador. This study examines the impact of the 2001 earthquakes within the historical context of Central America, where upper crustal earthquakes have caused far greater losses than subduction events. In particular the study re-visits proposals that have been made in the past to separate the two sources of seismic hazard in the drafting of zonation maps and design codes, in the light of the effects of the 2001 earthquakes and the strong-motion records obtained in these recent events.

Keywords: El Salvador; Crustal earthquakes; Subduction earthquakes; Seismic hazard; Seismic risk; Landslides.

INTRODUCTION
El Salvador, the smallest of the Central American republics, is located in a region of high seismic hazard primarily due to the convergence of the Cocos and Caribbean tectonic plates in the Middle America Trench [1, 2]. During the last 100 years, El Salvador has experienced a damaging earthquake or earthquake sequence on average once per decade, the most recent earthquakes occurring in the first two months of 2001. The unusual feature of the 2001 events is that two major earthquakes occurred within one month but each associated with a different seismogenic source: the first originated in the subducted Cocos plate offshore in the Pacific Ocean, the second within the overriding Caribbean plate, within El Salvador. Both events

caused very significant damage and were also well recorded by three networks of strong-motion accelerographs. One of the issues examined in this paper is the applicability of the current seismic design code in El Salvador in light of the accelerograms recorded during these earthquakes. In particular, we re-visit proposals that have been made previously – but never adopted – to consider the hazard from crustal and subduction earthquakes separately. A second, and possibly more important, issue is the extent to which the seismic design code is of importance in mitigating the growing levels of seismic risk in El Salvador, in view of impact of these recent earthquakes.

SEISMIC HAZARD AND ZONATION IN EL SALVADOR

El Salvador is located on the Pacific coast of the Central American isthmus, bordered by Guatemala to the west, Honduras to the north and the Gulf of Fonseca to the east. The country lies within 100 km of the western edge of the Caribbean plate whose limit is defined by the Middle America Trench where the Cocos plate is subducted at a rate of about 7 cm/year. Large magnitude earthquakes are generated in Benioff-Wadati zones in the subducted Cocos plate and these constitute an important source of seismic hazard in El Salvador. The northern boundary of the Caribbean plate is expressed as a series of right-lateral transform faults, including the Motagua and Chixoy-Polochic faults, that traverse Guatemala. Large earthquakes are also generated on the Caribbean-North American plate boundary but they are too distant from El Salvador to create significant seismic hazard within that country: the M_s 7.5 Guatemalan earthquake of 4 February 1976 generated a maximum MM intensity within El Salvador of V [3].

A second source of very significant seismic hazard in El Salvador are moderate magnitude, crustal earthquakes that occur along the volcanic axis that traverses the country from east to west along the southern flank of the Great Interior Valley, which includes six active volcanoes. These earthquakes are tectonic rather than volcanic in origin and have been interpreted as being the result of an oblique component of the Caribbean-Cocos collision creating a zone of right-lateral shear and fore-arc sliver [4]. Despite their moderate magnitude these crustal earthquakes have caused far greater destruction and loss of life in El Salvador and neighbouring Nicaragua than the larger magnitude subduction zone events [5]. The high hazard associated with these earthquakes is the result of their general shallow foci and their coincidence with zones of dense population, since settlement in the region has been largely dictated by coffee cultivation, which is concentrated on the volcanic slopes. During the twentieth century several earthquakes occurred in both of the major seismogenic sources, the upper crustal events being responsible for the vast majority of the total death toll. In general, the destructive crustal events appear to have been preceded in each case by a subduction zone earthquake between 2 and 4 years earlier: subduction earthquakes in 1915, 1932 and 1982 were followed by destructive earthquakes in 1917, 1919, 1936 and 1986. However, this pattern is by no means always observed as for example with the destructive moderate magnitude events of 1951 in Jucuapa and Chinameca [6] and 1965 in San Salvador [7].

Three seismic hazard studies have been published for El Salvador [8, 9, 10] and another for all of Central America [11], all of which have considered simultaneously the hazard due to both crustal earthquakes along the volcanic chain and to subduction zone seismicity; only the study by Alfaro *et al*. [9] derived separate attenuation relationships for crustal and subduction earthquakes. The most recent seismic hazard study published for El Salvador, carried out by researchers from UNAM [10], formed the basis for the zonation map that appeared in the 1994 seismic design code in El Salvador. As in the earlier codes, published in 1966 and 1989,

the zonation map simply divides El Salvador into a southern and a northern zone, the former containing the volcanic chain and the coast and being of greater hazard [12]. It is interesting to note that the first seismic code was introduced after the 1965 San Salvador earthquake and was essentially an adaptation of the code from Guerrero, Mexico, by the late Emilio Rosenblueth [13]. The code was proposed only as a temporary measure while a definitive document was drafted, although it remained unchanged until the 1986 San Salvador earthquake [14] prompted extensive revision. Rosenblueth and Prince [13] proposed that the definitive code should actually consider separately earthquakes of upper-crustal and subduction origin: *"Given that the earthquakes of very shallow origin, associated with the line that marks the volcanic chain, have different characteristics than those associated with the Pacific Trench, the procedure should be to elaborate not one but two regional seismicity maps, one for each kind of earthquake*." At the time this proposal was made there were no accelerograms recorded in El Salvador and relatively few large engineered structures existed at the time of the 1965 earthquake, but subsequent events tended to lend support to the proposal for two separate zonation maps and the different characterizations of the ground motion inferred by Rosenblueth and Prince [13]. A magnitude **M** 7.3 earthquake occurred in the subduction zone offshore from western El Salvador on 19 June 1983, triggering many landslides in the southwest of the country and causing damage to weak houses built from *adobe* (clay brick) and *bahareque* (wattle-and-daub); estimates of the death toll due to this earthquake range from 8 to 40 [15, 16]. Damage to engineered structures was very limited, despite the fact that some large buildings in the capital had been severely weakened by the local earthquake of 3 May 1965. On 10 October 1986 San Salvador was struck by an earthquake of very shallow focus with magnitude of only **M** 5.7, which caused a great deal of damage in the capital, triggering hundreds of landslides, which were mostly small although one killed an estimated 200 people. This earthquake also caused damage to both houses and large engineered buildings, several of which, damaged in 1965 and possibly further weakened in 1982, collapsed adding significantly to the total death toll of 1,500 [14].

A single accelerogram was recorded during the 1982 earthquake, obtained from an AR-240 instrument installed at the Seismological Observatory near San Salvador; the peak acceleration was just less than 0.2*g* [17]. The 1986 earthquake was recorded by six SMA-1 accelerographs installed at ground level, with the highest accelerations reaching almost 0.8*g* horizontally and 0.5*g* vertically [14]; these high accelerations may in part be the result of near-field directivity effects [18]. The shape of the response spectrum of the 1982 earthquake showed a greater content of long-period radiation than the 1986 ground motions, although the difference was less than might be expected for the difference in their magnitudes, hence it is unlikely that this could be the main reason why the resulting damage levels to engineered structures in the two earthquakes. The total Arias intensity of the strongest recording from 1986 was found to be identical to that from the single 1982 recording; since Arias intensity has been found to be a good indicator of the capacity of the ground motion to trigger landslides [19], this result would indicate why both the 1982 and 1986 earthquakes led to many slope failures in brittle volcanic soils. *Adobe* and poorly maintained *bahareque* can both be assumed to behave in a similar way to these soils, since they have strongly degrading characteristics when subjected to cyclic loading. The reason that the 1986 ground motions were so much more damaging to engineered structures than those generated by the 1982 subduction earthquake, has been interpreted as due to the much shorter duration of the former: the rate of energy input to structures was an order of magnitude higher, making dissipation possible in some cases only through cracking of concrete and yielding of steel [20]. In view of the different characteristics of the ground motions from these two earthquakes and the very different geographical distribution of the hazard associated with the

two types of earthquakes [21], the proposal of Rosenblueth and Prince [13] for separate zonation has been re-visited in recent years. Using the recordings of the 1982 and 1986 earthquakes, an exploratory analysis [22] proposed guidelines for deriving separate zonation maps, elastic response spectra and inelastic behaviour factors for the two types of earthquakes, the behaviour factors taking account of the fact that shallow earthquake along the volcanic chain frequently occur in clusters of two or three events [5]. Subsequent proposals were made to represent the two sources of hazard separately using a new mapping technique showing hazard-consistent magnitude-distance pairs [23, 24].

THE JANUARY AND FEBRUARY 2001 EARTHQUAKES

The 13 January 2001 earthquake had a magnitude **M** 7.7 and a focal depth of the order of 40 km, associated with a normal fault rupture within the descending Cocos plate with its epicentre offshore of eastern El Salvador. The source of the earthquake, at least in terms of depth and mechanism, was similar to that of the 1982 subduction earthquake. The earthquake was felt throughout Central America and very strongly throughout El Salvador; maximum intensities, in isolated locations where amplification occurred due to topography or surface geology, were of the order of VII-VIII on the European Macroseismic Scale (EMS-98). Throughout most of the south of the country, the intensity was estimated at VI-VII. Hundreds of landslides were triggered, particularly in the Balsamo and Tacuba coastal mountain ranges and along the volcanoes situated in the Great Interior Valley. The vast majority of the deaths caused by the earthquake were due to landslides, in particular the large debris flow at Las Colinas, Santa Tecla, to the west of the capital. Damage to engineered structures was limited and most non-structural [25]; San Salvador was affected very little and evidence of earthquake damage was hard to find in the capital. In towns and villages throughout the south of the country, and particularly in rural areas, there was extensive damage to *adobe* houses; recently built and well maintained *bahareque* houses generally performed well, but older buildings suffered varying degrees of damage. In contrast, timber and reinforced masonry buildings suffered significantly less damage and in many locations houses constructed from these materials remained intact whereas *adobe* houses collapsed (Figure 1).

Figure 1. San Agustin in eastern El Salvador after the 13th January earthquake: collapsed *adobe* in the foreground compared with intact reinforced masonry and timber frame (*lamina*) houses behind.

The 13 February earthquake was of magnitude **M** 6.6, associated with right-lateral rupture on an E-W trending fault located approximately between Lake Ilopango, to the east of San Salvador, and the San Vicente (Chichontepec) volcano further to the east. An earthquake of M_s 6.1 occurred in this area in December 1936, causing very heavy damage in the town on San Vicente and leaving more than 100 dead [26]. The focal depth of the 13 February 201 earthquake has been estimated at about 15 km, making it less superficial than earthquakes such as the 1951 Jucuapa-Chinameca events [7] and the 1986 San Salvador earthquake [14]. The 13 February earthquake, which caused the loss of a further 300 lives, triggered many landslides in central El Salvador and re-activated slides triggered by the 13 January earthquake. Despite the crustal origin and relatively large magnitude of this earthquake, it is estimated that the maximum intensity was of the order of VII; this relatively low intensity, compared to values of VIII-IX observed in other crustal earthquakes such as the 191 and 1986 events mentioned previously, is interpreted as being due to the fact that the event was not of very shallow focus, which is attested to by the absence of any observed surface fault rupture. In the towns of Guadelupe, Verapaz and Santa Cruz Analquito, located directly above the source as inferred from aftershock distributions, the same patterns of damage were observed as in locations in eastern El Salvaor following the 13 January event. Once again, houses of adobe and bahareque suffered heavy damage and collapse, particularly the former, whereas houses of reinforced masonry (known locally as *mixto*) did not show signs of serious damage (Figure 2).

Figure 2. Guadelupe after the 13 February earthquake: total collapse of *adobe* houses contrasting to almost undamaged state of reinforced masonry telecom building.

Two engineered buildings that did suffer some structural damage were the five-storey San Pedro Hospital in Usulutan and Santa Teresa Hospital in Zacatecoluca. These suffered damage at the upper ends of ground-floor and first-floor columns, respectively, and cracking of infill walls due to excessive lateral displacements.

RECORDED MOTIONS AND DESIGN CODE SPECTRA

Both the 13 January and 13 February earthquakes were recorded by three networks of strong-motion accelerographs: digital networks operated by the Universidad Centroamerciana

(UCA) and by the geothermal energy company GESAL, and a network of analogue SMA-1 instruments operated by the Centre for Geotechnical Investigations (CIG) of the Ministry of Public Works. Full details of these recordings are presented elsewhere [27].

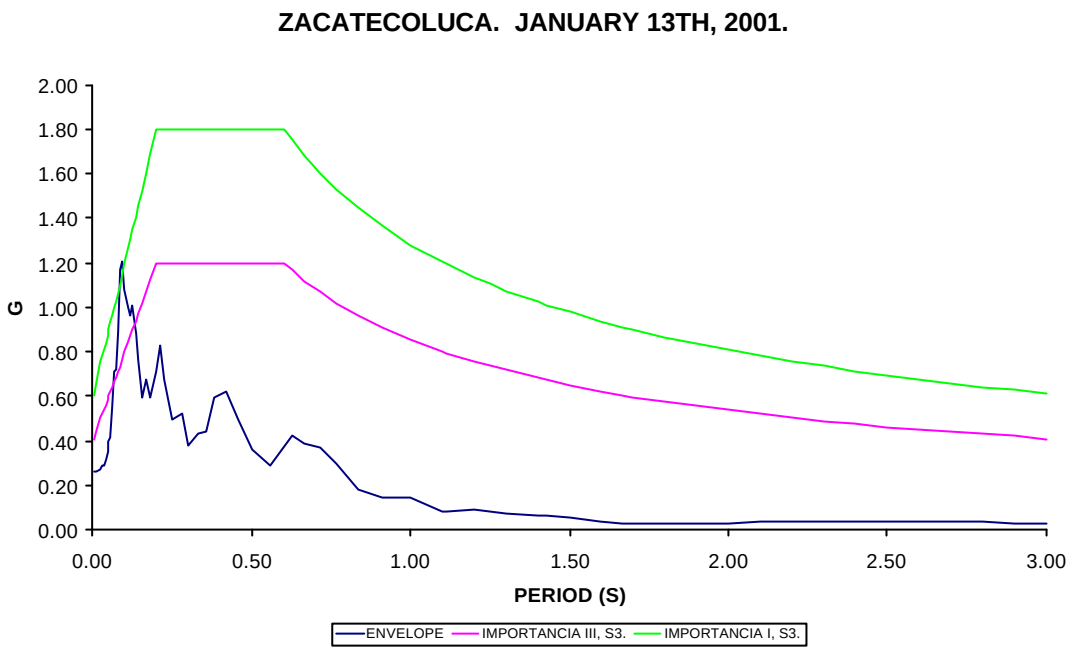

Figure 3. Envelope of the horizontal spectra of the 13 January accelerogram from Zacatecoluca compared to the spectrum from the 1994 design code for importance categories I and III.

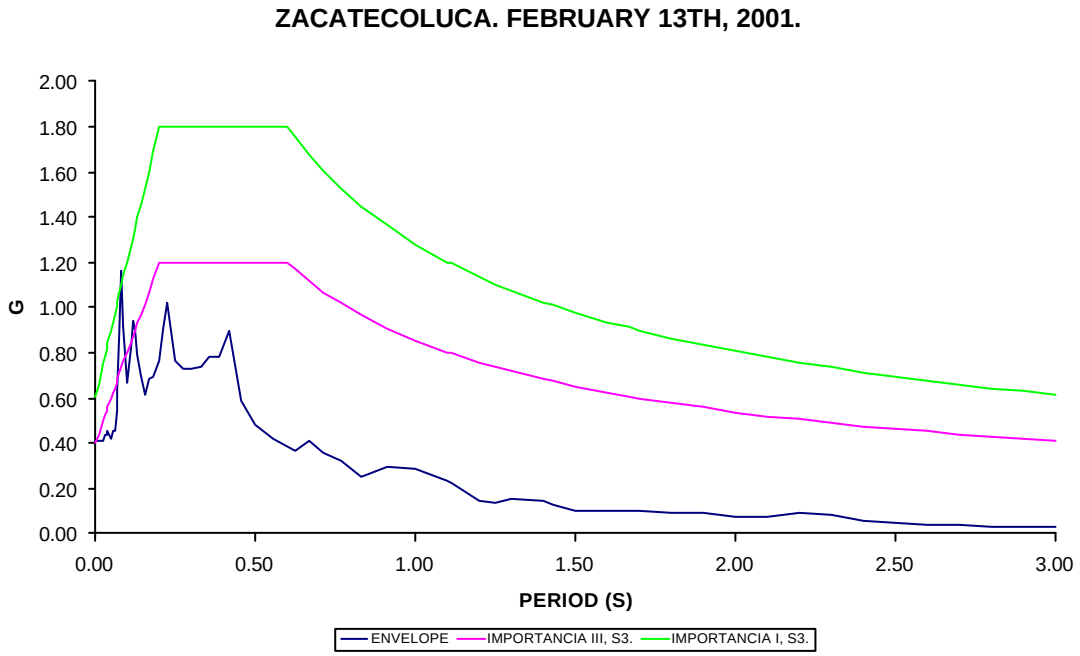

Figure 4. Envelope of the horizontal spectra of the 13 February accelerogram from Zacatecoluca compared to the spectrum from the 1994 design code for importance categories I and III.

The largest value of PGA recorded in the 13 January earthquake was in excess of 1.1g at the port of La Libertad, which was almost definitely the result of site amplification effects [27]; peak accelerations in San Salvador ranged from 0.25-0.30*g* and similar levels were recorded at Zacatecoluca. The highest acceleration recorded during the 13 February earthquake was 0.4g at Zacatecoluca; peak amplitudes recorded in the capital were only marginally above 0.1*g*. Figures 3 and 4 compare the spectra of the recorded motions at Zacatecoluca in the January and February earthquakes, respectively, with the spectra from the 1994 design code. The information available about the surface geology at most of the strong-motion sites is very limited but it is assumed, from the location of this station on the coastal plain, that the closest site category – of the four stipulated in the code – is S3. The code spectra are plotted for the limiting values of the importance factor reflecting use and occupancy of the structures. The plots show that with the exception of some isolated peaks at periods around 0.1-0.2 seconds, the code spectrum, even with the lower importance factor, is safely above the recorded motion and for periods beyond 0.5 seconds, very conservative. The recorded spectra from the two events are not very dissimilar, suggesting that the site response may play a very significant role in determining the nature of the recorded motion.

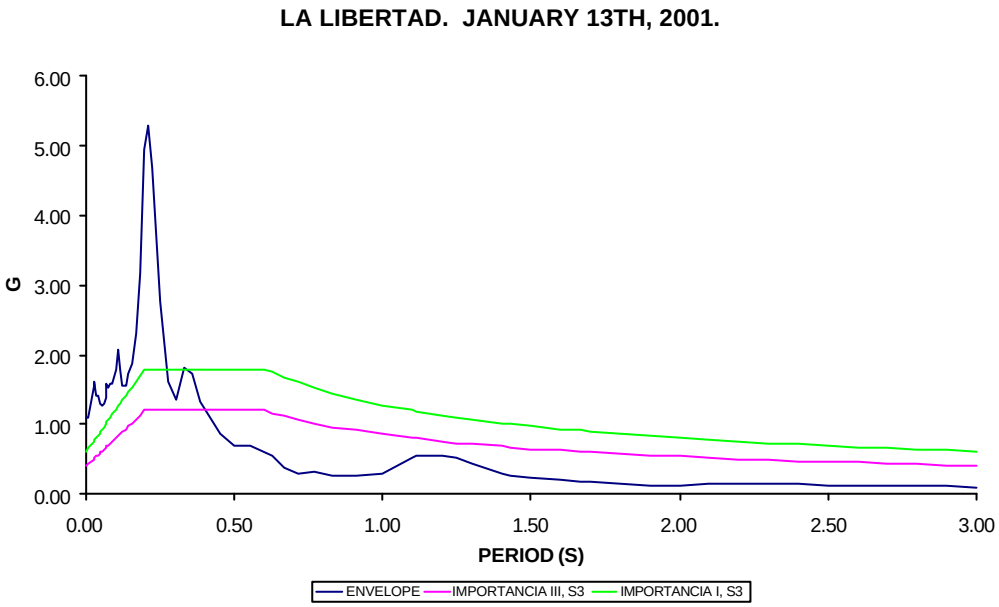

Figure 5. Envelope of the horizontal spectra of the 13 January accelerogram from La Libertad compared to the spectrum from the 1994 design code for importance categories I and III.

Figure 5 makes the same comparison for the spectra of the 13 January recording from La Libertad; the ordinate of the code spectrum at about 0.2 seconds is exceeded by a factor of more than 2.5, although at periods beyond 0.5 seconds the code spectrum is still safely conservative. This is the only record whose 5% damped spectral ordinates significantly exceed those of the code spectrum, and as mentioned previously, the very large short-period amplitudes at this location are very probably due to site effects [27]. Furthermore, structural damage in the port and town of La Libertad was very limited; the one-storey reinforced masonry building in which the accelerograph is housed (the local health centre), showed no signs of distress following the earthquake. Other buildings in La Libertad, whose natural

periods of vibration should have made them sensitive to the high peak in Figure 5, did not experience noticeable structural distress (Figure 6).

Figure 6. Vulnerable but structurally undamaged buildings in La Libertad, located less than 1 km from the site where a horizontal PGA of 1.1*g* was recorded.

DISCUSSION AND CONCLUSIONS

The earthquakes of 13 January and 13 February 2001 have confirmed that El Salvador is a region of very high seismic hazard. The areas affected by each of the two earthquakes generally conform to previous assumptions regarding the spatial distribution of hazard within the country. The recorded ground motions, however, do not show very clear differences in terms of the spectral shapes and to site response seems to play a significant role in the nature of the observed ground shaking. This points towards a need for microzonation studies in all urban areas and areas to be urbanised, extending the excellent study carried out by an Italian team for a large part of the capital after the 1986 earthquake. The ground motions recorded during the 2001 earthquakes suggest that the elastic response spectra in the current seismic design code are adequate and possibly even over conservative, although this may be fortuitous since the code also allows the use of behaviour factors corresponding to global ductilities that will often not be achieved by local engineering practices. In terms of the design motions, there is probably not yet sufficient data to definitively define separate response spectra and behaviour factors for crustal and subduction earthquakes. Nonetheless, there are compelling arguments for producing at least one zonation map that more accurately reflects the spatial variation of the seismic hazard. The current code treats all of the country south of the northern limits of the Great Interior Valley as being of uniform hazard. Both the historical data and the observations from these more recent earthquakes suggest that the hazard is actually negligible in the north of the country and is very high only in the areas around the volcanic centres that tend to be the focus of crustal earthquakes. Subduction earthquakes are more frequent offshore of western El Salvador than in the east, corresponding to a much slower rate of moment release in the portion of the Central American subduction zone in the region of central and eastern El Salvador and the Gulf of Fonseca [29]. There is also a greater concentration of earthquake foci in the western part of the volcanic chain, whence seismic hazard is highest in the southwest of El Salvador. Considerably more than half of the current population of 6.3 million is now crowded into the third of the national territory with highest seismic hazard: if the code zonation truly reflected this geographical

variation of the hazard, and there were consequent penalties in terms of construction costs and insurance premiums for locating housing and industry in this zone, this could help to motivate a redistribution of the population. At the moment, however, discussions regarding technical improvements to the seismic design code are largely academic because the codes have not generally been applied in construction practice [14] and there is still no official agency with responsibility for ensuring compliance with the requirements of the code. Even if the code were strictly imposed, however, to all new engineering constructions, it would not effectively address the three most significant components of the seismic risk in El Salvador. A major component of the risk is due to the high vulnerability of adobe houses: the code includes an appendix with guidelines on improving the seismic resistance of this building system, but the problem lies in disseminating this information to often isolated rural communities, where illiteracy is high. Another very important component of the seismic risk is a direct result of the high, and growing, hazard of earthquake-induced landslides. The code addresses issues of slope stability but effective stabilisation techniques for the brittle volcanic soils that dominate have not yet been identified [30]; the only effective response at the moment is effective land-use planning to prevent constructions in susceptible locations. There is no evidence that any such control is currently being applied. The third element of the seismic risk, not particularly evident in these earthquakes but likely to dominate in the next earthquake to affect the capital, is the effect of cumulative damage and inadequate repair and strengthening following earthquakes in this country where most structures can expect to experience at least two severe events during their design life.

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