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The role of source and site effects on structural failures due to Azores earthquakes



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ABSTRACT

The existing building stock in Azores islands (Portugal) was severely damaged during 1980 and 1998 earthquakes. Structural failure was probably caused by a combination of factors that are not yet well understood. Earthquake source characteristics, site effects and structural vulnerability may be some of those factors. However, it is very difficult to assess the influence of each factor on structural failure, mainly because recorded accelerograms used in nonlinear structural analysis are influenced by both source characteristics and site conditions. The only way to overcome this problem is to control each factor individually which can be done by using simulated accelerograms. In our previous work, stochastic ground motion simulations results were compared with earthquake records. Results seem to indicate that simulated accelerograms can match recorded accelerograms if proper source characteristics and geological site conditions are selected. In this work, simulated accelerograms were used for seismic nonlinear structural analysis. Simulations were carried out considering several 1980 Azores earthquake possible sources and for different geological site conditions. Simulated accelerograms were then used to evaluate the structural nonlinear behaviour of a reinforced concrete structure and of two masonry structures. The results of this work highlight the importance of site conditions and earthquake source characteristics to the determination of the design seismic actions of Azores islands. This work was performed in the scope of “Strong ground motion for Azores – SiGMA” project, financed by the Portuguese Science and Technology Foundation (PTDC/CTE-GIX/121957/2010).

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1. Introduction

The Portuguese Azores Islands are located in the middle of the North Atlantic Ocean, near the triple junction of the Euro-Asiatic, African and North American plate boundary. This region is capable of producing large magnitude events and has high seismic activity, related mainly with volcanic activity. The 1 January 1980 earthquake and the 9 July 1998 earthquake were the last two destructive events that affected Portugal.

The 1980 Azores earthquake was felt with an anomalous Mercalli modified intensity (MMI) distribution throughout the Terceira Island, with values varying between V and IX [1]. Studies using ambient vibrations have shown a good correlation

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between surface geology and observed structural damage [2]. Damage studies using basic nonlinear structural models also pointed out some correlation between soil characteristics and structural damage [3].

The 1998 Azores earthquake was strongly felt throughout Faial Island, where it reached maximum MMI intensities of VIII/IX. Site amplification of ground motions was also observed causing extensive damage [4].

Unfortunately, there are not many strong ground motion records of Azores earthquakes. The 1980 Azores earthquake was only recorded at Faial Island and the ground motion record exhibits a peak value of 53.51 cm/s^2 , but it is not complete [5]. The 1998 Azores earthquake was also recorded at Faial Island, at the same station, with an observed peak ground motion acceleration of 399 cm/s^2 [6]. This value is higher than the peak value prescribed for the Azores in the Eurocode 8 (EC8) Portuguese National Annex [7], which is 250 cm/s^2 for rock sites and 375 cm/s^2 for soft soils. This is one of the reasons why it is so important to carry out more studies to better understand the Azores seismic action. The use of earthquake simulation can be very useful, in this context.

The historical Angra do Heroísmo city centre was severely damaged during the 1980 Azores earthquake. This city area was composed essentially by masonry buildings. The existent reinforced concrete buildings performed quite well. However, some peculiarities have been observed and some questions need answers: why did a more vulnerable reinforced concrete structure have less damage than other designed to withstand an earthquake? Is this difference related to the earthquake characteristics? Or is related to site effects, because one was sited on a rock outcropping formation and the other on a soft soil?

Trying to answer this kind of questions, a multidisciplinary study was carried out. Some factors that have influence on seismic structural failure were studied, namely source characteristics, site effects and structural vulnerability.

To better control earthquake characteristics, stochastic earthquake simulations of the 1980 Azores earthquake were carried out for different site conditions and source characteristics. Several seismic nonlinear analyses of a reinforced concrete structure that sustained no damage during the 1980 Azores earthquake were performed using the simulated response spectra to evaluate the causes for this happening. Seismic nonlinear analyses of typical Azores masonry structures were also carried out to evaluate possible structural failures due to earthquake effects.

2. Stochastic ground motion simulations

Stochastic earthquake simulations considering geological site effects have been already carried out for Portugal [8,9]. The program SIMULSIS was used to carry out earthquake simulations for Azores. It is a user friendly freeware computer software for stochastic ground motion simulation, capable to reproduce earthquake accelerograms when proper source characteristics and site conditions are adopted [9,10].

It assumes that the fault plane is divided in N_F subfaults, each one considered as a point source event. A small earthquake is randomly generated for each subfault. In SIMULSIS the rupture spreads radially from the hypocenter, with a constant or a variable rupture velocity V_{ri} on each subfault i (Fig. 1).

Simulated time series results from a superposition of sinusoidal waves which are summed with a proper delay (Δt_i) and can be written as follows:

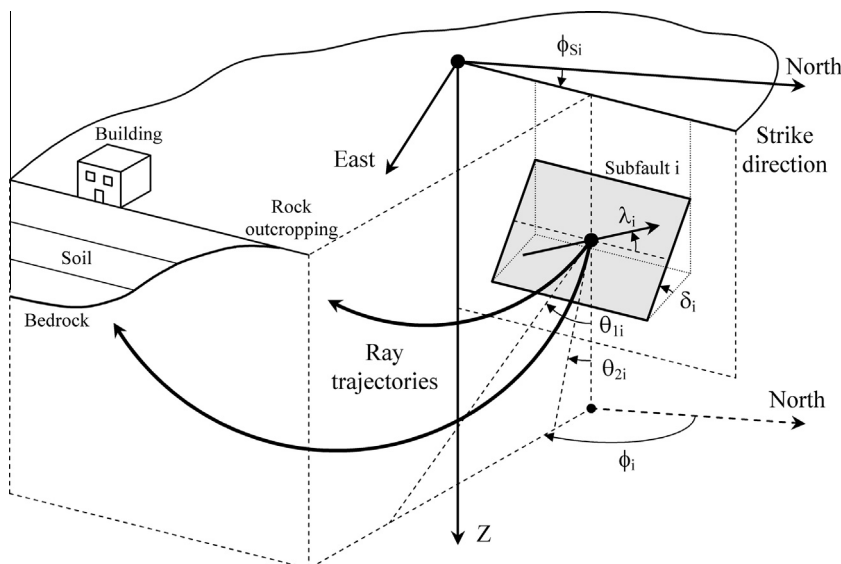


Fig. 1. Global SIMULSIS ground motion generation procedure.

$$a_{g(t)} = \sum_{i=1}^{N_F} \sum_{n=1}^{N_{\omega}} A_{i,n(t)} \cdot \cos(\omega_n t_i + \theta_{n,i}). \quad (1)$$

The wave amplitude $A_{i,n(t)}$ is the contribution of the point source i to the frequency ω_n (equal spaced at $\Delta\omega_i$), with random phase angles $\theta_{n,i}$, and

$$A_{i,n(t)} = g_i(t) \cdot \sqrt{\frac{2 \cdot \Delta\omega_i}{\pi \cdot T_F}} \cdot F_i(\omega_n, M_{0i}) \cdot P(\omega_n, R_i) \cdot H_R(\omega_n) \cdot H_S(\omega_n), \quad (2)$$

in which T_F is the total equivalent point source fault rupture duration, $g_i(t)$ is a deterministic envelope function, $F_i(\omega_n, M_{0i})$ is the point source spectrum of shear waves, $P(\omega_n, R_i)$ is a path attenuation function and $H_R(\omega_n)$ is a filter (function of a cut-off frequency f_{\max} and of a reduction parameter k_0) that accounts for the diminution of the high-frequency motions in a rock outcropping reference site. $H_S(\omega_n)$ is a nonlinear soil transfer function for S waves, obtained from an equivalent linear analysis of a one-dimensional “soil column” [9].

$F_i(\omega_n, M_{0i})$ is a function of the seismic moment of each subfault (M_{0i}), it is influenced by the radiation pattern $R_{\theta\phi i}$ of each subfault, which is a function of the strike (ϕ_S), the dip (δ), the rake (λ) and the azimuthal angle (ϕ) of subfault i , and it is a function dependent on the limits between two takeoff angles (θ_1 and θ_2) of seismic ray trajectories (Fig. 1).

Because of the random nature of wave phase angles, each SIMULSIS simulation gives a different result. For this reason, the response spectra presented in this work are the mean result of 100 simulations carried out for each site.

3. The 1980 Azores earthquake simulations

Borges et al. [11] studied the focal mechanism of the 1 January 1980 earthquake ($M_W = 6.8$). Based on this study, Estêvão and Oliveira [9] carried out several stochastic ground motion simulations using SIMULSIS program (Fig. 2). Results seem to agree with the earthquake observations.

In this work, SIMULSIS was used to simulate the 1980 Azores earthquake in Angra do Heroísmo, using the earthquake source proposed by Estêvão and Oliveira [9], but with different slip distributions and stress drop values.

3.1. Earthquake source characteristics

To evaluate the source characteristics effect on seismic structural failure, two source parameters were considered, namely the distance to an earthquake fault asperity and the stress drop value.

The 27 February 2010 Maule (Chile) earthquake suggested that the proximity to fault asperities can control structural failures, because the most damaged cities in Chile were close to two identified asperities [12]. The 11 March 2011 Tohoku (Japan) earthquake has reinforced the idea that strong effects due to local asperities, cause significant variability of ground motion parameters at short rupture distances and similar site conditions [13]. For these reasons, ground motion simulations were carried out with the source parameters used in earlier studies for the 1980 Azores earthquake [9], but isolating the previous adopted asperities for each new case slip distribution considered in this study (Fig. 3).

Earthquake fault slip distribution number 1 considered the existence of just one asperity (asperity 1 is located at 48 km from Angra do Heroísmo), and number 2 considered the existence of the other asperity, closer to Angra do Heroísmo (35 km). Asperity 1 is bigger in area (11/6 of asperity 2) but with a lower fault slip value (3 times lower).

Past earthquakes seem to indicate a great variability on stress drop values and that stiffness and stress drop distributions appear to be controlled by dimensions of the asperities [14].



Fig. 2. The 1980 Azores earthquake rupture location adopted for the simulations.

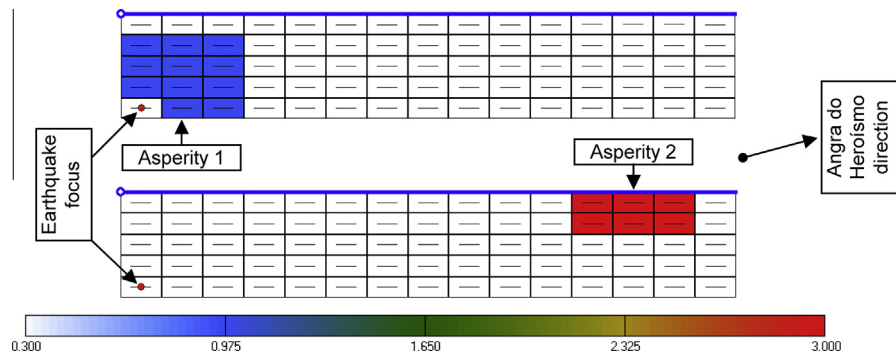


Fig. 3. Source fault slip distributions adopted for the simulations.

In this work two stress drop values were adopted: 30 bar, which was the value adopted in previous studies for the 1980 Azores earthquake [9], and a value of 150 bar to evaluate the influence of a stress drop increase in structural damage.

3.2. Site conditions

The large amount of information gathered after the 11 March 2011 Tohoku (Japan) earthquake, has shown the importance of geological site conditions on ground motions amplification [15]. For this reason, it is important to assess the influence of local soil characteristics on structural failures.

In past studies, SIMULSIS was used with success to capture the nonlinear soil behaviour due to several earthquakes [9,10].

In this work, simulations were carried out using different earthquake source characteristics and stratigraphic soil profiles. Nine soil profiles were selected for ground motion simulations (Fig. 4), which are representative of the geology of Angra do Heroísmo city centre [16].

The physical characteristics adopted for soil profiles used for the 1980 Azores earthquake simulations were based in Teves-Costa and Veludo [16] values. However, a variable shear wave velocity (parabolic) between the minimum and maximum values of that study was considered. This leads to a slightly different surface top 30 m mean shear wave velocity ($v_{s,30}$). Stratigraphic profiles 2, 6, 7 and 8 can be classified as EC8 ground type B and the others as EC8 ground type C [17].

3.3. Simulation results

The mean response spectra values ($\xi = 5\%$ damping) of 100 simulations carried out for each soil profile (1–9) and for each source characteristics (fault slip distributions 1 and 2) are presented in Figs. 5–8. Simulations for a rock outcropping reference site (EC8 ground type A) were also carried out and presented.

4. Structural vulnerability

Some structures had survived the 1980 Azores earthquake with only minor damage, while others have presented extensive damage or collapse, so it is important to figure out what is the overall contribution of structural vulnerability to the earthquake structural failures when combined with different earthquake source characteristics and geological site conditions.

4.1. Reinforced concrete structures

As described in previous studies [18], the reinforced concrete structure of “Monte Brasil” maritime signal house, in “Angra do Heroísmo”, did not suffer any visible damage. However, the city hospital, with a reinforced concrete structure suffered moderate structural damage on the ground floor columns, although it has been designed to sustain earthquakes [18].

The “Monte Brasil” maritime signal house had square columns (0.22×0.22 m) and rectangular beams (0.22×0.32 m). The column longitudinal reinforcement was $\phi 20$ (20 mm) bars with yield strength of 235 MPa and steel hoops of 5 mm in diameter at 30 cm spacing [18].

A pushover nonlinear analysis was performed using program SeismoStruct [19] to capture the overall seismic resistance. The control point was located at the roof of the building. The structural model and the obtained capacity curve are presented in Fig. 9.

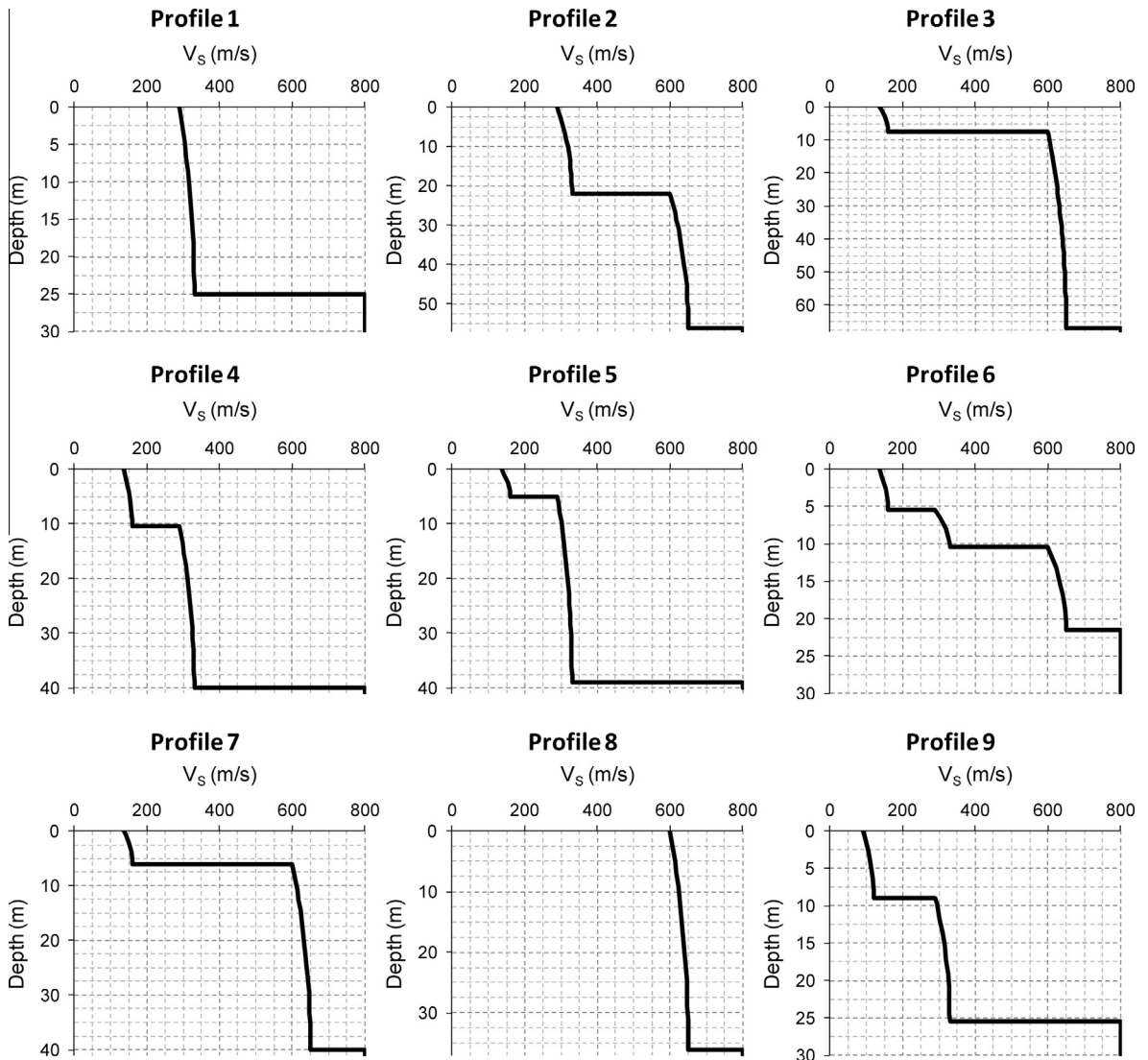


Fig. 4. Soil column shear velocity profiles selected for the 1980 Azores earthquake simulations.

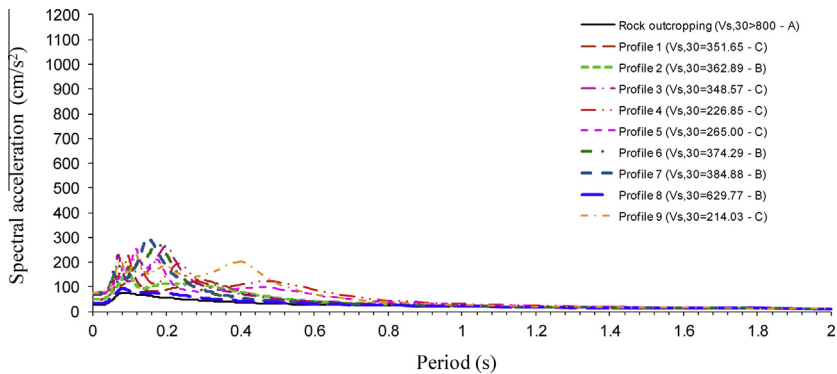


Fig. 5. Simulation response spectra results for slip distribution n. 1 and stress drop of 30 bar.

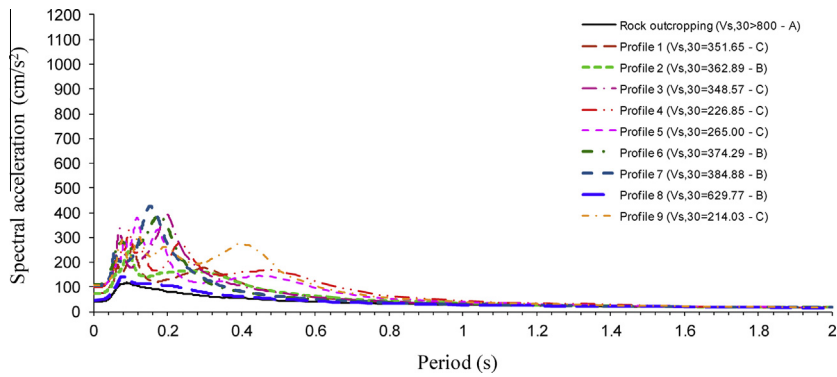


Fig. 6. Simulation response spectra results for slip distribution n. 2 and stress drop of 30 bar.

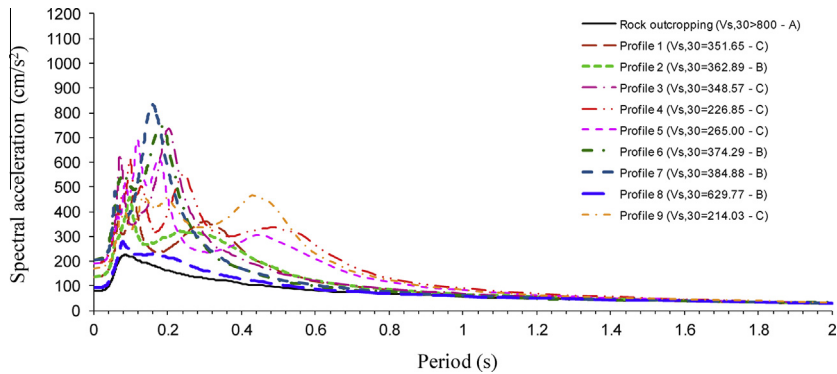


Fig. 7. Simulation response spectra results for slip distribution n. 1 and stress drop of 150 bar.

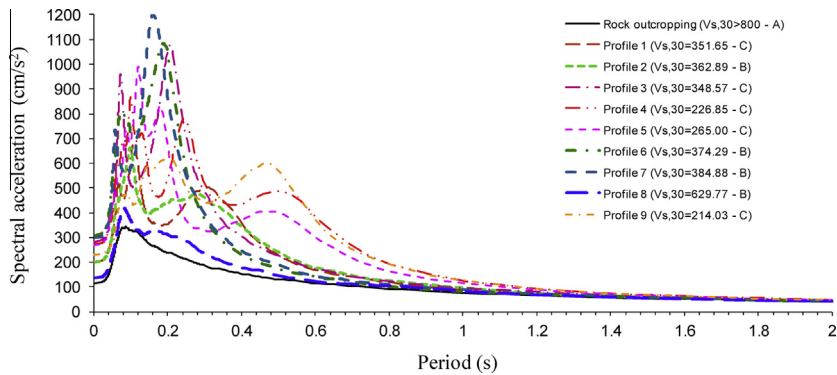


Fig. 8. Simulation response spectra results for slip distribution n. 2 and stress drop of 150 bar.

4.2. Masonry structures

Angra do Heroísmo masonry buildings were constructed from the XVII century until the decade of 1950–1960. Masonry walls were made of rubble stones of local volcanic material. During 1980 Azores earthquake masonry buildings presented damages and collapses in the central southern part of the town [2].

Structural failures often involve wall out-of-plane collapse. In-situ tests were carried out in the past to evaluate the resistance of typical Azores masonry buildings [20,21]. These test results were used to calibrate the nonlinear structural analyses carried out in this work.

The out-of-plane masonry walls capacity curve of a one-storey and a two-storey buildings was determined with the program Fiberbloc2D [22].

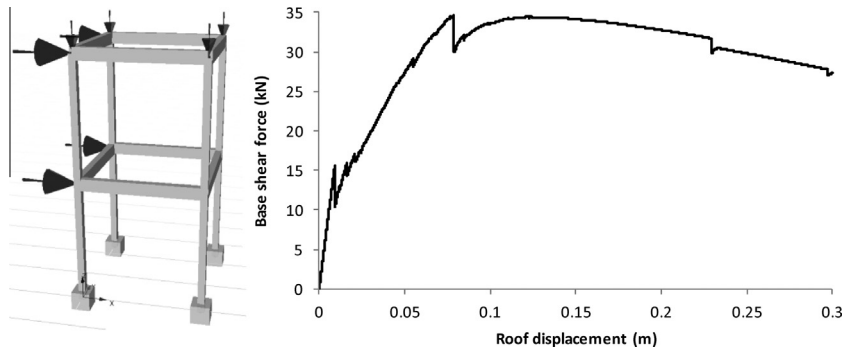


Fig. 9. The reinforced concrete structural model and capacity curve.

For the one-storey building vulnerability study, one masonry building used in Azores previous in-situ tests was selected (the S_01 specimen) [20]. The geometrical and material characteristics of the adopted model were the same as for the previous tested masonry wall. The obtained analytical results are presented in Fig. 10 and they are similar to the in-situ test results of the mentioned previous work [20].

The vulnerability of an Azores two-storey building was also assessed. A building that was subjected to a previous experimental evaluation was chosen (the CS_01 specimen) [21]. The obtained analytical capacity curve is presented in Fig. 11.

5. Earthquake failure analysis

There are many methods for seismic buildings failure evaluation. In this work we used the ATC-40 capacity spectrum method [23]. This is a nonlinear static analysis procedure that provides a graphical representation of the expected seismic performance of the existing structure by the intersection of the structure’s capacity spectrum with a response spectrum representation of the earthquake’s displacement demand on the structure (Fig. 12).

The capacity spectrum is the capacity curve transformed from shear force versus top building displacement coordinates into spectral acceleration (S_a) versus spectral displacement (S_d) coordinates, for a given period (T), being

$$S_d = \left(\frac{T}{2\pi}\right)^2 \cdot S_a. \tag{3}$$

An equivalent viscous damping is used to obtain the reduced demand spectrum, which is based on the inelastic capacity of building, and is equal to

$$\zeta_{eq} = \zeta + \zeta_0. \tag{4}$$

The equivalent viscous hysteretic damping (ζ_0) can be obtained from the bilinear capacity spectrum (Fig. 12), in which

$$\zeta_0 = \frac{1}{4\pi} \cdot \frac{E_D}{E_{s0}} = \frac{2}{\pi} \cdot \frac{S_{ayi} \cdot S_{dpi} - S_{dyi} \cdot S_{api}}{S_{api} \cdot S_{dpi}}. \tag{5}$$

Failure evaluation due to 1980 Azores earthquake was carried out for buildings located in Angra do Heroísmo. Four different source characteristics were considered with the same earthquake magnitude, epicentre location and fault dimensions (Figs. 2 and 3), nine soil profiles (Fig. 4), and three buildings. One building was a reinforced concrete structure (Fig. 9), and the other two were masonry buildings (Figs. 10 and 11). The combination of different earthquake stress drops, slip distributions, soil profiles and type of structures, resulted in a total of 108 case studies.

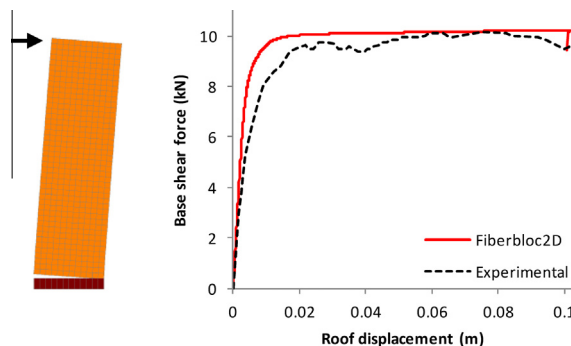


Fig. 10. The one-storey masonry building structural model and capacity curve.

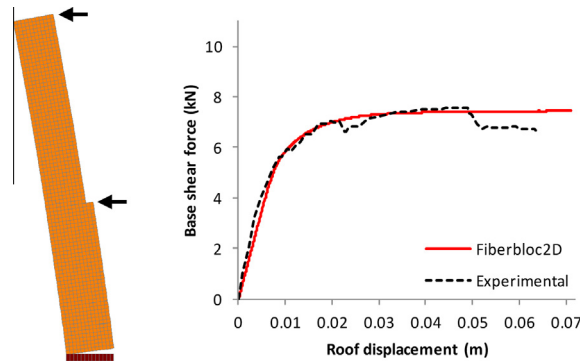


Fig. 11. The two-storey masonry building structural model and capacity curve.

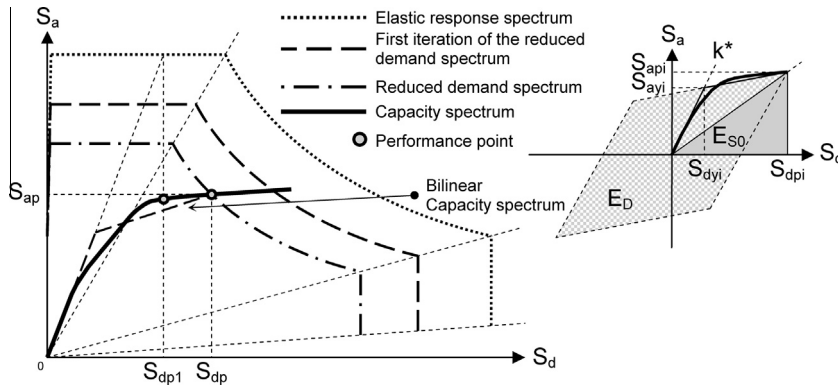


Fig. 12. ATC-40 capacity spectrum method procedure scheme.

The worst case earthquake scenario was obtained with the higher earthquake stress drop (150 bar), the closer asperity location (slip distribution 2) and soil profile number 4. The obtained results for the three structural types are presented in Figs. 13–15. In this case, slight damage, heavy damage and moderate to heavy damage was observed for the reinforced concrete structure, for the one-storey masonry structure, and for the two-storey masonry structure, respectively.

The best case earthquake scenario was obtained with the lower earthquake stress drop (30 bar), the farther asperity location (slip distribution 1) and soil profile number 8. Results are presented in Figs. 16–18. No damage whatsoever was obtained for all the three studied type of structures, because they behave elastically.

6. Discussion

Earthquake simulation results seems to show that the combination of source and site effects have a major influence on the ground motion level. In Fig. 19 it is possible to observe the huge differences between the minimum and the maximum obtained values.

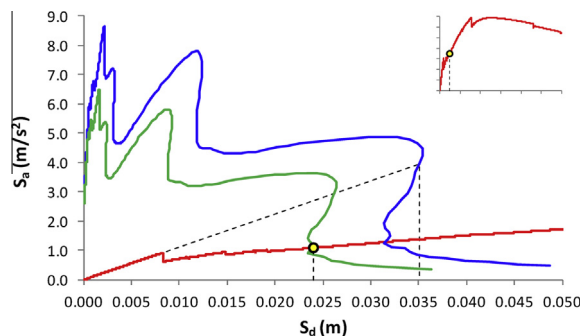


Fig. 13. Performance point determined for the reinforced concrete structure (worst case scenario).

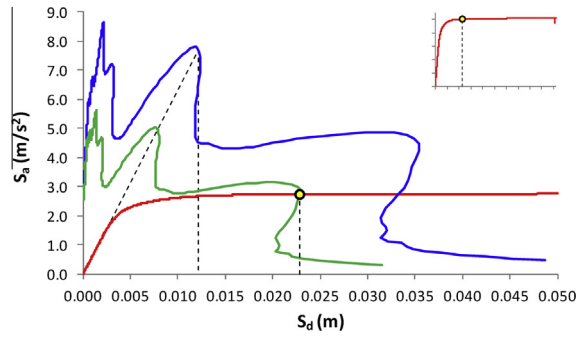


Fig. 14. Performance point determined for the one-storey masonry structure (worst case scenario).

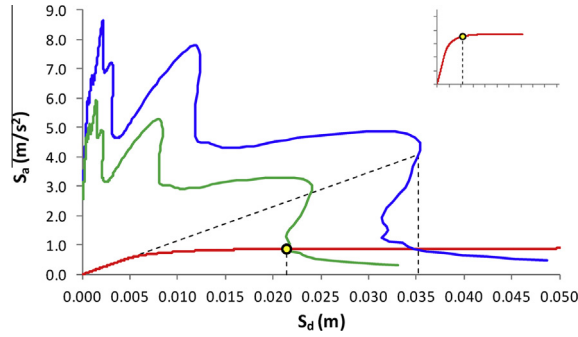


Fig. 15. Performance point determined for the two-storey masonry structure (worst case scenario).

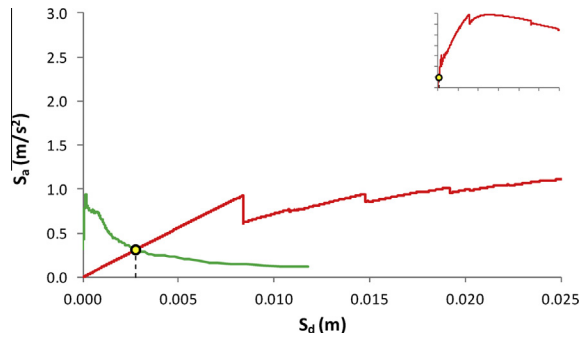


Fig. 16. Performance point determined for the reinforced concrete structure (best case scenario).

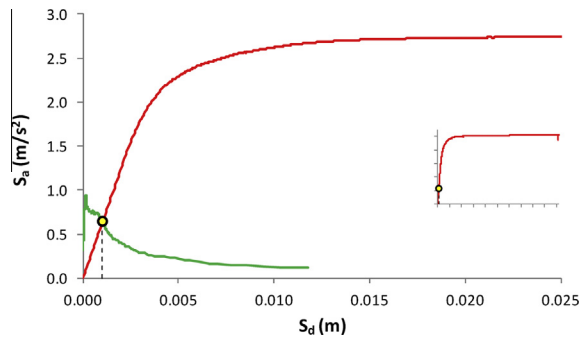


Fig. 17. Performance point determined for the one-storey masonry structure (best case scenario).

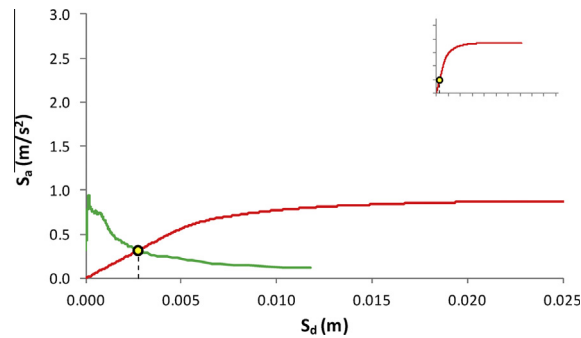


Fig. 18. Performance point determined for the two-storey masonry structure (best case scenario).

Minimum values were obtained with the lower earthquake stress drop (30 bar), the most distant asperity location to Angra do Heroísmo (slip distribution 1) and the stiffer soil profile (profile 8). On the other hand, maximum values resulted from the combined effect of a higher stress drop (150 bar), a closer asperity location (slip distribution 2) and a softer soil (profile 4).

When considering only the source effects, simulation results show that an increase on the earthquake stress drop value will increase spectral values for all spectral acceleration values. The maximum and the minimum increase factors when considering a stress drop of 150 instead of 30 bar is presented in Fig. 20. It is possible to observe that spectral increase factors (with a maximum of 3.59) are not proportional to the stress drop increase value (which is five times bigger), namely as result of nonlinear soil response.

The influence of asperity location is also evident. A closer asperity location combined with a higher fault slip value also increases spectral acceleration (Fig. 21).

The soil condition effects seem to be very important. Based on the obtained simulation results, it is possible to conclude that soil profile characteristics have a major influence on spectral amplification results. The maximum obtained amplification for peak acceleration (for $T = 0$ s), are similar for both EC8 type C and B studied soil profiles. However, softer soils (type C) exhibit a higher maximum spectral amplification and for higher period values (Fig. 22).

The uncertainty due to soil conditions seems to be a very important epistemic uncertainty, which have influence in seismic hazard analysis results (see Fig. 22). This uncertainty can only be minimized with a good characterization of site soil profiles. However, the uncertainties about source characteristics, such as fault slip distribution and stress drop values, are aleatory uncertainties that cannot be reduced, and they also have influence on seismic hazard results (see Figs. 20 and 21).

The uncertainty about the vulnerability of masonry walls is also an important issue. The differences between experimental and analytical results observed in Figs. 10 and 11 are an example of the difficulties of reproducing the exact nonlinear behaviour of real structures when using numerical models.

The in-plane resistance of masonry walls is usually higher than the out-of-plane resistance. This was the main reason why only out-of-plane wall behaviour was studied.

The determined damage due to earthquake simulations shows that the studied masonry buildings are more vulnerable than the studied reinforce concrete structure. For the worst case scenario, which is the same for the three analysed structures, a minor damage was obtained for the concrete structure and a moderate to high damage for the masonry structures. The studied masonry buildings were tested in Faial Island after the 1998 Azores and were sited in an area close to the earthquake epicentre, which suffered much damage. So, these surviving buildings are probably less vulnerable than others that

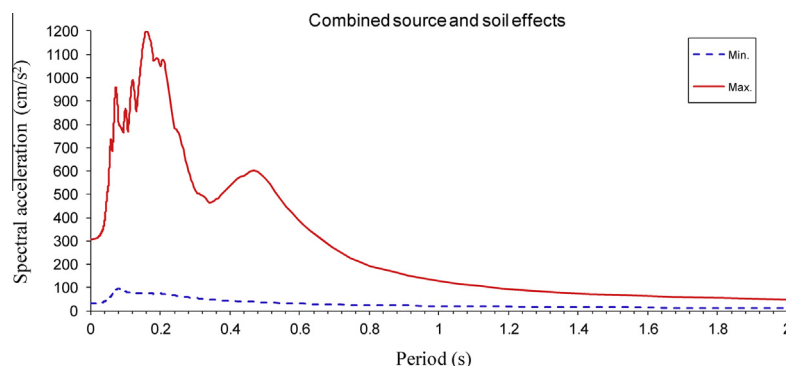


Fig. 19. Minimum and maximum spectral acceleration results when combining source and site effects.

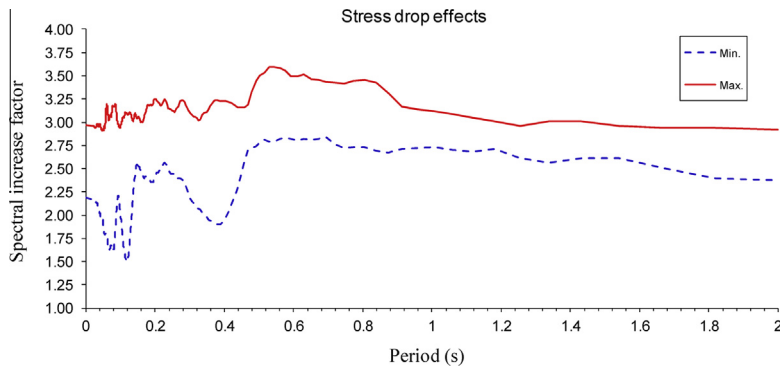


Fig. 20. Minimum and maximum spectral acceleration increase factors due to a higher stress drop (150 bar).

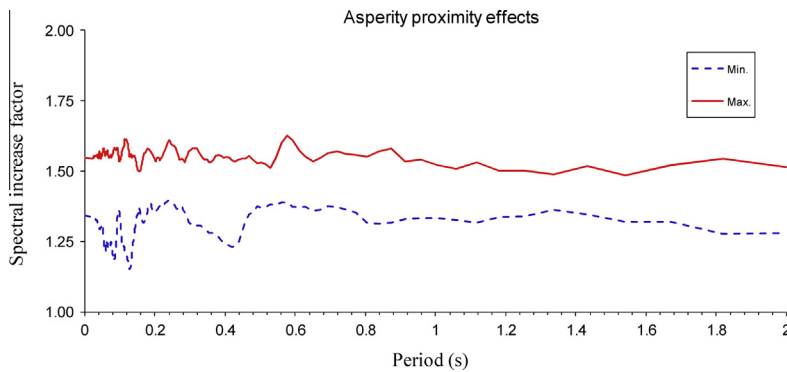


Fig. 21. Minimum and maximum spectral acceleration increase factors due to a closer asperity location.

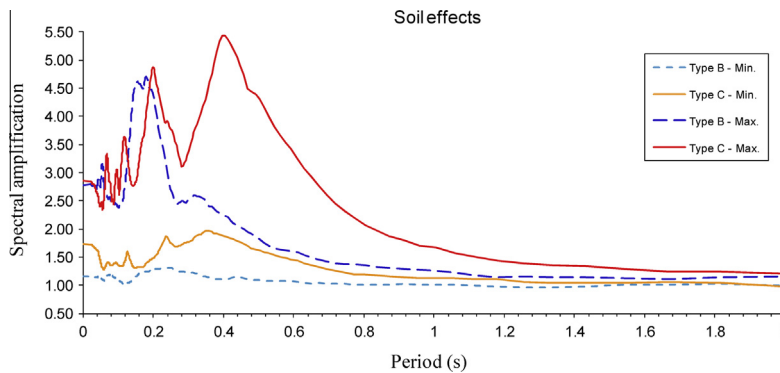


Fig. 22. Minimum and maximum spectral acceleration amplification obtained for EC8 soils type C and B.

collapsed in consequence of the earthquake. This means that for the worst earthquake case scenario obtained in this study, less resistant masonry buildings would probably totally collapse.

For the better case earthquake scenario, which is also the same for all the analysed structures, no damage was obtained.

7. Conclusions

The observed earthquake damage distribution in Angra do Heroísmo due to the 1980 earthquake (masonry structures sited on soft soils presented more damage) seems to be well correlated with site amplification and structural behaviour obtained in this work.

It seems that structural failures due to the 1980 Azores earthquake are probably related to the vulnerability of masonry structures located in sites which produced high ground motion amplification, namely the soil profile number 4.

The low stress drop evidenced in the 1980 Azores earthquake was probably the reason why reinforced concrete buildings suffered negligible damage. Simulation results also showed that the proximity to an asperity can increase ground motions.

Overall, it seems that the combination of source and site effects can induce huge variations on seismic action and can be one of the reasons for structural failures. This conclusion points out that design seismic actions should include these earthquake effects, in a nearby future, considering their importance.

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