AZORES '80

40 MEETING

06-07 October 2020

TÉCNICO LISBOA · UAc UNIVERSIDADE DOS AÇORES · UNIVERSIDADE DE ÉVORA

INTERNATIONAL MEETING
40 YEARS OF THE 1980 AZORES EARTHQUAKE

Congresso internacional
40 anos do sismo dos Açores de 1980

PROCEEDINGS BOOK

UNIVERSITY OF ÉVORA

PROCEEDINGS BOOK

Outubro 2020

Welcome Address

It is our great pleasure to organize the 40 Years of the 1980 Azores Earthquake (40|80) that will be held online between 6th and 7th October 2020.

As we move the 40|80 completely online, we look forward to offering you the same vibrant programming, impactful networking, and opportunities to reflect and connect over the emerging and salient topics in our field.

The theme of the 40|80 is to remind the 40 years of a devastating earthquake that affect mainly Terceira Island but also Graciosa and São Jorge Island. At 40|80, we would promote a state-of-the-art of the seismicity in general but also topics like volcanic seismicity, tsunamis, historical seismicity, crustal deformation, tsunamis, seismic hazard and risk. Since earthquakes cause economic and social losses, topics like case studies on the rehabilitation of buildings, retrofit techniques of heritage monuments, an overview of Eurocodes and construction codes, social and economic aspects are paramount to understand their impact and how to mitigate them. Thus, we would like at 40|80 to provide the time and place where attendees from around the world can share their experience and knowledge to build disaster-resilient societies and to create new directions through integrating various fields

The virtual meeting of 40|80 will include sessions and keynotes.

Organization

Organizing Committee:

Full Professor Carlos Sousa Oliveira – Chair – Instituto Superior Técnico, Lisboa, Portugal

Doctor João Fontiela – Vice Chair – University of Évora, Évora, Portugal

Professor Francisco Cota Rodrigues – University dos Açores, Azores, Portugal

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Full Professor Mourad Bezzeghoud – University of Évora, Évora, Portugal

Support

The 40|80 is a joint organization of the following institutions:

CONTENTS

40 years after the 1980 Azores earthquake: impacts and learning

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ABSTRACT

The January 1, 1980 earthquake in the Azores was the event with greatest material impact in Portugal since the 1755 earthquake. The most affected islands were Terceira, mainly on its west side and the city of Angra do Heroísmo, but also São Jorge and Graciosa. The death toll was around 70, hundreds of injuries and tens of thousands of homeless. Five years later almost 80% of the housing stock was rebuilt and population back in their rehabilitated homes or in new urban developments. Ten years later these numbers extended to almost 100% and most of the monumental park was completed. Many technical, scientific and cultural events took place along this period, and there is a great amount of information produced, including projects, reports and publications. The earthquake of July 9, 1998 in Faial, Pico and São Jorge, which caused also a great deal of societal disruption, kept the interest and discussion for another decade on matters related to earthquakes and the way to deal with that type of disgrace. However, the last 10-15 years are gone without much discussion. The 40|80 meeting will try to contribute to bring back the topic, promoting a reflection about the earthquake and reconstruction, as well as the evolution of knowledge in seismology, earthquake engineering, construction methods, and the management of events of this type. It is important to know well the premises that guided the action in the post-80 and how prepared we are for a potential earthquake that will occur in the future.
40 years after the event we go over several aspects deemed of more importance and how we can take the lessons got from all these years to increase the resilience against future events that may occur not only in the Azores but also in the Continent.

Keywords: Earthquake 1980, Azores, Impacts, DRM

INTRODUCTION. THE EARTHQUAKE

The 1980 earthquake occurred at a time of social stagnation 6 years after "the 25th of April 1974 Revolution in Portugal". Autonomy was taking its first steps when the Islands of Terceira, São Jorge and Graciosa were shaken by a strong earthquake, of the greatest magnitude known until then in the Azores Archipelago.
It was at 3 pm on the first of January on a calm afternoon with a great amount of people finishing their lunches. Not everyone was immediately aware of the impact inflicted because at the time there was no way to contact other people to find out what had happened elsewhere. Each one worked for itself without any chance of communication between people. National and international seismographic stations reported a strong earthquake occurring somewhere in the Central Group of the Archipelago.
Only when people went to the street and began to see the state of destruction of the houses, did they begin to know what was happening. Indeed, a Magnitude 7.2 earthquake (Richter) had just occurred with an epicenter between the islands of Terceira and São Jorge in a location that until then was not considered of great importance. It is now known that there is a fracture with the expression SE-NW, as it was identified from the aftershocks that followed and defined a small point cloud with the referred trend. Even today, this tectonic fracture is not properly identified. Earthquakes prior to this in the Terceira area had epicenters SE of Praia da Vitória, towards Serreta or in the interior of the island.

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The event was very disruptive in all senses for the unprepared population. The first hours were anguish as communications fell and the night without electricity was approaching. It was important to care of the 70 deaths, the hundred injured and the tens of thousands homeless. In many places it was impossible to move due to the blockage of many streets where façades or part of them collapsed. It wasn't until the next day that authorities look into settling immediate management. It was impossible to call technicians to help with surveys and the great need was to help the victims and the wounded.

Over time, political powers began to organize themselves to establish camps to shelter displaced populations, to prepare meals for all who lost their homes, to clean the streets in order to create mobility. The damage survey of the Casco's of Angra do Heroísmo is shown in Fig. 1a, where we depict the amount of destruction.

Figure 1. a) damage in downtown Angra do Heroísmo; b) New settlements 10 years later (Oliveira et al., 1992).

The "battle" against adversity started by arranging roads and pushing networks to function and reaching a normality in the movement of people. Special tent camps were set up. Soon after, the reconstruction of the dwellings for residence began as well as a few installations of critical need. Only much later the monumental park was taken care. The first 5 years after the earthquake were of great turmoil in which an enormous phase of construction of the thousands of houses that were damaged by the earthquake proceeded. The reconstruction started practically right after the cleaning and definition of the main intervention rules. Preference was given to the so-called "self-construction" in which the main players were the owners of the houses to whom construction material was distributed and given some simple rules for an earthquake resistance procedure. In many cases, the intervention was used to expand one or the other room and provide the houses with sanitary facilities connected to a system of municipal collectors. For the homeless without possibility of returning to their places, new urban settlements were built (Fig. 1b).

From a more theoretical point of view, there were many "experiments" not only dealing with social aspects, but also with political and administrative issues. Much work has been done around two fundamental axes: maintenance of the general appearance of the city in the same place, and ensuring a minimum of resistance to seismic actions to avoid the repetition of such a disaster. This culture-security binomial was very difficult to

manage at a time when the aspects of keeping traditional urban nature started being discussed. Angra do Heroísmo was pioneering in several aspects dealing with new concepts of patrimonial values and was elected "Património Cultural da Humanidade".

40 YEARS OF LIFE

Many technical, scientific and cultural events took place along this period, and there is a great amount of information produced, including projects, reports and publications. Among the most important ones are the "Problemática da Reconstrução…" (Cunha-Oliveira Ed. 1983) and the "Monograph…" (Oliveira et al., Eds., 1992). While "Problemática" is a compilation of many memories of the Azorean Culture, the Monograph tries to summarize the most salient technical aspects of what had happened and the way in which the reconstruction was carried out. Many of the answers to the problems that occurred and how they were overcome are contained in the various chapters of this monograph. The earthquake of July 9, 1998 in Faial, Pico and São Jorge, which caused also a great deal of societal disruption, kept the interest and discussion for another decade on matters related to earthquakes and the way to deal with that type of disgrace. The compilation made on "Sismo de 1998…" (Oliveira et al. Ed (2008) is a good example of dissemination. However, the last 10-15 years are gone without much discussion on the premises that guided the action in the post-80, the differences for the treatment of the 1998 crises and to know how prepared we are for a potential earthquake. Where does it stands the saying "Azores is a live laboratory in Disaster Risk!"

A few organizations developed well their own structures (Seismological Networks, Civil Protection policies), several scientific publications were made along this last period of time (most under the supervision of international colleagues), but many are not well disseminated, even in the scientific community. Very few Projects, Dissertations, local conferences, field campaigns, etc., were made lately!

Let us just enumerate a few topics deserving the attention.

Earth Sciences (Geology, Seismology, definition of seismic hazard and ground motion, etc.), Earthquake Engineering (Soil Dynamics, materials, old and modern, mathematical modelling and monitoring, construction techniques, etc.), Disaster Risk Management (DRM, 2017) for the immediate actions (satellite images, drones, surveys, etc.) and for the recovery process, Sciences for Communication and Education, Sciences for patrimonial and cultural values, impact studies on various different issues (housing, lifelines, critical infrastructures, population behavior and resilience), and for sustainability, are among those topics where we should understand what has been accomplished and which needs require further development and action.

Getting in more detail, we think that the approval of a new order of code for construction practice (EuroCodes - NP EN 1998 -1:2010 (2019)) should be seen with great care in order to check its viability and the consequences for the construction in general, and the way to conciliate patrimonial values with earthquake safety. The new technologies for construction and monitorization carried out along the aging process are of great importance and cannot be seen separately from the climate changes or resilient cities.

Early Warning Systems (for tsunami arrivals, for shaking, or for indirect effects as landslides as a sequence of shaking), are becoming state-of-the-art pro-active tools that deserve a good look in the near future.

The Enquire launched to the populations older than 40 years to tell their story about the 1980 event (http://sismo1980.ipma.pt) reveals a lot of interesting phenomena that were not considered important at the time. For example, the number of coincidences in responses cannot be overlooked, they really happened and experts in different fields of knowledge (seismologists, engineers, social scientists) should be able to give some explanation. A similar situation has been observed in relation to the 28 February 1969 earthquake (http://sismo1969.ipma.pt) which recalled the 50 anniversary last year. In both cases the laud noise prior to the arrival of strong shaking is a reality ignored until now but referred in many old treatises. Or how people react during and immediately after the event deserves a great deal of human perception to disasters. To finalize we would like to transcribe a few topics recommended by Rodrigues da Câmara (2010) in his Dissertation in relation to re-habilitation in the Azores:

"Analyze the chemical incompatibility between cement, regional stone and primitive mortar;
• Develop solutions that allow to increase the vapor permeability of reinforced plaster, bearing in mind the climatic conditions of the Azores, namely the high relative humidity levels;
• Develop a manual of good rehabilitation practices in the Azores, which brings together a set of techniques and integrated solutions, addressing concerns of a structural, thermal and acoustic nature as a whole and duly adapted to the regional reality, a little as it was developed by several technicians, but more focused on architectural and monumental aspects".

Other topics, such as "big data", Artificial Intelligence", genetic algorithms, the New materials and the "associated carbon footprint", etc., very fashionable nowadays, cannot be out of a list of new contributions.

FINAL CONSIDERATIONS

The 40|80 meeting will try to contribute to bring back the topic, promoting a reflection about the earthquake and the reconstruction, as well as how to deal with disaster management of events of this type. It is of great importance to understand well the past models of management and be prepared for the next event and check how seismology, earthquake engineering, old and new construction methods, etc. can help in this desideratum.

REFERENCES

Cunha Oliveira, A. (Editor) (1983). "A Problemática da Reconstrução – sismo de 1 de Janeiro de 1980", VI Semana de Estudos, Instituto Açoriano da Cultura, Vol. 1 e 2. (in portuguese).

Oliveira, C.S., Lucas, A.R., Guedes, Correia J.H. (Editores) (1992). "Monografia sobre os 10 Anos do Sismo de 1 de Janeiro de 1980 nos Açores". Edição SRHOP/LNEC. (in portuguese).

Oliveira, C.S., Costa, A.G., Nunes, J.C. (Editores) (2008). "Sismo 1998 – Açores. Uma década depois". Edição SPHRISA. Horta.

DRM 2017, Oliveira, C.S. et al. (2017). Sub-Chapter 5.3 "Recovery and Avoiding New Risk" (C.S.Oliveira Lead Author), Chapter "Disaster Risk Management", Joint Research Center (EU) in "Sendai Framework for Disaster Risk Reduction 20152030", in Poljansek, K., Marin Ferrer, M., De Groeve, T., Clark, I., (Edits) doi:10.2788/688605, JRC102482.

Rodrigues da Câmara, F.M.V. (2010). Tese de Mestrado, FEUP.

NP EN 1998 -1:2010 (2019). DN n.º 21/2019 de 17 de setembro, DR, 2.ª série, Parte C, nº 178 (NP EN 1998 -1:2010 Eurocódigo 8 -Projeto de estruturas para resistência aos sismos - Parte 1: Regras gerais, ações sísmicas e regras para edifícios).

http:// sismo1969.ipma.pt (consulted 5 Sept 2020) http://
sismo1980.ipma.pt (consulted 5 Sept 2020)

Crustal structure and earthquakes in the Azores Archipelago: complex faulting, magmatic perturbations and underplating

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ABSTRACT

We inverted teleseismic Rayleigh wave ellipticity measurements for 1-D shear wave speed (Vs) crustal models of the Azores Archipelago. Moreover, we tested these new models by using them in independent earthquake source inversions of local seismic data and demonstrated that our models improve the waveform fit compared to previous models. We found that by combining local and teleseismic data, our earthquake source models show a lower variability than in catalogues. We also studied in detail the Mw 5.9 2013 April 30 Povoação basin earthquake and found that it exhibits a persistent non-double-couple component of ~40–60 per cent, which is not due to a volumetric change. We suggest that it is potentially due to geometrically complex faulting in the Povoação basin, notably curved faults.

Our analysis showed that data from the westernmost seismic stations in the Azores require a shallower Moho depth (~10 km) than data from stations in the eastern part of the archipelago (~13–16 km). The 1-D Vs models obtained beneath the westernmost seismic stations also showed higher wave speeds than for the easternmost stations, which correlates well with the ages of the islands except Santa Maria Island. We interpret the relatively low Vs profile found beneath Santa Maria Island as resulting from underplating, which agrees with previous geological studies of the island. Compared to a recent receiver function study of the region, the shallow structure (top ~ 2 km) in our models shows lower shear wave speed, which may have important implications for future hazard studies of the region.
Keywords: Azores, crustal structure, local earthquakes

INTRODUCTION

Determining the crustal structure of ocean island volcanoes is important to understand the formation and tectonic evolution of the oceanic lithosphere and tectonic swells in marine settings, and to assess seismic hazard in the islands. The Azores Archipelago is located near a triple junction system (Figure 1), being at the locus of a wide range of geodynamic processes. A deep mantle plume has been proposed as the source of volcanism that led to the formation of the Azores Islands (e.g., Silveira et al., 2006). It may have interacted with the mid-Atlantic ridge, producing the elevated Azores Plateau. Possible magmatic intrusions and underplating below the oceanic crust have been suggested to affect the eastern islands of the archipelago (e.g.,

Ramalho et al., 2017). Magmatic underplating results from large igneous intrusions at the bottom of the crust with seismic wave speeds that are higher than those typical of the lower crust, but lower than in the mantle (e.g., Caress et al., 1995). In the Azores, these geological processes have been proposed to cause the recent uplift of the easternmost island of the archipelago, Santa Maria (Figure 1), which is also thought to be the oldest in the region (~6 Ma; e.g., Ramalho et al., 2017).

Figure 1. Tectonic setting of the Azores Archipelago. The tectonic boundaries between the North American, Eurasian and Nubian plates are shown. MAR: MidAtlantic Ridge, EAFZ: East Azores Fault Zone, PAR: Princess Alice Rift, TR: Terceira Rift and GF: Gloria fault. The location and the focal mechanism of the 2013 Mw 5.9 Povoação basin earthquake is also shown along with the seismic stations used in this study (red triangles). Topography and bathymetry are from Becker et al., 2009.
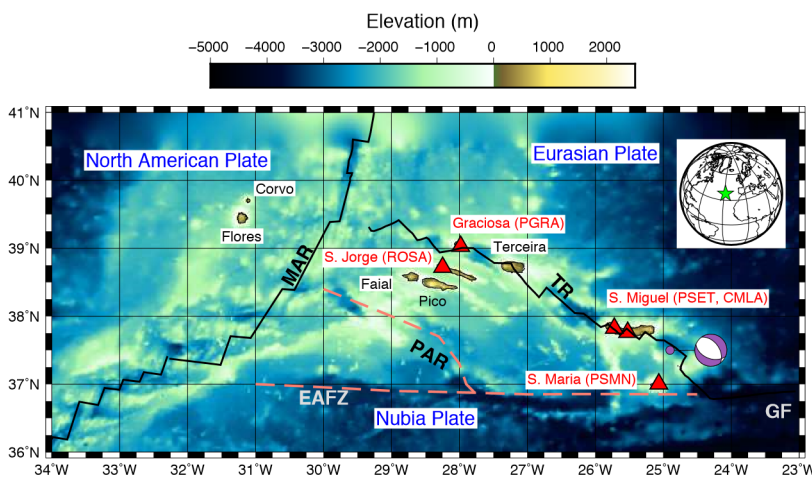
However, the crustal structure of the Azores is still poorly constrained due to the limited seismic coverage of the region and the peculiar linear geometry of the islands. To address these limitations, we inverted teleseismic Rayleigh wave ellipticity (the horizontal-to-vertical ratio of fundamental mode Rayleigh wave particle motion) measurements for 1-D shear wave speed (Vs) crustal models of the Azores Archipelago. Moreover, we tested the reliability of these new models by using them in independent earthquake source inversions of local seismic data.

Rayleigh wave ellipticity has a strong sensitivity to the uppermost crustal Vs structure in the immediate vicinity of a seismic station. Being a single-station measurement, Rayleigh wave ellipticity is particularly suited for illuminating crustal structure in regions with uneven seismic station coverage such as ocean islands, where application of seismic tomography is difficult. We used seismic waveforms from five permanent broadband seismic stations in the Azores: ROSA, PGRA, PSET, CMLA and PSMN (Figure 1) recorded in the period between January 2009 and February 2015 to measure Rayleigh wave ellipticity (RWE). Station CMLA in São Miguel Island is part of the Global Seismographic Network (GSN), while the other stations are all run and maintained by IPMA. We used recordings of 414 earthquakes with Mw 6.0-7.8 and with good azimuthal distribution. RWE was then inverted for Vs structure using a Monte Carlo inversion algorithm (Ferreira et al., 2020). In order to also constrain Moho depth, we performed several inversions whereby the Moho depth was successively fixed to different values in the range 5.5-30 km, with steps of 5 km and then finer steps were considered around the best-fitting models. For each station, we chose the model with the lowest cost function obtained from a stable inversion as our preferred model. Further, we performed moment tensor inversions of local and teleseismic waveforms recorded in the Azores for five events with Mw 4.6-5.9 that occurred in the region in 2013-2016.

MAIN RESULTS AND CONCLUSION

We found that by combining local and teleseismic data, our earthquake source models show a lower variability in the source parameters (Mw, fault strike, dip, rake) than in existing earthquake catalogues (Frietsch et al., 2018).
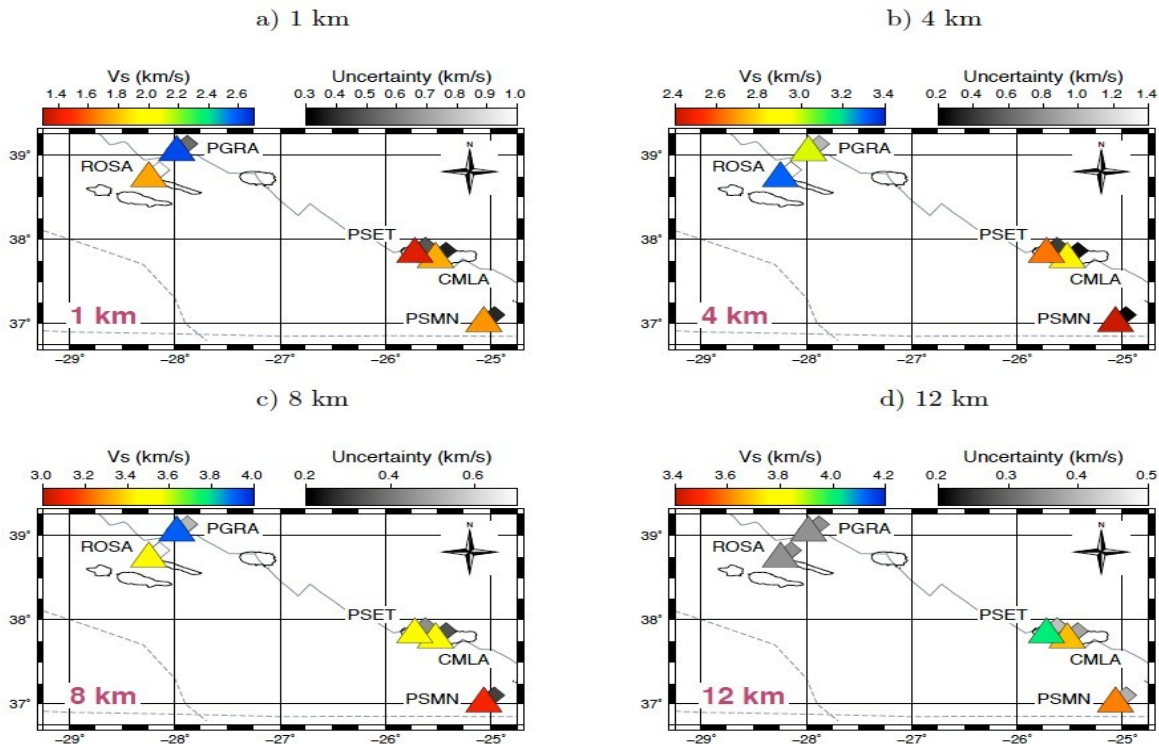
Figure 2. Geographical distribution of the Vs values obtained in this study (triangles) and their uncertainties (diamonds) for depths of 1, 4, 8 and 12 km. There is a tendency for slightly larger Vs values for the westernmost stations, notably for station PGRA. The best-fitting Moho depths are: ~10 km for stations ROSA and PGRA, ~16.5 km for PSET, ~15.1 km for CMLA and ~13.1 km for PSMN. There is no crustal Vs value for stations ROSA and PGRA at 12 km depth because their Moho depths are ~10 km.

We also studied in detail the Mw 5.9 2013 April 30 Povoação basin earthquake and found that it exhibits a persistent non-double-couple component of ~40–60 per cent. We suggest that it is potentially due to geometrically complex faulting in the Povoação basin, notably curved faults. In addition, we found that the 1-D crustal Vs models that were obtained using the RWE data improve the local waveform data fit compared to previous models. Thus, these source inversion tests show that our new 1-D crustal models of the Azores are reliable and useful for investigating the region's seismicity (e.g., hypocentral locations, moment tensors, etc).

The best-fitting Moho depths found in this study (see caption of Figure 2) broadly agree with estimates of 812 km from active seismic surveys, gravity and local earthquake tomography (e.g., Dias et al., 2007) as well as with the more recent estimates of ~15-17 km from receiver function analysis by Spieker et al., 2018. We found that the Moho depths beneath the two westernmost stations used in this study (ROSA and PGRA) are shallower than for the other stations (~10 km compared to ~13-17 km for the stations further east). Note that the five stations we use here are located between ~150 km (ROSA) and ~490 km (PSMN) from the MidAtlantic ridge, with the stations closest to the plate boundary having shallower Moho depths. Thus, the deepening trend of the Moho away from the plate boundary appears to be consistent with expectations from plate cooling models (e.g., Stein & Stein, 1992). However, the rate at which Moho deepens away from the MAR is greater than that predicted from a half-space cooling model. Such differences between theoretical predictions and empirical estimates are not surprising and can partly be attributed to local perturbations to the ambient thermal structure of the plate (e.g., Rychert and Harmon, 2018). Our results suggest that perturbations to crustal thickness are accentuated near ocean islands, where significant magmatic activity takes place (e.g., Métrich et al., 2014, Ramalho et al., 2017). This has been suggested also for the Cape Verde archipelago in the Atlantic (e.g., Ramalho et al., 2010a, Ramalho et al., 2010b).

Figure 2 presents the Vs models obtained from our analysis. It highlights that stations PSET, CMLA (both located in São Miguel Island) and PSMN (located in Santa Maria) show the lowest shear-wave velocity values in the top layer (~1.4-1.7 km s^{-1}) compared to ~1.7 and 2.6 km s^{-1} for stations ROSA (located in São Jorge Island) and PGRA (located in Graciosa), respectively. At ~3 km depth, the shear-wave velocity varies in the range ~2.4-3.3 km s^{-1}, which then increases to ~3.1-3.9 km s^{-1} at 8 km depth. At this depth, the westernmost stations (PGRA and ROSA) show the highest shear-wave speeds. The differences between the results for the westernmost and easternmost seismic stations correlate well with the ages of the islands except Santa Maria Island. We interpret the relatively low Vs profile found beneath Santa Maria Island as resulting from underplating, which agrees with previous geological studies of the island that suggested substantial magmatic intrusions driving island uplift (Ramalho et al., 2017). Alternatively, geomechanical processes such as porosity development and thermal stressing can reduce the strength of volcanic rocks and thus Vs (e.g., Loaiza et al., 2012). As expected, the 1-D Vs profiles for stations CMLA and PSET are quite similar, notably in the top ~10 km, since they are located in the same island (São Miguel) and only ~18.5 km apart. Compared to recent receiver function study of the region (Spieker et al., 2018), the shallow structure (top ~ 2 km) in our models shows lower shear wave speed, which may have important implications for future hazard studies of the region. This shallow lower Vs layer, where RWE sensitivity is optimum, is a robust feature required to fit the shortperiod RWE data. Future work using RWE measurements from seismic ambient noise data going down to shorter wave periods should enable us to obtain further detailed models of the shallow crust in the region (e.g., Berbellini et al., 2019).

REFERENCES:

Becker, J. J. et al. (2009). Global bathymetry and elevation data at 30 arc seconds resolution: SRTM30 PLUS. Marine Geodesy, 32(4):355-371.

Berbellini, A., Schimmel, M., Ferreira, A. M. G. & Morelli, A. (2019). Constraining S-wave velocity using Rayleigh wave ellipticity from polarization analysis of seismic noise. Geophysical Journal International, 216:1817-1830.

Caress, D., McNutt, M., Detrick, R. & Mutter, J. (1995). Seismic imaging of hotspot-related crustal underplating beneath the Marquesas Islands. Nature, 373:600-603.

Dias, N. A. et al. (2007). Crustal seismic velocity structure near Faial and Pico Islands (AZORES), from local earthquake tomography. Tectonophysics, 445(3-4):301-317.

Ferreira A.M.G., Marignier, A., Attanayake, J., Frietsch, M., Berbellini, A. (2020) Crustal structure of the Azores Archipelago from Rayleigh wave ellipticity data, Geophysical Journal International, 221 (2), 1232-1247.

Frietsch, M., Ferreira, A., Vales, D., & Carrilho, F. (2018). On the robustness of seismic moment tensor inversions for mid-ocean earthquakes: the Azores archipelago. Geophysical Journal International, (215):564-584.

Loaiza, S., et al. (2012). Mechanical behavior and localized failure modes in a porous basalt from the Azores. GRL, 39:6. Métrich, N. et al. (2014). Is the `Azores Hotspot' a Wetspot? Insights from the geochemistry of fluid and melt inclusions in olivine of Pico basalts. Journal of Petrology, 55(2):377-393.

Ramalho, R. et al. (2010a). Episodic swell growth inferred from variable uplift of the Cape Verde hot spot islands. Nature Geoscience, 3:774-777.

Ramalho, R. et al. (2010b). Vertical movements of ocean island volcanoes: insights from a stationary plate. Marine Geology, 275:84-95.

Ramalho, R. et al. (2017). Emergence and evolution of Santa Maria Island (Azores) - The conundrum of uplifted islands revisited. Bull. Geol. Soc. America, 129:372-390.

Rychert, C. A. & Harmon, N. (2018). Predictions and observations for the oceanic lithosphere from S-to-P receiver functions and SS precursors. GRL, 45:5398-5406.

Silveira, G. et al. (2006). Azores hotspot signature in the upper mantle. J. Volcanology and Geothermal Research, 156(1-2):23-34. Spieker, K., Rondenay, S., Ramalho, R., Thomas, C. & Helffrich, G. (2018). Constraints on the structure of the crust and lithosphere beneath the Azores Islands from teleseismic receiver functions. Geophys. J. Int., 213(2):824-835.

Stein, C. A. & Stein, S. (1992). A model for the global variation in oceanic depth and heat flow with lithospheric age. Nature, 6391(359):123-129.

Improving the monitoring of offshore earthquakes in the Azores using optical fiber cables

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ABSTRACT

The 1st January 1980 event is the outstanding example of the risk that offshore earthquakes pose to the Azores Archipelago. The mitigation of seismic risk requires that fast and reliable information on the source area and magnitude are timely provided to Civil Protection agents and authorities.

The current network of seismic stations operated by IPMA, based on land, has strong limitations in azimuthal coverage for many earthquake prone offshore areas. New developments in optical fibre cable technology allows the use of existing and new submarine telecommunication cables to provide seismic information that can be integrated in the monitoring network. In this work we explore the opportunities provide by three different technologies: i) DAS, Distributed Acoustic Sensing; ii) PEM, Photonics for Earthquake Monitoring; iii) SMART, Science Monitoring and Reliable Telecommunications.

The cable requirements are the following: DAS a piece of dedicated fibre off a Terminal Station, without amplification; PEM a free Standard ITU carrier channel in a fibre pair or the whole fibre pair in the cable; SMART can only be applied to new cables. DAS has a limited range (~150 km) while PEM uses the whole cable as a distributed sensor.
The investigation presented is one of the activities that have been conducted by LEA, Listening to the Earth under the Atlantic partnership which resulted from an agreement established between IT, IPMA and IDL. One of the main objectives of LEA is to promote research, development, training and outreach on the observation and recording of geophysical and oceanographic phenomena using submarine cables, fostering its applications to Science and Civil Protection..

Keywords: Submarine fibre optic cables, offshore earthquake monitoring, photonics

The Azores archipelago, located at a Triple Junction between the Eurasia, Nubia and North America plates, is the locus of frequent seismic crisis and occasionally destructive earthquakes, the most recent ones occurred the 1st January 1980 and the 9th July 1998. The 1st January 1980 (Mw6.9) is the largest instrumental

earthquake recorded in the Azores Archipelago, causing great destruction in Terceira and other central group Islands. A common feature of these seismic events is that they occur offshore, an area that is difficult to monitor from land-based instruments due to the elongated geometry of the Archipelago (figure 1). Fast and reliable information on the source area and magnitude are fundamental requirements by Civil Protection agents and authorities.
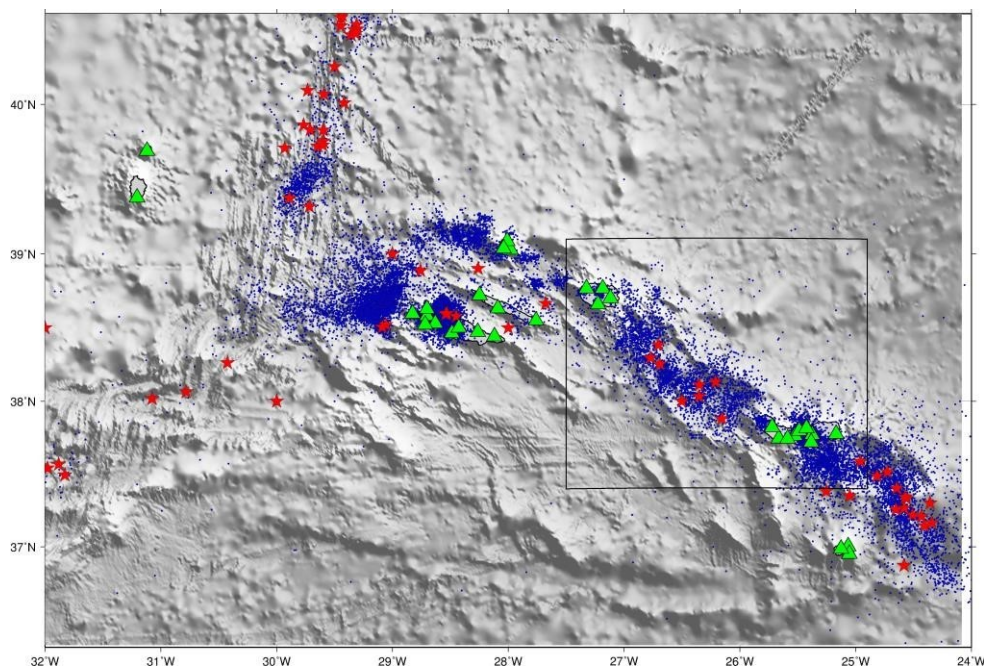
Figure 1. IPMA land-based seismic network (green triangles) with instrumental seismicity on the background. Red starts show events with M>5.0. The black box shows the area that will be investigated later.

The current network of seismic stations monitoring earthquake activity by IPMA are all located on land which, given the elongated shape of the Archipelago, results in poor azimuthal coverage and less than optimal computation of fast seismic parameters for many earthquake prone offshore areas. These geometrical limitations can only be overcome with seismic sensors operating on the seafloor transmitting data in real time. The most efficient way to obtain these data is by connecting the offshore sensors to shore by dedicated submarine cables, as it is done in Japan for more than 20 years. This is a very costly solution but new developments in optical fibre cable technology allows the use of existing and new telecommunication cables to provide seismic information that can be used by the monitoring network.

THE TECNOLOGIES AVAILABE FOR SUBMARINE OPTICAL FIBRE CABLES

In this work we explore the opportunities that optical fibre telecom cables can bring to the monitoring of offshore earthquakes in the Azores, presenting three different technologies: i) DAS, Distributed Acoustic Sensing; ii) PEM, Photonics for Earthquake Monitoring; iii) SMART. The first two technologies can be used on existing cables, while the 3rd can only be used on new cables. DAS requires a piece of dedicated fibre off a Terminal Station, without amplification. PEM. PEM requires a free Standard ITU carrier channel in a fibre pair or the availability of the whole fibre pair in the cable. Each of the technologies is better applied to different domains in the Azores, DAS to the Central Group, PEM to the Mid-Atlantic-Ridge region between Faial and Flores, SMART to the Gloria Fault zone East of the Azores.

EVALUATION OF THE GAIN OBTAINED WITH DAS

The gain in earthquake monitoring performance was evaluated considering the azimuthal gap between the minimum set of stations required for an earthquake location to be accepted (GAP) as the main quality parameter to be improved. We concentrated our efforts on the investigation of the offshore area between Terceira and S. Miguel Islands, a domain that includes the very active D. João de Castro Bank. The study domain is shown on figure 1 and the results are shown on figure 2.

INVESTIGATING PEM

The PEM technology has proved to work on land and along short marine cable sections (Marra et al 2018). It works very differently from DAS. In PEM the earthquake is detected by a single point on the cable, but this point can be placed anywhere along the cable. Furthermore, with PEM we know the azimuth of the incident waves (with a 180º). The longer the cable, the more useful PEM is. In the Azores we investigated the possibility of testing PEM using an existing submarine cable between Faial and Flores (figure 3) trying to answer the question: during the lifetime of the experiment, how many earthquakes do you expect the PEM cable to record? We first identified the possible earthquake locations where seismic waves would arrive first to PEM and then used the seismic catalogue to estimate the number of M>2.0 events that could be recorded by PEM over a period of 6 months (figure 3). We estimate that over that period there is a 50% probability to have 70 M>2 earthquakes or more.

EVALUATION OF THE GAIN OBTAINED WITH SMART FOR TSUNAMI EARLY WARNING

The ring-shaped telecommunication submarine cable joining Portugal Mainland (C), the Azores (A) and Madeira (M) archipelagos will end its service in 2024. This means that this infrastructure must be replaced in the next few years. As pointed out by ANACOM Chairman of the Board in several instances, this offers an opportunity for Portugal to be the first country to have in operation cables with SMART technology (Howe et al., 2019) dedicated to geo-hazard monitoring (earthquakes and tsunamis). Here we will present only the gain obtained in tsunami early warning time from a minimal proposal of only 10 SMART sensors along the new

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CAM cable ring (figure 4). The gain in tsunami early warning time is significant for most of the area investigated that includes the sources of the largest sources of tsunami known.
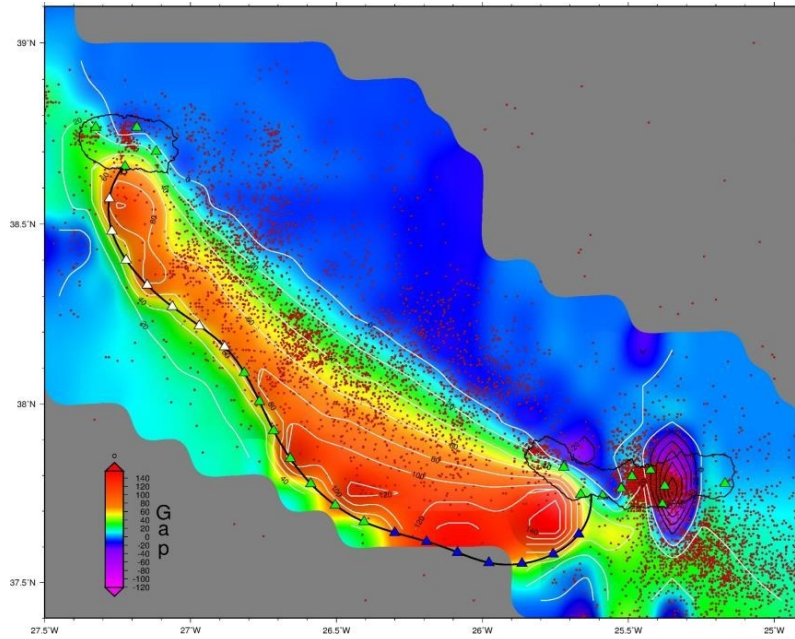
Figure 2. Changes in GAP between the IPMA only and the IPMA+DAS. DAS stations are shown as offshore colored triangles.
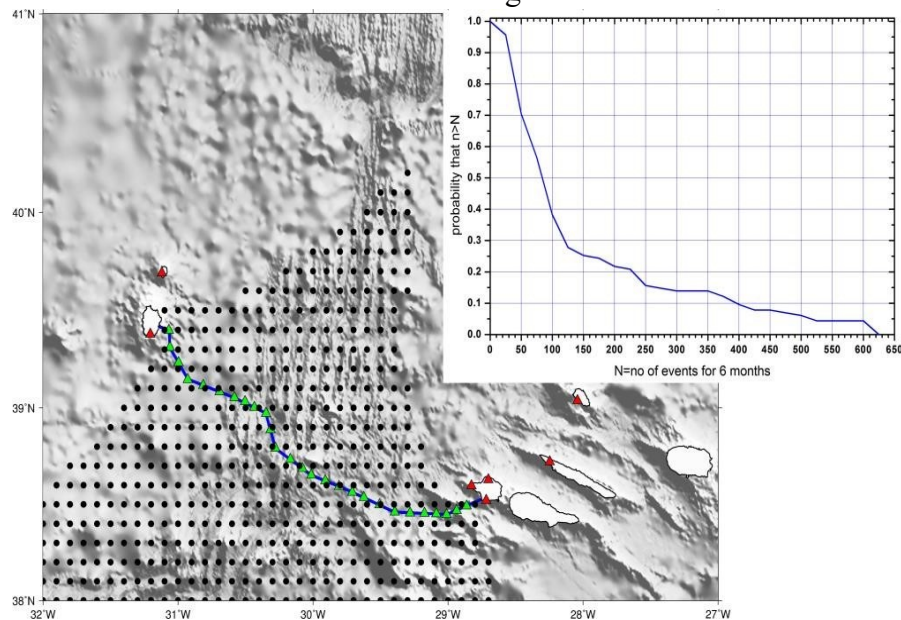
Figure 3. Dots show the location of events with seismic waves arriving first to the PEM cable (green triangles) than to the land stations (red triangles). Inset shows the cumulated statistics of 10 years of instrumental seismicity, for periods of 6 months.
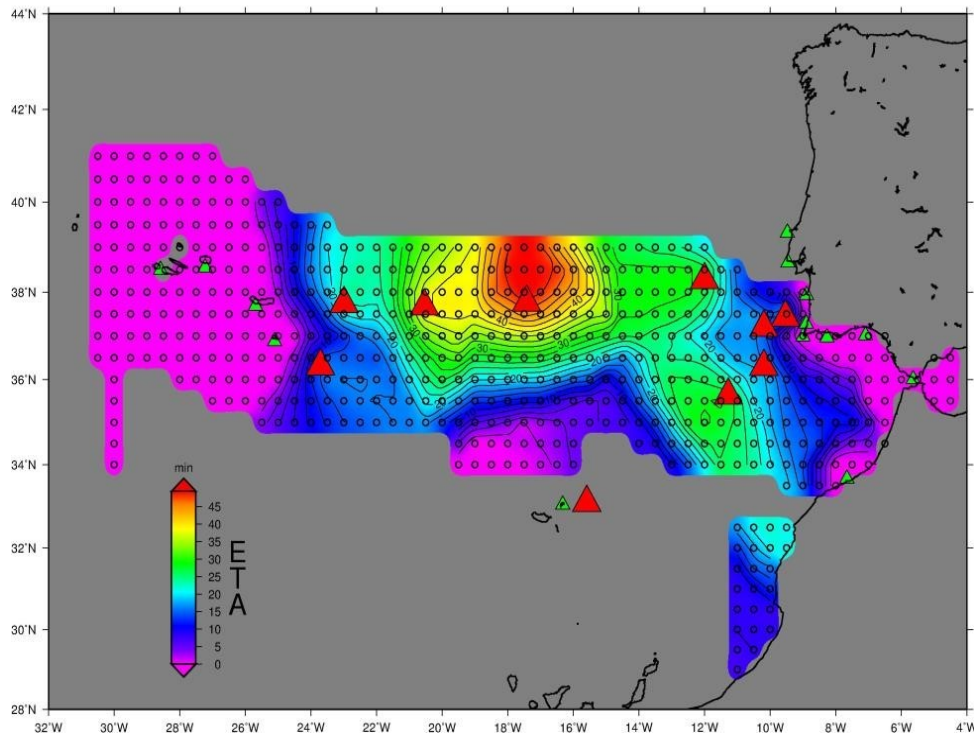
Figure 4. Open dots show the tsunami source locations tested. Green triangles show the coastal tide gauges with data recorded in real-time by IPMA. Large red triangles show the location of the SMART sensor pods considered for the minimal monitoring scenario. ETA scale and contours represent the gain in tsunami warning time provided by the SMART network for each source location.

REFERENCES

Howe, B. M., Arbic, B. K., Aucan, J., Barnes, C., Bayliff, N., Becker, N., Butler, R., Doyle, L., Elipot, S., Johnson, G. C. , Landerer, F., Lentz, S., Luther, D. S., Müller, M., Mariano, J., Panayotou, K., Rowe, C., Ota, H., Song, Y. T., Thomas, M., Thomas, P. N., Thompson, P., Tilmann, F., Weber, T., and Weinstein, S. on behalf of the Joint Task Force for SMART Cables (2019). "SMART cables for observing the global ocean: science and implementation", Frontiers in Marine Science, 6, 424.

Marra, G., Clivati, C., Luckett, R., Tampellini, A., Kronjäger, J., Wright, L., Mura, A., Levi, F., Robinson, S., Xuereb, A., Baptie, B. and Calonico, D. (2018). "Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables", Science, eaat4458.

Materials for Civil Engineering Structures - Potential Use in Seismic Areas

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ABSTRACT

This communication first presents a brief overview of fibre-reinforced polymer (FRP) composite materials used in civil engineering, addressing the four main types of FRP components available for structural applications: strips and sheets, rebars, profiles, and sandwich panels. Next, a summary of recent studies about the potential use of the above-mentioned FRP components in seismic areas is presented. In addition to the already well-established (and successful) (i) application of carbon-FRP (CFRP) systems in structural strengthening and seismic retrofitting, results of research projects conducted at IST about the structural behaviour of (ii) concrete columns reinforced with glass-FRP (GFRP) bars, (iii) connections and frames made of GFRP profiles, and (iv) GFRP sandwich panels for replacement of old building floors are presented - for each case, the main advantages, drawbacks and challenges regarding the use of FRP composites are highlighted.

Keywords: Composite materials; new structures; rehabilitation; strengthening; seismic behaviour.

INTRODUCTION

FRP composite materials are being increasingly used in civil engineering structures due to their advantages over traditional materials, such as lightness, high strength and durability in aggressive environments. However, these materials present some disadvantages, namely the initial costs, still relatively high for some applications, the susceptibility to elevated temperatures and the linear-elastic behaviour up to failure, which raises legitimate concerns, especially for seismic applications. The objectives of this communication are two-fold: (i) to provide a brief overview of composite materials used in civil engineering, including the main properties and applications of the different types of FRP components available for structural applications; and (ii) to present results of recent studies conducted at IST about their potential use in seismic areas, namely of carbon-FRP (CFRP) strips and sheets for structural strengthening and seismic retrofitting, glass-FRP (GFRP) rebars for concrete members, GFRP profiles for frames, and GFRP sandwich panels for the replacement of old building floors. For the different applications, the prospects of using FRP composites in seismic areas are discussed, as well as the main challenges and research needs.

FRP COMPOSITE MATERIALS FOR CIVIL ENGINEERING APPLICATIONS

This part of the communication starts with a brief overview of FRP composites, including the constituent materials (reinforcing fibres, polymeric matrices), manufacturing processes and inherent philosophy in the development of composite materials. The main FRP components used in civil structural applications – strips and sheets, rebars, profiles and sandwich panels (Fig. 1) - are also presented; for each type of component, the

most relevant physical and mechanical properties are described, together with typical applications and available design guidelines.
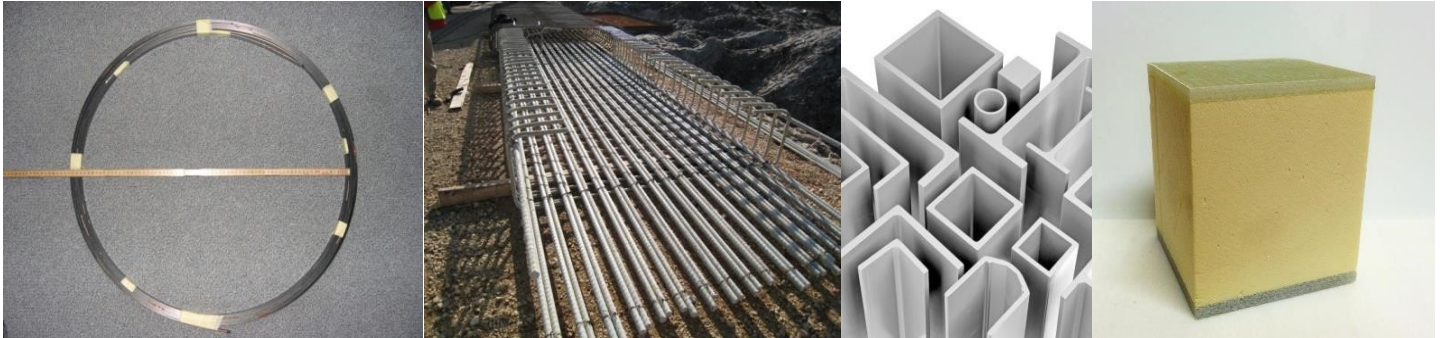
Figure 1. FRP components for civil engineering (left to right): strips, rebars, profiles and sandwich panels.

STRENGTHENING WITH CFRP STRIPS AND SHEETS

CFRP systems have been used since the 1980s for strengthening structurally deficient and deteriorated concrete structural members, being now unanimously recognized as an alternative to epoxy-bonded steel plates, especially due to their benefits in terms of durability and ease of application. There are now wellestablished codes and design guidelines for CFRP strengthening of reinforced concrete (RC) structures (e.g. ACI 440.2R-17, CNR-DT200-R1/2012, fib Bulletin 90) (and also steel and masonry). In spite of the intrinsic brittle nature of CFRP materials/systems, they can be effectively used for confining columns (Fig. 2a), enhancing their axial and shear capacities, and ductility. Intense research activity and numerous practical applications over the last decades have also demonstrated the effectiveness of CFRP sheets in confining joints of RC frames (Fig. 2b), increasing their flexural/shear capacity and ductility in the potential plastic hinge region. Although less common, CFRP systems have also been successfully applied in the seismic retrofitting of concrete and masonry shear walls (Fig. 2c).


Figure 2. Examples of seismic strengthening with CFRP systems: (a) Jacketing of column, (b) Confinement of beam-column joint (c) Strengthening of concrete wall (*S&P Clever Reinforcement*).

CONCRETE COLUMNS REINFORCED WITH GFRP BARS

GFRP bars are being increasingly used as internal reinforcement of concrete structures located in aggressive environments, mainly due to their improved durability and competitive costs when compared to conventional stainless steel rebars. In fact, there are now numerous applications of GFRP rebars in concrete members subjected to flexure (e.g. bridge decks, slabs of building parking garages). For applications in columns where the seismic action has to be considered, existing design codes and guidelines for GFRP-RC structures (e.g. ACI 440.1R-15, CNR-DT203) conservatively recommend assuming a linear elastic response of structural members when determining design values of internal forces; therefore, the design seismic action shall be derived from the elastic spectrum. However, the very few existing studies on this topic have pointed out that GFRP-RC columns may present non-negligible inelastic deformations and energy dissipation capacity. In this context, and to obtain a better understanding of the potential use of GFRP-RC columns in seismic areas, a comprehensive experimental, numerical, and analytical study is being conducted at IST. The present communication illustrates the preliminary experimental and numerical results obtained from two (full-scale) GFRP-RC columns (Fig. 3a and b), simultaneously subjected to 20% of their axial capacity and to monotonic or cyclic lateral loads; a steel-RC column was also tested as reference. Both experimental and numerical results (Fig. 3c) confirmed that GFRP-RC columns present non-negligible energy dissipation capacity, provided that the concrete is sufficiently well confined – this preliminary investigation is currently being pursued to investigate the influence of different parameters (e.g. axial load level, combination of stainless steel and GFRP rebars) on the cyclic behaviour of GFRP-RC columns.
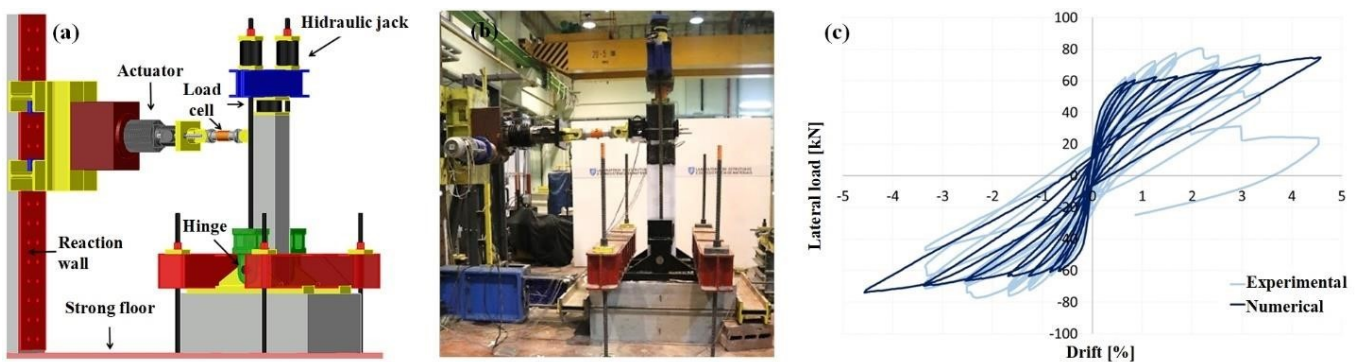
Figure 3. Cyclic tests on full-scale GFRP-RC columns: (a) and (b) test setup; (c) experimental and numerical *lateral load vs. drift* curves.

CONNECTIONS AND FRAMES MADE OF GFRP PROFILES

Due to their lightness and ease of assembly, frame structures made of pultruded GFRP profiles are a promising alternative to traditional steel or RC structures. However, their proneness to premature and local brittle failure modes at the connections raise well-founded concerns regarding their seismic behaviour. In the scope of the

FCT-funded "FRP-Quake" project, an extensive experimental campaign has been developed at IST aiming at developing GFRP frame structures with adequate ductility and energy dissipation capacity.

This study focused on three levels: (i) beam-to-column connections; (ii) 2D frames; and (iii) 3D frames. Thereafter, a novel connection system comprising stainless steel cleats has been developed and tested (Fig. 4a), showing improved ductility and energy dissipation capacity compared to commonly used FRPconnection technologies. The most promising connection systems were then used in 2D frames, which were subjected to monotonic and cyclic sway-tests (Fig. 4b). Additionally, these frames were also tested with an additional bracing system, comprising stainless steel cables, which provided significant improvements of the frames' energy dissipation capacity. Finally, the knowledge gathered in the previous tests was used in the development of a 3D frame, which is now being subjected to seismic tests in a shaking table (Fig. 4c).
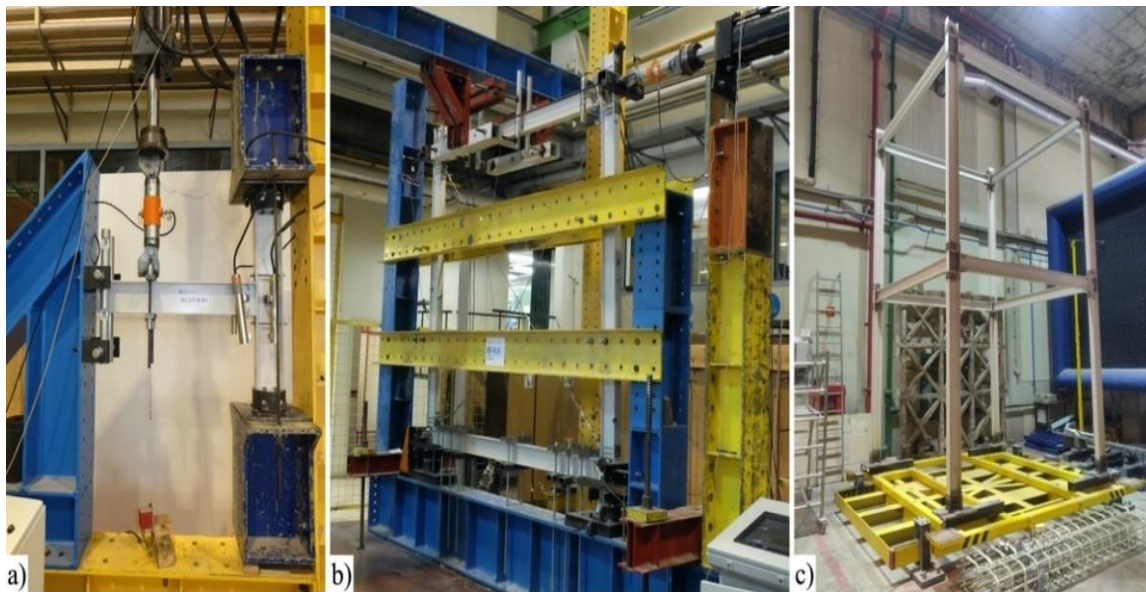
Figure 4. Connections and frames made of GFRP profiles: (a) full-scale beam-to-column connection tests; (b) 2D frame sway tests, and (c) 3D frame shaking table tests.

GFRP SANDWICH PANELS FOR BUILDING FLOORS REHABILITATION

In the rehabilitation of old buildings made of stone-rubble masonry walls, the need to replace existing timber floors often arises. Traditional solutions involve the application of relatively heavy RC or steel-concrete composite slabs; therefore, the strengthening requirements of other structural members (namely, the walls) are often increased, owing to the higher mass of such solutions compared to the original timber floors. An alternative floor system comprising GFRP sandwich panels allows replacing degraded timber floors with a more durable and equally lightweight structural system, which may be particularly advantageous for the seismic behaviour of the refurbished building. However, this new technology entails specific challenges, which have been addressed in recent research at IST (Fig. 5), such as the assessment of their static failure behaviour,

the long-term creep behaviour, the technology for panel-to-panel and panel-to-wall connections, the acoustic performance, and the fire resistance behaviour of the sandwich panel floors.

Figure 5. Research on GFRP sandwich panels for building floors rehabilitation (left to right): creep behaviour, panel-to-panel connections, panel-to-wall connections.

Potential Impact of Earthquakes during the 2020 COVID-19 Pandemic in Portugal

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ABSTRACT

The 2020 COVID-19 pandemic caused a human and economic impact of unprecedented magnitude in contemporary history. In an effort to reduce the rate of infection, the Portuguese government implemented measures to increase social distancing and to strengthen the capacity of the healthcare system. The occurrence of earthquakes coincident with the pandemic may prevent the effective practice of such measures, and consequently cause an increase in the virus spread. This study analyses the potential impact seismic events may have in Portugal during the pandemic, by exploring open software packages that can be employed to simulate the impact of future destructive earthquakes on the spread of an emerging virus. Recent data on the number of confirmed cases at the national or subnational level was combined with a global seismic hazard and risk map to produce a combined index. This index highlights regions where preparedness and contingency plans should be developed to account for the possibility of COVID-19 outbreaks due to the earthquake impact.

Keywords: seismic risk, COVID-19, earthquake scenarios.

INTRODUCTION

The 2020 COVID-19 pandemic has overwhelmed the healthcare system and emergency response capacity of several countries. In an attempt to reduce the number of new infections, several safety measures have been imposed by governmental authorities. Despite the positive impact of such measures, the occurrence of a sudden shock (such as an earthquake) could bring an otherwise stable emergency response past its coping capacity, causing an increase in the infection rates and associated mortality. The damage caused by seismic events on the residential building stock often requires housing hundreds or thousands of inhabitants in temporary shelters. The 2009 M6.3 L'Aquila earthquake damaged more than 35,000 buildings, and left over 45,000 people homeless (Dolce 2010; Dolce and Di Bucci 2015). Moreover, the need to treat the injured in the aftermath of an earthquake could cause an excessive influx of people in healthcare facilities and a temporary disregard for safety measures. In such conditions, social distancing might be impractical, and new clusters of virus spread may arise.

Epidemic outbreaks following destructive seismic events have been observed for centuries (Tsiamis et al. 2013), due to a multitude of reasons. An important factor is the accumulation of population in relatively small areas (i.e. crowding) due to the need to accommodate the population left homeless, thus creating ideal conditions for the transmission of communicable diseases such as the COVID-19 virus. For example, Petrazzi et al., (2013) investigated the incidence of infectious diseases following the 2009 M6.3 L'Aquila earthquake, and concluded that hospital admissions due to infectious diseases rose from 7.41% before the earthquake to 27.18% in the two months after the event. Another relevant case was described by PerezMartin et al. (2017)

for the city of Lorca in Spain, which was struck by a M5.1 earthquake in 2011. There was an outbreak of chickenpox prior to the earthquake, with 163 cases reported 8 weeks before the event.

After the earthquake 1,424 people were evacuated to a temporary shelter, and another 4 cases were detected leading to the declaration of an outbreak. Despite the rapid implementation of a vaccination programme, another 5 cases were identified in the shelter.

It is thus important to account for the possible occurrence of large natural hazards during the pandemic, and develop response plans that consider both the constraints due to the pandemic and the additional requirements caused by the natural hazard. As a response to this challenge, some governments have requested their civil protection authorities to create preparedness and contingency plans. However, given the unprecedented situation caused by the COVID-19 pandemic, empirical data are limited, and consequently such plans might be ill-informed. In the absence of empirical data, it is possible to explore analytical methodologies to simulate different scenarios of earthquake magnitude and COVID-19 infection rates. This process has been followed for decades for the development of post-earthquake response plans (e.g. Italy (DPC 2018), Turkey (Erdik and Durukal 2008), Portugal (Mendes et al. 1994), United States (Detweiler and Wein 2017)), and now it must be expanded to incorporate the potential effects in the spread of an emerging virus.

SIMULATION OF POTENTIAL COVID-19 SPREAD DUE TO SEISMIC EVENTS

The simulation of earthquake and infection scenarios can provide relevant information to support the development of preparedness and contingency plans. This process is demonstrated herein using two earthquake scenarios for Portugal with distinct geographical and tectonic characteristics. Then, using the displaced population estimates, several epidemiological simulations were performed considering different assumptions for the infection rates. The characteristics of these two events are summarized in Table 1.

Table 1. Characteristics of the selected earthquake ruptures.

Rupture	Magnitude (M_w)	Strike	Dip	Rake
Onshore	5.7	220 °	55°	0°
Offshore	8.7	35°	40°	90°

For the estimation of the impact in terms of fatalities and population displaced by the aforementioned earthquake scenarios, the fragility functions proposed by Martins and Silva (2020) and the exposure model developed within the H2020 European SERA project (Crowley et al. 2020) were employed. This exposure model was derived based on the latest national housing census for Portugal, and it includes information about the main construction material, lateral load resisting system, number of storeys, and date of construction (used herein as a proxy for the seismic design level). The exposure model was defined at the third administrative level (i.e. parishes), and the number of occupants per building was computed based on the average number of dwellings per building class and the average number of occupants per dwelling. The calculations were

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performed using the OpenQuake-engine (Silva et al. 2014), an open-source platform for seismic hazard and risk calculations. Figure 1 presents the mean number of people left homeless at the county level for the two earthquake scenarios. For what concerns human losses, the onshore and offshore scenarios caused a mean death toll of 292 and 1729, respectively.
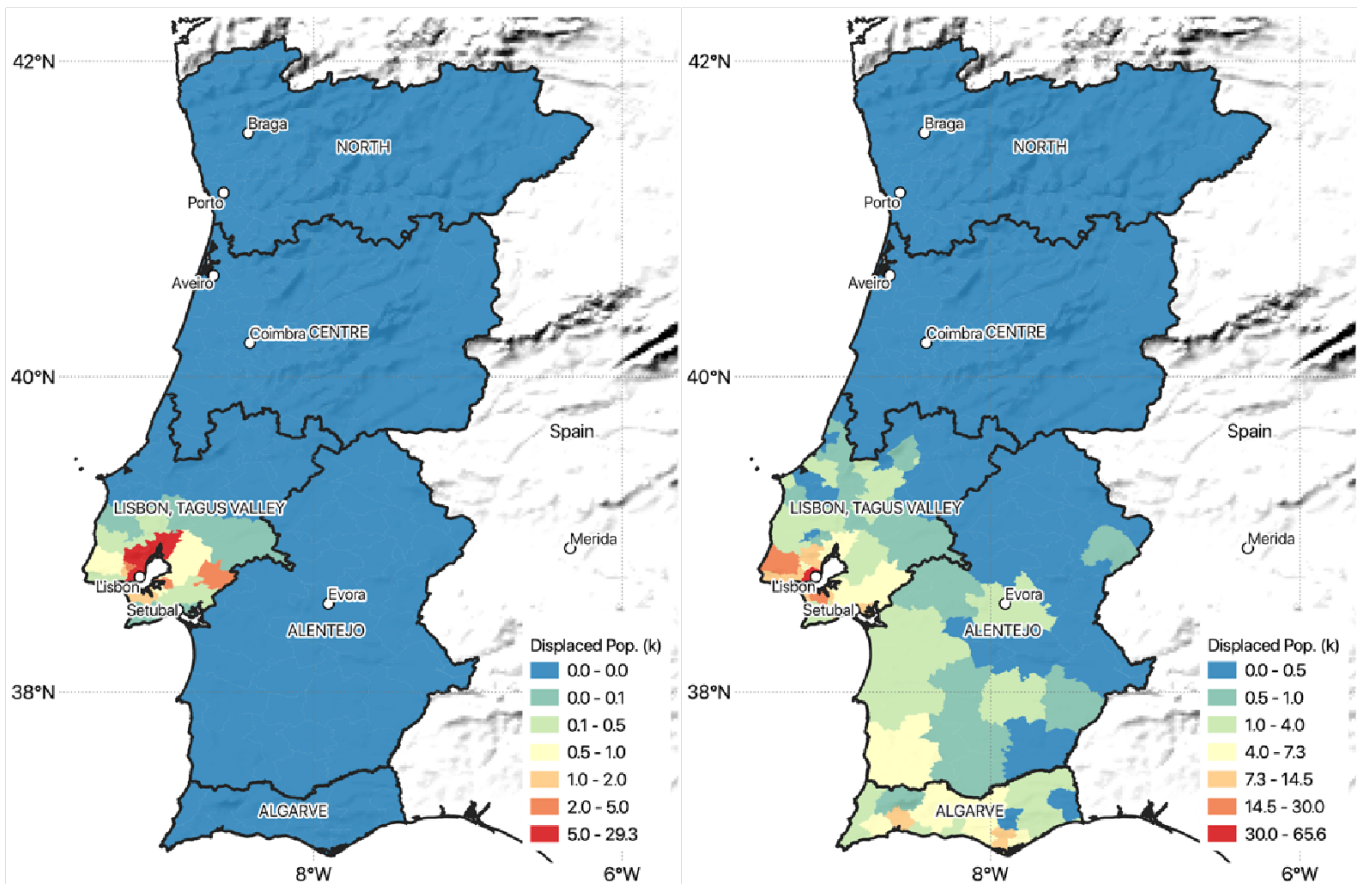
Figure 1 - Displaced population at the countoffshore (right) earthquake scenariosy level for the M5.7 onshore (left) and M8.7

The population left homeless was assumed to be more vulnerable to the pandemic and thus susceptible to higher infection rates. The data regarding the number of active cases in Portugal was extracted from the General Health Directorate. To forecast the evolution of the number of COVID19, a Markov Chain Monte Carlo (MCMC) sampling method was employed (e.g. Nouvellet et al., 2018). In this process, the reproduction number (R_t), is sampled from the joint posterior distribution, and at each MCMC iteration the new cases are incorporated in the sampling process. This procedure allows propagating the uncertainty in R_t, as well as to incorporate changes in the transmissibility due to the occurrence of external events (such as earthquakes) or the introduction of measures to reduce the infection ratio. As described in the previous section, current data regarding the occurrence of natural hazards during the 2020 COVID-19 pandemic is scarce and statistically insufficient to properly evaluate how natural hazards might aggravate the transmissibility. Nonetheless, it is possible to explore the limited data reflecting different stages of the pandemic to define plausible scenarios

of infection for the displaced population. We have defined two plausible cases of transmissibility as described below.

- o **Case A**: This case represents an optimistic scenario in which the R_t factor slightly increases after the seismic event, and then decreases at a rate similar to the one observed for the associated region prior to the seismic event. We assumed a value for Rt equal to the one registered 2 weeks after the declaration of the emergency state in Portugal (i.e. R_t ~ 2.5).
- o **Case B:** This case represents a more pessimistic scenario where the Rt would increase sharply after the seismic event. For this scenario, we assumed an increase of the Rt factor to the value registered in Portugal during the peak of the infection (i.e. Rt ~4.1, 20th-25th of March, as indicated by the General Health Directorate).

RESULTS

The increase in the number of COVID19 cases is reported (in terms of percentage) following the administrative regions endorsed by the General Health Directorate in Portugal, as illustrated in Figure 2 for the two scenarios and two cases of transmissibility.

These results illustrate important differences in the increase of COVID-19 cases across the three regions. For the onshore event which affects mostly the population in Lisbon and the Tagus Valley (i.e. 1.9%), when effective measures to limit the transmissibility of the virus are assumed (i.e. Case A), the impact is limited (i.e. less than 1% increase in the number of cases). On the other hand, for the case where the transmissibility rate increased considerably (i.e. Case B), even an event with limited impact was able to cause a significant increase in the number of cases (i.e. 10.3%). For the offshore event, which caused widespread damage and more than 350 thousand people were left homeless, the increase in the COVID-19 cases is substantial even in the more optimistic transmissibility case.

CONCLUSION

This study presented a framework for the analytical estimation of the amount of population left homeless due to an earthquake scenario, and simulation of the expected increase in the number of COVID-19 cases due to the plausible possibility that not all of the safety measures will be respected. Different cases of transmissibility (i.e. optimistic and pessimistic scenarios) were considered, leveraging on data regarding the effective reproduction number (R_t) and deceleration rates observed in Portugal since February 2020. Such analyses elucidate the factors driving the evolution of the number of daily cases in a particular region, and the potential additional strain upon the healthcare system if an event of similar characteristics were to happen. For the particular case of Portugal, it was observed that if the effects of an event with a localized impact are managed rapidly and efficiently (i.e. leading to low transmissibility rates), the increase in the number of additional COVID-19 cases would be negligible. For large events in which a considerable amount of the population is likely to be affected, a rise in the virus spread might be inevitable, even assuming an optimistic scenario of emergency response. Given the results presented herein, governmental agencies with the remit to rapidly estimate and communicate the direct impact of earthquakes could include information in such reports concerning the number of cases and highest observed reproduction number in the region. Additional information about the impact of earthquakes in the ongoing pandemic
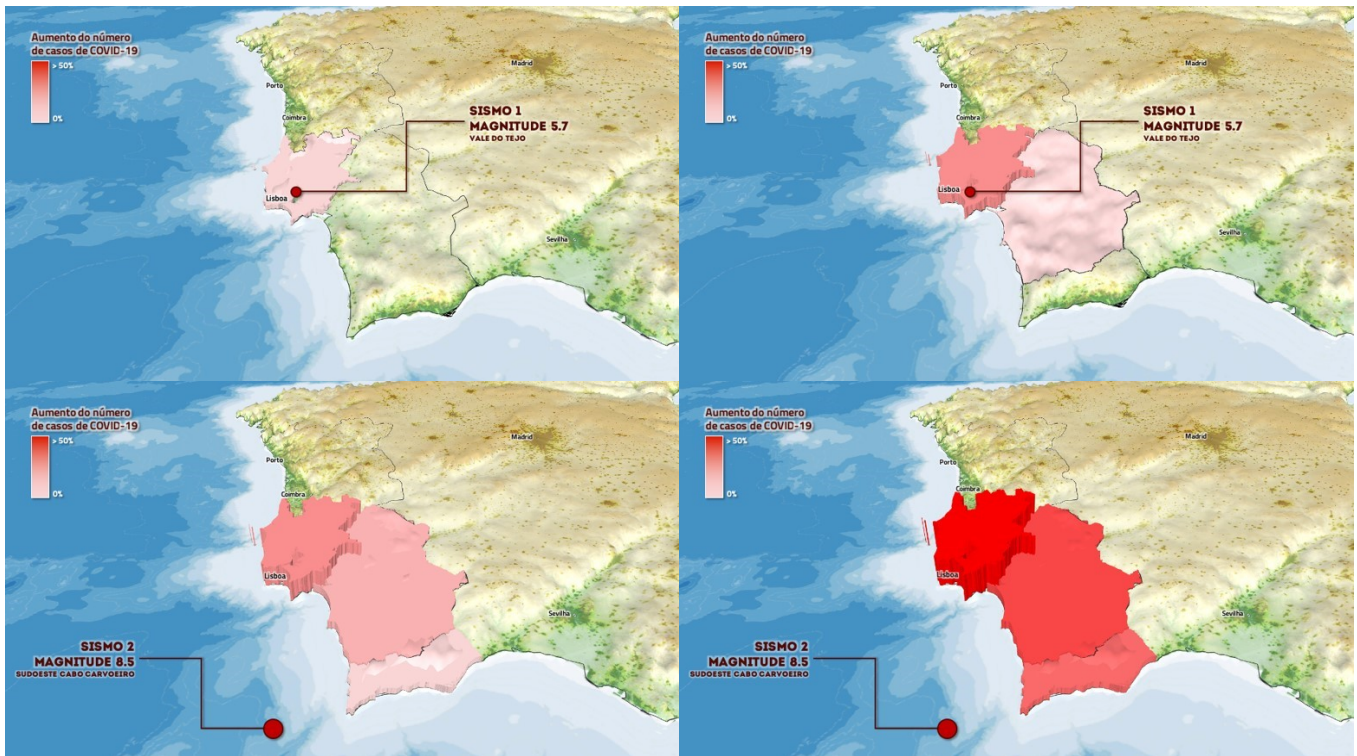
Figure 2 - Displaced population at the county level for the M5.7 onshore (left) and M8.7 offshore (right) earthquake scenarios

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REFERENCES:

Crowley H, Despotaki V, Rodrigues D, Silva V, Toma-Danila D, Riga E, Karatzetzou A, Zugic Z, Sousa L, Ozcebe S, Gamba P (2020). Exposure Model for European Seismic Risk Assessment. *Earthquake Spectra*.

Detweiler ST, Wein AM (2017). The HayWired earthquake scenario: U.S. Geological Survey Scientific Investigations Report 2017–5013, https://doi.org/10.3133/sir20175013.

Dolce M (2010). Emergency and Post-Emergency Management of the Abruzzi Earthquake, Theme-leader lecture. 14th European Conference on Earthquake Engineering, Ohrid, Macedonia, 3-8 September 2010, pubblicato in M.Garevski, A. Ansal (Eds.) in Earthquake Engineering in Europe, Springer, DOI 10.1007/978-90-481-9544-2_19.

Dolce M, Di Bucci D (2015). Comparing recent Italian earthquakes, *Bulletin of Earthquake Engineering*. Springer. DOI 10.1007/s10518-015-9773-7

DPC (2018). National risk assessment, Overview of the potential major disasters in Italy: seismic, volcanic, tsunami, hydrogeological/hydraulic and extreme weather, droughts and forest fire risks. Technical report by the Presidency of the Council of Ministers Italian Civil Protection Department, Rome, Italy.

Erdik M, Durukal E (2008). Earthquake risk and its mitigation in Istanbul. *Natural Hazards*, 44(2):181-197.

Martins L, Silva V (2020). Development of a Fragility and Vulnerability Model for Global Seismic Risk Assessment. *Bulletin of Earthquake Engineering*.

Mendes-Victor LA, Oliveira CS, Pais I, Teves-Costa P (1994) Earthquake damage scenarios in Lisbon for disaster preparedness. In: Tucker BE, Erdik M, Hwang CN (eds) Issues in urban earthquake risk. NATO ASI series E, Applied Science, vol 271. Dordrecht, Kluwer Academic Press, pp 265–289.

Nouvellet P, Cori A, Garske T, Blake IM, Dorigatti I, Hinsley W, Jombart T, Mills HL, Nedjati-Gilani G, Van Kerkhove MD, Fraser C, Donnelly CA, Ferguson NM, Riley S (2018). A simple approach to measure transmissibility and forecast incidence. *Epidemics*, 22:29-35.

Pérez-Martín JJ, Romera Guirado FJ, Molina-Salas Y, Bernal PJ, Navarro JA. (2017). Vaccination campaign at a temporary camp for victims of the earthquake in Lorca (Spain). Hum Vaccin Immunother 2017;13:1714–21.

Petrazzi L, Striuli R, Polidoro L, Petrarca M, Scipioni R, Struglia M, Giorgini P, Necozione S, Festuccia V, Ferri C (2013). Causes of hospitalisation before and after the 2009 L'Aquila earthquake. *Internal Medicine Journal* 2013;43:1031–4.

Silva V, Paul N (2020). Potential Impact of Earthquakes during the 2020 COVID-19 Pandemic. *Earthquake Spectra*.

Silva, V., Crowley, H., Pagani, M., Monelli, D., Pinho, R. (2014b). Development of the OpenQuake engine, the Global Earthquake Model's open-source software for seismic risk assessment. *Natural Hazards*, 72(3):1409-1427.

Tsiamis C, Poulakou-Rebelakou E, Marketos S (2013). Earthquakes and plague during Byzantine times: Can lessons from the past improve epidemic preparedness? *Acta Medico-Historica Adriatica* 11(1):55-64.

From Lisbon earthquake vulnerability knowledge towards an urban policy that can increase resilience on buildings

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ABSTRACT

Lisbon has been incorporating on its master plans the most updated information on earthquake vulnerability since before 2012. Strong and long-term collaboration with the scientific community and a consistent registration of geotechnical georeferenced data provided a sound technical base to design a policy that could work better. However, the size and complexity of the problem requires a more comprehensive approach and the mobilization of many and different types of stakeholders and recourses. The Lisbon policy and the design of an action plan will be the case for a discussion on how to mobilize the society to mitigate earthquake impacts on buildings.

The paper presents the vulnerabilities and capacities that we have to tackle in order to increase Lisbon earthquake resilience on buildings. The setting of targeted buildings allows a clearer definition of the needed incentives and the enforcement actions to make property owners to improve their buildings resilience to earthquakes. A smart combination of technical knowledge with political engagement and mobilization of financial incentives, building inspections, penalties, adequate regulation and technical support makes us believe we can be better prepared in the future.

Keywords: earthquakes impact, buildings resilience and conservation, society engagement, urban planning regulations

INTRODUCTION

Lisbon was affected by strong earthquakes along its history, such as in 1531 (M6.5-7.1), 1755 (M8.58.7), 1858 (M6.8-7.2) and 1909 (M6) (Custódio *et al.*, 2015). All these events caused several damages and losses (physical, social, economic, environmental and cultural), particularly the 1755 earthquake, followed by a tsunami and an urban fire, where 17.000 homes and monuments collapsed and around 10% of the population lost their lives (Pereira de Sousa, 1919-1932).

Strong and long-term collaboration with the scientific community led to the improvement of several projects regarding the development of landslide's susceptibility and seismic micro zoning map, based on geological and geotechnical GIS (geographic information system application: GeoSIG). Soil seismic behavior characterization was improved into a ground model using Eurocode 8 classification (Figure 1) (Oliveira et al., 2020). This information was integrated in Lisbon urban planning instruments since before 2012 for decision making support.

We need to move from the knowledge base to a local policy and action plan to increase Lisbon Buildings Seismic Resilience. This is the main topic to be discussed in the present paper.
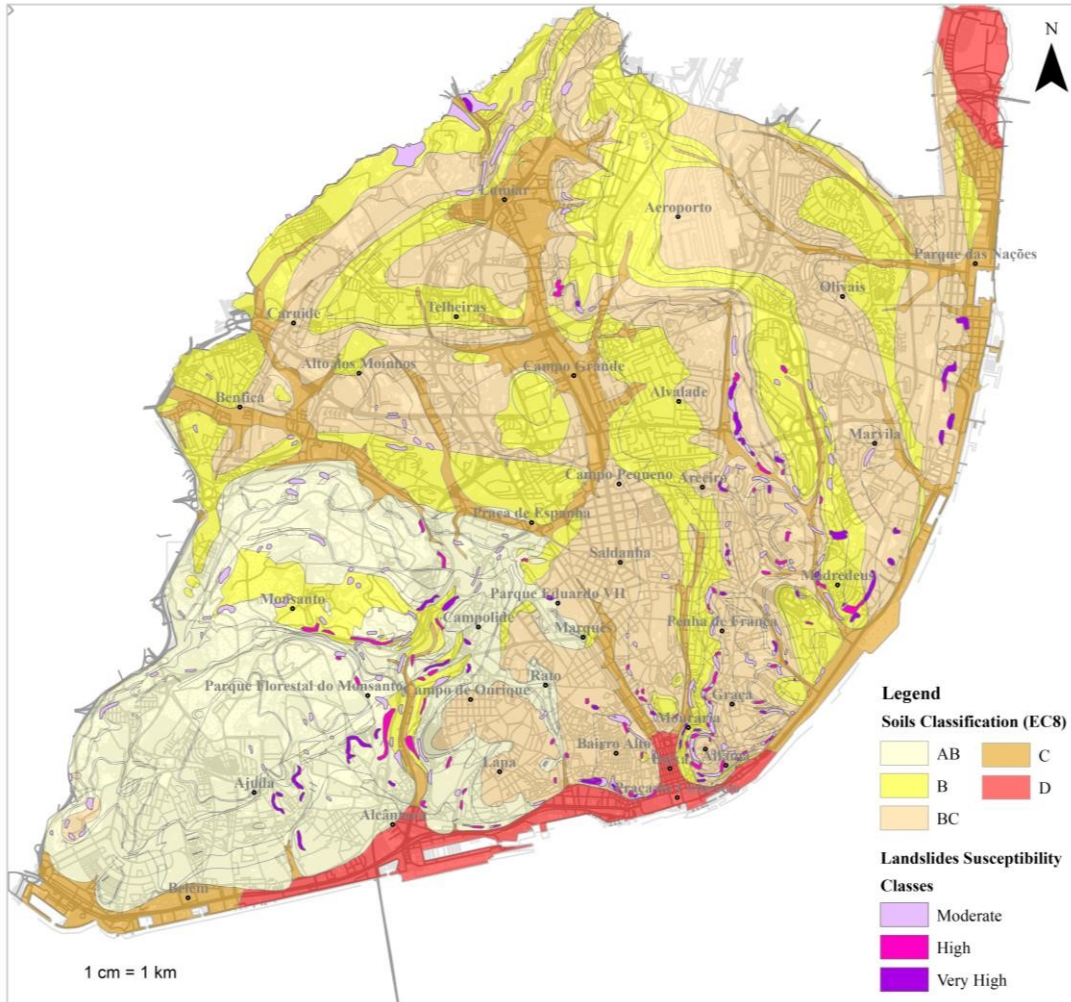
Figure 1. Lisbon landslide's susceptibility and ground classification map

LISBON BUILDINGS SEISMIC RESILIENCE POLICY

The "*Lisbon Buildings Seismic Resilience Policy*" has three pillars:

1 – Knowledge Infrastructure and modeling

A simulation model of earthquakes impact on building's as a result of their structural and conservation vulnerabilities will be developed.

This model will use geographical information on soils and buildings already available, namely type of soils, building's construction period, state of conservation, number of floors, etc.

The database updates will be developed using a standardized form for buildings inspections. This will provide a curated database where artificial intelligence (AI) can add value to prediction functions.

Vulnerability alerts will be also designed to support construction projects assessment, based on location and buildings vulnerability levels.

The goal is the identification and prioritization of the most critical areas targeting a preventive municipality inspection program of buildings and the respective owner's engagement with the conservation and safety works.

2 - Society Engagement

Society engagement will be supported in three ways:

-   Property owner's engagement will be promoted through awareness campaigns, technical support and incentives;

-   Property owner's enforcement to perform mandatory conservation and safety works as a consequence of building inspection actions by the City Council. A plan of inspections is being designed based on available information on soil and buildings potential vulnerability;

-   Expertise engagement will be called up to collaborate in the design and implementation of a suitable action plan to mitigate impacts on buildings, namely with the cooperation of private companies, universities and professional associations.

3 – Urban Planning Regulations and Construction Projects Assessment

Based on the knowledge infrastructure, and experience with construction safety incidents, urban planning regulations will continuously evolve to prevent or provide guidelines for certain types of works in designated areas of the city.

Construction (or rehabilitation) projects on higher risk areas / buildings will determine special care on the assessment and inspection of projects and constructions works compliance with regulations.

A conceptual model of the Policy is present in Figure 2.
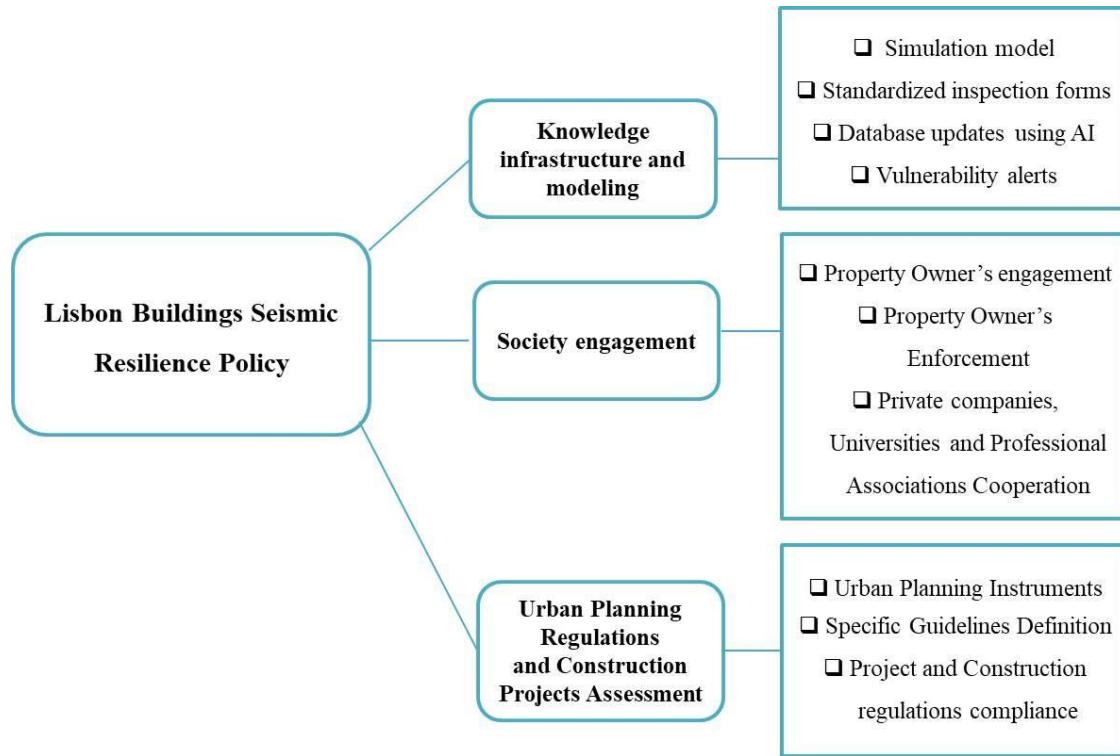
Figure 2. Lisbon Buildings Seismic Resilience Program – Conceptual Model

CONCLUSION

A smart combination of technical knowledge with political and society engagement and mobilization of financial incentives, building inspections, penalties, adequate regulation and technical support makes us believe we can be better prepared in the future.

REFERENCES:

Custódio, S., Dias, N.A., Carrilho, F., Góngora, E., Rio, I., Marreiros, C., Morais, I., Alves, P. e Matias, L. (2015). "Earthquakes in western Iberia: improving the understanding of lithospheric deformation in a slowly deforming region", *Geophys J. Int.* **203**:127-145.

Oliveira, L., Teves-Costa, P., Pinto, C., Gomes, R.C., Almeida, I.M., Ferreira, C., Pereira, T., Sotto-Mayor, M. (2020). "Seismic microzonation based on large geotechnical database: Application to Lisbon", *Engineering Geology*, **265** (2020), 105417.

Pereira de Sousa, F.L. (1919-1932). "The November 1st, 1755, earthquake in Portugal and demographic study", i*n:* Serviços Geológicos de Portugal. 4 volumes, Lisbon, Portugal.

Seismotectonics of Azores-Gibraltar: A review

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ABSTRACT

We present a review of the studies about the seismotectonics of the Azores-Gibraltar region from the beginning of the 20th century to the present. First studies, before plate tectonics, were based on macroseismic data and the distribution of instrumental epicenters, with very low accuracy. The installation of seismological stations with new instruments, especially, the WWSSN network, at the beginning of the 1960s, provided a better definition of the distribution of seismicity and the first determinations of the mechanism of earthquakes and allowed the interpretation of the region in terms of plate tectonics as the westernmost part of the plate boundary between Eurasia and Africa, part of the Mid-Atlantic Ridge and a triple junction at Azores. From the middle of 1980s, a more dense network and the new broad-band seismic stations have allowed a notably improvement on the determination of hypocenters and focal mechanisms resulting in a better interpretation of the tectonic of the region. In the last years, seismic surveys campaigns in land and sea (OBS), together with other types of data, such as GPS observations permit to get a more detailed picture of this tectonic complex region.

Keywords: Azores-Gibraltar, seismotectonics, review

INTRODUCTION

The Azores-Gibraltar region is a seismic active tectonically complex region which has received attention by many seismologists and geologists from an early time (Udías and Buforn, 2010) (Fig. 1). First studies about the seismotectonics of this region, before plate tectonics, based on macroseismic data and the distribution of instrumental epicenters with very low accuracy recognized that earthquakes continue in the Atlantic Ocean west of Spain and Portugal to the Azores Islands, but they do not extend further west. This was already pointed out by Montessus de Ballore (1906), Gutenberg and Richter (1949), and Rothé (1951). They explained this seismic activity as a continuation of the tertiary active structures of the Alpine belt present in Europe and northern Africa across the Atlantic Ocean as far as the Azores Islands, but not further west.

MAIN RESULTS

The installation of seismological stations with new instruments, especially, the WWSSN network, at the beginning of the 1960s, provided a better definition of the distribution of seismicity and the first determinations of the mechanism of earthquakes. It was now made clear that a line of earthquakes exists from Gibraltar to the Azores Islands. In those years the proposal of the new plate tectonic theory provided a new framework for the interpretation of the region. It was soon recognized that in terms of plate tectonics the region forms the westernmost part of the plate boundary between Eurasia and Africa, ending at the Mid-Atlantic Ridge, where it joins with the American plate at the Azores Islands. The
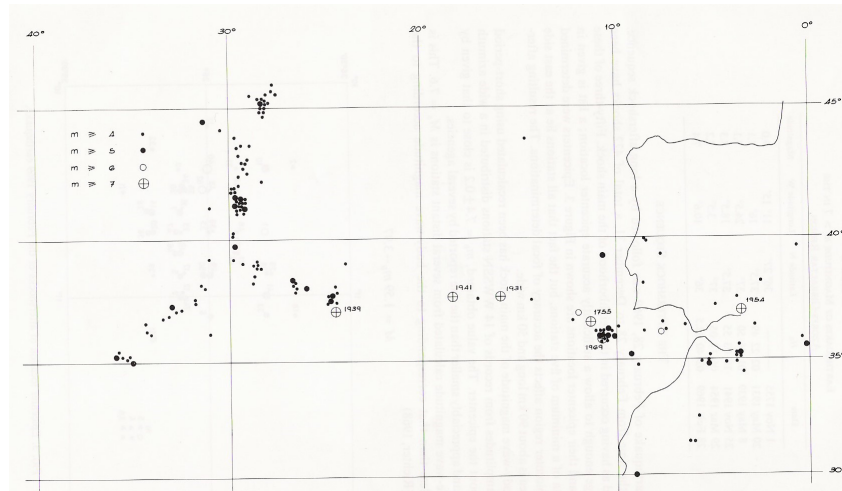
Figure 1. Seismicity of the region from Azores-Gibraltar (Udías and López Arroyo, 1972)

situation in the Azores was, then, interpreted as a triple junction of the three plates involved: Eurasia, Africa, and America. From Azores to Gibraltar the plate boundary was first considered as a ridge, called the Azores–Gibraltar ridge and afterward as a fault (Isacks *et al*., 1968, Banghar and Sykes,1969). In the context of the application of plate tectonics to the Mediterranean region, McKenzie (1972), clarified the situation along the plate boundary from Azores to Tunisia and arrived at the following conclusions: The triple junction at the Azores has a ridge structure in its three parts, which are dominated by oblique spreading of all the ridges involved; from Azores to Gibraltar, the boundary is formed by a transform fault, with the central part corresponding to dextral strike-slip faulting. Udías and López Arroyo (1970) made also an interpretation of this region in terms of plate tectonics using seismicity and focal mechanism of earthquakes. They showed that the boundary is under horizontal tension at the ridge part of Azores, rightlateral horizontal displacement with strike-slip faulting at the center, and horizontal compression at the eastern part with reverse dip-slip faulting. Near Cape San Vicente, they proposed downward motion of the Spanish block with respect to Africa, along a steep dipping plane. Further studies of the seismicity and focal mechanism of earthquakes have contributed to clarify the tectonics of the whole region (Buforn *et al.* 1998) (Fig. 2).

At the western end the Azores triple junction presents some features, which are considered anomalous, such as the aseismic west Azores and the seismically active east Azores fracture zones, the transverse islands chain, and the change of trend and broadening of the mid-Atlantic ridge. The Azores domain is, then, a diffuse plate boundary with non-conventional geometry, acting as an oblique ultra-slow spreading center and as a transfer zone that accommodates the differential shear movements between the Eurasian and African plates. Vogt and Jung (2004) propose the existence of a hot spot which generated the Azores plateau with its present thick elevated crust. The plateau was formed by successive NE jumps of the NW trending oblique spreading axis, which resulted in the present situation intersecting in the SE end with the East Azores fracture zone. The study of the mechanism of earthquakes, specially, that of 1980 provides important information about the tectonics of the islands. Two families of mechanisms (strike-slip and normal faulting), have been found with a consistent orientation of the horizontal tension axes in NE-SW direction (Borges *et al.*, 2007) .
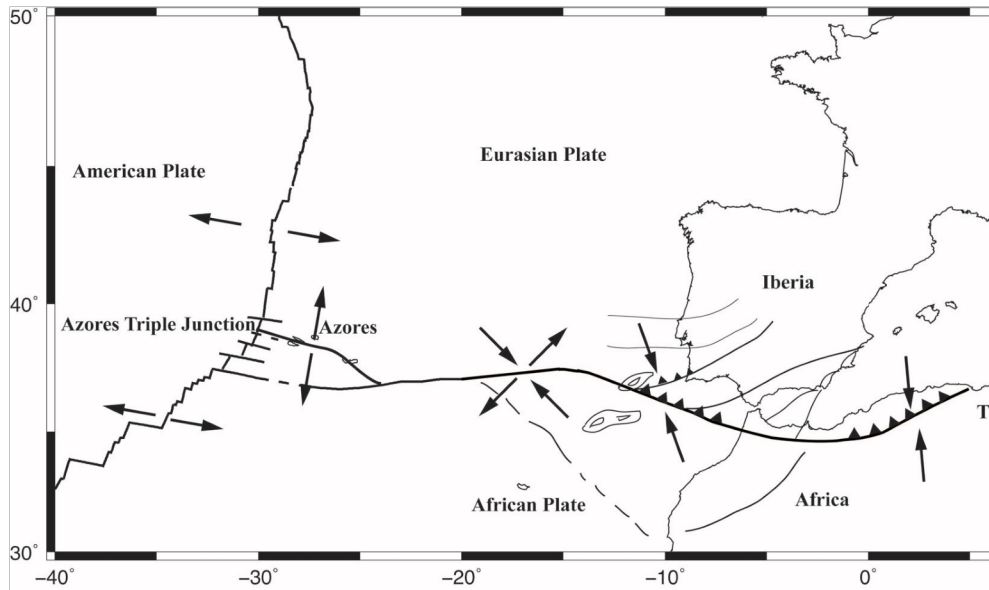
Figure 2. Tectonics, stress, and slip directions in the Azores-Gibraltar region (modified from Buforn *et al.*, 1988)

At the eastern end of the region, at the strait of Gibraltar, the plate boundary between Eurasia and Africa is affected by the collision between the Iberian Peninsula and northern Africa. This is a very complex region and abundant literature of geological and geophysical nature exists. West of Gibraltar offshore large earthquakes have taken place, especially, the socalled Lisbon earthquake in 1755 which generated a large tsunami and produce large damage in Portugal, Spain and western Morocco. East of the strait of Gibraltar, the plate boundary between Eurasia and Africa is affected by the collision between the Iberian Peninsula and northern Africa. Andrieux *et al.,* (1971) presented the first model of the structure and evolution of the Alboran Sea and the arc of Gibraltar, using the new ideas of plate tectonics. They distinguish between the internal and external zones in the Betics and Rif and propose that the internal zones do not belong to the border of either the Eurasian or African plate but constitute an intermediate rigid plate they called the subplate of Alboran. Toward the west this sub-plate joins with the Azores–Gibraltar transform fault. The relative motion toward the east of the European and African plates along this fault caused the overthrusting of the sub-plate of Alboran on both sides with the formation of the Betics, Rif, and Gibraltar Arc. Since the three plates involved have continental structure, the overthrusting of the Alboran sub-plate caused intense folding of the internal zones of the Betics and Rif. Another sign of the complexity of this region, from the point of view of seismology, is the presence of a nest of very deep earthquakes at 640 km depth and intermediate depth earthquakes, between 60 and 150 km, located in southern Spain between Granada and Malaga and in the Alboran Sea (Buforn *et al.*, 1991). Especially, the very deep earthquake (h = 640 km) of March 29, 1954, with magnitude 7 and epicenter near Durcal (Granada), poses a difficult problem concerning the tectonics of this region. Its occurrence puzzled seismologists, since no earthquake had ever happened at that depth in the Mediterranean region. This

earthquake has been interpreted as located in an isolated detached piece of lithosphere sunk in the mantle Although the general features of the tectonics of the region are fairly well understood, details of some of its aspects are still controversial. Different models have been proposed for the Betics–Rif–Alboran formation, including the presence of the Alboran sub-plate, some kind of subduction, rollback subduction, and lithospheric delamination. Certain features like the presence of very deep earthquakes under south Iberia, the rifting details in Azores, and the formation of the Alboran Basin are not yet fully explained and are still the subject of debate. The source of the large Lisbon earthquake of 1755, which generated such a large tsunami and was felt at so large distances, remains another subject of discussion.

CONCLUSION

The Azores-Gibraltar region is a seismic active tectonically complex region widely studied from the middle of the 19th century. Improvements in geophysical instrumentation together the development of numerical methods have allowed to improve the seismotectonics of this region. Detailed studies have been carried out for many authors, however, details of some aspects remain not clear, being the major unsolved question the source of the 1755 Lisboan earthquake and its devastating tsunami.

REFERENCES:

Andrieux, J., Fontboté, J.M., Mattauer, M., 1971. Sur un modele explicatif de l'arc de Gibraltar. Earth Planet Sci. Lett. 12, 191–198.

Banghar, A.R., Sykes, L., 1969. Focal mechanisms of earthquakes in the Indian ocean and adjacent regions. J. Geophys Res. 74, 632–649.

Borges, J.F., Bezzeghoud, M., Buforn, E., Pro, C., Fitas, A., 2007. The 1980, 1997 and 1998 Azores earthquakes and some seismo-tectonic implications. Tectonophysics 435, 37–54.

Buforn, E., Udías, A., Colombas, M.A., 1988. Seismicity, source mechanism and tectonics of the Azores-Gibraltar plate boundary. Tectonophysics 152, 89–118.

Buforn, E., Udías, A., Madariaga, R., 1991. Intermediate and deep earthquakes in Spain. Pure Appl. Geophys. 136, 375–393. Gutenberg, B., Richter, F., 1949. Seismicity of the Earth and Associated Phenomena. (Princeton, NJ.:Princeton University Press) Isacks, B., Oliver, J., Sykes, L.R., 1968. Seismology and the new global tectonics. J. Geophys. Res. 73, 5855–5899. McKenzie, D.P., 1972. Active tectonics of the Mediterranean region. Geophys. J. Roy. Astr. Soc. 30, 109–185.

Montessus de Ballore, F., 1906. Les tremblement de terre. Géographie séismologique. (Paris: Armand Colin).

Rothé, J.P., 1951. La structure de l'Atlantique. Annali di Geofisica 4, 27–41.

Udías, A., López Arroyo, A., 1972. Plate tectonics and the Azores-Gibraltar region. Nature 237, 67–69.

Udías, A and E. Buforn , 2010. Azores-Tunisia, a Tectonically Complex Plate Boundary. Advances in Geophysics, 52, 139-182.

Udías, A., López Arroyo, A., Mezcua, J., 1976. Seismotectonics of the Azores-Alboran region. Tectonophysics 31, 259–289. Vogt, P.R., Jung, W.Y., 2004. The Terceira Rift as a hyper-slow hotspot-dominated oblique spreading axis: A comparison with other slow-spreading plate boundaries. Earth Planet Sci. Lett. 218, 77–90.
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An Approach for the Estimation of the Magnitude of Historical Earthquakes: a sensitivity study of the 1980 and 1998 Earthquakes in the Azores

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ABSTRACT

In regions with low-to-moderate seismicity, the return-period of seismic events with large magnitudes is relatively high. Nevertheless, historical seismic events are relevant for the evaluation of seismic hazard in those regions. Thus, seismologists study the records of the effects of historical earthquakes to map the distribution intensity points, using an Intensity Scale. Afterwards, the maximum intensity point is identified as well as the probable epicentral location and magnitude. Another method, introduced by earthquake engineers, incorporates the knowledge of the behaviour of structures into posterior distributions of magnitude using fragility functions and the damage reported in historical documents. The method uses the total probability theorem to combine the uncertainty in the structural behaviour, ground motion intensity, site-to-source distance. Then, the Bayes's theorem is employed to update a prior magnitude model into a posterior magnitude distribution. Thus, the reduction of the uncertainty in the final estimates requires the preliminary application of the method to instrumental events in order to validate the appropriate framework to address historical seismicity, namely ground motion and structural response. This paper investigates the earthquakes of January 1st 1980 with M_w=6.8-7.2 and of July 9th 1998 with M_w=5.9-6.2 in Azores Islands (Portugal) as study cases to test the sensitivity to different attenuation models Ambraseys *et al.* (2005) and Akkar *et al.* (2014). A single set of fragility functions, derived from a detailed vulnerability assessment in Faial, is assumed to model the structural response in both events. The results show that, for both events, the attenuation model from Akkar *et al.* (2014) and the fault source model presented results closer to those of detailed methods. Discrepancies can also be explained by differences in the prior distance model resulting from source models assumptions. The intervals Mw=5.96±0.53 and Mw=6.91±0.42 have been estimated for the 1998 and the 1980 earthquake, respectively.

Keywords: fragility functions; historical seismicity; 1998 earthquake; 1980 earthquake;

INTRODUCTION

In regions with low-to-moderate seismicities, such as the Azores Islands (Portugal), the return period of seismic events with large magnitude is relatively high. This fact drove seismologists to investigate the historical ground motion intensities that are described in historical documents through earthquakerelated phenomena, as shakes in objects, cracks in the ground and walls, and even structural failure. Each intensity point is mapped using an intensity scale, as the Mercalli Modified Scale (MMI), enabling the identification of the probable epicentral location and intensity. Afterwards, an empirical relationship is utilized to calculate the likely magnitude of the historical seismic event. Nevertheless, the traditional methodologies translate the damage of structures into a single intensity value, leaving their behaviour out of consideration (Eisinger *et al.*, 1992).

Another method, proposed by earthquake engineers (Ryu *et al.*, 2009), uses fragility functions of the type $P(DM \geq ds_i | IM = im)$, which describe the conditional probability of exceeding a certain damage state in structures ds_i given an intensity measure IM, with instances im. This is possible because the method defines the damaging seismic event E in terms of damage occurrences using probability theory. The calculation process is schematised in Figure 1.
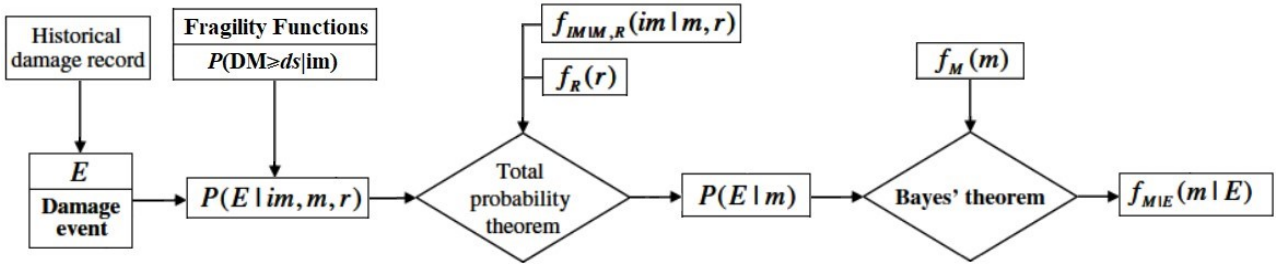
Figure 1. Flowchart of the magnitude estimation method (based on Ryu *et al.*, 2009).

The fragility functions are then utilized to compute the probability of observing single damage states $P(DM = ds_k | im)$ using Eq. (1).

$$P(\mathrm{DM} = \mathrm{dm}_k | \mathrm{im}) = P(\mathrm{DM} \geq \mathrm{dm}_k | \mathrm{im}) - P(\mathrm{DM} \geq \mathrm{dm}_{k+1} | \mathrm{im}) \tag{1}$$

Using Eq. (2), these probabilities are then combined with the number of damage occurrences $n_{ds,k}$ to find the probability $P(E | im, m, r)$ of a damaging event given an intensity measure im, magnitude m and distance r.

$$P(E | \mathrm{im}, m, r) = \frac{n_t!}{\prod_{k=0}^{n_d} n_k !} \times \prod_{k=0}^{n_d} P(\mathrm{DM} = \mathrm{dm}_k | \mathrm{im}, m, r)^{n_k} \tag{2}$$

This step is possible due to the assumption that the observed damage is also caused by magnitude and distance. Afterwards, the total probability theorem employed together with an attenuation equation $f_{IM|M,R}(im,m,r)$ and a prior distance distribution $f_R(r)$ to estimate the probability of the damage event given magnitude $P(E|m)$, as in Eq. (3).

$$P(E | M = m) = \int \int P(E | \mathrm{im}, m, r) \times f_{IM|M,R}(\mathrm{im} | m, r) \times f_R(r) \, d\mathrm{im} \, dr \tag{3}$$

Finally, the Bayes' theorem is employed as in Eq. (4) to update a prior magnitude distribution f_M into the posterior distribution of magnitude $f_{M|E}$.

$$f_{M|E}(m | E) = \frac{P(E | M = m) \times f_M(m)}{\rule{0pt}{0pt}} \tag{4}$$

$$\int P\,E\,M\big(\,|=m\big)\times f_M(m\,dm)$$

In order to apply this method to historical contexts, it is first necessary to validate the framework. One option is to utilize data from recent instrumental earthquakes. The present study cases are the January 1st 1980 with M_w=6.8-7.2 (Borges et al., 2007; Carvalho *et al.*, 2001) and of the July 9th 1998 with M_w=6.0-6.2 (Borges *et al.*, 2007; Matias *et al.*, 2007) in Azores Islands (Portugal). More specifically, the method (Ryu *et al.*, 2009) is here employed to study the sensitivity of the magnitude estimates to different attenuation models, namely Ambraseys *et al.* (2005) and Akkar *et al.* (2014), and soil types A, B and C. The fragility functions are derived from a detailed study of the structural vulnerability distribution of typical buildings from Faial damaged by the 1998 earthquake (Ferreira *et al.*, 2017). The same set of fragilities is extrapolated for the case of the 1980 earthquake, despite the different damage datasets ("Soeiro" and "GAR", from Lucas *et al.*, 1992).

MAIN RESULTS

The framework of assumptions for the presented approach, consistently with Figure 1, is endorsed by earlier studies on ground motion, building typologies and damage. The fragility functions – assumed as lognormally distributed with moments μ_{ds}={0.037 0.078 0.153 0.328 0.907} and σ_{ds}={0.126 0.132 0.210 0.212 0.212} –, attenuation equation for different Joyner-Boore distances R_{JB}, assuming a strike-slip fault type, M_w=6.1, and soil of type C (V_{s30}=270 m/s), as well as prior distance densities in the form of histograms are presented in Figure 2.
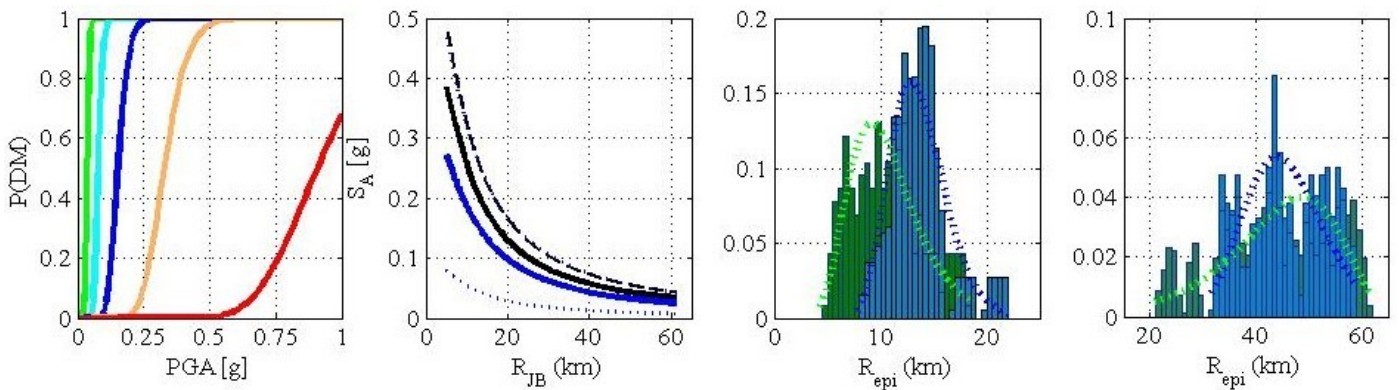
Figure 2. Sequence of fragility functions, on the left; attenuation models Ambraseys *et al.* (black) and Akkar *et al.* (blue), on the centre-left; histograms for the densities of the epicentral distances for Faial earthquake, considering epicentral locations Epi1 (blue) and Epi2 (green), on the centre-right, and for the densities of the epicentral distances in Terceira for "Soeiro" (blue) and "GAR" (green), on the right.

The epicentre of the 1980 earthquake was considered in 38.810ºN, 27.780ºW, and the epicentre of the 1998 earthquake in locations "Epi1" with 38.634ºN, 28.523ºW, and "Epi2" with 38.640ºN, 28.590ºW (Borges *et*

al., 2007). Additionally, the fault systems are also studied, considering Joyner and Boore distances R_{JB} to the edges of a 30 km fault, in the case of the 1980 earthquake (Estevão & Oliveira, 2012), of a 16.5 km fault, in the case of the 1998 earthquake (Estevão & Carvalho, 2014). The expected values of magnitude μ_M and respective standard deviations σ_M are presented in Table 1 and Table 2, respectively, for the 1998 and 1980

earthquakes. The distance model has a uniform uncertainty of ± 1.0 km on the site and point sources, while the fault sources are assumed as deterministic. The prior magnitude distribution is considered here as uniform in the strong magnitude range (5.0≤M_w≤8.0).

Table 1. Magnitude distribution moments $\mu_M(\sigma_M)$ for the 1998 "Faial" earthquake.

f_M	Ambraseys et al., 2005			Akkar et al., 2014								
	Fault						Epi1			Epi2		
	A	B	C	A	B	C	A	B	C	A	B	C
1	5.43	5.38	5.30	6.02	5.96	5.99	6.05	5.97	5.98	5.91	5.85	5.89
	(0.59)	(0.59)	(0.60)	(0.86)	(0.85)	(0.88)	(0.78)	(0.78)	(0.81)	(0.78)	(0.77)	(0.81)

Table 2. Magnitude distribution moments $\mu_M(\sigma_M)$ for the 1980 "Terceira" earthquake.

f_M	Soeiro			GAR			Soeiro			GAR			Soeiro			GAR		
	Ambraseys et al., 2005						Akkar et al., 2014											
	R_{JB} (Fault)												R_{epi}					
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
1	7.06	6.92	6.69	6.78	6.66	6.44	7.10	7.05	6.94	6.96	6.90	6.79	7.01	6.95	6.83	6.87	6.80	6.68
	(0.39)	(0.40)	(0.43)	(0.52)	(0.51)	(0.51)	(0.72)	(0.72)	(0.75)	(0.77)	(0.77)	(0.79)	(0.69)	(0.70)	(0.73)	(0.73)	(0.74)	(0.76)

The attenuation model Akkar et al. (2014) provided higher estimates with relatively higher standard deviations for both case studies. This trend is consistent with the spectral accelerations and standard deviations presented for the two attenuation models in the second plot of Figure 2. Within attenuation, the model from Akkar et al. (2014), provided magnitudes in between **6.05**(0.78) and **5.85**(0.77) for the 1998 earthquake, and **7.10**(0.72) and **6.68**(0.76) for the 1980 earthquake. The use of epicentral distances or the attenuation model Ambraseys et al. (2005) resulted in relatively smaller standard deviations.

CONCLUSION

This study aimed at understanding the impact of different attenuation and source models in the final magnitude estimates. The expected values of magnitude were found in ranges consistent with magnitude estimates obtained with instrumental data, namely in the case of the attenuation model Akkar et al. (2014), with M_w=**5.96** ± 0.53 for the 1998 earthquake, and M_w=**6.91** ± 0.42 for the 1980 earthquake (confidence level of 95%). The epicentre source model presents relatively lower standard deviations for both earthquakes, while the source models presented relatively more accurate values of magnitude. The resulting distance distributions can partially explain the discrepancies found between the results obtained from assuming the

"Epi1" and "Epi2" models, in the case of the 1998 earthquake, and between "Soeiro" and "GAR" damage datasets.

REFERENCES:

Ambraseys N.N., Douglas J., Sarma S.K. and Smit P.M. (2005) "Equations for the estimation of strong ground motions from shallow crustal earthquakes using data from Europe and the Middle East: horizontal peak ground acceleration and spectral acceleration", *Bull Earthquake Eng*, 3(1), 1-53.

Akkar S., Sandıkkaya M.A., Ay B.O. (2014) "Compatible ground-motion prediction equations for damping scaling factors and vertical-to-horizontal spectral amplitude ratios for the broader Europe region", *Bull Earthquake Eng*, 12(1), 517-47.

Borges J.F., Bezzeghouda M., Buforn E., Proc C., Fitasa A. (2007) "The 1980, 1997 and 1998 Azores earthquakes and some seismo-tectonic implications", *Tectonoph*, 435(1-4), 37-54.

Carvalho A.M., Sousa L., Oliveira C.S., Campos-Costa A., Nunes J.C., Forjaz V.H. (2001) "Seismic hazard for the central group of the Azores islands", *Boll Geof Teor App*, 42(1-2), 89-105.

Eisinger U., Gutdeutsche R., Hammerl C. (1992) "Historical earthquake research – an example of interdisciplinary cooperation between geophysicists and historians", *Abh Geol B-A*, 48(1), 33-50.

Estevão J.M.C., Oliveria C.S. (2012) Point and fault rupture stochastic methods for generating simulated accelerograms considering soil effects for structural analysis, *Soil Dyn and Earthq Eng*, 43(1), 329–341.

Estevão J.M.C., Carvalho A. (2014) Uncertainties in the stochastic simulation of earthquakes: the case of Azores. 5th JPEE; 2014 Nov 26-28; Lisbon, Portugal.

Ferreira T.M., Maio R., Vicente R. (2017) "Seismic vulnerability assessment of the old city centre of Horta, Azores: calibration and application of a seismic vulnerability index method", *Bull Earthquake Eng*, 15(7), 2879-99.

Matias L., Dias N.A., Morais I., Vales D., Carrilho F., Madeira J., et al. (2007) "The 9th of July 1998 Faial Island (Azores, North Atlantic) seismic sequence", *J Seismology*, 11(3), 275-98.

Ryu H., Kim J., Baker J. (2009) A Probabilistic method for the magnitude estimation of a historical damaging earthquake using structural fragility functions", *Bull Seismol Soc Am*, 99(2), 520-37.

Lucas A., Oliveira C.S., Guedes J.H.C. (1991) "Quantificação dos danos observados no parque habitacional e do processo de reconstrução", In: Oliveira CS, *et al.* (eds), *10 Anos após o sismo dos Açores de 1 de Janeiro de 1980*, GRA, LNEC, Lisbon, 667-742. (in Portuguese

Seismic Hazard and Risk Assessment for Azores Region, Based on Seismic Conditions

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ABSTRACT

It is intended to evaluate the seismic risk in the Azores region, based on the recent seismic conditions (i.e., occurrences, magnitudes). Since this region holds a variety of geological structures, such as faults, rifts, trenches and volcanoes, it was convenient to first model the spatial distribution of seismic phenomena.

Based on seismicity and magnitude of a sample of about a century, seven seismic zones had been defined. For each zone, it was estimated the probability of occurrence of a seismic event, given that the last occurrence took place in each seismic zone, using Markov chains. This reveals that the seismic process has "memory". This "spatial memory" decreases with time.

We are currently modelling the seismic process (time, space and magnitude) using Markov chains, allowing to estimate the seismic risk of a target zone, knowing the recent seismic past.

Keywords: Risk assessment, Spatial memory, Markov chains, Modelling natural phenomena

INTRODUCTION

Modelling natural phenomena is not an easy task. Traditionally, Poisson model is used assuming that there is no memory, i.e. the probability of earthquakes in an area is not affected by previous earthquakes in the region. But observations of both seismic records and the nature of the physical phenomenon, reveal memory in the seismic process of occurrences.

Since a long time ago several authors were not satisfied with memoryless models. Kiremidjien and Anagnos (1984) proposed models with memory, but in that time their approach was not greatly effective in practice. Nowadays, several authors recognise the importance of memory in the seismic process of occurrences such as Nava et al. 2005, Çelebioğlu and Ünal, 2011, Cavers and Vasudevan, 2015, Susilo et al. 2019 and Rodrigues and Oliveira 2020.

The proposed modelling will be developed in three phases:

1- Since Azores region holds a variety of geological structures, such as faults, rifts, trenches and volcanoes, it was necessary to first define seismic zones based on statistical and geological criteria;
2- Due to "spatial memory", the probability of an earthquake occurring in an area is not independent of the location of the last occurrence. Markov chains were used to quantify the probability of transition between zones, irrespective to time and magnitude.

3- This step completes the last, allowing to statistically quantify the common concerns: where will be the next earthquake? – Space variable (Zn); when? - Time variable (Dt) and how strong it will be? – Size (S) variable.

Data used in this study covers about a century and was not collected from a unique source. For the period 1915-1998 the catalogue of Nunes et al. (2004) was used. For the most recent period, 1999-2017, data were obtained from the archives (catalogues) of the Instituto Português do Mar e da Atmosfera (I.P.M.A.) (last accessed in December 2017). Therefore, for the Azores Archipelago, a total of 20,389 seismic records were gathered. These records will be designated as "data" hereafter. All records were considered, including aftershocks.

R® statistical programming software (see, e.g., Dalgaard 2008 or Venables et al. 2011), Turbo Pascal® and Visual Basic® were the software tools used to implement the statistical analysis that will be presented.

MAIN RESULTS

Based on statistical and geological criteria, seven seismic zones have been defined for Azores region (Rodrigues and Oliveira, 2013). This zone definition will be adopted. Fig. 1 shows a schematic representation of the referred zones as well as the main geological features.
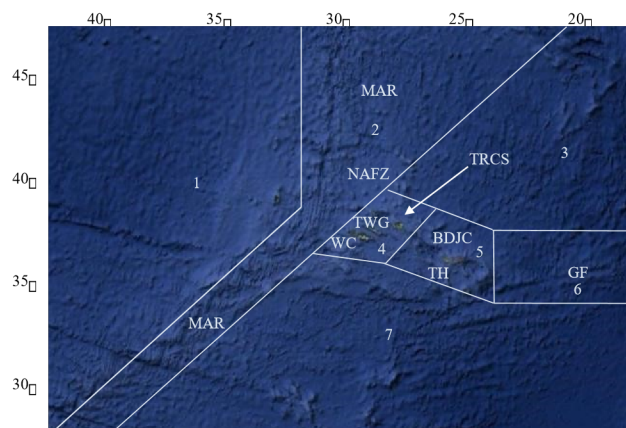
Figure 1. Schematic representation of the adopted zones, their numbering and the main geomorphological structures of the study area: (1) American Plate, (2) MAR = Mid-Atlantic Ridge, NAFZ = North Azores Fracture Zone, (3) Euro Asiatic Plate, (4) TRCS = Terceira Rift Central Sector, WC = West of Capelinhos, TWG = Trench West of Graciosa, (5) BDJC = Bank D. João de Castro, TH = Trench Hirondelle, (6) GF = Gloria Fault, (7) = African Plate.

For the period covered by data, the probability of an earthquake occur in each seismic zone may be computed given an unconditional probability. But if we know the location (zone) of the last earthquake, the corresponding probabilities may differ significantly.

Let Zn be the random variable representing each of the seven seismic zones. Zn {1, 2, 3, 4, 5, 6, 7}.

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zone is a *state* and each change of state is *a transition* and the moments at which the system is observed (in this case, earthquake events) are the *times*. If an earthquake occurs at time t in zone i, $Zn_t = i$, in the same way, if the following seismic event happens in zone j at time $t + 1$, $Zn_{t+1} = j$. $P[Zn_{t+1} = j \mid Zn_t = i]$ is the probability of seismic occurrence in zone *j* at time *t + 1* given that an earthquake has occurred in zone *i* at time *t*. Eq. (1) presents the one-step transition matrix, $T = [p_{i,j}] = P[Zn_{i+1} = j \mid Zn_i = i]$, $i, j = 1, 2, \ldots, 7, i \in \mathbb{N}$.
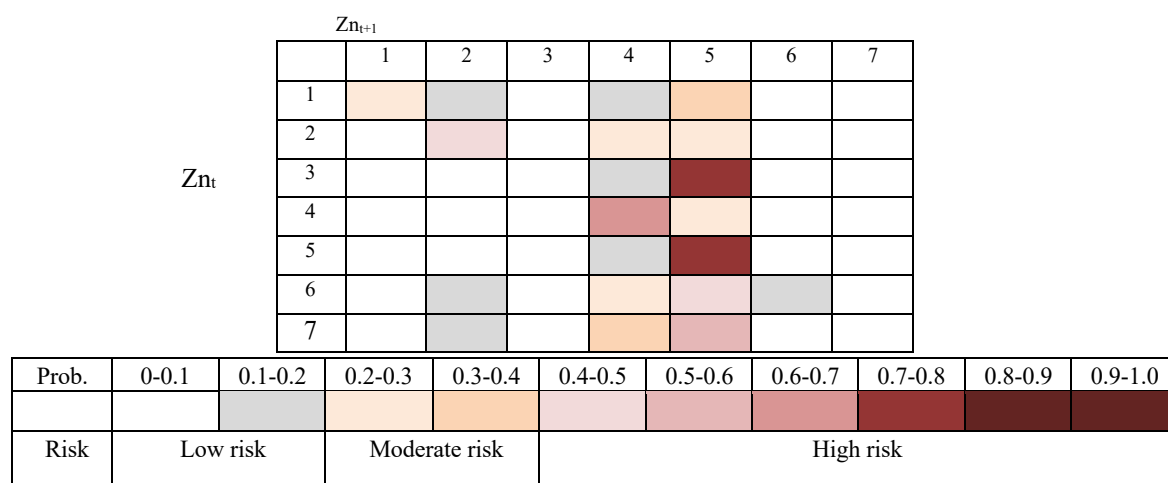
$$T = \begin{bmatrix} 0.287 & 0.165 & 0.008 & 0.176 & 0.303 & 0.057 & 0.004 \\ 0.019 & 0.491 & 0.001 & 0.204 & 0.241 & 0.042 & 0.001 \\ 0.059 & 0.059 & 0.015 & 0.132 & 0.706 & 0.015 & 0.015 \\ 0.006 & 0.076 & 0.002 & 0.628 & 0.249 & 0.037 & 0.001 \\ 0.008 & 0.051 & 0.004 & 0.151 & 0.744 & 0.040 & 0.001 \\ 0.015 & 0.118 & 0.000 & 0.257 & 0.482 & 0.124 & 0.003 \\ 0.000 & 0.100 & 0.033 & 0.300 & 0.500 & 0.033 & 0.033 \end{bmatrix} \quad (1)$$

For example, $p_{3,5} = 0.706$ is the probability of occurrence of an earthquake in zone 5, given that the last event has been in zone 3. The matrix T expresses clearly a "space memory". If the location of the last event did not influence the following, the elements of each column will be equal, with the values of the unconditional probability, $P[Zn = i]$, $i = 1, 2, \ldots, 7$.

Fig. 2 shows a schematic representation of the seismic risk based on matrix *T,* in which larger probabilities are highlighted with darker colours.

If an earthquake occurs in zone 2 at time t, i.e., $Zn_t = 2$, the probability of $Zn_{t+2} = 4$ is a two-step transition, $p_{24}^{(2)}$. According for example (Ravindran and Dolberg, 1987), for a stationary Markov chain, with transition matrix T:

$$T^{(n)} = T^n \quad (2)$$

	Zn_{t+1}						
Zn_t	1	2	3	4	5	6	7
1							
2							
3							
4							
5							
6							
7							

Prob.	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1.0
Risk	Low risk		Moderate risk		High risk					

Fig. 2 Schematic representation of seismic risk based on one-step transitions.

After 10 transitions, in matrix $T^{(10)}$, the values in each column are almost equal, an expected result, because matrices are expected to have equal values in each column as the order increases, and each line tends to the spatial (Zn) density function, that is, the process loose memory. After several events, the probability of occurrence among the seismic zones becomes nearly independent of the location of an earthquake that occurred a few steps before.

This procedure allows us to estimate the seismic risk among seismic zones in time, but it does not consider the magnitude or the time between consecutive occurrences.

To statistically quantify the three variables, it is necessary to redefine the *states*. Studies are ongoing to estimate the probabilities of $(Dt_{i-1}, S_{i-1}, Zn_{i-1}) \rightarrow (Dt_i, S_i, Zn_i)$, using suitable ranges of each variable. For each zone, if we divide the Size of an earthquake in *weak* or *strong*, and the time between earthquakes in *recent* and *not recent,* we will have a total of 28 states. Each seismic record will be associated with a *state*, that corresponds to a seismic condition. Knowing the current seismic condition, (information on Dt, S and Zn) it is possible to estimate the risk of the next *state*, using a 28 by 28 transition matrix.

CONCLUSION

A methodology is presented that allows estimating the seismic risk for a region based on the location of recent earthquakes, with a notorious spatial "memory".

Considering seismic conditions as *states* of a Markov chain, it is possible to assess the risk of a given region, based on the information of time, magnitude and location of the latest occurrences. Studies are ongoing to better characterize this 3-variable model.

REFERENCES:

Cavers, M. and Vasudevan, K. (2015). "Spatio-Temporal Complex Markovian Chain (SCMC) Model Using Directed Graphics: Earthquakes sequencing", *Pure Appl. Geophys*, 172, 225-241.

Çelebioğlu, S. and Ünal, E. (2011). "A Markov chain modelling of the earthquakes occurring in Turkey", *Gazi Univ. J. Sci. (GUJS),* 24(2), 263–274.

Dalgaard, P. (2008). " Introductory Statistics with R", Springer, Berlin.

I.P.M.A., Instituto Português do Mar e da Atmosfera. Archives. http://www.ipma.pt/pt/geofisica/sismicidade/. Accessed 2017.

Kiremidjien, A.S. and Anagnos, T. (1984) "Stochastic Slip-Predictable Model for Earthquake Occurrences", *Bull. Seismol. Soc. Am*. 74 (2), 739-755.

Nava, F.A., Herrera, C., Frez, J. and Glowacka, E. (2005). "Seismic Hazard Evaluation Using Markov Chains: Application to the Japan Area", *Pure Appl. Geophys*.162, 1347–1366.

Nunes, J.C., Forjaz and V.H., Oliveira, C.S. (2004). "Catálogo Sísmico da Região dos Açores", Lisbon, Portugal, (CDROM) (in Portuguese).

Ravindran, A., Phillips, D.T. and Dolberg, J.J. (1987). "Operations Research principles and practice", *John Wiley & Sons*, NY.

Rodrigues, M.C.M. and Oliveira, C. S. (2013). "Seismic zones for Azores based on statistical criteria", *Nat. Hazards Earth Syst. Sci*.13, 2337-2351. doi:10.5194/nhess-13-2337-2013.

Rodrigues, M.C.M. and Oliveira, C. S. (2020). "Considering spatial memory to estimate seismic risk: the case of the Azores Archipelago", *GEM - International Journal on Geomathematics*, 11:16.

Susilo, A., Hisyam, F. and Wasis (2019). "Earthquake analysis in Java, Indonesia between 1960-2017 using Markov chain model", *International Journal of Geomat*", 17, 63, 149-156.

Venables, W.N., Smith, D.M. and R Development Core Team. (2011). "An Introduction to R. Notes on R: A Programming Environment for Data Analysis and Graphics", Springer, Berlin

Seismic Retrofitting of Existing Buildings Using Cost-Benefit Analysis

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ABSTRACT

The improvement of the seismic performance of existing buildings is usually accomplished by adopting one or more retrofitting interventions. The selection of the retrofitting scheme is generally carried out considering conventional parameters, based on e.g. economic or structural considerations, recurring to past experience from practitioners and without employing a thorough and systematic evaluation procedure. Instead, it is recognized that, to identify an optimal retrofitting choice, it is necessary to include different evaluation criteria. This aspect becomes even more relevant when referring to buildings of strategic importance, such as school buildings, for which typical structural response-oriented criteria may not be enough to identify the best choice. This study comparatively assesses retrofitting options for an existing reinforced concrete (RC) school building, considering both the structural performance and a cost-benefit analysis. The comparative performance assessment is conducted on a detailed numerical model, able to reproduce the main structural deficiencies observed during past earthquakes in RC school buildings. Then, different retrofitting interventions are identified with the aim to solve the structural issues and improve the overall performance of the case-study school building. The seismic performance is quantified in terms of seismic losses, including the contribution of non-structural elements, amongst other metrics. Finally, the outcomes of the evaluation exercise are critically analyzed and recommendations are made.

Keywords: RC buildings; Performance assessment; Retrofit strategies; Cost-benefit analysis

INTRODUCTION

Seismic retrofitting addresses the aspects that render buildings vulnerable and compromise their proper performance during earthquake events. A rational approach for the selection of a retrofitting scheme should consider the seismic risk of the building, guaranteeing an adequate performance in terms of minimum level of safety against structural collapse and adequate protection of non-structural elements. (NSE), which can block exits and/or harm people. Despite their importance, most of the NSE are not seismically designed thus are vulnerable to relatively low levels of earthquake action, leading to high expected annual losses (EAL), as highlighted by Sousa and Monteiro (2018). It is essential to conduct a detailed performance assessment for every considered retrofitting strategy. A commonly adopted approach in retrofitting is to strengthen buildings in order to increase their lateral strength capacity. However, the benefits reached through strengthening and stiffening to improve the collapse capacity and to reduce drift-sensitive losses are many times counteracted by higher floor acceleration demands, thereby increasing losses in acceleration-sensitive non-structural elements (NSE) and subsequently resulting in a net increase in the EAL. This study identifies the most convenient intervention among a set of retrofitting strategies, using an existing RC school building as case-study, employing structural and economic criteria. The building typology was selected in view of the inadequate behavior of school buildings examined in previous studies (O'Reilly et al. 2018). The ranking obtained from the evaluation exercise is analyzed, considering the outcomes of a refined nonlinear performance assessment and loss estimation analysis.

CASE STUDY BUILDING AND RETROFITTING SCHEMES

The building considered for this study consists of a reinforced concrete (RC) school building located in central Italy, a region that has recently experienced important seismic events. The school building presents two stories and one underground portion (stair-case section) and the construction period is estimated at around 1960-1970. Given the decade of construction of the building, and to consider the possible structural deficiencies found in similar RC buildings in Italy, the simulation of the structural behavior of old RC frames was adopted, developing a full 3D nonlinear numerical model. In view of the identified structural deficiencies that compromise the overall performance of the case-study school building, different retrofitting strategies are proposed. The first retrofitting approach (A1) consists of applying carbon fiber reinforced polymers (CFRP) to the structural elements. The second retrofitting approach (A2) introduces cross steel braces in some parts of the school building. The third retrofitting approach (A3) is a hybrid retrofitting configuration between strategies A1 and A2 (CFRP and steel bracing). The last retrofitting approach (A4) combines CFRP with viscous dampers placed at different locations of the school building.

BUILDING STRUCTURAL PERFORMANCE

Uniform hazard spectra (UHS) were determined for the location of the case-study building, in the Abruzzo region. The Italian seismic design and assessment code specifies four limits states to which the performance of the building should be assessed. In case of school buildings (i.e. nominal life of 75 years for a building class III) these limit states are SLO: operational limit state; SLD: damage limitation limit state; SLV: life safety limit state; and SLC: collapse prevention limit state. The capacity points obtained for the case study school building are observed in the pushover curves of Figure 1a, represented in terms of base shear coefficient (base shear capacity/seismic weight of the building) and the building roof drift.
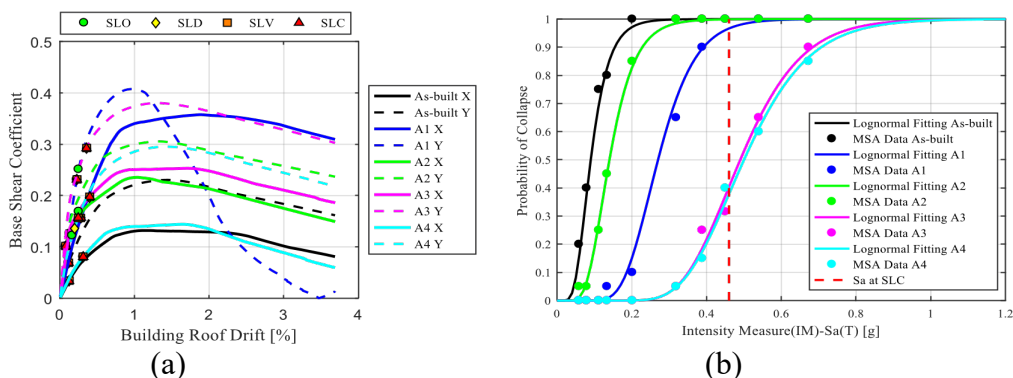
Figure 1. Normalized capacity curves of the as-built and retrofitted building (SLO: operational limit state; SLD: damage-control limit state; SLV: life-safety limit state; SLC: collapse-prevention limit state).

Due to the lack of capacity of some beam-column joints, premature failure of joints takes place even before the building reaches a roof drift of 0.3% therefore this critical aspect (i.e. red dots in Figure 1a) controls all performance points in the building. The performance at each limit state was assessed using the N2 method.

The as-built configuration is exceeding the code requirements on drift limitations, being more critical for the SLO in the X direction. Moreover, the strength and deformation checks carried out for SLV and SLC

demonstrate that many structural elements present a brittle failure mechanism (shear failure) and only in some few cases the flexural elements reach a plastic behavior. It was found that several beam-column joints do not follow a desirable ductile failure mechanism.

Any of the retrofitting configurations leads to an improvement of the lateral capacity of the case-study school building. Approach A1 yields higher strength capacity and makes the building stiffer at the same time, due to the effect of CFRP in increasing the strength of RC members, leading to improved performance points, which account for larger shear forces and lateral displacements. The use of steel braces (A2) also considerably rises the strength and lateral stiffness of the building, although it does so from a more localized perspective. In the case of the intervention A3, the structural characteristics of the building are substantially modified. The combined effect of CFRP and steel braces produces a larger lateral stiffness, which shortens the fundamental periods of the building. Finally, approach A4 amplifies the structural capacity of the building in the Y direction but, in the X direction, the improvement does not seem equally substantial. Even though the amount of CFRP in this direction increases the strength of joints their failure still takes place before the flexural failure of beams and columns.

Multiple-Stripe Analysis (MSA) was then carried out and the collapse fragility functions, illustrated in Figure 1b, were defined by the first failure of a RC member. The as-built configuration is very vulnerable, even for low-intensity levels. Nevertheless, all retrofitting strategies deal with this issue by shifting the collapse fragility function to a range of larger spectral accelerations, which quantifies the increase in the median probability of collapse for each retrofitting alternative. Strategies A3 and A4 are the only that resulted in a median probability of collapse larger than the spectral acceleration associated with SLC therefore being the ones that ensure a considerable reduction of the collapse vulnerability of the school building. Then, loss assessment, in terms of expected annual losses (EAL), was carried out following the FEMA P58 (2012) guidelines. Table 1 lists the EAL obtained for each model.

The replacement cost of the case-study school building was estimated using available information on Italian school buildings reported after the 2012 Emilia-Romagna earthquake. All solutions reduce the EAL. The effect of A1 on enhancing the deformation capacity of the building can be translated as fewer collapse cases and thereby less expected economic losses. A2 also decreases EAL but not as significantly. In the case of A3, the combined action of steel braces and CFRP control the deformation and stiffness of the building, resulting again in fewer collapse scenarios. However, its EAL is larger than that A1 due to the influence on the damage to acceleration-sensitive NSE. The higher PFAs induced to the school building results in larger expected

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economic losses and thereby higher EAL. On the other hand, A4 is the only strategy that achieves a substantial reduction of EAL, given that both demand parameters (PSD and PFA) are greatly diminished by the added viscous damping.

Table 1. EAL and total replacement cost for as-built and retrofitted building configurations.

As-built	1.56	Models	Expected annual loss, EAL [%]	Replacement Cost [€]
		A1	0.54	
		A2	1.15	
		A3	0.60	
		A4	0.24	
				2,652,465.00

COST-BENEFIT ANALYSIS

The cost-benefit analysis for each retrofitting strategy was conducted using the economic benefit (B) parameter. This analysis assumed a rate of return of 2% and set the lifespan of the building to 75 years (nominal life of building Class III]). The breakeven times of each retrofitting alternative are obtained when these ratios intersect the curves of economic benefit (B). The cost of each retrofitting intervention was estimated from published information and following recommendations by practitioners and manufacturers. The retrofit cost associated to A2 is 0.29% of the total replacement cost of the building, which makes A2 feasible from an economic point of view, i.e. the investment can be recovered right away (i.e. within the same year it has been applied). On the other hand, A1 needs more than 100 years to amortize the investment, thereby, this strategy is not economically favorable. Finally, the implementation cost of A3 and A4 will be fully amortized after 35 and 36 years, respectively. These values represent less than half of the lifespan of the building, which makes these alternatives also financially attractive for the case-study school building.

CONCLUSIONS

This study investigated four different retrofitting strategies (CFRP; steel braces; CFRP combined with steel braces; and CFRP combined with viscous dampers) applied to an existing vulnerable RC school building. An exhaustive seismic risk analysis was carried out, in terms of collapse performance and loss estimation, producing outcomes for a cost-benefit analysis. It was observed that only two of them (CFRP combined with steel braces and CFRP combined with viscous dampers) were able to considerably improve the overall performance of the building, providing also acceptable break-even times, according to the cost-benefit analysis, hence considered as the most suitable options. In addition to the fact that both strategies achieved a substantial structural performance improvement, the intervention consisting of CFRP and viscous dampers

also led to the best performance from the refined assessment and loss estimation analysis. From a purely economic viewpoint, the solution based on steel braces would be the most convenient strategy.

REFERENCES

FEMA P58-1. (2012) Seismic Performance Assessment of Buildings: Volume 1 - Methodology (P-58-1). vol. 1. Washington, DC.

O'Reilly G, Perrone D, Fox M, Monteiro R, Filiatrault A (2018). Seismic assessment and loss estimation of existing school buildings in Italy. *Engineering Structures*, 168, 142-162.

Sousa L, Monteiro R. (2018) Seismic retrofit options for non-structural building partition walls: impact on loss estimation and costbenefit analysis. *Engineering Structures*, 161, 8-27.

Seismic Assessment of Ancient Masonry Buildings – the In- and Out- Plane Responses

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ABSTRACT

Ancient masonry buildings generally show high seismic vulnerability, as they have been designed only for gravitational loads. Most of these buildings have flexible timber floors, with low in-plane stiffness and insufficiently connected to the perimeter walls, to assume that they can distribute the inertia forces among the vertical elements as a rigid diaphragm. Thus, for this type of masonry buildings, nonlinear analyses need to be used for their seismic assessment. For the global analysis of the masonry buildings, a structural modelling approach, based on the equivalent frame method, is recommended. Such an approach requires a limited number of degrees of freedom, allowing the analysis of complex three-dimensional models with a reasonable computational effort and maintaining an acceptable level of accuracy in representing the nonlinear behaviour of the structure.

This document addresses the problems on the evaluation of the seismic response of existing masonry buildings, and the equivalent frame modelling and the nonlinear static analyses as a practical approach for the calculation and interpretation of the global response. The main characteristics of 3Muri program are presented, not only the main features, dedicated to the global analysis of the structure, but also the optional modules available. 3Muri has proved particularly reliable through experimental tests and analysis of damage in real structures due to seismic events. According to the authors' opinion, this program is adequate for the seismic assessment and retrofit of structures built in masonry and mixed materials (e.g. masonry and reinforced concrete) as it is easy to use and trustworthy.

Keywords: Seismic Assessment, Masonry Buildings, Equivalent-frame modelling, 3Muri

INTRODUCTION

Earthquakes are the main cause of damage in ancient masonry buildings. Their high seismic vulnerability is mainly due to the characteristics of the material (low tensile and shear strengths), flexibility of the floors, weak connections between floors/roofs and masonry walls and high mass of these walls. In order to reduce these buildings' seismic vulnerability, it is fundamental to have accurate analysis models able to capture the nonlinear behaviour of masonry.

The seismic behaviour of masonry buildings is usually divided between the out-of-plane response and the inplane response. The first is related to local mechanisms, typically consisting on the overturning of parts of the structure, including monolithic masonry walls with some interlocking across the thickness, which would prevent the masonry disintegration, and also parts insufficiently connected to the rest of the structure (Figure 1, left). The second is related to the occurrence of a global (box-type) behaviour controlled by the in-plane capacity of walls and the in-plane stiffness of horizontal diaphragms (Figure 1, right).

Figure 1. Damage in Angra do Heroísmo, Azores, due to the 1980 earthquake. Example of local mechanisms (left) and of damage in the piers (right) (DGPU, 1980).

Typically, for the seismic assessment, the in-plane and out-of-plane responses are carried out by developing nonlinear analysis and neglecting their interaction, since out-of-plane mechanisms usually involve local parts of the structure. The in-plane response may be determined through nonlinear static (pushover) analysis considering the equivalent frame model approach. The out-of-plane response denotes the activation of local mechanisms, typically consisting of the overturning of building parts. The out-of-plane response may be evaluated by nonlinear kinematic analyses considering the macroblock modelling approach.

According to the equivalent-frame modelling, each masonry wall is discretized into a set of panels (piers and spandrels), in which the nonlinear response is concentrated and modelled by nonlinear beams, connected by a rigid area (nodes) where damage does not occur. The idealization as an equivalent frame easily allows to introduce other structural elements, such as reinforced concrete beams or columns, together with the masonry ones. Thus, it is particularly versatile to model mixed structures (e.g. mixed masonry and reinforced concrete structures which are quite common in existing buildings). For the assessment of local mechanisms, the response nonlinearity is concentrated on the interfaces between the different blocks involved in the formation of the kinematism.

3Muri program (Lagomarsino et al., 2013) is devoted to the implementation of the equivalent-frame model for the global nonlinear seismic analysis of masonry buildings. 3Muri has optional modules available for local mechanisms analysis and sensitivity analysis. The former is dedicated to the verification of possible local mechanisms on the structure. The later aims to reach a better knowledge of the structure's characteristics and the single elements contribution to the global functioning, including the identification of parameters that express the degree of uncertainty about the structure and modelling. Different studies successfully compared the results of experimental campaigns on shaking table and damage on real structures struck by earthquakes (L'Aquila 2009 and Emilia 2012, both in Italy) with the numerical ones obtained with 3Muri (e.g. Cattari et al., 2014, Lagomarsino and Cattari, 2014, Galasco et al. 2006). This has proven the reliability of the program for the seismic assessment of masonry buildings.

MAIN RESULTS

To illustrate the potentiality of the 3Muri program and the use of structural modelling approach for the seismic analysis of the masonry buildings two case studies are presented. The first one is the study of traditional masonry Azorean buildings, inserted in an aggregate, including buildings with different height and floor levels (Fagundes et al., 2017) (Figure 2 a).
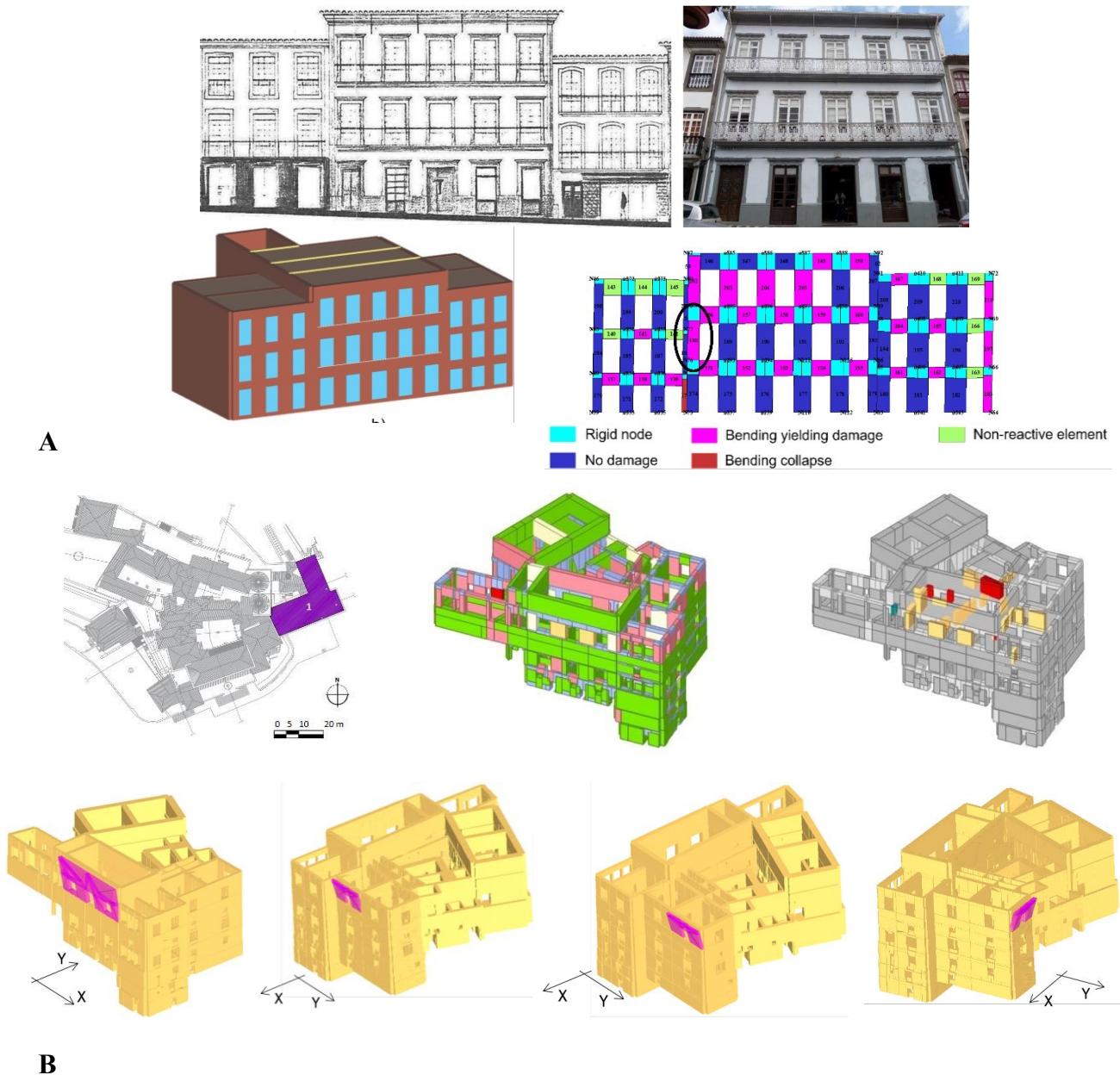
Figure 2. (a) Front facade of the aggregate of traditional masonry Azorean buildings, the 3Muri model and the damage pattern of the front façade; (b) Manueline building of National Palace of Sintra: 3Muri model, main vulnerable walls and local mechanisms studied for the out-of-plane response.

The seismic performance-based assessment was addressed with 3Muri program and the global behaviour was determined by nonlinear static analyses. The effects of some relevant modelling options were considered, including the analysis of the building as an isolated structure and inserted in its aggregate. With this study, it was shown the relevance of taken into account in the numerical modelling the impact of the floors in adjacent buildings, if adjacent buildings have different height or/and different floor levels. The second case study corresponds to the seismic assessment of the Palace National of Sintra, where both out-of-plane response and the in-plane response were studied (Ponte et al., 2019).

CONCLUSION

This document addresses the problems on the evaluation of the seismic response of existing masonry buildings and the adoption of the equivalent-frame modelling approach. Two case studies are presented to illustrate the potentiality of the 3Muri program for the analysis of the global seismic response of the buildings and the possible activation of local mechanisms.

The main distinctive features of the modelling approach are: (i) the implementation of specific elements allowing for the representation of the main characteristics of nonlinear response of masonry piers and spandrels, as well as other structural members (e.g. reinforced concrete and steel members); (ii) the explicit modelling of flexible horizontal diaphragms, which are very common, particularly in ancient existing buildings, (iii) an original algorithm for the pushover analysis, suitable for assessing the nonlinear evolution of the lateral response of three-dimensional masonry buildings, including the deterioration of the base shear for increasing lateral displacements after the attainment of peak strength, (iv) the three-dimensional assembling of masonry walls and floor/roof diaphragms, drastically reducing the number of degrees of freedom and the computational effort, particularly relevant when modelling groups of buildings (as the first case study – aggregate of traditional masonry Azorean buildings) and complex buildings (as the second case study – Manueline building of National Palace of Sintra), (v) the analysis of local mechanisms, (vi) the quick development of sensitivity analysis, and (vii) the implementation of different strengthening solutions for the improvement of the seismic behaviour. 3Muri program is a framework in continuous progress for the development and implementation of new advanced nonlinear elements and analysis procedures, both at research level and engineering practice.

REFERENCES:

Lagomarsino, S., Penna, A., Galasco, A., Cattari, S. 2013: "TREMURI Program: an equivalent frame model for the nonlinear seismic analysis of masonry buildings", Engineering Structures, Elsevier, 56(11), 1787-1799. DOI: 10.1016/j.engstruct.2013.08.002.

Cattari, S., Chioccariello, H., Degee, H., Doneux, C., Lagomarsino, S., Mordant, C. (2014) Seismic assessment of masonry buildings from shaking table tests and nonlinear dynamic simulations by the proper orthogonal decomposition (POD), Second European Conference on Earthquake Engineering and Seismology, Istanbul, Turkey.

Direcção-Geral do Planeamento Urbanístico (DGPU). Records of the Architectonic Inventory. Angra Do Heroísmo: 1980.

Fagundes, C., Bento, R., Cattari, S, 2017: "On the seismic response of buildings in aggregate: analysis of a typical masonry building from Azores", Journal of Structures, Elsevier, 151, 682–703. DOI: 10.1016/j.istruc.2016.09.010.

Galasco, A., Lagomarsino, S., Penna, A. (2006) On the use of pushover analysis for existing masonry buildings. First European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland.

Lagomarsino, S., Cattari, S. 2014: "Verifica sismica di edificio esistenti in muratura: validazione dei metodi di analisi non lineare su un caso studio", Ingenio – Sistema Integrato di Informazione per l'Ingegnere, 4.

Ponte, M., Bento, R., Silva, D.V. 2019: "A multi-disciplinary approach to the seismic assessment of the National Palace of Sintra", International Journal of Architectural Heritage, Conservation, Analysis, and Restoration, Taylor & Francis. DOI: 10.1080/15583058.2019.1648587.

Three-dimensional crustal image of Arraiolos aftershock sequence, earthquake of M=4.9, in Alentejo region, Portugal.

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ABSTRACT

This work presents the results obtained after the Arraiolos aftershock sequence tomographic inversion in terms of velocity distribution. The study deals with the 4.9 ML magnitude earthquake (M_w4.3, Vales et al., 2018) which occurred on January 15th, 2018 at 11:51 UTC in *Aldeia da Serra* in the Northeast of Arraiolos (Alentejo, Portugal). The hypocentral location, determined by the Instituto Português do Mar e da Atmosfera (IPMA), has coordinates 38.79 N, 7.93 W at 11 km depth. After the main shock occurred, 437 events were recorded and inverted in order to obtain a three-dimensional velocity image of the region. These records were performed by 34 temporary stations during a period of 6 months including IDL and Evora stations. On a first stage of study, preliminary results were presented by *Hamak et al. (2020)* coming from the tomographic inversion of 317 aftershocks recorded by 21 short-period stations (CDJ, 2.0 Hz), of the Instituto Dom Luiz (IDL, Lisbon), along a month of records. After analysing the obtained three-dimensional velocity model, a poor ray coverage has been noticed leading to a poor model resolution especially on the edges of the studied area. Thus, additional stations and local data have been integrated to this second stage of study in order to increase the ray coverage which leaded to a more accurate three-dimensional velocity model.

Local Tomography Software (LOTOS program, Ivan Koulakov (2009)) was used to perform all the inversions, in order to relocate accurately the aftershock sequence and obtain velocity contrast over the entire region of interest. This program gives the ability to perform a simultaneous inversion of sources location and velocity model. Comparison between preliminary and new aftershock sequence inversion results are presented in this study in order to show the evolution and improvement of the 3D velocity model quality.

Nevertheless, despite the increasing model resolution, the studied area is still too small for a good understanding of the complex tectonic of the area. Therefore, in order to extend the area of study, local, regional and teleseismic events must be integrated. As tomographic resolution is related to waves propagation, as this second stage of study demonstrated, by increasing the ray density of the region a more accurate and reliable 3D velocity model will be obtained. Thus, the tectonic features responsible for the seismic activity in the region will be better constrain.

Keywords: Local seismic tomography, Arraiolos earthquake, seismicity, seismogenic zone, LOTOS-09 code

INTRODUCTION

An earthquake occurred in *Arraiolos* a region localised in the north of *Évora (Portugal)* on the 15th of January 2018. This earthquake has recorded a magnitude of ML4.9 which was the highest magnitude in the region since 1969 (~M8.0) and has been located in a depth of 11km. After this main shock occur, several questions about the tectonic of the region were generated.

Therefore, geological and seismological studies have been carried out in the region (Wachilala et al (2019), Araújo et al (2018), Matos et al (2018), Borges et al (2018), Matias, et al (2019)), putting in light a moderate seismicity with an apparent difficulty to find correlation between outcropping faults and earthquakes distribution. Indeed, this is due to the slow plate deformation that generates earthquakes with a magnitude that barely reach M5. Also, the mapped faults are not active and not responsible for the seismicity observed in the studied region. This complexity in the understanding of tectonic events bring difficulty to seismological interpretation.

Nevertheless, a geological study made by Araujo et al. (2010), have detected lineaments which had been related to active faults. These faults are *São Gregorio* and Ciborro faults describing a strike slip focal mechanism, that are intersecting in Aldeia da Serra, highest point of the region, which shows compression motions. Indeed, this geological model proposed by Araujo et al. (2010*)* is a hypothetical model that must be explored. Thus, the two different types of deformation bring us to image the earth interior in order to figure out in more details the deformation within depth.

For this, a Local Tomography Software called LOTOS created by Ivan Koulakov in 2009 were used for the inversions. The choice of this program was based on its capacity to perform a simultaneous inversion of sources location and 3D velocity model. In a first stage of study, the aftershock sequence of 317 earthquakes recorded, along a month, by 21 short period stations coming from Arraiolos temporary seismic network (ATSN) were inverted in order to obtain a preliminary three-dimensional velocity distribution.

In the other hand a second stage of study was conducted performing an inversion of 437 aftershocks using the same program in order to increase the ray coverage and obtain a model with better quality. This aftershock sequence was recorded by 34 temporary stations composed of the 21 short-period stations (CDJ, 2.0 Hz) of the Instituto Dom Luiz (IDL, Lisbon) used in the first stage of study and 13 broad-band stations (CMG 6TD, 30s) of the Institute of Earth Sciences (ICT, Évora). By observing images of velocity distribution in three directions, an improvement of the model quality and resolution were observed.

Before proceeding to real data inversion an evaluation of the resolution limits of the area should be conducted. Thus, synthetic tests with several types of parametrization are set using checkerboard method. The reconstructed model obtained will be analyzed in order to target regions of poor and good resolution that must be considered in the interpretations. After performing the synthetic inversion, it is the place of real data to be inverted. A three-dimensional velocity distribution is obtained, and the sources relocated in a narrow area within this model. By observing the anomalies and the events location, we concluded that more data must be added to this study in order to extend and image the region with a better resolution.

MAIN RESULTS

By comparing preliminary and current results, an improvement of model quality and resolution were observed. By increasing the ray distribution, adding the 13 broad-band stations and aftershock sequence to the study, the area was better covered by waves and thus leaded to results improvement. Moreover, the aftershock distribution is starting to show a slight trend within depth and an anti-correlation between P and S velocity anomalies is still observed beneath both cross sections. The spatial distribution of aftershocks, along axis 2A2B (Fig. 1), shows alignment of aftershocks with a length of 8 km between 12 and 14 km depth. Nevertheless,

despite the increasing resolution of the model, additional data still have to be integrated to the study in order to obtain better results and constrain accurately the seismogenic zone.

CONCLUSION

This tomographic study was performed for the first time in Arraiolos, in order to find geological features which could be responsible for the seismicity of the region. Also, it allows us to relocate sources within depth that knows an improvement simultaneously with the 3D velocity variations.

Nevertheless, despite the improvement of model resolution the ray distribution is still poor to image the entire area. The software is going to select the area of best ray coverage which tended to be smaller than the one that we wanted to image in the beginning of the inversion. Even across this small region, the ray distribution was not sufficient for an optimal coverage. Hence, more data must be added to this study in order to have a better coverage of the area in terms of ray distribution that will allows us to make more consistent interpretations. Data that we need to introduce, besides local events, are regional and teleseismic events recorded by the same temporary station network as used for the 437 aftershocks recordings. In addition to this temporary station network, we thought about considering the Instituto Português do Mar e da Atmosfera (IPMA) and DOCTAR networks which will bring supplementary records. By integrating these additional data to the study, we will manage to explore in more details the subsurface and figure out more accurately the causes of the seismic activity which drives the region.

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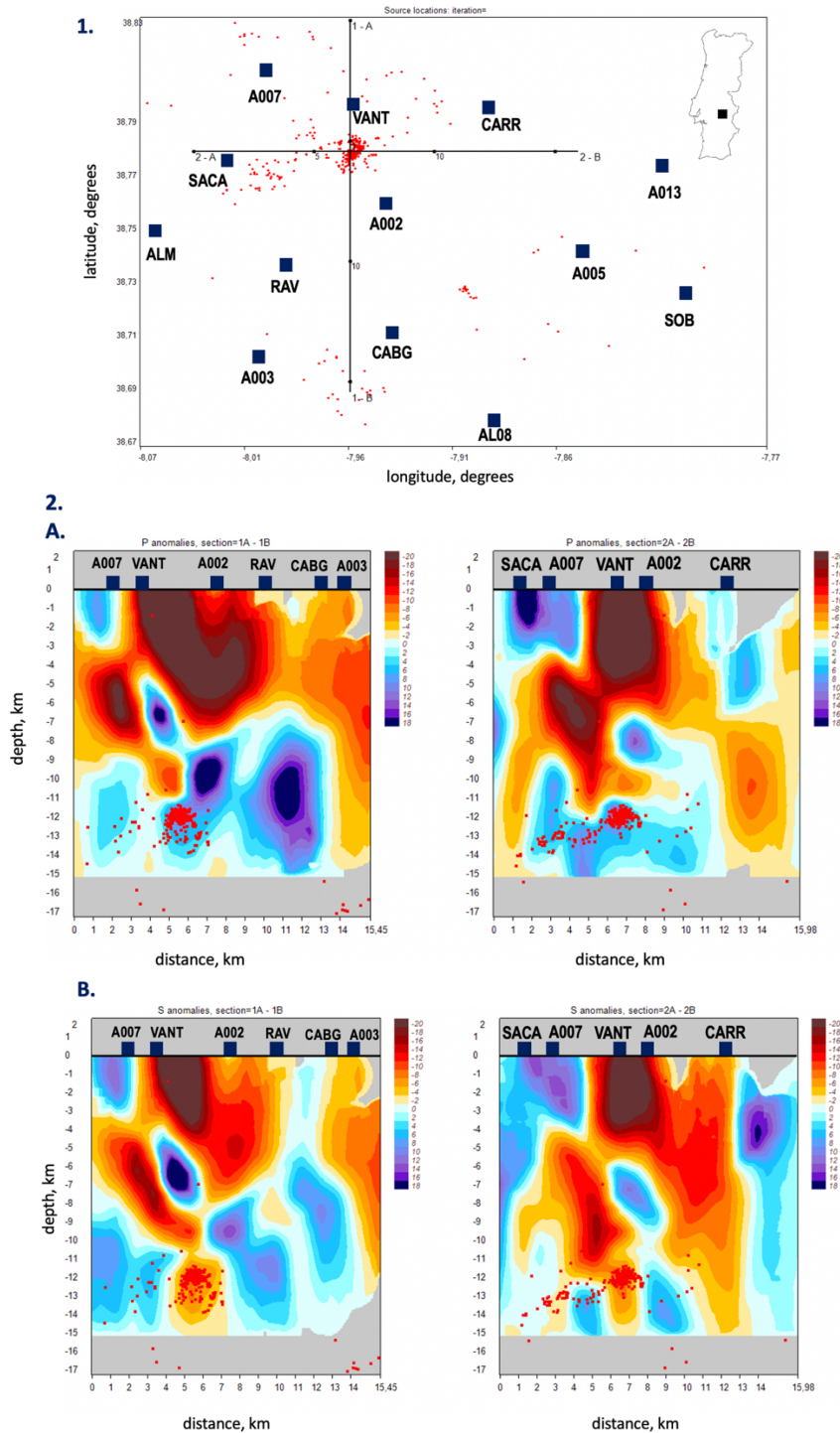
Figure 1. 1- Localization of earthquakes and stations used. 1A-1B and 2A-2B represents the selected cross sections. 2 - Real data inversion results A- P anomaly distribution beneath the two cross sections 1A-1B and 2A-2B. B- S anomaly distribution beneath the two cross sections 1A-1B and 2A-2B. *Blue squares* represent seismological stations and *red dots* indicate aftershocks locations. The scale anomalies shown at the top right of each figure is given in %.

REFERENCES:

Araújo, A., Caldeira, B., Martins, A., Borges, J,F., Araújo, J., Moreira, N., Maia, M., Vicente, S., Afonso, P., Espanhol, D., Bezzeghoud, M. (2018). Macrossismicity associated with the Arraiolos earthquake of January 15, 2018with M = 4.9 and possible implications in the geometry of the rupture. *Revista Portuguesa de Vulcanologia.*

Borges, J., Caldeira, B., Fontiela, J., Custódio, S., Dias, N. A., Waschilala, P., Oliveira, R., Vales, D., Bezzeghoud, M., Araújo, A., Carrilho, F., Corela, C., Rio, I., Vaz, J., & Matias, L., 2018. *Earthquake of January 15 and aftershocks : Preliminary results. 2018, European Seismological Commission.*

Koulakov, I. (2009). LOTOS code for local earthquake tomographic inversion: Benchmarks for testing tomographic algorithms. *Bulletin of the Seismological Society of America*, **99(1)**, 194–214. https://doi.org/10.1785/0120080013

Vales, D., 2018. Nota Técnica: Mecanismo Focal do Sismo de Arraiolos de 15 de janeiro de 2018. Instituto Português do Mar e da Atmosfera (IPMA), Lisbon, Portugal

Wachilala, P., Borges, J.F., Matias, L., Rio, I., Fontiela, J., Oliveira, R., Caldeira, B., Bezzeghoud, M., Araújo, A., Custódio, S., Vales, D., Carrilho, F., Dias, N. (2019). Análise da distribuição espaço-temporal da sismicidade na zona de Arraiolos no período de janeiro - maio de 2018, *APMG 2019.*

Matias L., Rio, I., Waschilala, P., Vales, D., Borges, J.F., Dias, N., Carrilho, F., Caldeira, B., Custodio, S., Fontiela, J., Bezzeghoud, M., Araújo, A., Corela, C. (2019). The seismic sequence of Arraiolos, Portugal, in January 2018. *EGU General Assembly 2019.*

Matos, C., Custódio, S., Batló, J., Zahradník, J., Arroucau, P., Silveira, G., & Heimann, S. (2018). An Active Seismic Zone in Intraplate West Iberia Inferred From High-Resolution Geophysical Data. Journal of Geophysical Research: Solid Earth, 123(4), 2885–2907. https://doi.org/10.1002/2017JB015114

Hamak, I.,J. Borges, M. Bezzeghoud and P. Washilala, (2020): Three-dimensional crustal image of Arraiolos aftershock sequence, earthquake of M=4.9, in Central Portugal. In M. J. Costa & R. Salgado (Eds.), Book of the Online Workshop on Earth and Space Sciences - Atmospheric Physics and Climate. ISBN: 978-989-98836-3-5.

DRR and DRM for cultural heritage: needs and challenges of current practice

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ABSTRACT

The implementation of effective actions for disaster risk reduction (DRR) and disaster risk management (DRM) in cultural heritage has been slow, despite the awareness regarding the risks to cultural heritage and the several initiatives recognizing the importance of cultural heritage for society. Aspects related to this lack of changes are addressed, highlighting the need of further research to achieve a successful implementation of DRR/DRM practices for immovable cultural heritage.

Keywords: Risk management, risk assessment, preparedness

INTRODUCTION

Numerous international institutions connected to disaster risk reduction (DRR) and disaster risk management (DRM) are increasingly echoing concerns about the protection of cultural heritage from disasters. Existing international frameworks and programmes for DRR emphasizing the need to develop and implement measures to reduce hazard exposure and vulnerability to disasters also recognize the importance of cultural heritage and its irreplaceable value for society. Furthermore, several initiatives have also started to recognize the importance of cultural heritage as a sustainable resource for economic growth and for addressing several societal challenges. Despite this awareness increase regarding the overall risks to cultural heritage, the implementation of effective actions for DRR and DRM in cultural heritage has been slow. Despite the many reasons for this lack of tangible changes, the current paper addresses a few questions requiring further discussion and research that, in the opinion of the authors, would support the successful implementation of DRR/DRM practices for immovable cultural heritage.

DO WE KNOW HOW MUCH CULTURAL HERITAGE WE ARE LOSING TO DISASTERS?

The availability of disaster damage and loss data is essential to ensure adequate DRM/DRR processes (i.e. for loss accounting, disaster forensics and disaster risk modelling). Hence, developing systems and methodologies to collect and handle such data is now a global priority. Disaster loss databases like EMDAT/CRED, NATCAT/MünichRe or DesInventar/UNISDR are important sources of worldwide data on damages and losses. However, they do not include cultural heritage damages and losses since, currently, there is no systematic collection of data on impacts of disasters to cultural heritage. To address this issue, the Faculty of Engineering of the University of Porto and the International Committee on Risk Preparedness of the International Council on Monuments and Sites are developing a database for collecting worldwide data on immovable cultural heritage disaster losses. This database will then be able to provide institutions managing and protecting cultural heritage with a systematic recording of cultural heritage disaster-related data, from natural and man-made

hazards, a reliable accounting of heritage losses, and adequate data to analyze disaster trends and risk mitigation needs in cultural heritage. Despite the availability of this database, populating the database is still challenging due to lack of resources to establish a team of analysts to search and process data and to manage the database, to the unavailability of sources willing to provide adequate data. Still, given that recently adopted indicators to monitor the global targets of the Sendai Framework for Disaster Risk Reduction include the need to report on cultural heritage losses (UNISDR, 2017), *there is a need to address this issue to support in-depth analyses of their impact and the development of efficient DRM strategies.*

DO WE UNDERSTAND AND KNOW THE RISKS TO OUR CULTURAL HERITAGE?

It is believed that numerous cultural heritage assets require risk mitigation measures. Still, developing such measures needs to be based on adequate knowledge about the risks these assets are facing. However, for most countries, carrying out multi-hazard risk analyses for a large number of cultural heritage assets requires efforts and budgets that are frequently unavailable. Thus, assessing the risks for a large number of assets with limited resources is only feasible when based on simple methodologies. Risk analysis usually requires the probabilistic quantification of hazard and vulnerability. Probabilistic representations of those components require both sufficient/reliable data and adequate analytical/numerical procedures. For the particular case of vulnerability, its definition relies on the availability of procedures able to forecast the effects of a particular hazard on a certain asset under analysis. For cultural heritage assets, their complexity and the lack of knowledge about their behaviour are often obstacles to a detailed definition of their vulnerability. Moreover, when the risk analysis addresses a large amount of assets, those difficulties are amplified due to resource-related restrictions.

Despite the complexity of modelling the vulnerability, the availability of human, time and economic resources usually sets the boundaries of the scope and comprehensiveness of a risk analysis for cultural heritage assets. Moreover, it will also be fundamental for the successful regular update and monitoring of the risk assessment results over time. Therefore, when dealing with a large number of cultural heritage assets, it is important to have a simple methodology that can be used for the preliminary risk analysis of those assets to establish risk mitigation priorities or to identify assets requiring more detailed and resource-demanding analyses. In light of this, the use of a qualitative risk analysis approach is seen to be adequate for these requirements, especially in situations where theory, data, time or expertise are limited, since they may provide adequate results when decision makers only need a qualitative assessment of risk. For example, the qualitative analysis of a large number of cultural heritage assets (e.g. nationwide) may be a suitable way to identify situations where a more detailed assessment is needed, or to provide stakeholders with enough information for decision-making. To address this issue, a simplified methodology for the risk assessment of cultural heritage assets was recently proposed (Romão et al, 2016). This approach can be used as a screening procedure for the preliminary assessment of a large number of heritage assets with limited resources or for the preliminary identification of assets that require a more detailed and resource demanding risk evaluation. The methodology includes specific forms and guidelines for the seismic risk assessment of cultural heritage masonry constructions. *However, further refinements of the framework are being developed in the project RIACT - Risk Indicators for the Analysis of Cultural heritage under Threat to include other construction types and define similar guidelines for other hazards.*

DO WE KNOW ENOUGH ABOUT OUR CULTURAL HERITAGE?

Documentation practices and inventories with relevant data are essential for the management and preservation of cultural heritage assets, as well as to develop effective risk and disaster management strategies. However,

developing such inventories is complex due to difficulties deriving from the large variety of data that can or needs to be recorded for multiple purposes due to the multidisciplinary nature of cultural heritage preservation. Still, inventory systems have been evolving to reflect more holistic approaches of cultural heritage data recording. From initial systems that were more focused on recording historical data, the evolution of heritage assets from an archaeological or architectural point of view, current heritage inventories evolved considerably, embracing digital technologies and including other data features. Other difficulties can also be related to data updating issues and the resources it involves. For inventories to be effective tools for the preservation of cultural heritage assets, the information they contain needs to be up-to-date to reflect the various changes in the state of that heritage over time. These and other concerns have been driving the evolution of the documentation and inventory practices for cultural heritage management. However, the level of evolution varies from case to case and according to the type of data. For example, inventories with technical characteristics (e.g. geometric surveys, data on the construction techniques or material properties) of built heritage assets as well as information about recent interventions undertaken on those assets are not so common.

In the context of having to manage intensive and extensive risks in cultural heritage, having specific engineering-related data organized in a standardized format is an advantage since risk assessment and mitigation can then be performed in a systematic and effective way. Data standardization is particularly relevant for managing heritage properties with similar construction processes and architectural features. An example of such type of inventory system was recently developed (Nunes et al, 2017) for 44 churches of the Portuguese Romanesque period. For each church, the specific data collection form that was developed records the geometric characteristics, structural typology, construction process(es), level of damage, changes and works carried out over time, the existence of heritage assets attached to the building, and its interaction with the surrounding environment. The collected data forms a database that complements existing inventories and provides information for developing a comprehensive property management system. Potential losses can be estimated by correlating this information with a certain type of intensive or extensive hazard and the urgency of mitigating measures can be determined from the hazard likelihood. For frequent/persistent hazards, the ability to identify the conservation state of the load-bearing structure of heritage assets and the sources of existing damage and/or of ongoing degradation phenomena through systematic surveys provides fundamental data for risk mitigation. Moreover, adequate knowledge about the materials, geometry and building processes of these heritage assets also allows estimating risk mitigation costs and performing cost-benefit analyses to minimise losses. Extending these analyses to a large group of heritage properties with similar characteristics facilitates the identification of common issues and the planning of risk mitigation actions.

Data on the presence and type of decorative cultural heritage assets that are attached to a given heritage construction (e.g. mural paintings, tiles) is another component that needs to be included in engineeringrelated inventories. This information is important for estimating potential heritage damage and losses when a certain hazard intensity that is not expected to cause damage to the component supporting those assets may in fact cause a substantial loss in value to those assets. Another category of information that should be included in these inventories is related to the landscape and environment that surrounds a given heritage construction. Information about nearby water sources or forest sites, the type of terrain (material and slope) or other relevant

environmental data is essential for risk management related to hazards such as landslides, fire, floods or heavy rains. Given these issues, developing or extending cultural heritage inventory systems to include these types of data should be promoted. *Having this additional data allows for a more holistic approach of heritage management, providing support for a realistic analysis of potential losses and of the existing constraints for defining risk mitigation actions.*

FINAL REMARKS

International frameworks for DRR/DRM are clear in their objectives of reducing hazard exposure and vulnerability to disasters. Moreover, the importance of cultural heritage and its irreplaceable value for society is also clearly acknowledged in these objectives. Still, the implementation of effective DRR/DRM actions in cultural heritage has been slow. Some aspects connected to this issue were addressed given they require further research and development. The importance of each topic was briefly reviewed and the current state of knowledge was discussed within the objectives of existing DRR/DRM initiatives. Although some research and development needs are identified, the main objective of the paper is to draw attention on a few fundamental aspects of DRR/DRM for cultural heritage to foster further in-depth discussions on these topics.

REFERENCES:

Nunes, A., Paupério, E., Romão, X., Varum, H. (2017) Risk management potential of technical data inventories on built cultural heritage: a case study for the churches of the Portuguese Route of the Romanesque. CIPA-ICORP-ISCARSAH 2017 Joint Meeting. ICOMOS General Assembly, India.

Romão, X., Paupério, E., Pereira, N. (2016) A framework for the simplified risk analysis of cultural heritage assets. *Journal of Cultural Heritage*, 20, pp. 696-708.

UNISDR (2017) Technical Guidance for Monitoring and Reporting on Progress in Achieving the Global Targets of the Sendai Framework for Disaster Risk Reduction. Draft for consultation. United Nations Office for Disaster Risk Reduction.

Conception stage of AGEO Citizens' Observatories

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ABSTRACT

Interreg Atlantic Area AGEO Project will deploy 5 pilots Citizens' Observatories, to prevent, mitigate and manage geohazard risk through citizens engagement, Copernicus products and services, as well as other common methodologies. Two examples are provided about the conceptual idea of citizens' observatories.

Keywords: Citizens' Observatory, Earthquake, Risk management, Geohazards

INTRODUCTION

Citizen Science is commonly defined as the participation of people, from outside professional organisations, in the process of gathering and analysis of scientific data; this form of research is a new important trend in the scientific practice (Bonney et al., 2009b; Haklay, 2013). This tool is not only useful in collecting and analysing large amount of information and scientific data, but has also an important function of generating and sharing information (Irwin, 1995). The positive contribution of citizens involvement in research can be shown by example about the avian biological patterns (e.g., Sullivan et al., 2009) and galaxy classification (e.g., Fortson et al., 2013).

Until now, the development and the application of citizens' observatories focused on natural hazard has not reach maturity, although citizens can be an invaluable source of ground-truth for authorities and rescuer during disastrous events, as flooding, earthquake and critical weather conditions. Another important value of citizens' involvement is represented by the possibility of sharing knowledge of hazardous phenomena, improving the communication, rising the resilience of communities at risk and preparing them for future events.
High-impact and low-probability hazardous natural events related to climate change are increasing, and the actions taken to reduce and mitigate these risks or to build up the resilience against them is increasingly becoming more demanding.

The Disaster Risk Reduction (DRR) agenda aims to predict and reduce damages generated by hazardous natural events. These actions are achieved by the Disaster Risk Management (DRM) that is composed by measures that create an ethic of prevention and can involve efforts in analyse and reduce casual factors of disaster risk (Hicks et al., 2019). Although, citizen science method for DRR, such as using sensors to collect data about hazards,

are conventional initiatives and have been very effective, Information and Communication Technologies (ICT) is not always assuring the participant engagement and a high quality of data (Wiggins, 2013). Natural hazards,

such as earthquakes and landslides can be monitored with recent and innovative technologies (e.g. smartphone accelerometers, uploading images or texting information).

Citizens' Observatories are defined as communities of citizens that can share information and scientific data, through different technological solutions and community participatory governance methods. The main objectives are complementing environmental observation systems and improving the local decision-making. European Union is actively promoting Citizens' Observatories to enhance the participatory democracy, to empower citizens to make more informed decisions and to raise awareness. Moreover, Citizens' Observatories are heading to approaches considered more participatory, more community-based and with a bottom-up approach.

The AGEO Project, funded by INTERREG Atlantic Area through the European Regional Development Fund, aims to launch 5 Citizens' Observatories pilots (Portugal, Spain, France, United Kingdom, and Ireland) on natural hazardous events to strengthen national and regional risk management systems.

EXPERIENCE WITH EARLY WARNING SYSTEMS

Early Warning Systems (EWS) are crucial tools to reduce and mitigate risks, such as earthquakes, floods or landslides, through personal preparedness, situational awareness and automated controls. These elements make citizens safer (Zschau et al., 2009; Earthquake Country Alliance, 2014a), allow the authorities to have a faster and more organised mobilisation (Zschau et al., 2009) and prevent secondary induced effects in public and private infrastructures (Heaton et al., 1985; Zschau et al., 2009). Early Warning Systems have been working already since the 1960s and nowadays are present worldwide. The Mexican EEWS ('80s) was the first EWS to send public warnings (Espinosa-Aranda et al. 1995). The Japanese EEWS ('60s) has been initially used to prevent train wrecks and in 1998 the system was updated to a more rapid system (Compact UrEDAS). New technologies, such as satellite data (Copernicus constellation) and ground-based InSAR, are nowadays being used, to monitor and prevent disastrous consequences. An example of continuous monitoring is the case in Tuscany region in which since 2016 a continuous, near real-time, monitoring through maps of ground motions (Bianchini et al., 2018; Raspini et al., 2018), using the Sentinel-1 data is performed. The Maoxian landslide is an example of how an EWS could have been fundamental to prevent from losses and casualties. After sliding, Fukuzono method was applied in the back-analysis of the data gathered by ESA Sentinel-1 to assess if the slide could have been predicted. It was concluded that pre-failure movements detected by the InSAR analysis using Fukuzono method could have been used to issue an early warning on time to have cleared the area.

AGEO CONCEPTUAL CITIZENS' OBSERVATORY

AGEO Project conceived 5 Citizens' Observatories pilots covering several geohazards across 5 different regions of the Atlantic Area: Hierro Island (Canary Island – Spain); Lisbon multi-hazard (Portugal); Brittany coast (France); Cliffs of Moher (Ireland); Cuilcagh Mountain (Northern Ireland – UK).

The conception of the citizens' observatories is divided in the three temporal stages of natural hazardous events: pre-event, during event and post-event (Figure 1). The sources of information are divided into Copernicus, engaged citizens and other traditional sources of information. The challenge is to combine all these sources for each temporal stage in a model that combined with exposure (e.g. population, built environment, infrastructures) provide risk assessment to be incorporated in risk management tools.
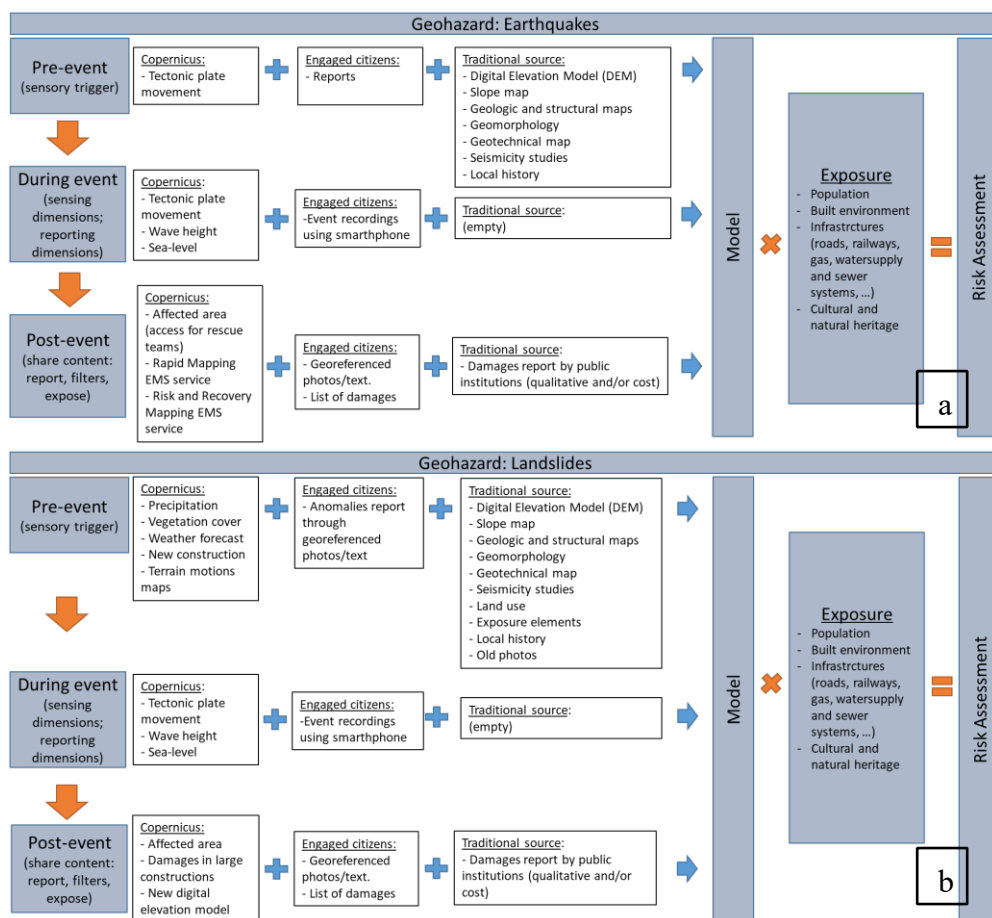
Figure 1. AGEO citizens' observatories concept for earthquakes (a) and landslides (b).

In pre-event phase, the main action taken is to identify models and information that can be used to predict the event, such as predict the time (e.g. day) of a landslide or to anticipate of a few seconds of the arrival of strong earthquake-induced shaking.

During the event, the objective is to collect data and information to sense and report the extension of the event, which is particularly relevant for floods, not so much for earthquakes and landslide due to short time window of these events.

In the post-event phase, citizens have the possibilities to share information (e.g. text or photo), which complements the satellite images and other common sources of information, fundamental to have a clear realtime scenario of damage extent.

The sources of data and information, that are used during all stages, will be extracted by the ESA Copernicus satellite constellation (Sentinel-1 and 2), citizens that will send text, images or other contents through smartphone, tablets or other technologies, and finally from other sources.

Taking as example the Lisbon pilot, Figure 1 shows the proposed flowchart in which citizens' information and Copernicus' data are coupled with common sources of information through a model, in order to reach the risk assessment.

DISCUSSION AND CONCLUSIONS

The mitigation of hazardous natural events combining new technologies with citizens participation through Citizens' Observatories is gaining maturity so that, in a near future, it will become the "new normal". Exploiting a new way of educating citizens and leading to more conscious decision making requires the gain of experience by launching pilots.

AGEO project has conceived Citizens' Observatories that will start to be implemented in a near future. Examples of how to address two geohazards were presented and discussed in this paper. Further discussion is needed in the implementation stage.

Acknowledgement

REFERENCES:

Bianchini S, Raspini F, Solari L, Del Soldato M, Ciampalini A, Rosi A and Casagli N (2018) From Picture to Movie: Twenty Years of Ground Deformation Recording Over Tuscany Region (Italy) With Satellite InSAR. Front. Earth Sci. 6:177. doi: 10.3389/feart.2018.00177

Bonney, R, Cooper, CB, Dickinson, J, Kelling, S, Phillips, TB, Rosenberg, KV and Shirk, J. 2009b. Citizen Science: A Developing Tool for Expanding Science Knowledge and Scientific Literacy. Bioscience, 59(11): 977–984. DOI: https://doi.org/10.1525/bio.2009.59.11.9   Earthquake Country Alliance, 2014a

Espinosa-Aranda, JM., Jimenez, A., Ibarrola, G., Alcantar, F., Aguilar, A., Inostroza, M., Maldonado, S., (1995). Mexico city Seismic Alert System. Seismol Res Lett 66(6): 42-53.

Fortson, L. F., Willett, K. W., Raddick, M. J., Schawinski, K., Skibba, R. A., Simmons, B. D., et al. (2013). Galaxy Zoo 2: detailed morphological classifications for 304 122 galaxies from the Sloan Digital Sky Survey. Mon. Notic. R. Astronom. Soc. 435, 2835–2860. doi: 10.1093/mnras/stt1458

Haklay, M., 2013, Citizen Science and Volunteered Geographic Information – overview and typology of participation in Sui, D.Z., Elwood, S. and M.F. Goodchild (eds.), (2013). Crowdsourcing Geographic Knowledge: Volunteered Geographic Information (VGI) in Theory and Practice . Berlin: Springer. pp 105-122 DOI: 10.1007/978-94-007-4587-2_7

Heaton, TH., Series, N., May, N., (1985). A model for a seismic computerized alert network, Science 228, 987–990 https://arcticaok.org/about/

Hicks, A., Barclay, J., Chilvers, J., Armijos, MT., Oven, K., Simmons, P., Haklay, M., (2019). Global Mapping of Citizen Science Projects for Disaster Risk Reduction. Front. Earth Sci. 7:226. doi: 10.3389/feart.2019.00226

Irwin, A., (1995). Citizen science: A study of people, expertise and sustainable development. New York, NY: Routledge. doi:10.5334/opt.101109

Intrieri, E., Carlà, T., Gigli, G. (2019). Forecasting the time of failure of landslides at slope-scale: A literature review. Earth Sci. Rev. 193: 333–349.

Sullivan, B. L., Wood, C. L., Iliff, M. J., Bonney, R. E., Fink, D., and Kelling, S. (2009). eBird: a citizen-based bird observation network in the biological sciences. Biol. Conserv. 142, 2282–2292. doi: 10.1016/j.biocon.2009.05.006

Wiggins, A. (2013). Free as in puppies: compensating for ICT constraints in citizen science. Proceedings of the 2013 conference on Computer Supported Cooperative Work. San Antonio, Texas, USA (23-27 February 2013).   DOI: https://dor.org/10.1145/2441776.2441942

Zschau, J., Gasparini, P., and Papadopoulos, G., (2009). Seismic Early Warning for Europe Final Rept, http://www.amracenter.com/SAFER/doc/dissemination/SAFER_Final_Report.pdf

Documentation and Digital Representations of a Pombaline Cage

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ABSTRACT

In 1755, a violent earthquake, followed by a tsunami and multiple fires devastated Lisbon. In response to this event, a system was designed and built with the capacity to ensure the structural strength of several buildings simultaneously. The Pombaline Cage represented the rebirth of the city and a landmark in its history: it allowed its total reconstruction using an innovative seismic resistant construction system. Given its patrimonial value, it is necessary to proceed to its preservation and valorization, which have been compromised by successive interventions in the buildings of Baixa Pombalina, unaware of its understanding, especially since the last century. Therefore, its registration and documentation are essential not only to linger in memory, but also to allow its study, dissemination, and preservation.

The present study explores digital workflows applied to the registration, documentation and representation of a section of an original Pombaline Cage structure belonging LERM (Materials Strength Engineering Laboratory) (Técnico, Lisboa). The section of the structure (about 3.30mx3.30m) and a foundation stake (circa 1,20m height and 0,14m maximum diameter) were recorded using a 3D automatic, non-intrusive survey technology: laser scanning. From point cloud models face meshes models were created, as well as physical replicas, at a reduced scale, through 3D FFF (Fused Filament Fabrication) printing process. The aim was to test documentation capacity of geometries, textures, characteristic details and time marks. It was possible to conclude about the authenticity of the virtual and physical models developed, i.e., their ability to represent the formal values of the original objects. Based on the obtained results, it was possible to reflect regarding the potential for knowledge transfer (e.g. training and teaching, scientific dissemination, experiments) of these representations.

Keywords: Pombaline Cage, Digital Reconstruction, Laser Scanning, 3D Printing, Mesh Modelling.

INTRODUCTION

The documentation of heritage buildings is the preliminary procedure essential to its preservation. It allows to support actions of diagnose of the constructions existing state, planning interventions, recording actions, and monitoring the evolution of the building. Automatic non-contact 3D surveying methods, such as, laser scanning and photogrammetry, have proven their effectiveness in terms of the ability to generate reliable and very detailed documentation, nodal factors with regard to the study of historical structures and to feed digital workflows (Brumana et al, 2020; Nieto-Julián et al, 2019; Mondello et al, 2019; Bevilacqua et al, 2017; Bruno et al 2017).

On the other hand, wooden construction systems constitute a vast and unique heritage, with diverse examples in European territory that must be documented given the limited information available. The European project PreserWoodenHeritage (Cordis EU Research Results, 2017) explores methods of monitoring wooden structures using laser scanning technology. Balletti et al (2014) makes use of photogrammetric methods to

digitally map and reconstruct the wooden dome of the Basilica of St. John and St. Paul in Venice. Lee et al (2015), using laser scanning, evaluates the displacement of a famous wooden temple of the Ming dynasty.

The Pombaline Cage is described and discussed in detail in the works of Mascarenhas (2004) and Appleton (2011). The first uses freehand drawing and the second uses schemes and photographic records. It would be important to complement this knowledge with the survey and documentation of real structures. Therefore, it would be possible, through the documentation of specific case studies, to file relevant information, as well as, to deepen the study on this seismic resistant structure and, indirectly, in recognition of the technical paradigm that the Pombaline Cage represents, to contribute to strengthen the seismic culture in Portugal (Correia and Carlos, 2015) and minimize negative interventions that can compromise its performance (Lopes, 2012).

AIM AND METHODOLOGY

The objective of this work is to evaluate the potential of representation of specific digital technologies - survey by laser scanning, modeling through the use of mesh objects and 3D printing for the creation of physical models - to study an existing Pombaline Cage section and a foundation stake its contemporary.

Thus, the methodology used for the development of this study is divided between the fieldwork component, the laser scanning survey, and, the laboratory component, based on the processing and treatment of the information collected. Regarding fieldwork, the laser scanner BLK 360 (Leica) was used for data collection and its most recent application, Cyclone Field 360, for pre-registration of the information collected. In the laboratory, registering the information was the first step, followed by processing and subsequent treatment, in order to be able to isolate the elements so that, finally, they can be printed three-dimensionally.

Laser scanning survey. The surveys carried out using the most recent contactless mapping technologies, such as laser scanning, allow the registration of very complex elements with great level of detail. However, it is necessary to pay attention to the constraints of the survey environment, which can positively or negatively influence the results obtained. Both elements presented conditions that interfered with the data collection. The Pombaline section, attached to a wall (its fragility implied risk of damage if moved), did not allow a complete and effective survey (Figure 1). The stake, due to its irregular and pointed shape, demanded a procedure to keep it immobile for the entire duration of the mapping. Another constraint was the lighting lack of the space. It was necessary to resort to the use of illuminators that gave a much needed uniformity of light in the space. The surveys were developed very fluidly and quickly, due to Cyclone Field 360 application. The processes are automatic allowing to check the quality and relevance of the data collected in real time, and making possible to redo any deemed necessary mappings.

Registration and data processing. The registration process (connecting scans to achieve point clouds) starts by importing the data collected to Register 360 work environment (Leica), only being necessary to check the connections that were created automatically. The processing work is carried out in the Recap software by isolating the desired element(s) – a points subset of the main point cloud – to export a file in .pts format. With this file it is possible to create a mesh object in the CloudCompare software through the functions provided.

Finally, in MeshLab, the mesh objects are processed in order to improve and treat the triangular mesh created automatically in the last step.

3D printing. The FFF printing process basically considers the construction of 3D objects by depositing successive layers of a thermoplastic material, heated to a suitable temperature, on a plane. This way, objects grows upwards. To perform a 3D printing is essential to have a mesh object entirely closed. Another important point is to understand if the solid to be printed needs supports during printing, this was the case of the stake.

Printing parameters (e.g., layers height, infill density, extruders and bed temperature, printing velocity) influence directly the quality of the printing results and must be adjusted. Printing tests were made recurring to a low-cost printer (Snapmaker) and using PLA (polylactide), a thermoplastic polyester filament.

MAIN RESULTS

The main results obtained (Figure 2) consider not only the point clouds models referring to each mapped object, which are a very precise and complete source of documentation, but also the printed threedimensional elements. These printed objects due to their quality, allow the documentation of the real state of the stake as well as a reliable source of documentation.
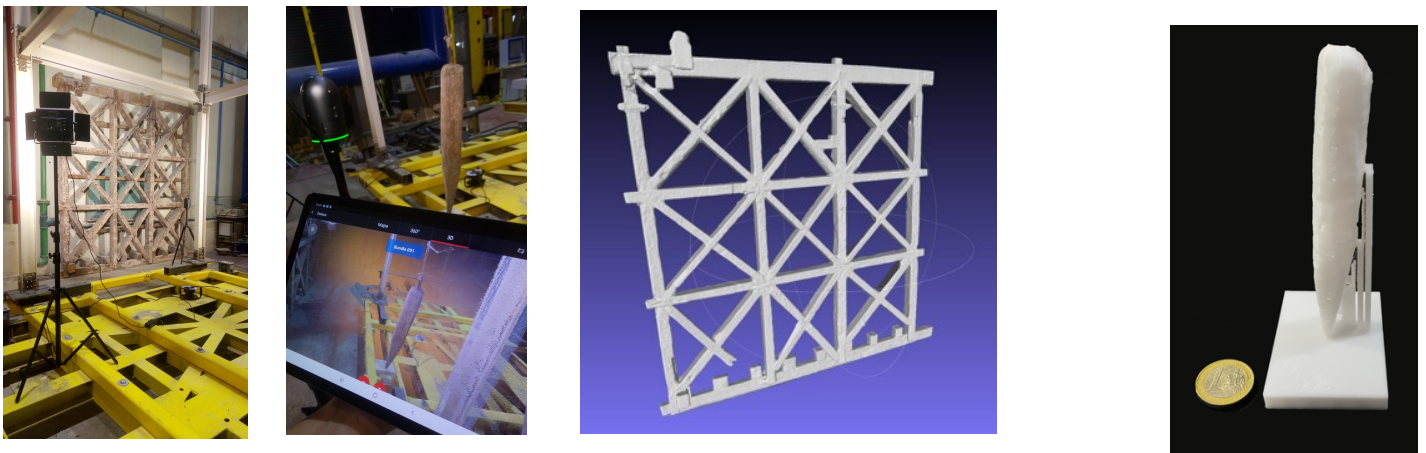
Figure 1. Laser scanning survey. Pombaline Cage **Figure 2.** Results. Pombaline Cage mesh object (left). Physical model 3D section (left). It is possible to see the illuminators printed (scale 1:12) and model point cloud of the stake (right). Even at a used. Foundation stake (right). In first plane, it is reduced scale, it was possible to reproduced the geometric features of the possible to see the stake point cloud in Cyclone Field original stake with high reliable degree. environment.

CONCLUSION

In short, it was possible to conclude that associating automatic survey means to the documentation and representation of the Pombaline Cage section and stake reveal a great potential. The elements obtained give value to the mapped structures and preserve their authenticity and real condition. By using the information collected, it was possible to generate mesh objects that enabled expressive 3D printing elements. Due to their

similarity they can be classified as digital and physical twins, which means that the three-dimensional virtual representations can also aspire to be classified as digital heritage (Unesco, 2003).

REFERENCES:

Appleton, J. (2011). "Reabilitação de Edifícios Antigos: Patologias e Tecnologias de Intervenção", 2ª edição, Editora Orion.

Balletti, C., Berto, M., Gottardi, C., and Guerra, F. (2014). "3D Technologies for the Digital Documentation of an Ancient Wooden Structure», International Journal of Heritage in the Digital Era, 3(1), 19-32.

Bevilacqua, M.G., Caroti, G., Piemonte, A., Ruschia, P., and Tenchinia, L. (2017). "3D Survey Techniques For The Architectural Restoration: the Case of St. Agata in Pisa", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-5/W1, 2017, GEOMATICS & RESTORATION – Conservation of Cultural Heritage in the Digital Era, 22–24 May 2017, Florence, Italy.

Brumana R., Oreni D., Barazzetti L., Cuca B., Previtali M., and Banfi F. (2020). "Survey and Scan to BIM Model for the Knowledge of Built Heritage and the Management of Conservation Activities". In: Daniotti B., Gianinetto M., Della Torre S. (eds) Digital Transformation of the Design, Construction and Management Processes of the Built Environment. Research for Development. Springer, Cham. https://doi.org/10.1007/978-3-030-33570-0_35.

Bruno, N., Coïsson, E., and Cotti, M. (2017). «Laser-Scanner Survey of Structural Disorders: An Instrument to Inspect the History of Parma Cathedral`s Nave», The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-5/W1, 2017, GEOMATICS & RESTORATION – Conservation of Cultural Heritage in the Digital Era, 22–24 May 2017, Florence, Italy.

Cordis EU Research Results (2017). "PreserWoodenHeritage - Preserving Wooden Heritage. Methods for monitoring wooden structures: 3D laser scanner survey and application of BIM systems on point cloud models". H2020-EU.1.3.2.https://cordis.europa.eu/article/id/418124-3d-laser-technology-to-preserve-europe-s-wooden-built-heritage (accessed: 2020-09-08).

Correia, M.R. and Carlos, G.D. (ed.) (2015). "Cultura Sísmica Local em Portugal", Argumentum, ISBN: 978-972-8479-88-6.

Lee, M.C., Tsai, Y.L., and Lin, M.L. (2015). "Finding the Displacement of Wood Structure in Heritage Building by 3D Laser Scanner", ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume II-5/W3, 2015, 25th International CIPA Symposium 2015, 31 August – 04 September 2015, Taipei, Taiwan.

Lopes, M. (2012). "Estrutura Sismo-Resistente da Gaiola Pombalina: Passado e Futuro". CIRea2012 – Conferência Internacional sobre Reabilitação de Estruturas Antigas de Alvenaria, Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa.

Mascarenhas, J. (2004). "Sistemas de Construção V - O Edifício de Rendimento da Baixa Pombalina de Lisboa", 3ª edição, Livros Horizonte.

Mondello, A., Garozzo, R., Salemi, A., and Santagati, C. (2019). "HBIM For The Vulnerability Assessment of Traditional Bell Towers", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII2/W15, 2019, 27th CIPA International Symposium "Documenting the past for a better future", 1–5 September 2019, Ávila, Spain.

Nieto-Julián, J.E., Antón, D., and Moyano, J.J. (2019). "Implementation and Management of Structural Deformations into Historic Building Information Models", International Journal of Architectural Heritage, Taylor & Francis, 1-14. https://doi.org/10.1080/15583058.2019.1610523.

UNESCO (2003). "Charter on the Preservation of the Digital Heritage". Adopted at the 32nd session of the General Conference of UNESCO, 17 October 2003. Available at: UNESCO Digital Lybrary, https://unesdoc.unesco.org/ark:/48223/pf0000179529.page=2 (accessed 2020/09/12).

Physical Model of a Pombaline Building Printed in 3D – essays for educational and training purposes

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ABSTRACT

The Pombaline Cage is a seismic resistant wooden structure, thought and applied massively in buildings during the reconstruction of Lisbon, after the 1755 earthquake. Despite being a system that has been extensively studied in its structural and constructive essence, it appears that there is no global and accessible representation, as a whole, that facilitates its study and understanding. The existing representations of the Pombaline Cage are, essentially, based on drawings and physical models of parts of the Cage. They are unique specimens, some integrating museum collections. The known virtual representations are scarce and difficult to access. This study explores the potential of 3D printing technology FFF (fused filament fabrication) to recreate physical models, at scale, of a pombaline building archetype: a typical building composed by three aerial floors, ground floor and roof. The requirements of the models were essentially based on educational and training objectives. They are intended to support the classes of the students from the DECivil, Instituto Superior Técnico. They can also be used in training and awareness activities among younger people, whether in their schools, or during Técnico summer courses.
The model scale (1:50) considered the general description of the structure. The workflow developed considered: a virtual recreation of the pombaline building in a CAD environment; study of the building's components; planning of the model; execution of preliminary printing tests; 3D printing of the final elements; and assembly of the final model.
The option for low-cost 3D printing processes aimed to enhance the dissemination model replicas and thus contribute to the study and understanding of this innovative and heritage seismic resistant system. The results obtained demonstrated the ability to describe the Pombaline Cage as a whole.

Keywords: 3D Pombaline cage, 3D printing, Physical model, Didactic model.

INTRODUCTION

There are countless works on pombaline construction in its multiple angles: studies on its architectural and cultural value, experimental essays on its structural behavior, and several articles on its innovative character and influence on the evolution of construction (França, 1998; Lopes, 2012; Teixeira, 2010).

Regarding the representation of this structure, there are several bi-dimensional representations, such as drawings, diagrams and photographs (Langenbach, 2007; Nunes, 2017; Augusto Leitão, 1896). For the present work has been very important the study developed by Mascarenhas (2009), an exhaustive survey of the components of the pombaline cage and pombaline buildings, through freehand drawings. Another example is Appleton (2011), which presents several schemes and photographic records of real cases. Physical representations are scarce. The available ones focus on specific components, not allowing a global understanding of the structure. There are two known physical models: one belongs to the Civil Museum of the Instituto Superior Técnico; the other to the Sapadores Firefighters Regiment of Lisbon. The first is a wooden model that represents the development of stairs along a floor. It does not show the connection details, or connections with other elements of the building. The second is a simplified model of two floors, also in wood, which show part of the pombaline structure, not complete, so that it could be studied by firefighters. Cóias (2007) presents a complete virtual model but it's access is difficult.

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The study of this patrimonial structure nowadays is of great importance, since there are several buildings, mainly in Lisbon's downtown, that presents this type of structure. The remodeling of pombaline buildings is frequent, but the structure is often not properly considered (Teixeira, 2010). In most cases the pombaline cage is treated as a decorative element, completely deconstructed, with only its exposed skeleton. Such reveals that there is no in-depth understanding of this structure. For its correct functioning the pombaline cage must be properly filled and plastered. The set of the wooden pieces, by itself, are not sufficient to guarantee the correct anti-seismic functioning (Nunes, 2011).

The elaboration of a complete model of the pombaline cage is directly related to the non-existence of one. The existing physical models do not guarantee the global understanding of this structure in its relationship with all elements of the building. The developed model aims to associate essential and relevant knowledge about the pombaline cage resulting in an integrative representation. We choose a physical model and not a virtual one because this type of representation allows a much more direct reading of the object under study, and a more immediate and interactive sharing of knowledge. The use of 3D printing, according to the FFF (Fused Filament Fabrication) method, uses the fusion and deposition of a thermoplastic material allowing the creation of pieces with different formats, whether regular or organic, according to successive layers that are deposited on a tray. The printed models have good finishes and support any type of detail. The low costs associated with the process facilitate experimentation and model reproduction.

OBJECTIVE AND METHODOLOGY

The main objective of this study is the development of a complete model of a pombaline building, intended essentially for educational purposes, i.e., aiming at its use in educational environments. As the main requirements of the model, three were defined: lightness, portability and adequate degree of detail. The 1:50 scale was adopted, as appropriate to the objective of the study and model requirements. The final model would have about 30 cm in length, 26 cm in width and 32 cm in height (fig.1). Previously, an architectural survey was made based at bibliographic and documentary sources; the study of existing models of the pombaline cage was also carried on.

The development of the physical model involved upstream the realization of a complete virtual model of a pombaline building, highlighting the structure. In the AutoCAD Autodesk environment, each component part of this structure was reproduced, as well as its relationship with the building. The ground floor structure, defined by pillars and masonry walls that end in a vaulted ceiling (fig. 2), was also designed.

In the printing phase, a Creality3D CR-10 V2 3D Printer (printing volume: 300x300x400mm) was used. The material used was a resistant and affordable PLA (Polylactic acid), a thermoplastic filament. Different colors were tried to highlight the structure of the pombaline cage and obtain a more expressive result.

MAIN RESULTS

The result is a well-executed replica of the pombaline type buildings and the pombaline cage, which allows a global understanding of how the structure connects with the rest of the building.

This model shows the general appearance of what is a pombaline building on the outside and also shows the structure, from the ground floor to the roof. The pombaline cage structure is highlighted by the use of a distinct color, which emphasizes the simplicity of the structure and alludes to its material, wood.

Through this model, it is possible to observe how the cage develops above the vaulted ground floor, how the stairs develop, how the beams and floors are connected to the structure of the cage and how the roof develops (fig. 3).

This model allows a generalized, complete and global observation of what a pombaline structure is, as well as the possibility of understanding it from different angles.
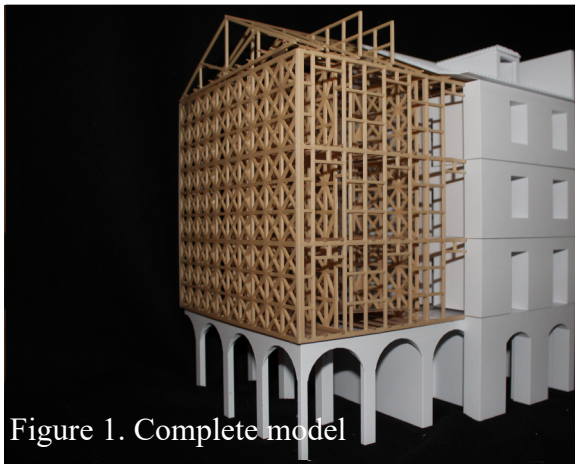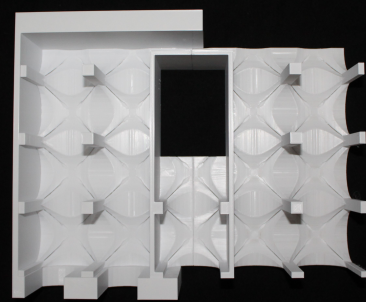

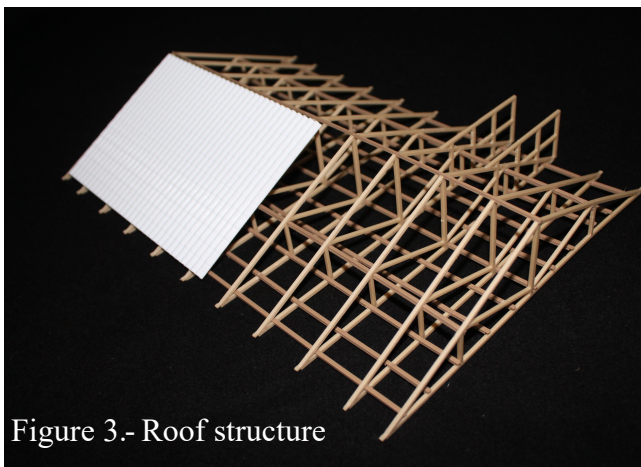Figure 1. Complete model

Figure 2.- Bottom view of the ground floor

Figure 3.- Roof structure
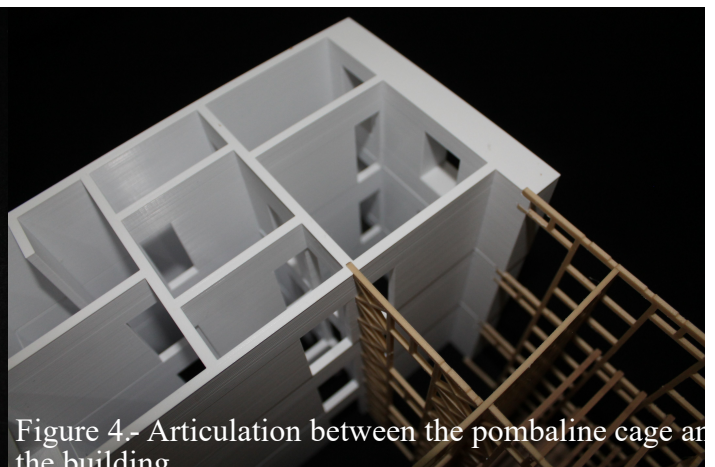
Figure 4.- Articulation between the pombaline cage and the building

CONCLUSION

The model obtained responds to the intended objective, since it reliably represents the seismic resistant system of the cage. It is possible to observe, from multiple angles, the development of the structure along the four floors. Through its observation it is possible to describe, in general, how this structure evolves, providing a global understanding of it, in contrast to what happens with pre-existing models.

The model developed can contribute to the dissemination of knowledge about the pombaline cage since it can be used, for example, in the context of training and awareness-raising actions on seismic safety for different target audiences.

The digital workflow considered and the use of 3D printing technology allowed the development of the physical model in a with a relatively easy and quick way, at moderate costs. Because of these advantages, the

model can be reprinted easily – an importante factor for (in contrast with the previously models referred) its sharing and the dissemination of the knowledge contained.

REFERENCES:

Appleton, J. (2011). 'Reabilitação de Edifícios Antigos: Patologias e Tecnologias de Intervenção'. (ORION, Ed.) (2nd Edition).

Augusto Leitão, L. (1896). 'Arma de Engenharia - Curso Elementar de Construcções'. (I. Nacional, Ed.).

França, José-Augusto, (1989). 'A reconstrução de Lisboa e a arquitectura pombalina'. Instituto de Cultura e Língua Portuguesa.

Langenbach, R. (2007). 'From "Opus Craticium" to the "Chicago Frame": Earthquake-Resistant Traditional Construction.'

Lopes, M. (2012). 'Estrutura Sismo-Resistente da Gaiola Pombalina: Passado e Futuro'. CIRea2012 – Conferência Internacional sobre Reabilitação de Estruturas Antigas de Alvenaria, Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa.

Lourenço, P. B., Vasconcelos, G., and Poletti, E. (2014). 'Edifícios Pombalinos: Comportamento e reforço'. In Seminário Intervir em construções existentes de madeira.

Mascarenhas, J. (2009). 'Sistemas de Construção V - O Edifício de Rendimento da Baixa Pombalina de Lisboa. Materiais Básicos (3ª Parte): o vidro'. Livros Horizonte.

Nunes, R. D. (2017). 'Constructive Characterization of Pombaline Buildings and Simplified Pushover Analysis of Frontal Walls'. Dissertação de Mestrado em Engenharia Civil, Faculdade de Ciência e Tecnologia da Universidade Nova de Lisboa.

Paula, F., Barreto, L., Silva, F.A., Lima, F., Morais, V. (2014). 'Maquetes Híbridas: Diálogos Entre as Técnicas Tradicionais e as Tecnologias Digitais no Processo Projetual'. XVII Congresso da Sociedade Iberoamericana de Gráfica Digital.

Santos, S.L.B. (2016). 'IMPRESSÃO 3D – PERSPETIVAS DE ADOÇÃO NA INDÚSTRIA PORTUGUESA'. Instituto Superior de Estatística e Gestão de Informação. Universidade Nova de Lisboa.

Teixeira, M. J. F. (2010). 'Reabilitação de edifícios pombalinos: Análise experimental de paredes de frontal'. Instituto Superior Técnico de Lisboa. Universidade de Lisboa

Base Isolation, a Leading Solution for the Seismic Protection of Important and Critical Structures

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ABSTRACT

Between 2008 and 2013 was built in Angra do Heroísmo, Azores the then designated "Laboratório Regional de Investigação Veterinária (LRIV)", a laboratory for studies on veterinary research. This laboratory was the second building using base isolation to be constructed in Portugal. The maximum risk of biological contamination imposed zero level of allowable cracking. Performance requirements as well as construction zone's seismic hazard justified the adoption of a base isolation system. The complex is composed by several buildings but just one, the one with the more critical laboratory, was base isolated. In the paper the project of this important structure is presented and the problem of the seismic performance of critical buildings is discussed.

Keywords: Critical Structures, Base Isolation, Seismic Protection

INTRODUCTION

Recent earthquakes have tested the performance of old and modern buildings in different parts of the world, and the results have led to discussions about the adequacy of current building and construction technologies and also about the performance objectives of the current design standards (CERC, 2012).

After the Canterbury earthquake crisis (2010 and 2011), significant building damage were reported. Around 200 buildings with 5 or more stories were identified as dangerous and requiring stabilization, and half of them were reported as non-repairable (CERC, 2012). The government authorities stated that the cost will be as much as 30 billion NZ dollars, including costs such as business disruption, inflation, insurance and rebuilding to higher standards.

In New Zealand the modern buildings should meet the goal of life-safety, the base of the local code (and of Eurocode also), however this was accompanied by major structural and non-structural damage. The Canterbury Earthquake Recovery Authority (CERA) estimated that 1100 buildings in the Christchurch area were fully or partially demolished. The cost of the repairing, the number of demolitions and the business disruption for more than 17 months, has led to important economic losses and social impacts.

In the post-earthquake it was evident that the observed level of damage was not anticipated by the building owners or occupiers. They had different expectations regarding the likely behavior of an "earthquake-resistant" building. The important conclusion was that it will be desirable to lessen the potential for economic loss as result of future earthquakes (CERC, 2012).

As a consequence of the discussions about the adequacy of the modern codes, alternative methods are appearing focused on a low-damage design of earthquake-resistant structures (CERC, 2012). The main goal is to design new forms of seismic resisting structures, where damage is limited or suppressed. Low damage solutions are not a complete innovation: base isolation can be considered a low-damage technology and is available for more than 30 years.

The goal of base isolation is to separate the building from the destructive horizontal components of the seismic ground motions. This goal is achieved by the interposition of an horizontal flexible layer between the base of the building and their foundations.
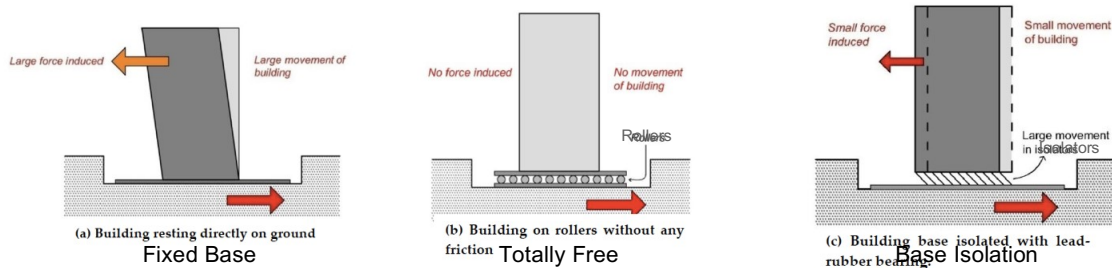
Figure 1. The concept of Base Isolation

Decoupling the horizontal movement of the building from the destructive ground movement, the accelerations on the building are largely reduced, protecting the structure and their contents of possible damage. The acceleration reduction is accompanied by an increase in the total horizontal displacements, but with almost no deformation of the structure. This behavior allows the structure to remain operational during and after the earthquake, guaranteeing full operation and no disruption in the building functionality.

The first examples of isolated buildings were buildings considered vital or very important for the emergency network, or buildings with special contents that must be preserved in case of a seismic event. Recently, the number of buildings with more common uses (residential buildings, for example) protected with base isolation started to increase. One important example is the reconstruction of L'Aquila, after the earthquake of 2009. The increasing concern about the costs that can result from a seismic occurrence, has fueled the search for this type of seismic protection.

Hospitals are critical structures that should be base isolated in seismic regions. The requirement of operationality after a seismic occurrence to provide health assistance to the population, and the value of the equipment installed, are two major reasons to use base isolation in the seismic protection of the hospitals.

THE REGIONAL VETERINARY LABORATORY OF AZORES

In the beginning of 2010 decade it was built in Vinha Brava, Terceira, Azores, the then denominated Regional Veterinary Laboratory of Azores (RVLA) complex. According to the specifications, one of the buildings should house a laboratory with safety conditions necessary to fulfill the biosafety level 3 requirements.

Biosafety level 3 is commonly used for research and diagnostic work involving various microbes which can be transmitted by aerosols and/or cause severe disease. One of the main concerns was to guarantee that the exterior walls remain without any cracking, even during a major earthquake, to avoid any league with contamination risk.

The demanding performance requirements combined with the important local seismicity led the designers to the decision to use base isolation in the building that would house the referred laboratory (Figure 2). This Laboratory building became the second building protected with base isolation in Portugal, after the Hospital da Luz (2007).
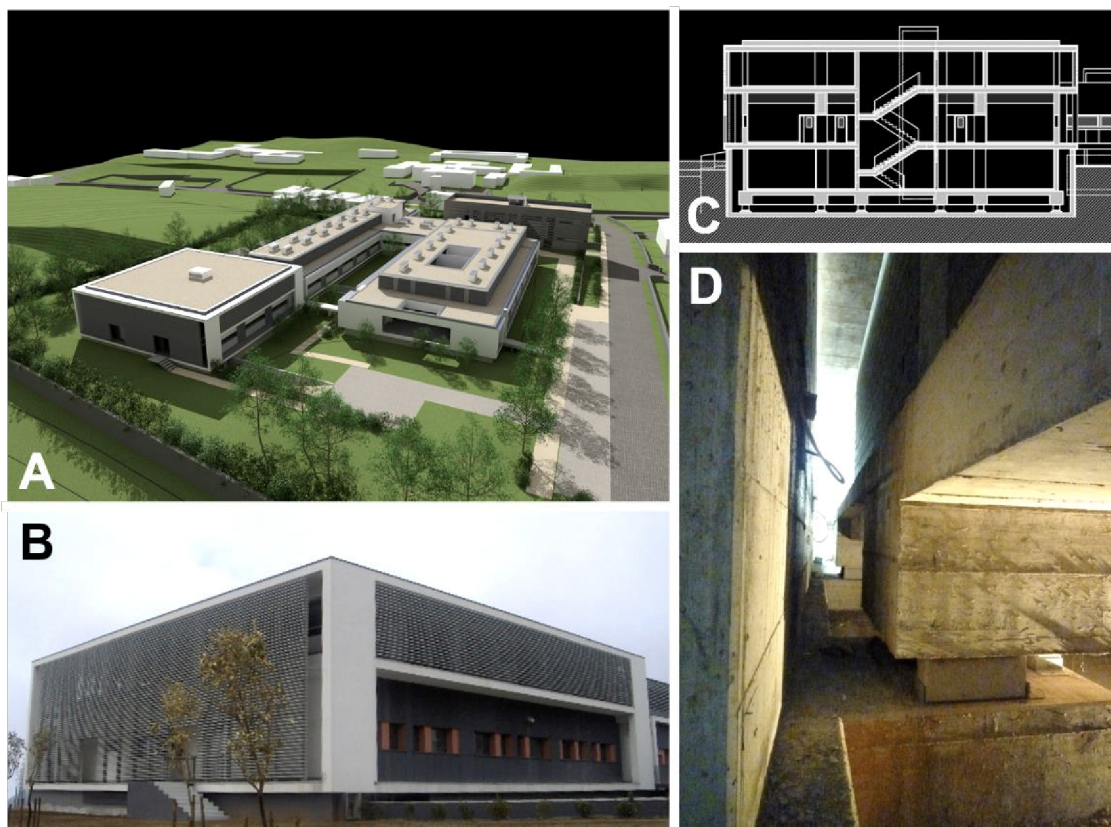
Figure 2. LRVA complex (A); Isolated Building (B); Architecture scheme of isolated building (C); Seismic gap detail (D) (adapted from Amaral, 2013).

On the seismic isolation of the RVLA were used High Damping Rubber Bearings (HDRB) devices. The structure is in reinforced concrete class C25/30 and consists of three elevated floors of square plan. The structural system has a central core, 8 interior columns and a peripheral frame system. The total weight of the building (dead load + reduced live loads) is about 3854 tons, irregularly distributed on 28 base isolation devices.

The fixed base frequencies of the building were around 2,0 Hz. With the base isolation solution the frequencies decreased to 0,5Hz, for the first three modes of vibration (two translational and one rotational). In the base isolated solution the total participating mass of these three modes were around 99% in each direction. The seismic response was reduced in the order of 5 times when compared with the fixed base solution.

FINAL REMARKS

In the cases where the goal is to maintain the full operationality of the building after and during an earthquake, base isolation is an undeniable solution.

Recently, the pandemic state that affected all of us, showed how important is the reliability of the health care system, when a situation with a large flux of patients occur. It would be not acceptable that some of the hospitals could be declared as inoperable.

After a destructive earthquake the flux of injured people to the hospitals is expected to be large, and is impossible to admit that, in such situation, the hospitals cannot receive the patients due to poor seismic performance of the structures.

The RVLA Laboratory is an example of an important structure, with a strict set of safety requirements, where it was decided to use base isolation to guaranty a full operational behavior in case of an earthquake.

This is the example that should be followed when designing an hospital or other vital structure, in seismic areas like the Azores Islands, or in the southern part of Continental Portugal.

REFERENCES:
Amaral, F. (2013). "Análise da influência da componente vertical da acção sísmica na resposta de Apoios Pendulares com Atrito", Master dissertation, Instituto Superior Técnico (in Portuguese).
CERC - Canterbury Earthquakes Royal Commission (2012) "Final Report Volume 3 – Low-Damage Building Technologies".

Characterization of Volcanic Rocks Using VRS Empirical System

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ABSTRACT

A new empiric system was developed for volcanic rocks, designated VRS. For the VRS system, geotechnical information was collected from samples from several Atlantic Ocean islands that include Madeira and Canarias archipelagos, taking also into consideration data from other different sources.

Keywords: Volcanic rocks, Geomechanical characterization, VRS empirical system.

INTRODUCTION

Preliminary calculation of the geomechanical parameters of rock masses can be carried out using empirical classification systems. These systems consider, between others, the properties like the strength of the rock, density, condition and orientation of discontinuities, groundwater conditions and the stress state. To evaluate these properties, a numerical measure is given and, subsequently, a final geomechanical coefficient is obtained by applying a numerical expression associated with the system. For volcanic rocks, a new empiric system was developed designated VRS (Volcanic Rock System), from the adaptation of the RMR (Rock Mass Rating) system and by using a classification developed at São Paulo, for the design of several tunnels in basaltic formations (Ojima,1981; Miranda et al., 2018). This followed the experience acquired in Brazil during the construction of a wide number of large dams in volcanic foundations, in particular the dam of Itaipú, and the dam of Água Vermelha (Pedro et al.,1975; Abrahão, 2020).

For the VRS, geotechnical information was collected from samples from several Atlantic Ocean islands that include Madeira and Canarias archipelagos, taking also into consideration data from other different sources (Costa et al., 2002; Cafofo and Sousa, 2007; Vallejo et al., 2007; Miranda et al., 2018). The various rock types are described with particular emphasis on the Madeira rock formations and their geomechanical properties.

The new empirical system is based on the consideration of six geological-geotechnical parameters to which relative weights are attributed. The final VRS index value, which varies between 0 and 100, is obtained through the algebraic sum of these weights. With this index, it is possible to obtain strength properties, deformability moduli, and description of the rock mass quality, as well as recommendations for excavation and support needs and support loads, using correlations with other geomechanical indices.

The following geomechanical parameters were considered: P_1 - UCS; P_2 - rock weathering characteristics; P_3 - intensity of jointing; P_4 - discontinuity conditions; P_5 - presence of water; and P_6 - disposition of blocks. Different weights are assigned to each parameter (Figure 1). In relation to RMR, the properties were identical for P_1, P_4 and P_5, but have different weights. The parameter due to discontinuities orientation P_6, as an adjustment of the sum of the remaining five parameters, was difficult to assign a weight, because it depends on groundwater conditions. Instead, it was substituted by another parameter related to the disposition of blocks. This parameter is considered to evaluate block stability. Four situations were considered: blocks of very favorable, favorable, acceptable and not acceptable which refer to the stability of the geotechnical structure. The VRS considers for P_2 the rock weathering effect which is not considered by the RMR system, while P_3 is related to the joint intensity combining the effects of parameters P_2 (RQD) and P_3 (discontinuity spacing) considered by RMR.

Figure 1. Volcanic rock mass classification VRS and weights

A database composed of 99 examples with 29 attributes (Cafofo and Sousa, 2007; Concha-Dimas and Vargas-Godinez, 2007; Miranda et al., 2018) was obtained. The data were mainly obtained from Madeira Island (76%), with the rest from Canarias Islands (18%) and Mexico (6%). The information covers different

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rock types, such as basalt (42), breccia (33), tuff (15) and pyroclasts (9). In the database, the deformability modulus of the rock mass (E_{RM}) was derived from the Serafim and Pereira (1983) formula, assuming the restriction of RMR<80. GSI was only calculated for RMR>23 according to the Hoek and Brown (1997) criterion. The values of cohesion and internal friction angle were obtained through the software RocData (Rocscience, 2015).

RESULTS

Some representative correlations were obtained between VRS coefficients and RMR values. The relationship between VRS and RMR was the following:

$$VRS = 1.063RMR - 3.134$$

Another representative correlation was obtained between E_{RM} and VRS with an exponential expression (Miranda et al., 2018). The correlations between E_{RM} and VRS for each rock type are illustrated in Figure 2.
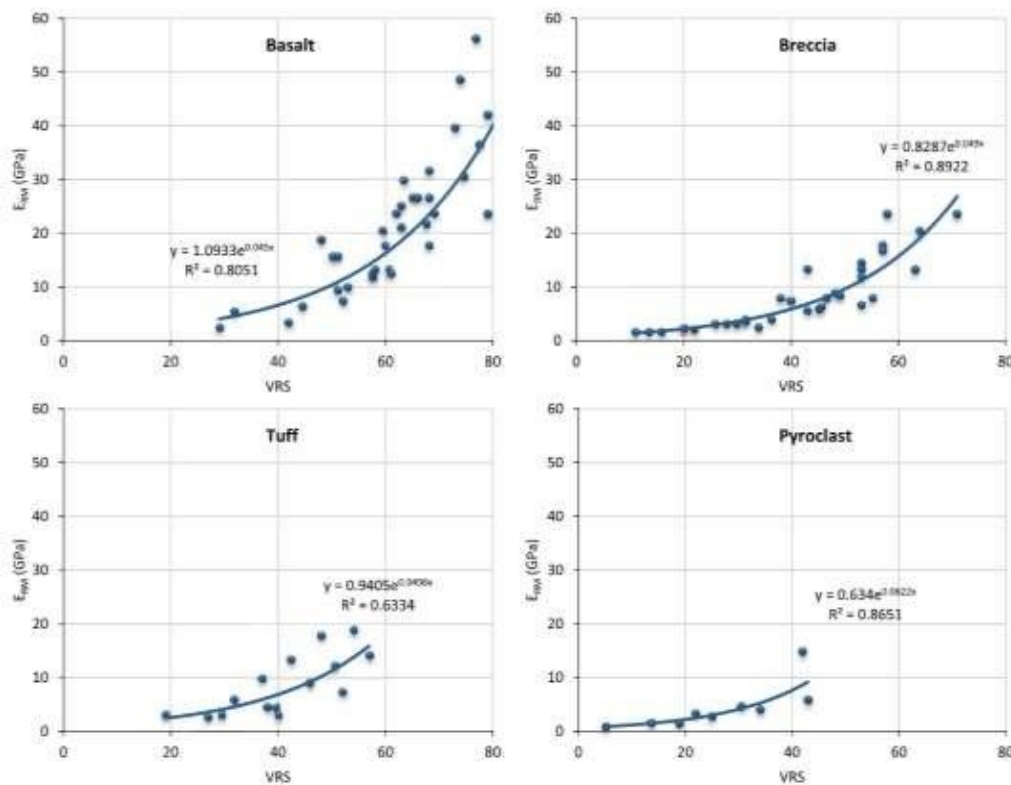
Figure 2. Deformability modulus of the rock mass versus VRS for each rock type

Finally, Data Mining techniques were applied to predict volcanic rock masses classes, using different algorithms (Miranda et al., 2018). Considering variables from the VRS and RMR systems, two main observations were made: a better performance is achieved using attributes from the VRS; and ANN and MR algorithms present very similar performances that are superior to the SVM.

CONCLUSION

Calculation of the geomechanical parameters for volcanic rocks can be carried out using a new empirical system designated VRS (Volcanic Rock System), recently developed. The VRS system was applied on samples from Atlantic Ocean islands including mainly information from Madeira Island. The updating of the database with information of Azores Islands is very important permitting to obtain new correlations of the more relevant geomechanical parameters, and to include new types of rocks. Geotechnical information from Azores, will permit to establish new correlations for different volcanic formations and to refine the proposed empirical system.

REFERENCES:

Abrahão R. (2020). Soft rocks in dam foundations and dam sites. Soft Rock Mechanics and Engineering, Eds. Kanji, He & Sousa, Chapter 24, 699-718.

Cafofo P., Sousa L.R. (2007). Innovative underground works at Socorridos, Madeira island, Portugal. Workshop on Volcanic Rocks, Ponta Delgada, 73-80.

Concha-Dimas A., Vargas-Godinez J. (2007). Effects of flow structure in lavas from Sierra de Guadalupe, Northern Mexico City, on point load index and rock mass quality evaluation. Workshop on Volcanic Rocks, Ponta Delgada, 67-72.

Costa, P.; Monteiro, A.; Oliveira, R.; Gaião, R.; Baião, C.; Sousa, L.R. (2002). Geotechnical analysis of the Caniçal tunnel, Madeira Island. ISRM Symp. EUROCK 2002 on Rock Engineering for Mountainous Regions, Eds. Gama and Sousa, Funchal, 579588.

Hoek E., Brown E. (1997). Practical estimates of rock mass strength. Journal of Rock Mechanics and Mining Sciences, 34(8):11651186.

Miranda T., Sousa L.R., Gomes A.T., Tinoco J., Ferreira C. (2018). Geomechanical characterization of volcanic rocks using empirical systems and data mining techniques. Journal of Rock Mechanics and Geotechnical Engineering, 1-13.

Ojima L. (1981). Methodology of rock mass classifications for tunneling. LNEC Thesis. Lisbon, Laboratório Nacional de Engenharia Civil, LNEC, Lisbon (in Portuguese).

Pedro J., Sousa L.R., Ramos J., Teles M. (1975). Study by the finite element method of the Água Vermelha dam foundation. LNEC Technical Report. Lisbon (in Portuguese).

Rocscience (2015). RocData, Version 5.003, https://www.rocscience.com.

Serafim J.L., Pereira P. (1983). Considerations on the geomechanical classification of Bieniawski. Symposium on Engineering Geology and Underground Construction, 33-42.

Vallejo L.I., Hijazo T., Ferrer M., Seisdedos J. (2007). Geomechanical characterization of volcanic materials in Tenerife. Workshop on Volcanic Rocks, 21-28.

Integrated Seismic and Tsunami Hazard Assessment in the Atlantic: a Methodology

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ABSTRACT

Decision makers are often confronted with the need to allocate limited resources to the mitigation of multiple threats. The assessment of risks needs therefore to lead to intercomparable results. Because the assessment of hazard is the first step towards risk assessment, the methodologies adopted to estimate hazards should not jeopardize the comparison of results for different phenomena.

Although earthquake and tsunami occurrence are strongly correlated, the approaches adopted to estimate the associated hazards are very different. In most studies seismic hazard is estimated with a probabilistic approach, which incorporates all the plausible scenarios of earthquake occurrence in the area of influence for a particular site. Tsunami hazard, on the contrary, tends to be assessed for a single scenario, or at best a few scenarios. It becomes therefore impossible for a decision maker to compare, for a particular site, the level of seismic risk and tsunami risk.

We propose a methodology for the North Atlantic which uses the earthquake to characterize the recurrence of different area sources. Next, a synthetic catalog with the same statistical parameters but longer duration (typically a few thousand years) is generated. After purging the synthetic catalog of low magnitude hence non-tsunamigenic earthquakes, we model tsunami generation and propagation for the remaining earthquakes (typically a few hundred) to the sites under study. After selecting an intensity measure, e.g., runup height, we then proceed to estimate the probability of exceedence for different levels of intensity. These tsunami hazard results can be presented as hazard curves (probability of exceedance as a function of intensity for a site) or as hazard maps (intensity level with a given return period on a grid of sites). A fragility curve of the infrastructures at the site then allows the computation of tsunami risk. Preliminary results for the Oeiras waterfront will be presented.

Keywords: tsunami hazard, probabilistic assessment, North Atlantic

INTRODUCTION

Probabilistic seismic hazard assessment (PSHA) is a well-established practice, with five decades of use and improvement since A. Cornell proposed the methodology back in 1968. This contrasts with the analysis of tsunami hazard, for which the deterministic approach is dominant. Because earthquakes are the leading cause of tsunamis, either directly through deformation of the seabed or indirectly by triggered submarine landslides, it seems desirable to integrate the two approaches, so that both assessments reflect the same regional seismicity model. Only in this way can the level or risk associated with these two adverse phenomena be compared.

In PSHA, the following question is asked: at a given site, what is the probability that the intensity of ground motion (measured by macrosismic intensity, peak acceleration, spectral acceleration, or any other adequate

quantity) exceeds a given value in a given period of exposure (typically 50 years)? In tsunami hazard assessment, the question is often put in the following terms: if an earthquake occurs with certain characteristics what intensity measure of tsunami flooding is to be observed at a given site? In other words, tsunami hazard analysis tends to consider only one scenario of seismic occurrence (often the worst case scenario) while seismic hazard analysis integrates the effects of all plausible scenarios during the exposure period, weighed by their probability of occurrence according to a given seismic recurrence model. It is easy to conclude that the results of probabilistic analysis of seismic hazard cannot be compared with the results of deterministic tsunami hazard analysis.

Prevention of natural disasters is an exercise of allocating limited resources to the mitigation of multiple risks, and this allocation must be guided by the level of risk associated with each type of adverse natural phenomenon. The risk – understood as the probability that the damage caused by the adverse phenomenon exceeds a given value during a period of exposure - is a probabilistic concept by definition, and can only be calculated taking into account the probabilistic hazard, the vulnerability of the exposed elements (level of damage for different values of intensity) and the respective value. About 72% of tsunamis are caused by ocean earthquakes (source: http://tsunami.org/what-causes-a-tsunami/). Submarine landslides triggered by earthquakes are also a significant cause of tsunamis, thus increasing the percentage of tsunamis whose ultimate cause is seismic activity. It therefore makes sense to integrate the analysis of the seismic hazard with the probabilistic analysis of the tsunami hazard.

Probabilistic tsunami hazard assessment (PTHA) must answer the following question: for a given value I of the intensity of the phenomenon (measured by peak tsunami amplitude, runup height or other adequate quantity), what is the probability that this value will be exceeded in a given period of exposure (for example, In the next 50 years)? By the total probability theorem - and admitting for now that only an earthquake can cause a tsunami - the answer can be calculated as

$$P(i > I) = \sum_n \sum_k P(M_n, r_k) P\left(i > I \middle| (M_n, r_k)\right)$$

where $P(M_n, r_k)$ is the probability that an earthquake of magnitude M_n will occur at location r_k (i.e., in a

cell around the position vector r_k) and $P(i > I)|(M_n, r_k)$ is the conditional probability that the intensity will exceed the value I if an earthquake of magnitude M_n occurs at position r_k. The calculation of $P(M_n, r_k)$ is an integral part of the probabilistic analysis of seismic hazard, while the calculation of $P(i > I)|(M_n, r_k)$ can be done through systematic tsunami modeling for all relevant scenarios (M_n, r_k) (for example, with $M_n > 7$). Sharing the same probability function $P(M_n, r_k)$ in both the seismic and the tsunami hazard assessments will link the two evaluations and make them intercomparable.

The calculation of $P(M_n, r_k)$ is based on a model of seismic recurrence, which is derived from the analysis of a catalog of past events. As the return period for tsunamigenic earthquakes is high, the range of magnitudes of interest is generally underrepresented in historical catalogs. This difficulty can be avoided by using a synthetic catalog, characterized by the same values of the Gutenberg-Richter relation parameters which are inferred

from the historical catalog, but having a much longer duration. This approach was applied by Sorensen et al. (2012) to the calculation of the probabilistic tsunami hazard in the Mediterranean.

EXAMPLE OF USE

A PTSA study for the Oeiras Municipality is underway which applies the methodology of Sorensen et al. (2012) to the Northeast Atlantic. A synthetic catalog with a duration $T_C = 10000$ years was produced for the region, adhering to the area source model developed for the European-scale EMSH2013 and EMSH 2020 seismic hazard models. The corresponding ruptures are depicted in Figure 1. Current work consists of modeling the tsunami propagation and impact for all the relevant ruptures in the synthetic catalog (it is broadly accepted that earthquakes with magnitude below 7 are not tsunamigenic). The modeling starts with the computation of vertical displacement at the seabed with the equations of Okada (1985), and follows with the wavefield propagation with the TUNAMI Code for shallow water using leap-frog finite differences, as described in Imamura (1995). Details on the methodology can be found in Santos and Koshimura (2015).

If it is concluded through the modeling that, at a particular coastal site, the tsunami intensity I_t is exceeded n times throughout the duration of the synthetic catalog, then that intensity can be associated with a return period $T_R = T_C / n$. The probability of exceedence of tsunami intensity I_t in a period of exposure T can then

be computed, assuming a stationary Poissonian process of occurrence, through $P(i > I) = 1 - e^{-\frac{\Delta T}{T_R}}$ (e.g., Reiter, 1991). Given the long return periods that are to be expected in the region for tsunamigenic earthquakes by comparison with the adopted period of exposure $T = 50$ years, the probability of exceedence can be safely computed through $P(I > I_t) = T/T_R$, a Taylor series expansion of the previous expression. Alternatively, a large collection ($N > 100$) of synthetic catalogs with duration equal to the period of exposure could be produced, allowing the direct counting of exceedences and the estimate of probability of exceedency (if a level of tsunami intensity is exceeded in k out of N catalogs, its probability of exceedence during the period of exposure is k/N).

CONCLUSION

In order to be intercomparable and allow the sound choice of risk mitigation measures, seismic hazard and tsunami hazard need to take a probabilistic approach and adopt the same regional seismicity model. We present a methodology that fulfils this goal and give very preliminary results from its application in Oeiras Municipality near Lisbon.
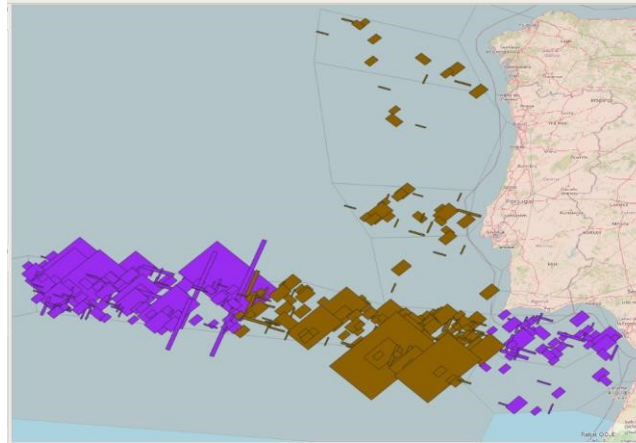
Figure 1. Seismic ruptures of the synthetic catalog used in this study. The duration of the catalog is 10000 years, and the magnitudes are between 4.0 and 8.7. Purple ruptures occur in active crust, while brown ruptures occur in stable continental crust.
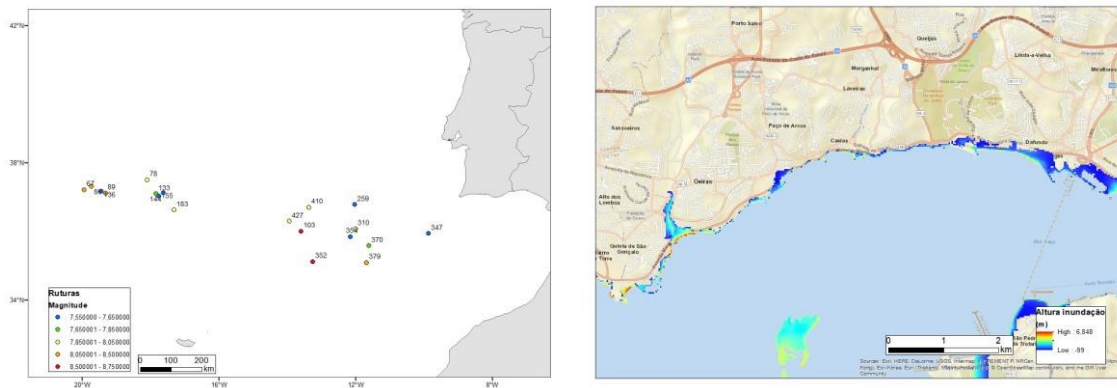
Figure 2. a) Selection of potentially tsunamigenic ruptures from the synthetic catalog, whose impacts will be individually modelled; b) preliminary results of the modeling of the inundation height caused by rupture 103 (M8.75) in the Oeiras Municipality coastal area.

REFERENCES:

Imamura, F. (1995). "Review of tsunami simulation with a finite difference method", In Long-Wave Runup Models, Ed. World Scientific, Singapore, pp. 25–42.

Okada, Y. (1985). "Surface Deformation due to Shear and Tensile Faults in a Half Space", BSSA, 75, 1135–1154.

Reiter, L. (1991). Earthquake Hazard Analysis: Issues and Insights, Columbia University Press, New York.

Santos, A. and Koshimura, S. (2015). "A criterion for tsunami hazard assessment at the local scale", Journal of Geodesy and Geomatics Engineering, 2, 87-96. DOI: 10.17265/2332-8223/2015.06.004

Sørensen,M.B.,Spada,M.,Babeyko,A.Y.,Wiemer,S.,Grünthal,G.(2012). "Probabilistic tsunami hazard in the Mediterranean Sea", Journal of Geophysical Research, 117, B01305

Seismic risk scenarios in Faial island, Azores, using QLARM

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ABSTRACT

The Azores islands, located near the Mid Atlantic Ridge near the junction of three tectonic plates, is frequently shaken by earthquakes. Since the XVIth century, more than 30 damaging earthquakes have been reported, which caused about 6,300 fatalities, mainly due to the earliest events. Recent advances in seismic risk analysis are applied to estimate building damage and human losses in Faial Island, using the tool QLARM. The dataset and tool are validated using the data available for the 1980 (M7.2) and 1998 (Mw6.2) earthquakes. The population and building model, including site conditions, developed for this island is applied two likely earthquake rupture scenarios; one inland of magnitude 6.9 and another offshore of M6.0. Fatalities and injured may range between 110 to 620 and 330 to 1750, respectively, depending on the selected scenarios.

Keywords: Azores, seismic risk, QLARM,

INTRODUCTION

The Azores volcanic archipelago is located near the Mid Atlantic Range (MAR) and rests on a plateau built by tectonic and/or magmatic activity (Vogt and Yung, 2017). It includes nine islands; seven of them (Graciosa, Faial, Pico, São Jorge, Terceira, São Miguel and Santa Maria) are on the eastern side of the MAR close to the Eurasian and Nubian tectonic plates boundary; the other two islands (Flores and Corvo) are located west of the MAR on the American tectonic plate (Figure1).
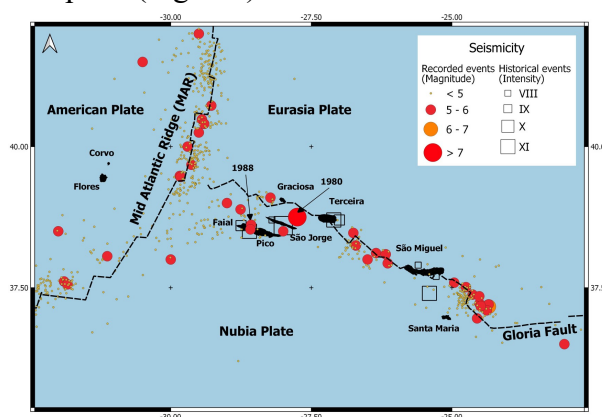
Figure 1. Map of the Azores archipelago and the Mid Atlantic Ridge with tectonic plates. Instrumentally located epicenters are marked as red dots with sizes proportional to magnitude, and epicenters of historical earthquakes are marked by open squares proportional to the maximum reported intensities.

The Azores are frequently shaken by earthquakes and the largest have induced building damage, landslides and fatalities. Fontiela et al. (2017) compiled intensity reports from 167 earthquakes of the period 1522–2012

to map maximum observed intensities (MOI) on each island. They have shown that the MOI varies from VII to XI for the islands on the eastern side of the MAR. Fontiela et al. (2018) have shown that the seismicity rate of this region is high with earthquakes of relatively low magnitude.

Since its settlement in the 15th century, 33 earthquakes with intensity higher than VII have been reported (Fontiela et al., 2017). These earthquakes killed at least 6300 thousands people. The most recent destructive events occurred in 1980 (M7.2) and 1998 (Mw6.2) and caused 61 and 8 fatalities, respectively. The latter generated heavy damage in several settlements of Faial and Pico islands.

In order to provide the civil protection with information on the potential damage and losses for likely earthquakes in Faial Island, we have developed a specific building and population model including information on soil conditions. This model includes the 13 settlements of the island for which the distribution of buildings and population in the buildings has been defined following the EMS-98 classification. Table 1 shows the information collected for each settlement, using data from the 2011 census and damage surveys after the 1998 earthquake.

Table 1. Building and population model for Faial island.

Settlement Name	Population (2011)	Number of buildings	Site factor (intensity)	Distribution of buildings by EMS-98 classes (in %)				Distribution of population by EMS-98 classes (in %)			
				A	B	C	D	A	B	C	D
Capelo	486	416		1.5	58.8	17.3	22.3	1.9	60.9	16.9	20.3
Castelo Branco	1304	563	+1	35.4	14.7	33.7	16.1	33.6	14.3	35.7	16.4
Cedros	906	547	+1	4.7	76.7	16.3	2.3	3.9	70.6	23.7	1.9
Feteira	1896	768	+1	7.9	53.9	32.9	5.3	7.5	52.9	34	5.6
Flamengos	1599	594	+2	1.6	40.5	55.3	2.6	1.6	40.3	55.6	2.6
Horta (Angústias)	2402	996		3.8	48.6	22.8	24.8	3.6	46.5	25.2	24.7
Horta (Conceição)	1138	459		8.3	41.4	21.4	28.8	6.6	36.8	23	33.6
Horta (Matriz)	2404	856		1.2	64.4	13.2	21.1	1.3	57.1	17	24.7
Pedro Miguel	753	313	+1	25.4	13.2	45.6	15.8	24.2	13.3	46.4	16.1
Praia do Almoxarife	834	361	+1	4.3	37.5	52.1	6.1	4.7	38.4	50.9	6.0
Praia do Norte	250	225		5.8	75.3	17.4	1.6	5.2	49.3	43.7	1.8
Ribeirinha	426	175	+1	1.3	23.5	73.8	1.3	1.3	18.9	78.4	1.4
Salão	401	174	+1	11.3	16.5	53.4	18.8	10.7	14.3	55.7	19.2

The data of the model have been included into the database of QLARM (earthQuake Loss Assessment for Response and Mitigation) in order to calculate building damage and human losses. QLARM calculates the ground motion for each settlement around the epicenter subsequently used to estimate the damage to the building stock, divided into the six damage grades of the EMS-98 scale, using the European Macroseismic Method. The human losses are then estimate using a casualty event-tree model and are given into two classes, injuries requiring hospital care and fatalities (Trendafiloski et al., 2011). The best intensity relationship from

several tests has been selected by comparing calculated and reported values for both the Terceira (1980, M7.2) and Faial (1998, Mw6.2) earthquakes. The reported casualties for the two past events are within the ranges of the calculated ones, using the validated attenuation relation. Two line fault rupture scenarios are proposed, based on the paleo-seismological information for Faial Island (Madeira et al., 2015); a M6.9 inland and a second one offshore of M6.0, located along the seismogenic source of the 1926 earthquake (black lines in Figure 2).

MAIN RESULTS

A pilot study of the seismic risk analysis in Faial island has been published (Fontiela et al., 2020) using QLARM, a tool used at different scales for loss alerts and scenarios since 2013 (e.g. Rosset et al., 2020; Wyss, 2014). They show that the M6.9 inland Faial scenario strongly affects most of the settlements of the island, Flamengos being the village where the highest damage is expected with a calculated intensity of XI due to site amplification. The population affected by intensity VI and higher is estimated to be approximately 25,600, which is the total population of Faial and the western part of Pico Island. The range of estimated fatalities varies between 580 and 710 and approximately three times more injuries are expected. These numbers represent 3% and 5% of the total population of the island, respectively. The influence of the seismic wave attenuation is reduced in this case because the distances to affected settlements are short and 35% of the buildings are estimated to be highly damaged. The map of Figure 2 shows the building damage in each settlement by grades of damage. A similar calculation for daytime occupancy rate reduces by two the numbers of casualties, on average.

The M6.0 offshore scenario affects both Pico and Faial Islands with a maximum intensity of X in Flamengos. The population affected by intensities VI+ is estimated as about 22,500 in this case. Average numbers of estimated fatalities and patients are 110 and 330, respectively. The affected population by damage to houses is about 24,000.

CONCLUSION

This analysis of the seismic risk provided the opportunity to build a population and building model for Faial Island, including information on the site conditions. The proposed earthquake scenarios show that major damage is expected in Faial, but is extended to Pico and São Jorge islands. For that reason, the database of QLARM for settlements of the other islands needs to be updated, following the approach used for Faial Island. The soil conditions have been shown to increase the damage during the 1998 earthquake, especially the volcanic alluvium deposits. Particular attention should be paid to urban areas where such deposits are present. This analysis considers residential buildings, but could be extended to critical facilities such as health centers and buildings accommodating children.
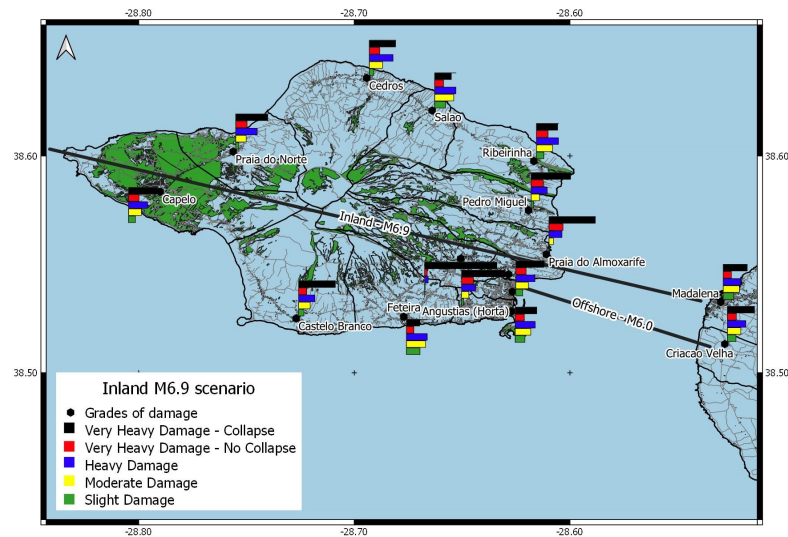
Figure 2. Map of settlements showing building damage by grades in the case of the inland M6.9 earthquake scenario. The assumed rupture faults are shown by black lines. Damage is divided into five grades for each settlement (in %).

REFERENCES:

Fontiela, J., Sousa Oliveira, C., and Rosset ,P. (2018). "Characterisation of Seismicity of the Azores Archipelago: An Overview of Historical Events and a Detailed Analysis for the Period 2000–2012". In: Kueppers U., Beier C. (eds) *Volcanoes of the Azores. Active Volcanoes of the World*. Springer, Berlin, Heidelberg, 8, 127-153.

Fontiela, J., Bezzeghoud, M., Rosset, P., Cota Rodrigues, F. (2017). "Maximum Observed Intensity Map for the Azores Archipelago (Portugal) from 1522 to 2012 Seismic Catalog". *Seismological Research Letters*, 88 (4), 1178-1184

Fontiela, J., Rosset, P., Wyss, M., Bezzeghoud, M., Rodrigues, F. (2020). "Human losses and damage expected in future earthquakes in Faial Island - Azores". *Pure Appl. Geophys.,* 177, 1831–1844.

Madeira, J., Brum da Silveira, A., Hipólito, A., & Carmo, R. (2015). Chapter 3: Active tectonics in the central and eastern Azores islands along the Eurasia–Nubia boundary: a review. *Geological Society*, London, Memoirs, 44(1), 15–32.

Rosset, P., Tolis, S. and Wyss, M (2020). "The use of QLARM to estimate seismic risk in Kirghizstan at the regional and city scales". *Acta Geophysica.* 68, 979–991.

Trendafiloski, G., Wyss, M. and Rosset, P. (2011). "Loss estimation module in the second generation software QLARM". In: Spence R, So E., Scawthornp C. (eds), *Human Casualties in Natural Disasters: Progress in Modeling and Mitigation*, Springer: Dordrecht, Heidelberg, London, New York, 2011, 95-104.

Vogt, P. R., and Jung, W. Y. (2017). "The "Azores Geosyndrome" and Plate Tectonics: Research History, present understanding, and unsolved puzzles". In: Kueppers U., Beier C. (eds) *Volcanoes of the Azores. Active Volcanoes of the World*. Springer, Berlin, Heidelberg, 3, 27-56.

Wyss, M. (2014). "Ten years of real-time earthquake loss alerts". in *Earthquake Hazard, Risk, and Disasters*, M. Wyss (Editor), Elsevier, Waltham, Massachusetts, 143-165.

The macroseismic questionnaire "Did you feel an earthquake?" and its automatic evaluation

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ABSTRACT

The macroseismic questionnaire "Did you feel an Earthquake?" was designed based on EMS-98 scale and consists on simple questions, most with multiple choice answers. The questionnaire was implemented at the webpage of Portuguese Institute for Sea and Atmosphere (IPMA) and could be accessed by the link: https://www.ipma.pt/pt/geofisica/informe/ and by the APP sismos@IPMA. The Portuguese seismic service started to collect macroseismic data directly from Internet users that report their experiences after felt earthquakes, using a web macroseismic questionnaire, since 2006. To make a quick analysis of the reported effects at the questionnaires and convert them into degrees of seismic intensity, an algorithm and a computer application (WebMInt) were developed and implemented in 2010. The WebMInt interacts with other tools of the operational seismic center, such as, the earthquake analysis software SEISAN, the in-house program W_Emap and the software ShakeMap (V3.5). The results of the questionnaires evaluation process feed the ShakeMap in order to produce constrained maps of seismic intensity distribution, published since 2014 at IPMA ShakeMap webpage (http://shakemap.ipma.pt/). At the end of 2019, and after a revision, a major upgrade of the method was implemented. New questions were added and other were updated to have more answer options, etc. This automatic method allowed collect thousands of reports after felt earthquakes. For example, after the 2020, 5.2ML, Madeira archipelago earthquake, 1700 answers to the new questionnaire were received in 1 week from 51 different parishes in Madeira and Porto Santo islands.

Keywords: Questionnaire, Macroseismic data, Seismic intensity, Automatic evaluation

INTRODUCTION

The macroseismic questionnaire "Did you feel an Earthquake?" implemented at the IPMA's webpage is a tool to quickly get non instrumental data related to effects on people, objects, nature and buildings when an earthquake is felt in a given region. The macroseismic questionnaire was designed based on the EMS-98 scale (Grünthal, 1998) and consists of simple questions, most of them with multiple-choice answers (Alves, P.M., 2004). For nearly 13 years (2006-2019) the Portuguese seismic service used the web questionnaire to collected macroseismic information based on voluntary collaboration of Internet users that report their experiences after felt earthquakes. During this period, were received thousands of responses (~17800) to the questionnaire, after the occurrence of hundreds of earthquakes that were felt in Azores archipelago, Madeira archipelago and Portugal mainland.

The manual evaluation of a great number of responses to determine macroseismic intensities at different locations, is a time consuming task, for these reason was necessary develop an automatic process to have results rapidly. An algorithm and a computer application written in C programming language (Kernighan,

1998) were developed to analyze the reported effects and convert them into degrees of seismic intensity (Alves, P.M. et al., 2012; Marreiros, C. et al., 2018). The good performance of the developed automatic process, providing quantitative and qualitative information about seismic intensities led to a fully integration at the seismic processing routine of Portuguese seismological service. The primary objective of the macroseismic questionnaire and its automatic evaluation implementation is to provide seismic information to the civil protection authorities, after felt earthquakes with impact on the population. Secondly, feed the IPMA´s Macroseismic database with macroseismic information.

Although the good performance, the stability and the coherence with other methods (manual and ShakeMap), the process had some limitations, and some aspects had to be improved specially what concerns with hardware support, damages on buildings and indicators for intensities exceeding V. At the end of 2019, after a revision of the questionnaire and the algorithm, a major upgrade of the method was implemented (Alves, P.M. et al., 2018). The new version of the questionnaire was created using LimeSurvey , a free and open source survey tool. The software package LimeSurvey (GmbH, Hamburg, Germany. URL http://www.limesurvey.org) consists mainly of the Apache Server, MySQL database, and interpreters for scripts written in the Hypertext Preprocessor and Perl programming languages.

The major new features of the new questionnaire include: 1) A list of last earthquakes that may have been felt in Portugal region, that allows select the felt earthquake; 2) A redesigned process to indicate the geographic location of the observer when the earthquake was felt, that incorporate an interactive map with zoom, a drop-down menu with the Portugal administrative regions (region, district, county and parish) and text boxes to fill with the coordinates, allowing to choose the mode how to provide the information; 3) A redesigned interactive schema of questions following the EMS-98 scale, using branch logic, with conditions implemented related to some questions and their answers, in order to display some questions if some conditions are met; 4) More questions and details were included, such as, a new question based on the Rudolph scale, related to effects felt in offshore boats and a completely new group of questions, related to damages on buildings; 5) Multiple language implemented (English, French, Portuguese and Spanish); 6) A code was incorporated to convert the questions and answers into another form that is the same in the different languages; 7) Possibility of upload of documents and photos; and 8) Possibility to be displayed in PC or/and mobile devices (smartphones and tablets).

The questionnaire has now 5 main groups of questions related to time and date of observation, geographic location of observer, effects on people, effects on objects and nature, building damages and has the possibility to add some comments on the earthquake, in free text. The algorithm and the WebMInt program were adapted and upgraded according to the new features of the questionnaire and some other improvements were made. For example, analyses question by question the responses associated to the same location (still in test), quality control strategies implemented were refined, perform quantile 75 calculation, etc. The main steps of the algorithm are: 1) read and filter data; 2) conversion of answers to numbers; 3) analysis of answers; 4) summary by Macroseismic Data Point (MDP); and 5) writing results. The program interacts with other tools of the operational seismic center (figure 1), in particular with the earthquake analysis

software SEISAN (Havskov J., and Ottemoler L., 2005), the program W_Emap (Carrilho F., 2005) and the software ShakeMap (Wald et al., 2005).

MAIN RESULTS

The new questionnaire is available, to the public in general, since the end of 2019 and in the first 8 months of operation were collected more than 8500 responses. The event with more responses received, after the beginning of availability of the new questionnaire on IPMA's webpage, was the 2020 magnitude 5.2ML Madeira earthquake, with 92 responses received in the first hour and 1700 responses received in 1 week, from 51 different parishes in Madeira and Porto Santo islands. The first response was received ~8 min after the event. The automatic macroseismic evaluation process was applied to the responses received and the results presented are intensity degree (number) by MDP at the figure 2 (the color of the circle indicates the intensity degree and the size indicates the number of questionnaires used for calculations). The program took about 1 minute to process all responses and the results were obtained for 51 MDP's. The MDPs used are associated to the district, county and parish (DCF – Portuguese acronym for administrative regions terminology) where the responses are coming from. In addition, a quality factor by MDP is associated to each intensity degree as result of quality control applied to the responses of the questionnaire. From the total of responses, 88% are from Madeira Island, 2% are from Porto Santo Island and 10% are responses without DCF. After all the internal quality controls, 1257 questionnaires passed successfully the process. Some responses were excluded from the process and a special code indicating the reason for their exclusion is assigned, such as, repeated responses (when there are multiple responses sent by the same person only the last one is considered), responses without DCF, observations on the 6th floor or upper, unreliable intensity, with values much higher than expected, etc. The DCF´s with more responses were: São Martinho (204), Caniço (174) and Santo António (155), all in Madeira Island, and the closest was Caniço, 37 km away from the epicenter. The effects of this earthquake were felt in almost every region of Madeira Archipelago, particularly in all south coastal areas. According to various reports this earthquake was felt with maximum intensity V in the region of the Jardim da Serra (Câmara de Lobos) while in other sites of Madeira Archipelago was felt with lower intensities.

CONCLUSION

The macroseismic questionnaire is well known by the IPMA web users and allowed collect thousands of reports after felt earthquakes over the past few years. Another approach to get fast user feedback with the new questionnaire is the possibility to be displayed in mobile devices, mainly at the smartphones. The automatic evaluation method is well integrated with the other tools of the operational seismic center, analyze the available information in almost real time and is an efficient method to feed by routine the IPMA´s Macroseismic database. The use of this information in the first report to authorities, in general, can not be possible, once the first responses start to arrive few minutes after the initial report is published. Typically 2 or 3 minutes after it, is possible to have a glimpse about real impact.

The updated automatic macroseismic evaluation process was applied to the responses of the new questionnaire received after 41 earthquakes recently felt in Portugal. In addition, shakemaps were generated

with macroseismic information for 9 earthquakes felt (with ML >= 2.5) in Portugal mainland and Madeira Archipelago. The macroseismic information combined with specific attenuation laws and site corrections is used as an important constraint to shakemaps produced.

This is a process in permanent evolution with improvement of some small aspects or addition of new developments in order to get better results and more complete information.
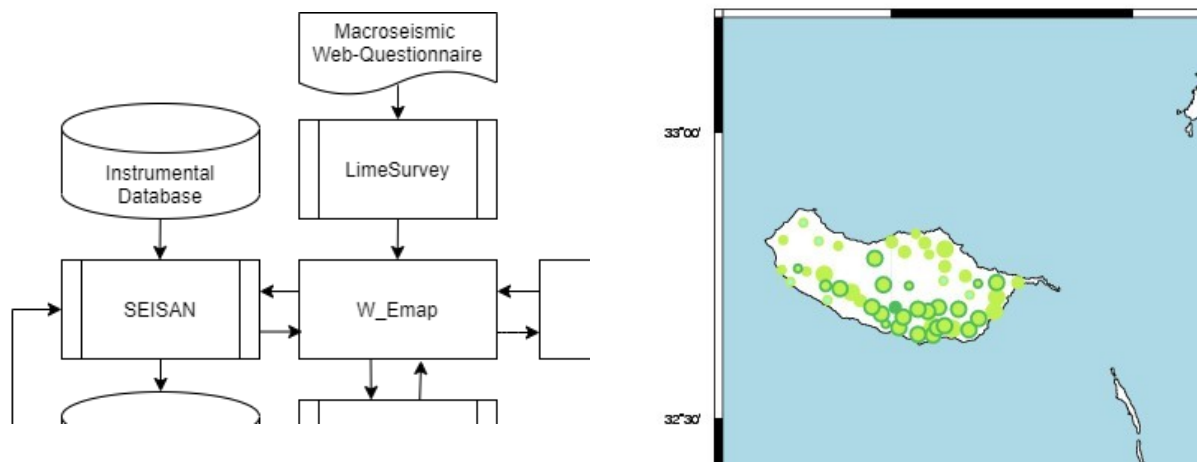
Figure 1. The program WebMInt interacts with Figure 2. Distribution of intensities associated to other tools of the operational seismic center. the 7/3/2020 5.2ML, Madeira earthquake.

REFERENCES:

Alves, P.M. (2004). Proposta de Questionário para a Escala Macrossísmica Europeia de 1998. Notas de utilização e exemplos, 6º Congresso Nacional de Sismologia e Engenharia Sísmica, Guimarães, 329-338.

Alves, P.M., Marreiros, C. and Carrilho, F. (2012). New Developments on Automatic Macroseismic Evaluation Based on Internet Questionnaires at I.M., I.P. The 15th World Conference on Earthquake Engineering (15WCEE), Lisboa, Portugal, pp. 10.

Alves, P.M., Marreiros, C., Deus, R. and Carrilho, F. (2018). Evolution of macroseismic procedures at Portuguese seismic network. Proceedings of the 36th General Assembly of the European Seismological Commission, ESC2018-S17-362, Malta.

Carrilho, F. (2005). W_EMAP Manual, version 4.5, Instituto de Meteorologia, Portugal.

Grünthal, G. (1998). European macroseismic scale 1998 (EMS-98). Cahiers Centre Europeen Geodynamique Seismologie Luxembourg 15,1–99.

Havskov, J. and Ottemoler, L. (2005). SEISAN: The Earthquake Analysis Software. Department of Earth Science, University of Bergen, pp 254.

Kernighan, B.W. and Ritchie, D. M. (1988). The C Programming Language, 2nd edition, Prentice-Hall.

Limesurvey GmbH. / LimeSurvey: An Open Source survey tool / LimeSurvey GmbH, Hamburg, Germany. URL http://www.limesurvey.org.

Marreiros, C., Alves, P.M., Deus, R. and Carrilho, F. (2018). Evaluation of 12 years of data from web macroseismic questionnarie at Portuguese seismological service. Proceedings of the 36th General Assembly of the European Seismological Commission, ESC2018-S17-363, Malta.

Wald, D.J., Worden, B.C., Quitoriano, V. and Pankow, K.L. (2005). ShakeMap Manual: Technical Manual, User's Guide, and Software Guide. USGS Techniques and Methods 12-A1, 156 pp., http://pubs.usgs.gov/tm/2005/12A01/.

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