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RISK-TARGETED MAPS FOR ALICANTE PROVINCE (SPAIN)

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Abstract. *The areas with higher seismic risks in Spain are located in the South and South-East of Spain. For instance, the recent seismic hazard analysis performed in the Alicante and Elche have obtained a PGA of 200 cm/sec² approximately in the region and indicated that the highest contribution to the seismic hazard comes from the seismicity due to the Crevillente and the Bajo Segura faults. Many studies have demonstrated that the design of structures in the region through the use of “uniform hazard” principle, does not guarantee that the collapse risk in the region is uniform as well, i.e., even in those regions with similar PGAs corresponding to the same mean return period, the seismic risk in terms of failure probability will be significantly different. A new approach called “risk targeting” has already been adopted by new generations of seismic codes and associated research, where the parameters are specified to ensure a tool for the design of buildings with a probability of collapse alike or at least harmonized throughout the area concerned. Consequently, in this study, we will focus on the evaluation of the collapse probability of the buildings and then developing the risk-targeted maps of the Alicante. Finally, the preliminary obtained results will be discussed.*

1 INTRODUCTION

Seismic assessment and structural designs are continually evolving, as evidenced by the rapid development of new procedures illustrated by the Pacific Earthquake Engineering Research Center (PEER); performance-based earthquake engineering framework [1]. Numerous studies aimed to integrate the principle of probability into seismic performance evaluation, taking into account the uncertainties related not only to seismic input but also to structural properties, capacity and model [2, 3, 4, and 5]. In order to estimate the seismic demand at a specific location, the vast majority of the Earthquake Design Codes rely on a seismically defined return period (for example, 10% in 50 years) of intensity measures. The decision to design the structure in accordance with a “uniform hazard” level is based on the idea that a process like this leads to the same annual probability of collapse as anywhere, in the buildings. Nevertheless, this fact happens only if the collapse probability of the structure will be a certain value that is infeasible in real cases. Recently, multiple studies have demonstrated that a design-based earthquake determined on a uniform hazard theory does not necessarily lead to the design of structures with a consistent risk of collapse in different areas. These inconsistencies are due to the different shape of the hazard curve for different regions and uncertainties in failure capacity of structures [6] arising from a set of factors, such as different material properties, differences in design, and among others. Hence, a structure can collapse for a different ground motion with what it was designed for. Moreover, as the shape of the hazard curve depends on the site location, even the buildings designed for the same ground motion will have different values of collapse probability.

Based on the work by [6], it would be more consistent to use “uniform risk” assumption in which the design ground motion is estimated to provide a constant level of risk. This algorithm was used to present the risk-targeted maximum considered earthquake (MCER) ground motion (ASCE7-10) [7]. Accordingly, using the proposed method, Douglas et al. [8] presented a risk-targeted seismic design map for France. In the study by [9], various parameters involved in developing risk-targeted design maps are analyzed and maps for Europe developed using SHARE seismic hazard results (www.share-eu.org). The risk-targeted map of Romania was developed by [10], using the hazard model of SHARE. [11] applied site- and structure specific fragility curves to estimate the risk-targeted design ground motion. [12] addressed some research results relating to the risk of failure in residential and industrial construction, in compliance with the Italian code. They showed that seismic structural reliability tends to decrease with increasing seismic hazard to the building site, despite the homogeneous return period of excess of seismic design ground motion. [13] presented a review of the state of the art of this technique, highlighting efforts to constrain better some of the input parameters. In addition, they discussed the problems in the practical implementation of this approach and the alternative forward paths. [14] have performed the probabilistic seismic hazard analysis and a risk-targeted map for Tehran provided based on the hazard curves achieved. [15] presented a risk-targeted seismic design map for Iran, considering the seismic hazard models from the EMME14 project [16] and STD-2800 [17]. Recently, [18] performed a review and comparison among the existing approaches with regard to the implementation of uniform-risk concepts in the performance-based design of structures. Among these, one based on the use of risk-targeted behavior factors (RTBFs) has been recently considered for the development of future versions of Eurocode 8 [19]. [20] demonstrated the effects of the RTBF approach being applied to the concept of risk-targeted maps for Italy.

In this study, using the updated seismic hazard in the regions of Alicante and Elche [21] and employment of generic fragility curves, the distribution of the risk-targeted ground motion has

been estimated for these areas. This study aims at evaluating the relevant peak ground accelerations for a given target annual collapse probability and different collapse probability for a given peak ground acceleration which corresponds to a specific mean return period of seismic action.

2 SEISMIC HAZARD MODEL

The seismic hazard map of Spain was recently updated after the events occurred in the Murcia region, such as the 1999 earthquake in Mula ($M_w=4.7$), 2002 in Bullas ($M_w=5.0$), 2005 in La Paca ($M_w=4.8$) or the destructive Lorca earthquake occurred in 2011 ($M_w=5.2$) with catastrophic consequences in Lorca town despite being a relatively small event. None of those events were included in the seismic hazard map published under the framework of the current Spanish seismic code NCSE-02. For example, the PGA at rock for a 0.1 probability of exceedance in 50 years was 0.14 g and 0.15 g for Alicante and Elche respectively (according to NCSE-02) and it has been increased to 0.18 g and 0.20 g with the updated of the seismic hazard map [21].

In this work, we have carried out a specific analysis of the seismic hazard map in both municipalities using the Spanish seismic catalog updated until 2018. The computation was done using the seismic zones proposed by IGN-UPM Working Group and updating the activity rate and beta values of the zone within the influence area of both cities (150 km). The software R-CRISIS [22, 23] was used to compute the seismic hazard map in terms of PGA for a probability of exceedance in 50 years (Figure 1).

As we can see, the seismic hazard results have slightly increased regarding previous studies.

Figure 1: Seismic hazard map (PGA at rock) for the municipalities of Elche and Alicante for 0.1 exceedance probability in 50 years.

Therefore, we have chosen two sites (one in each municipality) as representatives of the PSHA values in the urban areas. Figure 2 represents the seismic hazard curves of PGA in terms of annual probability of exceedance and probability of exceedance in 50 years which will be used for the calculation of the risk-targeted hazard.

Figure 2: Seismic hazard curves for Alicante and Elche.

3 CALCULATION OF RISK-TARGETED MAP

In order to perform a risk-targeted analysis, it is necessary to develop the fragility curve corresponds to the structures under study. Considering that in this approach, the fragility curves should cover the vulnerability of a large range of different building typologies and on the other hand, developing these curves are too expensive for a specific building class and location, the generic collapse fragility curves will be used for all building classes in the desired area. It should be noted that the provided curve must be sufficiently generic to capture all possible vulnerabilities [8]. The fragility function is conditional upon the values of ground motion design and outlines the conditional probability of exceeding a limit state, which hereinafter is the collapse of a structure, for a given design ground motion with a specific mean return period (RP). In this study, the 475-year mean return period was implemented (i.e., 10% probability of exceedance in 50 years), since it is the most widely accepted value in Europe. The fragility functions are presented as lognormal distributions with two parameters: the median value of PGA and the logarithmic standard deviation of PGA (β). Hence, one can say, in order to develop a generic fragility curve for risk-targeted analysis, it is necessary to define the parameters of $P_c|gm$, and β . The latter ($P_c|gm$) is the conditional probability of collapse under the design ground motion with 475-year return period and the former (β) is taking into consideration several sources of uncertainty in the collapse capacity, such as the record-to-record variability, the uncertainty in the collapse definition, and, ideally other sources such as human error, that even the most advanced numerical models cannot accommodate [9].

Regarding with logarithmic standard deviation of the fragility functions, there are significant different values proposed by other researches. As an example, Luco et al. [6], used a β value of 0.8, while Douglas et al. [8] suggested value of 0.5. the β value of 0.6 was considered in the study by [9], while Vanzi et al. [24] used a value of 0.2. It is important to note that, using the higher values of β more than 0.8, provides a low probability of collapse even in highly seismic regions, which seems an unrealistic scenario. On the other hand, assuming low values of β (e.g.,

less than 0.2), leads to more steep collapse fragility curves that could provide 100% probability of collapse even at low ground motion levels. The estimation of $P_c|gm$, needs the design and evaluation of a large number of structures and a wide range of hazard levels. As stated earlier in this study, the probability of collapse corresponds to the peak ground acceleration of the hazard curve with a mean return period of 475 years. Several studies suggest different values of $P_c|gm$. For instance, Douglas et al. [8] suggested a $P_c|gm$ value of 10^{-5} , while Silva et al. [9] used a value of 10^{-3} . Ulrich et al. [25] proposed a value of 10^{-7} for low, frequent design ground motion levels and 10^{-5} for higher and rarer design ground motion in their study. However, Silva et al. [9], believe this range of probability of collapse (i.e., 10^{-7} to 10^{-5}) is too extremely low for ordinary structures. Luco et al. [6], have selected 10% probability of collapse under MCE, which corresponds to the probability of collapse at 475-year ground motion ranging from 10^{-2} to 10^{-3} [9]. Fajfar and Dolšek [26] have computed the value of $P_c|gm$ in the range of 10^{-4} to 10^{-5} and Vanzi et al. [24] used the value of 1.3×10^{-6} for the probability of collapse under gravity loads.

According to the PBEE method and using the seismic hazard curve and collapse fragility function the annual collapse rate of a structure, λ_c is determined using the following classic convolution products given by [27]:

$$\lambda_c = - \int_0^{+\infty} F(s) \cdot \frac{dG(s)}{ds} ds \quad (1)$$

Where $F(s)$ is the fragility function (conditional probability of collapse for a given ground motion) and $G(s)$ is the hazard curve. The integration in equation (1) does not have a closed-form solution [28], therefore an iterative process is required for calculation of annual collapse rate. As suggested by [9, 28] the annual failure probability will be computed by dividing both the fragility curve and the seismic hazard curve into a large number of segments and then numerically integration the distribution. Based on the Poisson assumption, the annual collapse rate is converted into the annual probability of collapse. It should be noted that since we are targeting the very low values, there is a negligible difference between the values of the annual probability of collapse P_c and the annual collapse rate (i.e., mean annual frequency of collapse, MAF). Since, the main objective of the risk-targeted analysis is the estimation of ground motion consistent with the target risk (i.e., accepted annual P_c), it is necessary to define an acceptable level of seismic risk, which can be expressed as annual collapse probability. Hence, in the iterative process, the value of design ground motion changes in each step until reaching the desired value of annual collapse probability. The obtained design ground motion at the final step will be the risk-targeted ground motion. Based on the study by [6], for each seismic site, the risk coefficient is calculated by dividing the obtained former value and the uniform hazard ground motion. Finally, the values of risk-targeted design ground motion are created by multiplying this coefficient to the current seismic design ground motion maps. Regarding with acceptable annual probability of collapse, there are different suggestions from other researches and seismic codes. For example, ASCE 2010 [7], proposed value of 2.0×10^{-4} for the United States. Douglas et al. [8], suggested using the value of 1.0×10^{-5} as a reasonable value. In the work by Silva et al. [9], the value of 5.0×10^{-5} established as an acceptable annual probability of collapse.

In order to investigate the effect of these parameters on the annual probability of collapse, a simple sensitivity analysis has been performed. In this analysis, different combinations of values for β and $P_c|gm$ are considered (i.e., $\beta = 0.5, 0.6, 0.7$, and, 0.8 and $P_c|gm = 10^{-2} \dots 10^{-5}$). Then values of P_c (annual probability of collapse) will be calculated by developing the generic fragility curves and the computational approach described above. Figure 3a and 3b show the

relation of the annual probability of collapse with the parameters of $P_c|g_m$, and β for Alicante and Elche, respectively.

Figure 3: Relation of annual probability of collapse with $P_c|g_m$, and β

As shown in Figure 3, for both sites, the annual probability of collapse converges to a certain value when the conditional probability of collapse for a given design ground motion with a 475-year return period rises up to 10^{-2} . According to the analysis, in this study, we considered the values of 0.7, 10^{-2} , and 10^{-4} for β , $P_c|g_m$, and P_c , respectively. Moreover, in the following sections for risk targeting analysis, the values proposed by other researches such as [6, 9] will be considered for a better comparison of the obtained results.

4 RESULTS FOR ALICANTE AND ELCHE

In this section, the risk-targeted maps for Alicante and Elche are built with the combination of target annual collapse probabilities and standard deviations suggested by [6, 9] as well as the ones assumed in this study. In order to evaluate the effect of two main input parameters, namely the standard deviation β and the probability of collapse for a given design ground motion with a 475-year mean return period (defining the fragility function) a series of maps were generated.

The first two tables (i.e., Table 1 and Table 2) show the annual probability of collapse for Alicante and Elche, respectively. These values are corresponding to the PGA with a mean return period of 475 years. The standard deviation is considered as 0.6, 0.7, and 0.8 while the $P_c|g_m$ was taken as 0.1 and 0.001.

	$\beta = 0.6$	$\beta = 0.7$	$\beta = 0.8$
$P_c g_m = 0.1$	8.090×10^{-4}	8.054×10^{-4}	8.264×10^{-4}
$P_c g_m = 0.001$	4.421×10^{-5}	2.990×10^{-5}	2.207×10^{-5}

Table 1: Annual probability of collapse for the PGA corresponding to a mean return period of 475 years in Alicante

	$\beta = 0.6$	$\beta = 0.7$	$\beta = 0.8$
$P_c g_m = 0.1$	8.081×10^{-4}	8.077×10^{-4}	8.319×10^{-4}
$P_c g_m = 0.001$	4.089×10^{-5}	2.788×10^{-5}	2.071×10^{-5}

Table 2: Annual probability of collapse for the PGA corresponding to a mean return period of 475 years in Elche

Table 1 and Table 2 show the distinctive values of the annual probability of collapse. In the case of the $P_{c|gm} = 0.001$, Alicante has the highest probability of collapse, whereas in the case of $P_{c|gm} = 0.1$, the largest collapse probability is observed in Elche. Based on the seismic hazard map of the Alicante and Elche (Figure 1), it should be concluded that Elche has the highest collapse probability, but as it was observed above, using different values of $P_{c|gm}$ in this approach, may lead to opposite results. A similar observation has been reported in the works by [9, 10] in which reveals some questions about this approach.

The four maps shown in Figure 4, represent the risk-targeted ground motions for the municipality of Elche corresponding to the annual collapse probability of 2×10^{-4} . The PGAs were calculated for $\beta = 0.6$ and 0.8 and using $P_{c|gm} = 0.1$ and 0.001 .

Figure 4: Risk-targeted ground motion maps for Elche

A comparison between Figure 4a and Figure 4b, indicates the larger values of β , results in the lower risk-targeted ground motion (almost 20% reduction). On the contrary, Figure 4c and Figure 4d show an increase of 7% by increasing the value of β . The risk-targeted ground motions in the Figure 4a and Figure 4c, show that for a given value of acceptable collapse probability and standard deviation, the ground motion level leads to larger values by increasing the

value of $P_c|gm$. A comparison between Figure 4b and Figure 4d displays the same trend as mentioned before.

Finally, assuming $\beta = 0.7$ and $P_c|gm = 10^{-2}$ and target annual collapse probability of 10^{-4} , the risk-targeted ground motion maps for municipalities of Alicante and Elche are shown in Figure 5.

Figure 5: Uniform ground motion maps for Alicante (a and b) and Elche (c and d)

According to Figure 5a and Figure 5b, the risk-targeted ground motion in the municipality of Alicante varies between 0.05g and 0.153g with an average value of 0.098g indicating an almost 11% increase in the ground motion level. Figure 5c and Figure 5d show that the risk-targeted acceleration in the municipality of Elche changes from 0.106g to 0.246g with the average value of 0.162g representing 10% increase approximately. Clearly, the results of risk-targeted maps would be considerably different by variation of $P_c|gm$ threshold in which considered in this study.

5 CONCLUSIONS

In this study, risk-targeted maps are developed for municipalities of Alicante and Elche based on the updated seismic hazard map of Spain [21]. The annual probability of collapse was calculated by using the convolution product between seismic hazard and fragility function. The relevant parameters suggested by [6, 9] and the results of the sensitivity analysis were also used to establish the generic fragility curves. Furthermore, by considering an acceptable collapse probability and the approach explained earlier in previous sections, the risk-targeted ground motion maps revealed. The results highlight the preliminary conclusions as follow:

- The influence of standard deviation on the annual probability of collapse is relevant, but no clear trends are observed.
- The influence of $P_c|g_m$ on annual collapse probability is significant.
- Given that these parameters (i.e., acceptable collapse probability, standard deviation, and distribution of collapse) can allocate different values proposed in the past works, different risk-targeted maps will be obtained for the considered regions in this study.
- Based on the assumed parameters and obtained results, it can be shown with some minor changes to the uniform hazard maps (up to 10%), the uniform risk of collapse will be achieved in the municipalities of Alicante and Elche.

Based on the obtained results, it is clear that risk-targeted seismic maps need to be created for the other municipalities and in the more extended work for Spain.

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REFERENCES

- [1] Porter KA (2003) An overview of PEER's performance-based earthquake engineering methodology. In: Proceedings of ninth international conference on applications of statistics and probability in civil engineering.
- [2] Dolšek M (2009) Incremental dynamic analysis with consideration of modeling uncertainties. *Earthq Eng Struct Dyn* 38(6):805–825.
- [3] Liel AB, Haselton CB, Deierlein GG, Baker JW (2009) Incorporating modeling uncertainties in the assessment of seismic collapse risk of buildings. *Struct Saf* 31(2):197–211. <https://doi.org/10.1016/j.strusafe.2008.06.002>
- [4] Tubaldi E, Barbato M, Dall'Asta A (2011) Influence of model parameter uncertainty on seismic transverse response and vulnerability of steel–concrete composite bridges with dual load path. *J Struct Eng* 138(3):363–374.
- [5] Fib (2012) Probabilistic performance-based seismic design, bulletin 68, International federation of structural concrete, Lausanne, CH.

- [6] Luco N, Ellingwood B, Hamburger RO, Hopper JD, Kimball JK, Kircher CA (2007) Risk targeted versus current seismic design maps for the conterminous United States. In: Proceedings of the 2007 Structural Engineers Association of California (SEAOC) Convention, Lake Tahoe, CA.
- [7] American Society of Civil Engineers (ASCE), 2010. Minimum Design Loads for Buildings and Other Structures (ASCE 7-10), Reston, VA.
- [8] Douglas J, Ulrich T, Negulescu C (2013) Risk-targeted seismic design maps for mainland France. *Nat Hazards* 65(3):1999–2013. <https://doi.org/10.1007/s11069-012-0460-6>
- [9] Silva V, Crowley H, Bazzurro P (2016) Exploring risk-targeted hazard maps for Europe. *Earthquake Spectra* 32(2):1165–1186. <https://doi.org/10.1193/112514EQS> 198M
- [10] Vacareanu R, Pavel F, Craciun I, Coliba V, Arion C, Aldea A, Neagu C (2018) Risk-targeted maps for Romania. *J Seismol* 22:407–417. <https://doi.org/10.1007/s10950-017-9713-x>
- [11] Spillatura A (2018) “From record selection to risk targeted spectra for risk-based assessment and design,” Ph.D. Thesis, Dipartimento di Costruzione Infrastrutture, Istituto Universitario degli Studi Superiori (IUSS), Pavia, Italy
- [12] Iervolino I, Spillatura A, Bazzurro P (2018) Seismic reliability of code conforming Italian buildings. *J Earthq Eng* 22:5–27. <https://doi.org/10.1080/13632469.2018.1540372>
- [13] Douglas J., Gkimprixis A. (2018) Risk Targeting in Seismic Design Codes: The State of the Art, Outstanding Issues and Possible Paths Forward. In: Vacareanu R., Ionescu C. (eds) *Seismic Hazard and Risk Assessment*. Springer Natural Hazards. Springer, Cham. https://doi.org/10.1007/978-3-319-74724-8_14
- [14] Zaman M, Ghayamghamian MR (2019) *Bull Earthq Eng*. <https://doi.org/10.1007/s10518-019-00625-0>
- [15] Taherian, A.R., Kalantari, A. Risk-targeted seismic design maps for Iran. *J Seismol* 23, 1299–1311 (2019). <https://doi.org/10.1007/s10950-019-09867-6>
- [16] Danciu L et al (2017) The 2014 earthquake model of the Middle East: seismogenic sources. *Bull Earthq Eng*:1–32
- [17] BHRC (2014) Iranian code of practice for seismic resistant design of buildings, Standard 2800, 4th edn. Building and Housing Research Center, Tehran
- [18] Gkimprixis A, Tubaldi E, Douglas J (2019) Comparison of methods to develop risk targeted seismic design maps. *Bull Earthq Eng* 17:3727–3752. <https://doi.org/10.1007/s10518-019-00629-w>
- [19] EN 1998-1 cEN, Eurocode 8 – Design for Structures for Earthquake Resistance, Part 1: General Rules, Seismic Actions and Rules for Buildings, European committee for Standardization (cEN), Brussels, Belgium, December 2004.
- [20] Douglas, J., Gkimprixis, A., & Tubaldi, E. (2019). Derivation of risk-targeted maps for Italy based on a simplified approach. Derivation of risk-targeted maps for Italy based on a simplified approach, XVIII Convegno ANIDIS L'ingegneria Sismica in Italia : Ascoli Piceno, 15-19 settembre 2019 2-9.

- [21] IGN-UPM Working group (2017). Actualización de Mapas de Peligrosidad Sísmica de España 2012. Instituto Geográfico Nacional, Universidad Politécnica de Madrid. Centro Nacional de Información Geográfica, 267 pp. (in Spanish).
- [22] Ordaz, M., Martinelli, F., D'Amico, V., & Meletti, C. (2013). CRISIS2008: A flexible tool to perform probabilistic seismic hazard assessment. *Seismological Research Letters*, Vol. 84, No. 3, pp. 495-504, DOI: 10.1785/0220120067.
- [23] Ordaz, M., Martinelli, F., Aguilar, A., Arboleda, J., Meletti, C., & D'Amico, V. (2017). R-CRISIS. Program and platform for computing seismic hazard. <http://www.r-crisis.com/>
- [24] Vanzi I, Marano GC, Monti G, Nuti C (2015) A synthetic formulation for the Italian seismic hazard and code implications for the seismic risk. *Soil Dyn Earthq Eng* 77:111–122
- [25] Ulrich, T., Negulescu, C., and Douglas, J., 2014. Fragility curves for risk-targeted seismic design maps, *Bulletin of Earthquake Engineering* 12, 1479–1491
- [26] Fajfar, P., and Dolšek, M., 2012. A practice-oriented estimation of the failure probability of building structures, *Earthq Eng Struct Dynam* 41, 531–547
- [27] Kennedy RP (2011) Performance-goal based (risk informed) approach for establishing the SSE site specific response spectrum for future nuclear power plants. *Nucl Eng Des* 241(3):648–656. <https://doi.org/10.1016/j.nucengdes.2010.08.001>
- [28] Eads L, Miranda E, Krawinkler H, Lignos DG (2013) An efficient method for estimating the collapse risk of structures in seismic regions. *Earthq Eng Struct Dyn* 42:25–41. <https://doi.org/10.1002/eqe.2191>