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Preliminary study on the impact of time-dependent seismic hazard on design capacity

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ABSTRACT
Recent works on seismic hazard have introduced the concept of time-dependent seismic hazard and different models have been proposed to predict the inter-arrival time between consecutive events. Currently, the reliability assessment of structures and relevant design rules proposed by the codes are based on the Poisson recursive model, for which the frequency of the occurrence of seismic events does not change in time. This paper presents some preliminary results on the impact of TDSH on structural design, by evaluating the strength required by the structure (seismic capacity) for different time intervals elapsed from the last event. "Seismic capacity" is understood here as the capacity required to provide a fixed reliability level, measured by the failure rate.

1 INTRODUCTION

Risk assessment basis on a prediction of possible hazardous events, in terms of recurrence in time, and is oriented to the estimation of potential consequences, considering potential sources of uncertainty. In this paper, attention is focused on the probability of construction failure (consequence) due to a strong earthquake (event).

Generally this type of risk analysis is developed within the context of the PEER framework (Porter 2003, FIB 2012) where the seismic hazard assessment is based on a constant rate of occurrence in time, described by the Poisson recursive model, and involves potential sources with different locations and different intensities.

However, it is observed that small and medium magnitude events generally show different occurrence properties with respect to large magnitude events. The former generally occur as independent events, for which the recursive Poisson model is adequate, while the occurrence of the latter events is notably influenced by the previous history of the source activity. In this case, the earthquake sequence tends to show a periodic trend and the fault activity provides earthquakes with similar magnitudes, also denoted as characteristic earthquakes (Schwarz et al. 1984, Wesnousky et al. 1994, Kramer 1996; Tondi and Cello, 2003).

From a theoretical point of view, approaches considering the recursive properties of strong events and models providing a time dependent prediction of the interarrival time passing between two events dates back to the 80s. An overview of different models and a proposal for their classification is presented in (Anagnos and Kiremidijan 1988). Only more recently have time-dependent models found practical applications thanks to the improvements in fault mechanism knowledge in some earthquake prone areas. Some studies, mainly limited to an assessment of the seismic hazard, have been proposed (Petersen et al. 2007, Akinci et al. 2009, Chan 2013, Jalalalhosseini 2017, Mousavi 2018).

From a structural engineering perspective, it is of interest to evaluate the potential impacts of time dependent models describing the external actions, on the structural dimensioning and, more generally, on the design process.

Regarding this, it is useful to recall that the final objective of structural engineering consists of bounding the probability of failure of constructions during their lifetime and some target values are proposed in codes of practice, such as Eurocode 0 or ASCE 7 (Fajfar 2018, CEN 2006, ASCE 2017). This objective is generally obtained by simplified procedures that permit a full probabilistic analysis to be avoided and many recent works have been oriented to improving these methods in order to control the effective probability of failures (Fiorini et al. 2014, Franchin et al. 2018, Gkimprixis et al. 2019).

This study presents some preliminary results on the impacts of a time dependent prediction of strong events on the structural capacity required to ensure a target failure rate is not exceeded. The required capacity varies as the time elapsed from the last event varies and the final result is influenced by either uncertainties due to the propagation of the seismic wave or the response of the structural system. A simple case, considering an earthquake point-source, is studied and results obtained by using the time dependent Brownian Passage Model (Mattheus et al. 2002) are compared with results obtained with the time independent Poisson model. The influence of site-to-source distance as well as structural response dispersion are analyzed. It is noteworthy that a more realistic failure prediction generally involves more than one source of strong event and includes widespread sources with no recursive properties. These last two issues should mitigate the overall influence of recursive models on the variation in time of capacity required to ensure the target failure rate is not exceeded. Therefore, presented results should be considered as the upper bound of the potential impact of time dependent models on structural design.

2 METHODOLOGY

The earthquake is here considered as an event E whose occurrence in time is described by $f_T(t)$ providing the probability density function of the time elapsed from the last event (inter-arrival time). The origin $t=0$ of the time axis is placed at the instant of occurrence of the last event. Different models have been proposed to describe the probabilistic distribution of inter-arrival time in literature and a review can be found in (Anagnos and Kiremidjan, 1988). These models are generally based on the mean value of the inter-arrival time T_R and on one or more parameters describing the expected dispersion of the inter-arrival time.

Starting from $f_T(t)$ and the relevant cumulative density function $F_T(t)$, it is possible to evaluate the hazard rate function $h_T(t)$ using the following expression:

$$h_T(t) = \frac{f_T(t)}{1-F_T(t)} \tag{1}$$

This function provides the instantaneous probability of occurrence at the time *t*, given that no event had occurred previously, and describes the hazard variation in time.

The probability of occurrence of one event within a time interval Δt (e.g. construction lifetime) starting at t , given that the event had not occurred before, can be obtained by integrating the ratio $f_T(t+\tau)/(1-F_T(t))$. In the case of time intervals notably shorter than T_R, the likelihood connected to multiple events can be neglected and the occurrence of only one event can be considered as representative of the total probability of failure (Takahashi et al. 2004)..

The system reliability can be measured by the failure rate $p_f(t) \cong h_T(t) P_f$, expressing the instantaneous probability of failure at time t. It is obtained by combining the hazard rate function with the probability of failure P_f conditional to the event occurrence .

Structural reliability requires that the failure rate be lower than a threshold p_f^* suggested by the codes and this paper focuses on the evaluation of the structural seismic capacity necessary to strictly satisfy the safety requirement $p_f(t) \le p_f^*$ for different values of time elapsed from the last event.

The failure rate of the structural system, given the event occurred, depends on the system properties that can be collected in a vector $\vartheta \in \Theta$ of parameters describing dynamic properties and capacity limits, so it is possible to associate to each instant *t* the relevant set of system properties $\vartheta^* \in \Theta^* \subset \Theta$ necessary to strictly satisfy the condition $p_f^* = p_f(t) \cong h(t) P_f(\vartheta^*)$.

As a final result, the relationship $t \leftrightarrow \vartheta^*$ between the time elapsed from the last event and the minimum capacity required to achieve a fixed safety level is presented and discussed in the numerical application.

It should be noted that the recurrence models $f_T(t)$ proposed in literature are generally continuous and start from a probability density equal to 0 at the initial instant (in many models the function slope is also 0 at the initial instant), so previous equality can be evaluated only for $t > \bar{t}$ with $\bar{t} : h(\bar{t}) = p_f^*$, i.e. when the instantaneous probability of occurrence of the event becomes larger than the acceptable failure rate, otherwise inequality also holds for $P_f = 1$. This is not a marginal point because $P_f = 1$ means that no seismic capacity is required for an elapsed time shorter than $\bar{t}$ and models proposed in the literature sometimes provide quite large values for time $\bar{t}$.

In this paper some preliminary results are presented concerning the case of strong recursive seismic events with magnitudes M varying close to a reference value (characteristic earthquake), coming from a seismic point-source, placed at a distance r from the site of interest. It is assumed that the random values of M are described by a known probability density function $f_M(m)$ defined on the magnitude interval Ω_M. In this study it is assumed that the earthquake properties do not depend on the inter-arrival time and renewal models are consequently considered for $f_T(t)$.

The seismic intensity at the site is a random variable denoted by I and its probability density function $f_I(i)$ can be determined on the basis of Ground Motion Prediction Equations (GMPE), providing the conditional probability density function $f_I(i|M,R)$. Generally, GMPEs are in the form $\ln(I) = g(M,R) + \varepsilon_g(0,\sigma_g)$, where ε_g is a Gaussian random variable with 0-mean (Pinto et al, 2004). In the case considered the distance $r = \bar{r}$ is fixed and random properties of the seismic intensity are obtained using Equation (2).

$$f_I(i) = \int_{\Omega_M} f_I(i|m,\bar{r})\, f_M(m)\, dm \tag{2}$$

The response properties of the structural system are described by using the parameters providing the fragility curve, in order to obtain results potentially of interest for different structural typologies. The fragility curve, $F_C(i,\vartheta) = P[\,failure|i,\vartheta\,]$, is described by using a log-normal cumulative density function (Kennedy and Short, 1994, Cornell et al. 2002), whose characteristic parameters are $\hat{c}$ and β, $\vartheta = [\hat{c},\beta]$, the former is the intensity measure producing 50% of failure and the latter is the logarithmic standard deviation describing the dispersion of results.

So, the conditional probability of failure can be obtained by the convolution integral given in Equation (3):

$$P_f(\vartheta) = \int_{R^+} F_C(i,\vartheta)\, f_I(i)\, di \tag{3}$$

3 CASE STUDY

Results presented in the following concern the case of a point-source located at variable distances from the site of interest. The characteristic earthquake refers to the Paganica fault located in central Italy and relevant properties have been chosen according to (Pace et al 2006, Polidoro et al 2013). The return period is $750yr$ and it is assumed that magnitude M follows a truncated Gaussian distribution centred at $m = 6.3$ and spanning the range $[5.8, 6.8]$ with a standard deviation 0.1667.

Presented results compare outcomes deriving from a Poisson recursive model, providing a constant hazard rate, with results coming from a time dependent recursive model. The Poisson model is defined by Equation (4).

$$f_T(t) = \frac{1}{T_R} e^{-t/T_R} \tag{4}$$

Only one parameter is necessary and it coincides with $T_R = 750y$. In this case, the hazard rate defined in Equation (5) does not change in time and it is $h_T(t) = h_0 = 0.00133$.

The distribution of the inter-arrival time of the time dependent hazard is described by the Brownian Passage Time model (Mattheus, 2002), based on rebound theory (Reid 1910) and often used in the description of characteristic earthquake recurrence (e.g. WG of California Earthquake Probabilities 1999, Takahashi et a 2004, Polidoro et al 2013). Its expression is as follows:

$$f_T(t) = \sqrt{\frac{T_R}{2\pi\alpha^2 t^3}} \cdot e^{\frac{(t-T_R)^2}{2T_R\alpha^2 t}} \quad (5)$$

This is a renewal model depending on two parameters, the mean inter-arrival time $T_R = 750yr$ and the parameter α ruling the aperiodicity, intended as the possible deviation from the reference return period T_R. In this case study, the value $\alpha = 0.43$ is assumed, according to the study on seismic scenario considered (Pace, 2006). In this case the hazard rate varies in time and it can be evaluated from Equation (5). Trends of interarrival time probability density functions and hazard rates of the two models are reported in Figure 1. It can be observed that the time-dependent model provides the same hazard rate as the Poisson model at the time $t_0 = 416yr$.

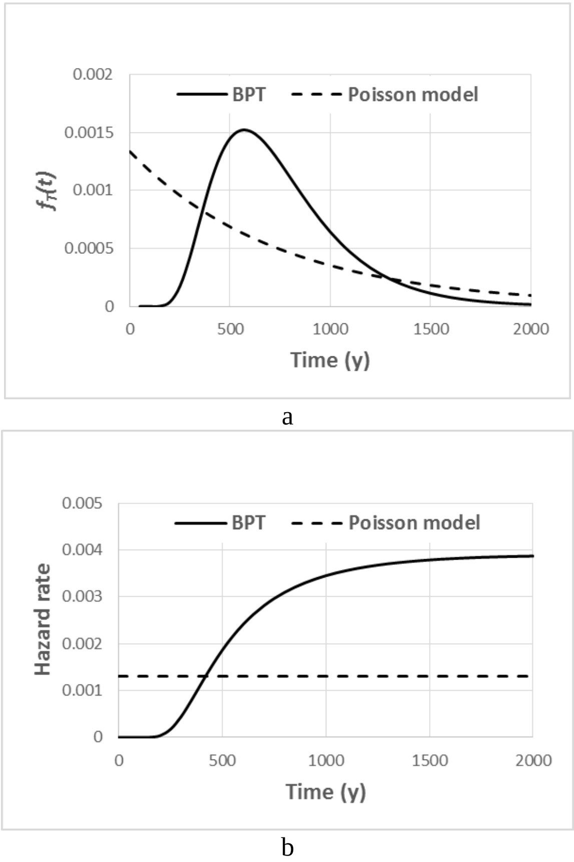

Figure 1 (a) Probability density functions of interarrival time and (b) hazard rates for the Poisson model and the Brownian Passage Time model.

The seismic intensity is measured by the peak ground acceleration (PGA), obtained by the GMPE proposed in Equation (6) (Sabetta and Pugliese, 1996). The logarithm of the seismic intensity I produced by an event with intensity m, at a distance r, can be evaluated by the Equation (6):

$$\log_{10}(I) = a + bm - c\log_{10}\sqrt{r^2+h^2} + \\ +e_1S_1 + e_2S_2 + \varepsilon \quad (6)$$

where ε is a 0-mean Gaussian random variable. In this study the following values are assumed for the parameters: $a = -1.562$, $a = -1.562$, $b = 0.306$, $c = 1$, $S_1 = 1$, $e_1 = 0.169$, $S_2 = 0$,and $h = 5.8$. The standard deviation of ε is equal to 0.173.

4 RESULTS AND DISCUSSIONS

In this section the seismic capacity required to ensure a target failure rate equal to p_f^* is evaluated for different time intervals t elapsing from the last event.

The seismic capacity is described by the parameter $\hat{c}$, introduced in section 2,

The target value of the failure rate is assumed equal to $6.667 \cdot 10^{-5}$. It is obtained by combining the conditional probability of failure $P_f = 0.05$ with the reference value of the hazard rate $h_0 = 0.00133$ provided by the Poisson recursive model for the seismic scenario considered.

The following results report numerical values referring to 3 special times [331yr, 416yr, 663yr]. The intermediate value is equal to the time t_0 introduced in the previous section and corresponds to that instant in which the hazard rates provided by the time-independent Poisson model and the time-dependent BPT model are the same. The time-dependent hazard rate is half of h_0 at the first time value, i.e. $h_T(331yr) = 0.5h_0$, and it is two times h_0 at the third time value, i.e. $h_T(663yr) = 2.0h_0$.

Finally, the variation of required capacity for t larger than the limit value $\bar{t}$, such that $h_T(\bar{t}) = p_f^*$, is graphically reported.

Two parametric analyses are separately developed in order to study results for source-to-site distances r varying from 5km to 20km, and capacity dispersion β varying from 0.5 to 0.8 (FEMA P-750, ASCE 7-16). In the former analysis the site-to-source distance varies and capacity dispersions are fixed, in the latter the parameter β varies and results are evaluated at a fixed distance.

4.1 The impact of site-to-source distance on the required capacity

The effect of the distance on the required capacity is evaluated by changing site-to-source distance, *r*, from 5 km to 20 km in steps of 5 km (5, 10, 15 and 20 km) whilst parameter β remained the same.

Figure 2 permits a comparison between seismic demand and required capacity, given event occurred. The continuous line reports the complementary cumulative density function $G_I(i)$ of seismic intensity I , describing the probability of exceedance of I . The dashed line reports the probability of failure for systems with different capacities, expressed by the seismic intensity $\hat{c}$. As expected, the two curves intersect approximately when the median value of the expected seismic demand coincides with the capacity parameter $\hat{c}$, while probability of failure is larger than the probability of intensity exceedance for rare events as a consequence of the capacity dispersion.

Figure 2 also permits a comparison of results concerning different site-to-source distances. It is evident that the capacity corresponding to the target conditional probability of failure $P_f^* = 0.05$ decreases by increasing the site-to-source distance. More precisely, the capacity necessary for P_f^* is $\hat{c} = 1.46g$ for the smallest considered distance equal to 5km, and it decreases by 33%, 52%, and 62% passing from 5km to the larger values 10km, 15km, and 20km, respectively.

In the following, the influence of the time passed from the last event is considered.

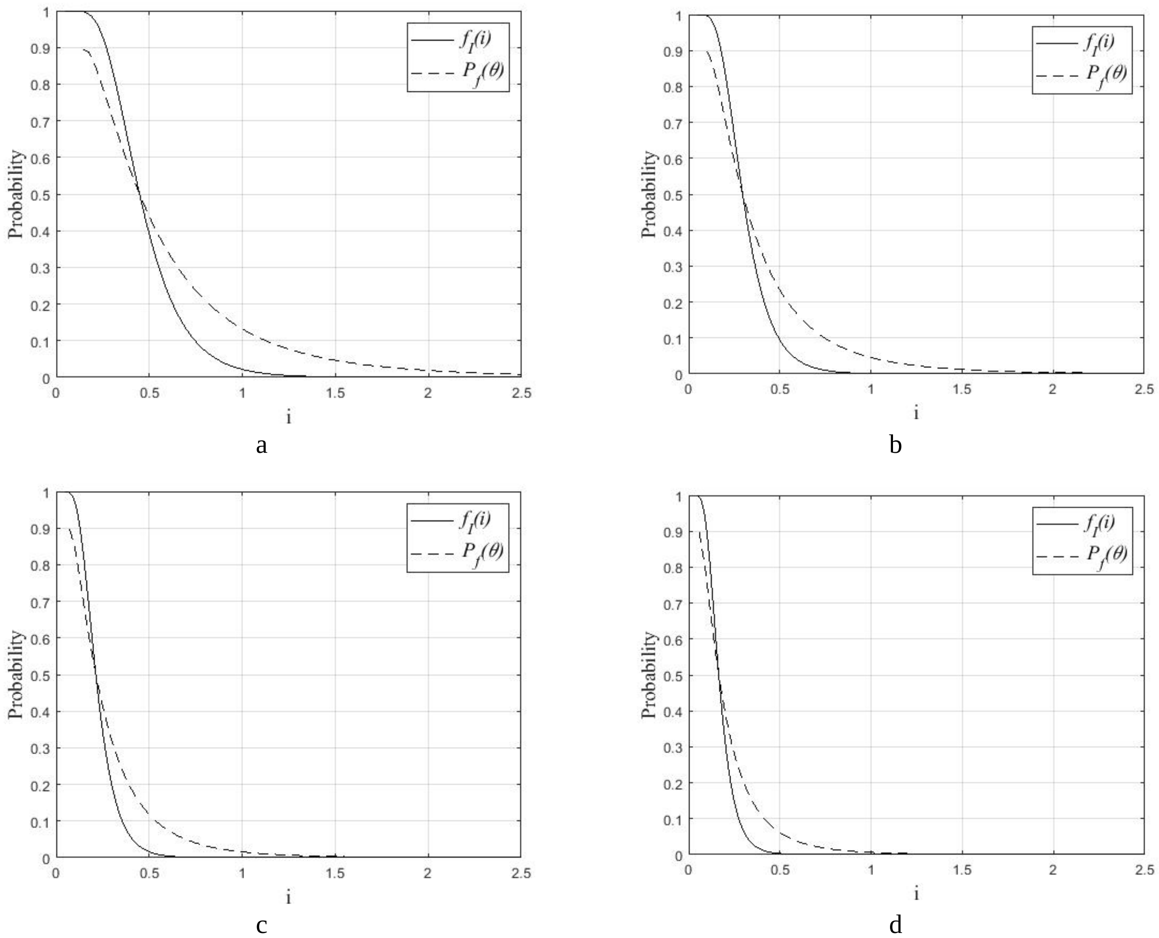

Figure 2. $G_I(i)$ and $P_f(\hat{c})$ curves 416 years after the last events for β=0.6 and a) *r*=5 km, b) *r*=10 km, c) *r*=15 km and d) *r*=20 km.

Table 1 provides the data related to the required capacity for the three special instants discussed previously, i.e. 331*yr*, 416*yr*, and 633*yr*, and compares results obtained for the 4 different site-to-source distances. As mentioned in section 4, the reference time is 416yr, in this case the hazard rates provided by the Poisson model and BPT model are the same. According to the data reported in Table 1, by elapsing time from the last event, required capacity, $\hat{c}$, increases. However, the variation of the required capacity is notably smaller than the variation of event occurrence. In this regard, it is useful to recall that the hazard rate at 331*yr* is equal to $0.50h_0$, where h_0 is the reference hazard rate evaluated at 416*yr*, and the capacity reduction is approximately 0.22-0.23 for all the distances considered. On the other hand, the hazard rate at 633*yr* is equal to $2.00h_0$ but the required increment in the capacity parameter is limited to the range 0.24-0.26. So a strong variation in time of the hazard rate does not translate into a similarly strong variation in the capacity required for the structure. Based on the percentages of the differences provided in the last column of Table 1, it can be observed that the rate of increase of $\widehat{c}$ by elapsing time is approximately the same for different values of r.

Table 1 Required capacity for the target failure rate, β=0.6, different distances and different times

Site to source distance	Median value of demand	Elapsed time [*yr*]	Required capacity $\widehat{c}$	Variations from reference case
r=5 km	0.450 g	331	1.131 g	-22%
		416	1.463 g	0%
		633	1.841 g	26%
r=10 km	0.303 g	331	0.750 g	-23%
		416	0.977 g	0%
		633	1.223 g	25%
r=15 km	0.232 g	331	0.548 g	-22%
		416	0.704 g	0%
		633	0.875 g	24%
r=20 km	0.204 g	331	0.423 g	-23%
		416	0.551 g	0%
		633	0.688 g	25%

For a deeper insight into the trend in time of the capacity required for the target failure rate, the values of $\widehat{c}$ obtained in the range $\left[250yr, 1400yr\right]$ are reported in Figure 3, for the 4 distances previously considered.

Based on the curves shown in Figure 3, it can be said that when the site is close to the source (*r*=5 km) elapsing time affects the structure response considerably more than the case in which the site is far from the source (*r*=20 km in this study). Values of $\widehat{c}$ change considerably up to $600yr$, while variations decay for longer periods and become negligible for elapsed time over $1200yr$.

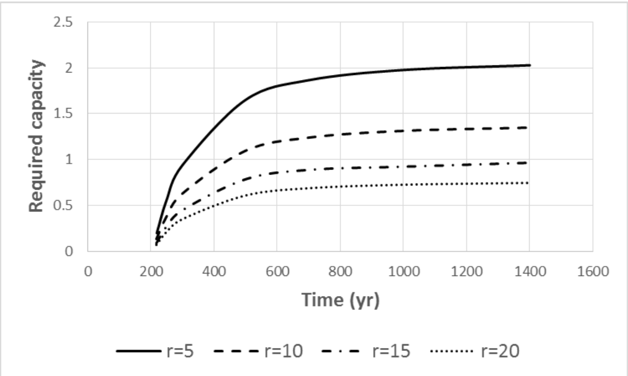

Figure 3 The change of required capacity by elapsing time for constant β=0.6 and variable *r*.

Results concerning short time intervals are not reported because the capacity required for intervals shorter than the limit value $\overline{t}$ is equal to 0, as discussed in the previous section. In the case study considered, the time limit $\overline{t}$ is equal to $219yr$.

4.2 The impact of β on the required capacity

The influence of parameter β, describing the dispersion of the seismic intensity producing failure, is analysed in this section considering a fixed site-to-source distance $r = 5km$ and variable values of β (0.5, 0.6, 0.7, and 0.8).

As above, Figure 4 provides a comparison between seismic intensity and required capacity, given the earthquake occurred.

The continuous line reports the complementary cumulative density function $G_I(i)$ of seismic intensity I and the dashed line reports the conditional probability of failure for systems with different capacity parameters $\hat{c}$.

Figure 2 also permits a comparison of results concerning structural systems with different dispersion β. The capacity corresponding to the target conditional probability of failure $P_f^* = 0.05$ notably increases by increasing the capacity dispersion. More precisely, the capacity necessary for P_f^* is $\widehat{c} = 1.286g$ for the smallest considered value of β, equal to 0.5, while it increases by 14%, 31%, and 52% passing from $\beta = 0.5$ to the larger values 0.6, 0.7, and 0.8, respectively.

In the following, the influence of the time elapsed from the last event is considered.

Table 2 provides the data related to the required capacity for the three particular instants discussed previously, i.e. 331*yr*, 416*yr*, and 633*yr*, and compares the results obtained for the 4 different values of β. As expected, by elapsing time from the last event, required capacity $\hat{c}$ increases.

Also in this case, the variation of the required capacity is notably smaller than the variation of event occurrence. The hazard rate at 331yr is equal to $0.50h_0$, while the capacity reduction spans the range 0.21-0.37 for the considered values of β.

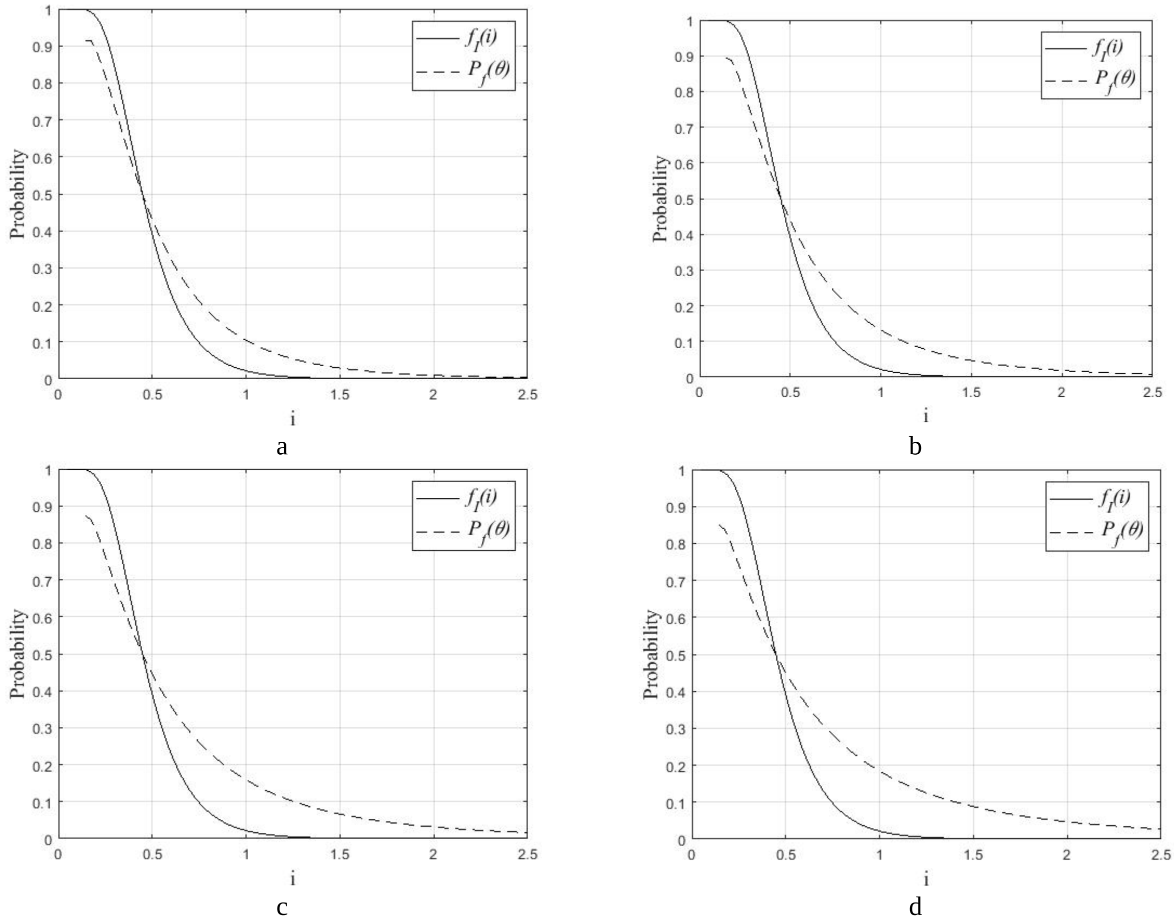

Figure 4 $G_I(i)$ and $P_f(\vartheta)$ curves 416 years after the last events for *r*=5km and a) *β*=0.5, b) *β*=0.6, c) *β*=0.7, and d) *β*=0.8

Table 2 Required capacity for the target failure rate, $r = 5\ km$, different β and different times

β	Median value of demand	Elapsed time [*yr*]	Required capacity $\hat{c}$	Variation from reference case
0.5	0.450 g	331	1.016 g	-21%
		416	1.286 g	0%
		633	1.572 g	22%
0.6	0.450 g	331	1.131 g	-22%
		416	1.463 g	0%
		633	1.841 g	26%
0.7	0.450 g	331	1.256 g	-25%
		416	1.688 g	0%
		633	2.171 g	29%
0.8	0.450 g	331	1.411 g	-37%
		416	1.949 g	0%
		633	2.582 g	32%

Differently from the previous case, where the influence of the distance r was analysed, the parameter β strongly influences results and the required capacity parameter becomes approximately double passing from $\beta = 0.5$ to $\beta = 0.8$.

On the other hand the hazard rate at 633yr is equal to $2.00h_0$ and the required increment in the capacity parameter is bounded in the range 0.22-0.32.

Finally the trend in time of the capacity required for the target failure probability is discussed and the value of $\hat{c}$ obtained in the range $[250yr, 1400yr]$ are reported in Figure 5 for the 4 values of β considered.

As expected, the changes in required capacity by elapsing time are almost the same as the changes shown in Figure 3. The curves of Figure 5 show that the required capacity increases as the time elapsed form the last event grows and the rate of this increment is not constant but decreases with elapsing time. In other words, the required capacity increases sharply up to approximately 600*yr* from the last event. Then, it increases slightly for elapsed time from 600*yr* to 1200*yr* and finally it remains almost the same from 1200*yr* to 1400*yr* after the last event. The other significant point which can be concluded is that after approximately 250*yr* from the last event, required capacity for different values of β is roughly the same. Nonetheless required capacity starts to vary for different values of β with elapsing time over 250yr. Finally, It can be said that the slope of curves for different values of β is not the same. In other words, the larger β is, the greater the slope will be.

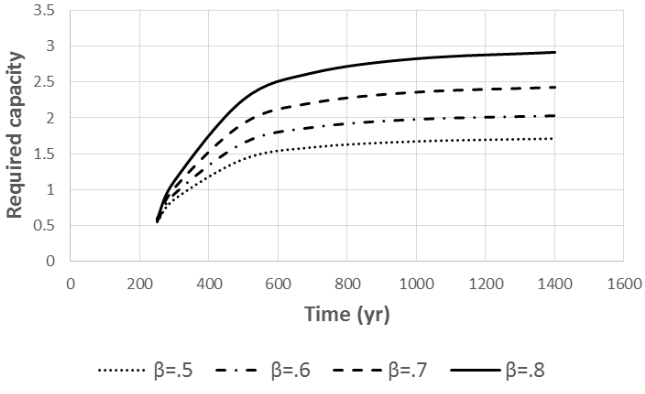

Figure 5 The change of required capacity by elapsing time for constant $r = 5km$ and variable β.

5 CONCLUSIONS

The Impact of Time-Dependent Seismic Hazard on design capacity was assessed in this study by evaluating the strength required by the structure for varying time intervals elapsing from the last event, in order to ensure a target value of the failure rate is not exceeded. A point-source is considered and results concerning different site-to-source distance r, and capacity dispersion β are discussed. The case study presented concerns the Paganica fault, located in central Italy.

Based on the results, the following conclusions can be drawn.

- High variations in hazard rates do not translate into similar variations in the capacity required to ensure the target failure rate, and capacity variations observed in the case study are moderate.
- For the case considered (point-source, BPT model, $T_R = 750yr$) required capacity drops to 0 at a critical instant , $\bar{t} = 219yr$ and variations in time become negligible for $t > 600yr$.
- As expected, required capacity decreases by increasing the source-to-site distance. The variation in the time trend is similar for all the distances considered.
- The response parameter β notably influences the required capacity and different trends are observed in time.

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