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COST-BENEFIT ANALYSIS OF SEISMIC MITIGATION MEASURES FOR WINE BARREL STACKS

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Abstract

Several mitigation techniques and initiatives such as the Good Practice Manual have been proposed to reduce the earthquake damage in wine barrels stacks. However, a common practice in most wineries is to restack the barrels in the same way as before the earthquake, mostly because the elevated costs of implementing the mitigation measures. Therefore, the barrel storage facilities are still highly vulnerable to earthquake damage and similar damage costs are expected in future seismic events.

This study conducts a cost-benefit analysis of alternative seismic risk mitigation methods of wine barrel stacks. The Chilean wine industry is presented as an illustrative case study, in which performance metrics such as the expected annual loss (EAL) and the probable maximum loss (PML) are computed for wineries at different locations.

The systematic procedure for evaluating decisions related to strategic risk management is divided in five steps: (1) To characterize a stochastic set of events collectively exhaustive and mutually exclusive, that describe the spatial distribution, the annual occurrence frequency and the aleatory variability of ground motions at the sites of interest, (2) To define exposure of wine barrel stacks at risk, (3) To compute vulnerability functions of barrel stacks with and without seismic mitigation measures, (4) To carry out a probabilistic seismic risk analysis taking into account all locations of wine barrel stacks in Chile, and (5) To perform a cost-benefit analysis assuming current condition and different seismic mitigation costs and actions. This analysis can be implemented at three different levels: i) a comparative analysis of vulnerability functions of individual wine barrel stacks considering the mitigation measures, ii) a comparative analysis of PML (implicitly loss exceedance curves) and EAL considering current condition and different mitigation alternatives of wine barrel stacks, and finally iii) a cost-benefit analysis (loss reduction due to mitigation measures). This is required in order to estimate the benefits of mitigation actions assuming that economical resources are limited. By computing seismic risk within a consistent framework, this study shows the value of cost-benefit simulations for defining the best mitigation strategies and allowing decision-maker allocate the economic resources. Another benefit of this approach is that the information to decision-makers is presented in an easier and transparent way even if they are not familiar with formal risk studies.

Keywords: Cost-benefit analysis, wine barrel stacks, seismic mitigation measures, Cradle Extender

1. Introduction

Several mitigation techniques and initiatives such as the 'Good Practice Manual' have been proposed to reduce the earthquake damage in wine barrel stacks. However, a common practice in most wineries is to restack the barrels in the same way as before the earthquake, mostly because the elevated costs of implementing the mitigation measures. Therefore, the barrel storage facilities are still highly vulnerable to earthquake damage and similar damage costs are expected in future seismic events.

Most wineries in Chile are located in the central valleys along active tectonic margins. According to INE [1], Chile has 339 wineries with capacity of at least 300,000 liters, which are distributed regionally in 133 wineries (39.2%) in Maule, 81 in O'Higgins (23.8%), 62 wineries in the Metropolitan Area (18.2%) and other 63 in Coquimbo, Valparaiso, Biobío and Atacama (18.8%). The storage capacity of the wineries reached 1950 million liters in 2011, however, only of 37.9 million liters are kept in barrels.

In the 2010 Chile earthquake, 120 million liters of wine were lost (approximately 6.15% of storage capacity in 2011) for that single event, and a significant amount of the wine stored in barrels was lost due to partial or total collapse of barrel stacks. The reconnaissance teams identified several response modes and failure modes, including vertical drifting, stack overturning, and top barrel ejection, with most of the damage concentrated in the Maule region where PGA was approximately 0.35g. It was also observed that the ability of the lower rack to slide prevented the overturning of the stacks [2].

This study conducts a cost-benefit analysis of alternative seismic risk mitigation methods of wine barrel stacks. The case of the Chilean wine industry is presented as an illustrative example, in which performance metrics such as the expected annual loss (*EAL*) and the probable maximum loss (*PML*) are computed for wineries at different locations.

2. Cost-benefit analysis procedure of seismic mitigation measures for wine barrel stacks

In this study, we propose to perform the cost-benefit analysis at a regional level as follows:

2.1 Step 1: characterize earthquake events

The seismic hazard must be defined as a stochastic set of events, collectively exhaustive and mutually exclusive, that describe the spatial distribution, the annual occurrence frequency and the randomness of the hazard intensity at the site of interest. The seismic hazard intensity must be quantified in terms of relevant seismic intensity related to damage. As discussed in the vulnerability section, this study uses the peak ground acceleration (PGA) as the ground motion intensity parameter, though other parameters, such as incremental ground velocity or rocking spectra [3], have been proposed to describe the rocking response of rigid bodies assemblies. The ground motion intensity of each event is represented as a random variable by, at least, its first two probabilistic moments: the expected value and the variance. For this purpose, an *.ame* type file is created (*ame* comes from amenaza -hazard- in Spanish) which includes a description header and multiple geocoded grids representing a hazard event set for each event with its associated rate of occurrence. The uncertainties considered for the variance estimation are those related to the data and the simplifications of the model. Although there are no formal approaches to evaluate these kinds of uncertainties, they must be estimated and included in the risk assessment. A sensitivity analysis to compute the variation coefficient of the intensity could be useful for this. The process must be made using historic data for the region studied, if this exists, evaluating the severity and the occurrence frequency of the seismic event.

2.2 Step 2: define exposure model of wine barrel stacks at risk

For characterizing the inventory of wine barrel stacks, it is necessary to identify each asset, considering location, physical characteristics, vulnerability and economic value. The replacement value of the asset may be that given directly by the owner or that estimated from secondary sources (*e.g.* [1]). The precision of the results will depend on the level of resolution and detail of the available information.

2.3 Step 3: vulnerability functions of each of the wine barrel stacks with and without seismic mitigation measures

The vulnerability function expresses the relation between the expected ground motion level and a quantitative measure of expected damage cost for a given wine barrel stack, as a percentage, or in monetary terms, if the value of the wine barrel stack is known. In this study, the vulnerability function is the expected damage cost caused to each of the barrel stacks as a result of a given seismic intensity, obtained from analytical or empirical models or by statistical relationships between seismic intensities and observed costs. The stack configurations used in this study are 3-levels and 6-level wine barrel stacks with the ground motion applied in the transverse direction, i.e. perpendicular to the barrel axis, as shown in Fig. 1.

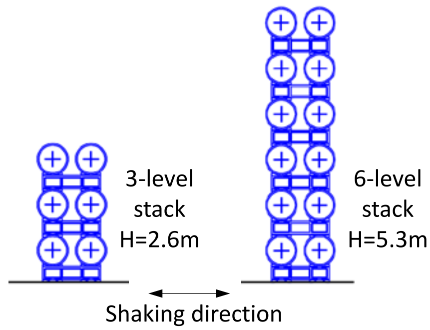


Fig. 1 – Wine barrel configurations considered in the analysis

In this study, the relative damage, *d*, is defined as the ratio of the expected cost of repairs to the cost of replacement of the wine barrel stack. A vulnerability curve expresses the relative damage of the wine barrel stack, *d*, at a given ground motion intensity, in this case PGA. Based on the work by [3], the expected damage $E(d \mid y_i)$ is computed as

$$E(d|y_i) = L_{Ns} - L_{Ns}\exp\left(\frac{y_i^a}{b}\right) \tag{1}$$

where y_i is the PGA at site *i*; L_{NS}, *a* and *b* are calibration parameters specific to each barrel stack configuration.

A vulnerability function is not deterministic, *D* is a random variable whose expected value is given by Eq. (1). As is commonly assumed (e.g. [4]), in this work the probability density function of the loss is assumed to be Beta, and its variance, $\sigma^2(d \mid y_i)$, given by

$$\sigma^2(d|y_i) = c\cdot\left(E(d|y_i)\right)^g\cdot\left(L_{NS} - E(d|y^i)\right)^g \tag{2}$$

Also, parameters *c* and *g* are specific to each configuration.

2.4 Step 4: event-based seismic risk assessment

The desired risk outputs, such as percentages of economic damage costs, are evaluated in an event-based probabilistic framework, where damage costs are estimated for each of the hazard events, and then all these results are integrated. The most common way to express risk is by means of the expected annual loss. As will be explained later, the risk assessment can be performed for a single wine barrel stack or for two or more wine barrel stacks.

2.4.1 Seismic risk assessment of a single wine barrel stack

For a single wine barrel stack, the evaluation of the expected annual loss, *EAL*, consists of evaluating the expected damage cost, $E(d \mid y_i)$, for each one of the events that collectively describe the seismic hazard, and then integrating the results using the occurrence frequencies of each event as weight factors.

$$EAL = \sum_{i=1}^{\#Events} E\left(d \mid y_i\right) \cdot f_A\left(Event\ i\right) \tag{3}$$

where y_i corresponds to the *i-th* event, and $f_A(Event\ i)$ is the annual occurrence frequency of the *i-th* event. Eq. (3) is one of many ways of presenting the total probability theorem [5].

The risk due to seismic hazard is commonly expressed in terms of the mean annual rate of exceedance of the loss or Loss Exceedance Curve (LEC), defined by the following equation [6]:

$$\nu(d) = \sum_{i=1}^{\#Events} \Pr\left(D > d \mid Event\ i\right) \cdot f_A\left(Event\ i\right) \tag{4}$$

where $\nu(d)$ is the exceedance rate of d, $\Pr(D > d \mid Event\ i)$ is the probability that the damage cost is greater than d given that the *i-th* event has occurred, and $f_A(Event\ i)$ is the annual rate of occurrence of the *i-th* event. The sum in the previous equation is carried out for all potentially damaging events. The exceedance probability of the damage cost d, conditioned on the occurrence of the *i-th* is.

$$\Pr\left(D > d \mid Event\ i\right) = \int_y \Pr\left(D > d \mid y\right) \cdot f_A\left(y \mid Event\ i\right) dy \tag{5}$$

where $\Pr(D > d \mid y)$ is the exceedance probability of the damage cost d, y is the local intensity, and, $f(y \mid Event\ i)$, is the probability density of the intensity, conditioned to the occurrence of the *i-th* event; this term takes into account the uncertainty of the ground motion intensity.

2.4.2 Seismic risk assessment for several wine barrel stacks

The total damage cost in several wine barrel stacks is the sum of the damage costs of individual wine barrel stacks located in multiple, geographically disperse sites. Therefore the damage costs are partially correlated. Considering that $E(d)$ and $\sigma^2(d)$ are the expected value and variance of the damage cost, respectively, for the *j-th* wine barrel stack, the total damage cost, C_D, will have the following properties:

$$E\left(C_D\right) = \sum_{j=1}^{N} M_j \cdot E\left(d_j\right) \tag{6}$$

$$VAR\left(C_D\right) = \sum_{j=1}^{N} M_j \cdot VAR\left(d_j\right) + 2\sum_{j=1}^{N}\sum_{k=j}^{N} M_j \cdot M_k \cdot \rho_{jk} \sqrt{VAR\left(d_j\right) \cdot VAR\left(d_k\right)} \tag{7}$$

where ρ_{jk} is the correlation coefficient between the damage costs j and k; N is the number of wine barrel stacks; and M_j and M_k are the values of the wine barrel stacks j and k, respectively. It is impractical, and sometimes even impossible, to estimate the probability distribution of the damage costs based on Eq. (7); therefore it is customary to assign a Beta function with two parameters using the first two probabilistic moments of the vulnerability function.

2.5 Step 5: Cost-benefit analysis

The economic efficiency of a pre-earthquake strengthening of wine barrel stacks can then be determined in term of the net present value of the investment of the retrofit. If the expected benefits exceeds the total cost, the present value is positive (benefit/cost ratio greater than one) and the retrofit investment is economically justified [7, 8, 9]. The benefit/cost ratio (due to the retrofit) is computed as [7, 8, 9]:

$$B/C = \frac{L_U - L_R}{C_R} \tag{8}$$

where L_U is the damage cost in terms of present worth due to all future earthquakes for the current condition; L_R is the damage cost in terms of present worth due to all future earthquakes for the retrofitted case and C_R is the retrofitting cost.

The values of L_U and retrofitted L_R are estimated under the assumption that, in the long term, the expected damage costs would be equal to the sum of total damage cost, $E(C_D)$ (*e.g.* [9]). Therefore, the expected values of L_U and L_R included in Eq. (8) is calculated as follows:

$$L = \frac{E(C_D)}{\tau} \tag{9}$$

where τ correspond to the discount rate.

On other hand, the expected damage costs for a given lifespan, t_{life}, it is necessary to consider that both the expected damage costs and the time when they occur are random variables. Then, based on the loss exceedance curve (LEC), stochastic damage cost events could be generated for a given lifespan t_{life}. On this basis, the present value of damage costs L can be obtained as in Eq. (10) (*e.g.* [9]).

$$L = \sum_{i=1}^{t_{life}} d_i \cdot e^{-\tau \cdot t_i} \tag{10}$$

where L is the present value of damage costs, t_{life} is the lifespan of the barrel stacks under study and t_i is the time of occurrence of the damage cost event d_i. The lifespan of the barrel stacks could be larger than 80 years.

3. Application of the methodology for wine barrel stacks in Chile

3.1 Seismic hazard characterization

To model the seismic hazard, we developed a set of stochastic events corresponding to a significant number of earthquakes of different magnitude and different hypocenters (over 1000 earthquakes), each one associated with an annual frequency of occurrence, in a way that the seismic environment of Chile is defined completely. For this, we used the CRISIS program developed by [10], which employs seismicity parameters and seismogenic source models obtained from registered historical seismicity, which cover the whole of Chile, conserving the general seismicity conditions and their regional variation.

On the other hand, for considering the influence of the seismic activity, we must consider seismological and engineering parameters, such as magnitude, intensity, wave attenuation and site amplification, among others. However, considering the high degree of uncertainty involved, it is necessary to implement a probabilistic approach. In order to do so, the seismic hazard must be considered as a set of stochastic events that describes the spatial distribution, the annual frequency and the randomness of the intensity of the hazard at the site of interest, using the methodology originally proposed by Esteva-Cornell [11] and implemented in CRISIS 2007 [10]. The events must be collectively exhaustive (they must include all the possible earthquake occurrence types), and they also must be mutually exclusive (two or more events of the same set cannot occur at the same time). In most cases, the earthquake occurrence is assumed to follow a Poisson process within a seismic source.

The seismic sources affecting Chile, seismicity and geometry, were taken from the study of [12], who obtained the rate of exceedance of magnitudes, $\lambda(M)$, using statistical analyses of the available earthquake catalogues from 1906-1985. These rates are the number of earthquakes that characterize the seismicity of each of the sources, per unit of time, where the magnitude M is exceeded. The seismic modelling must consider the attenuation effects of the seismic waves, through ground motion prediction equations (GMPE), known as attenuation laws, which include several sources types. In this study, the types of earthquakes that each seismic source can generate are classified in three groups [13]: interplate, intraplate and shallow crustal earthquakes in Chilean subduction zone. A different GMPE on rock is associated with each one of these types of earthquake, described as follows:

(1) Interplate earthquakes. For the peak ground acceleration caused by earthquakes generated on Chile, the attenuation law of [14] is used. This GMPE was developed based on a database worldwide from 63 slab earthquakes (including Chilean earthquakes) which includes a correction factor for great earthquakes (e.g. Maule 2010 M8.8 and Tohoku 2011 M9).
(2) Intraplate earthquakes. In this case, an attenuation model also developed by [14] called *BC Hydro* is employed.
(3) Shallow crustal earthquakes. In order to model the attenuation of shallow earthquakes, the GMPEs developed by [15] with data recorded in California are employed.

Figure 2 shows the peak ground acceleration on rock in Chile with 10% probability of exceedance in 50 years.

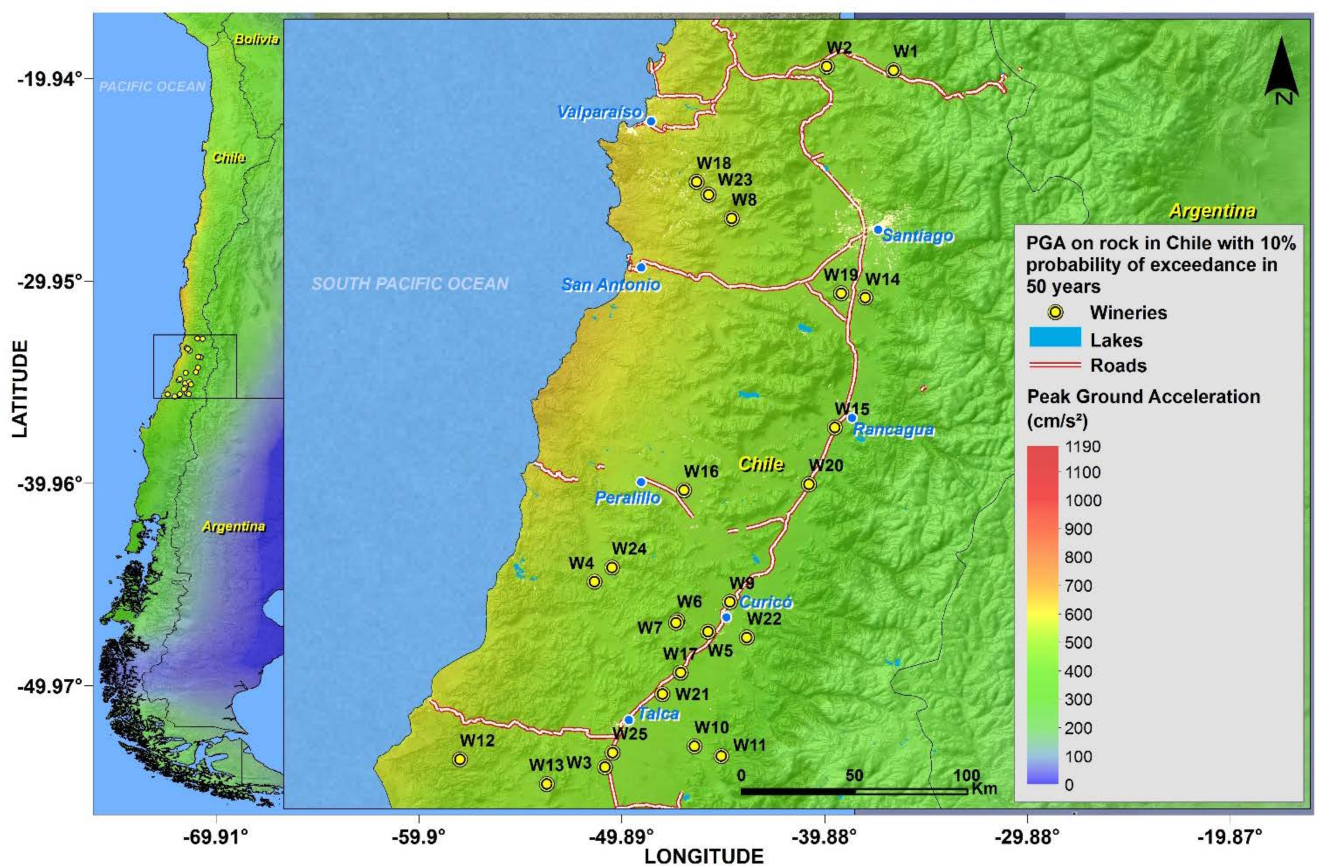


Fig. 2 – Peak ground acceleration on rock in Chile with 10% probability of exceedance in 50 years, and location of wineries studied

3.2 Defining wine barrel stacks at risk

The wine barrel stacks inventory used herein consists of 25 wineries located in South Central Chile. For each wineries, latitude and longitude, economic value (standard replacement cost), configurations were defined. Two scenarios were assumed: 1) all wine barrel stacks are 3-level high and 2) all wine barrel stacks are 6-level high. Fig. 2 shows the inventory of 25 wine barrel stacks at risk.

3.2.1 Replacement and retrofitting costs

In this case study, the cost-benefit analysis of four alternatives are compared:

1) a_1 is all 3-level wine barrel stacks without mitigation measure.
2) a_2 is all 6-level wine barrel stacks without mitigation measure.
3) a_3 is all 3-level wine barrel stacks with mitigation measure. Here, we use a top-barrel restrain called Cradle Extender [16]; the Cradle Extender is a bracket-and-pin that attaches to onto the side of the steel cradle of any existing portable steel wine barrel rack. The function of the Cradle Extender is to prevent the top barrels ejection failure mode.
4) a_4 is all 6-level wine barrel stacks with mitigation measure. Similar to a_3.

The decision maker is assumed to be the owner of the 25 wineries. The owner is responsible not only of the cost of repair or replacement of the wineries, but also for any loss of profit of the wineries is damaged. The replacement cost of alternatives a_1, a_2, a_3 and a_4 are US$150,000, US$300,000, US$151,500 and US$301,500. These values were obtained as follows: replacement costs were assume as US$1000 per wine barrel. Therefore, for a 3-level wine barrel stack, the cost would be $US6,000 and for a 6-level wine barrel stack would be $US12,000, which multiplied by the number of wineries obtain the values above. On the other hand, retrofitting cost are related to the mitigation measure adopted in order to increase the safety of wine barrel stacks. In this study, we estimated the retrofitting as US$60 per wine barrel stack [17].

3.3 Vulnerability functions

There are several methods to define vulnerability curves, in this study, that proposed by Candia *et al*. (2016) is employed. After analyzing all the information about the characteristics of wine barrel stacks, two configurations were defined as the most representatives for the entire database. Table 1 shows the parameters *a*, *b*, *c* and *g* to each configuration without and with mitigation measures given in Eqs. (1) and (2). Fig. 3 shows the vulnerability curves without mitigation measures and with mitigation measures for a 3 level stack (left) and a 6 level stack (right); they correspond to each configuration proposed.

Table 1 – Parameter values of vulnerability functions

		Without mitigation measures				***With mitigation measures***			
Stack Height	L_{NS}	***a***	***b***	***c***	***g***	***a***	***b***	***c***	***g***
6	10/12	2.65	0.63	0.54	0.97	2.22	1.02	0.54	0.96
3	4/6	3.13	0.60	1.07	1.50	8.99	0.10	0.08	0.34

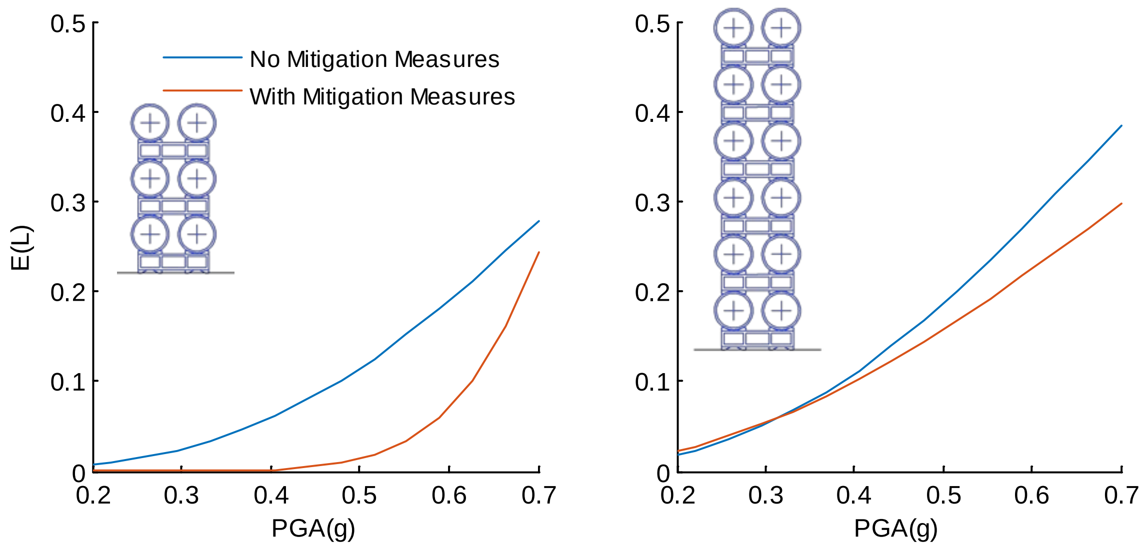
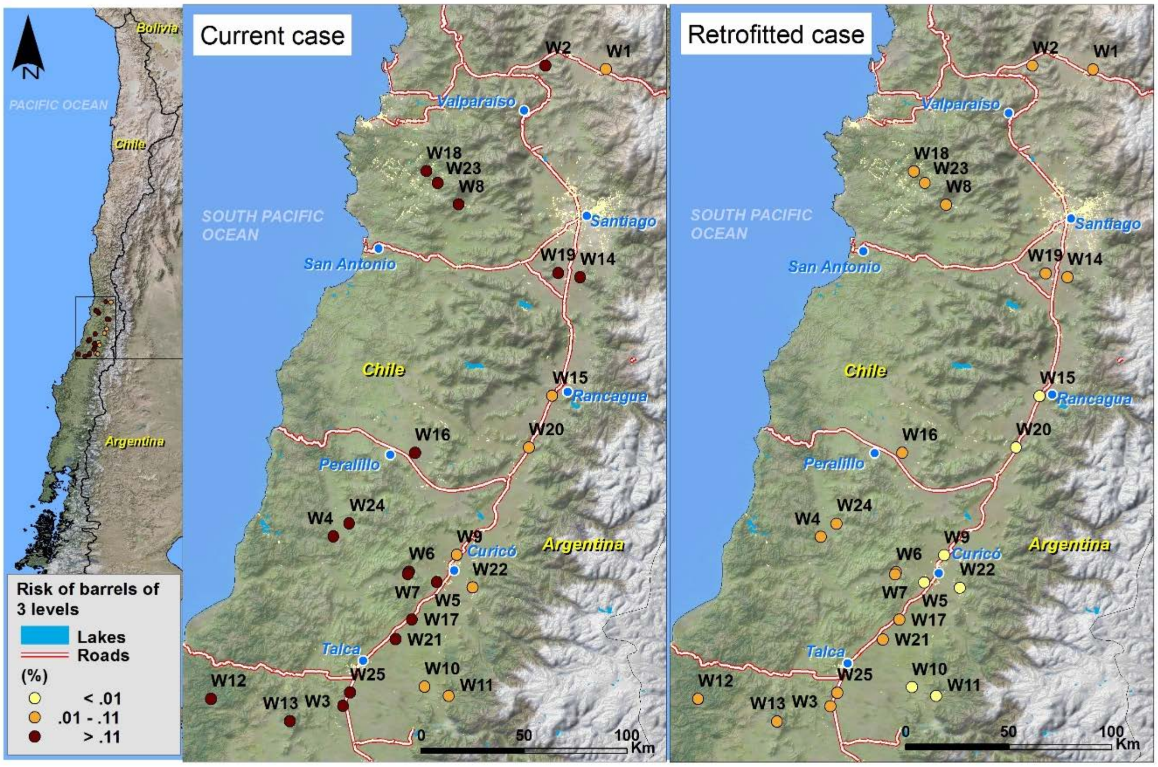


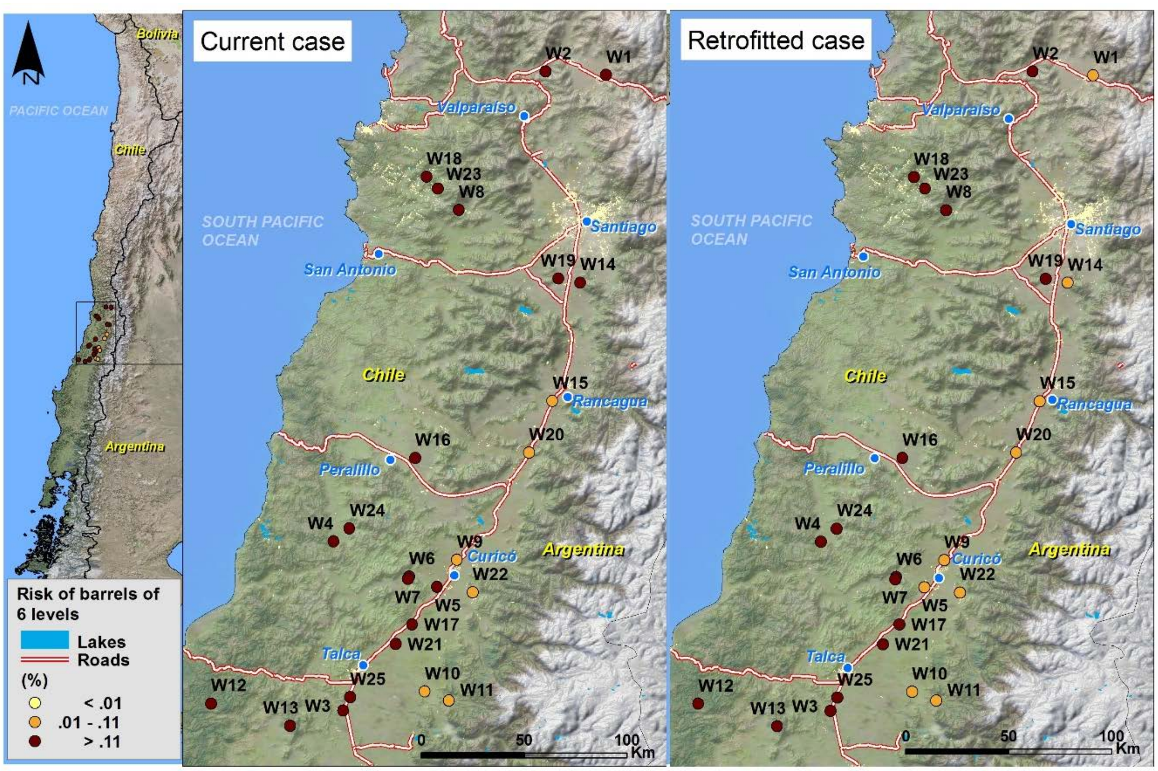
Fig. 3 – Vulnerability curves for barrel-stack systems, with and without mitigation measures on a 3 level stack (left) and a 6 level stack (right).

3.4 Probabilistic seismic risk analysis

The physical seismic risk for the barrel-stack systems was evaluated by the convolution of the hazard with the vulnerability of the wine barrel stacks at risk. To accomplish this task, the CAPRA (ERN-AL, 2010) software was used. This software computes damage costs based on a probabilistic approach. The results presented here are the potential economic consequences expressed in terms of the average annual loss (*AAL*) or pure premium for each exposed element, or in probabilistic terms, the expected annual loss (*EAL*) given by Eq. (3). Fig. 4 shows the distribution of the *AAL* due to earthquake due to earthquake for barrel-stack systems of 3 levels (top) and 6 levels (bottom), without mitigation measures (left) and with mitigation measures (right). Three value intervals of the *AAL* without mitigation measures (Fig. 4a) and with mitigation measures (Fig. 4b) were considered: *AAL* less than 0.01%, 0.01-0.11% and greater than 0.11%. For the case of 3 level barrel-stack systems (Fig 4a), results show that from a total of 25 wine barrel stacks without mitigation measures, 18 (72%) have an *AAL* greater than 0.11% (this value was established as a quantitative level of the risk, easy to communicate to decision-makers but other could be established); however, if it is considered mitigation measures all wine barrel stacks have an *AAL* less than 0.11%. Based on these results, special attention must be paid to the wine barrel stacks with more serious damage costs and further action taken to estimate the risk more reliably, using site inspections. For the case of 6 level barrel-stack systems (Fig 4b), there are not remarkable differences because the collapse of barrel stacks with more than 3 levels is dominated by overturning modes rather than top barrel ejection (Candia *et al.*, 2016). This seismic risk map is a useful tool for developing appropriate strategies for regional planning.



a)



b)

Fig. 4 – Distribution of the annual average loss due to earthquake for barrel-stack systems of 3 (top) and 6 (bottom) levels, without mitigation measures (left) and with mitigation measures (right)

Fig. 5 shows the Loss Exceedance Curve for all wine barrel stacks computed with Eq. (4); this curve represents the mean annual rate of exceedance (or its inverse, the return period, T_R) of the damage costs. For instance, the damage costs of alternatives a_1, a_2, a_3 and a_4 for an annual exceedance frequency of 0.004 (T_R = 250 years) are US$7,490, US$22,950, US$2,490 and US$19,900. Depending on the stakeholder's risk tolerance, the risk manager may decide to manage for damage costs up to a given return period.

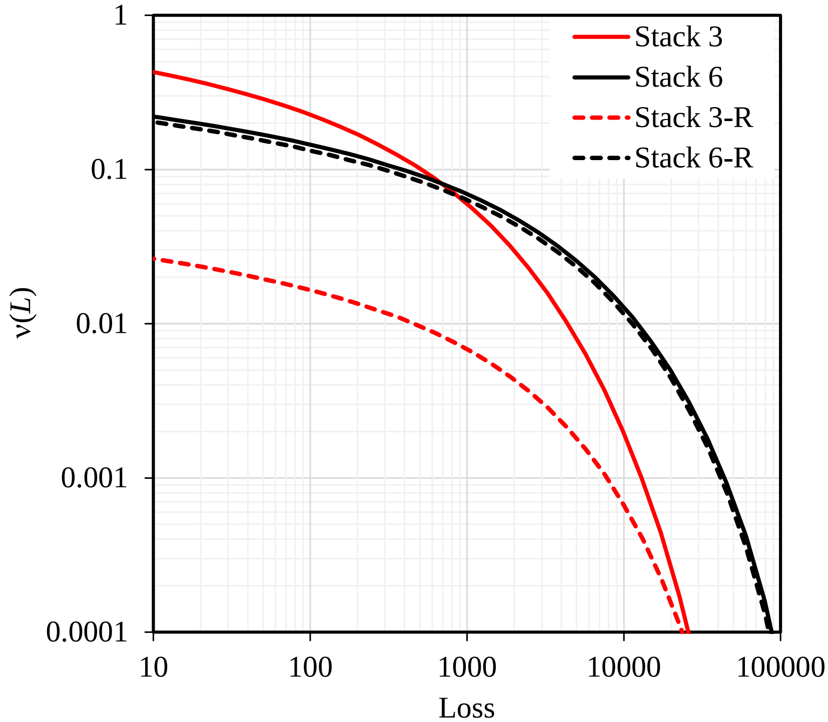


Fig. 5 – Loss exceedance curve for wine barrel stacks due to earthquake events computed with Eq. (4).

3.5 Cost-benefit analysis

Table 2 shows a summary of the exposed values, the damage cost in terms of present worth, the retrofitting cost, and the calculated B/C. In order to reflect the preferences of the decision market, the benefit-cost ratio were calculated. It is observed that alternative 4, a_4, all 6-level wine barrel stacks with mitigation measure, avoids a large number of collapses of barrels and, thereby, significantly increase the benefit-cost ratio computed using Eq. (8). A discount rate of 4% was considered.

Table 2 – Summary of the results

Alternatives	**Exposed value $US**	***E*(*P*) (Eq. 6)**	***L* (Net present value) (Eq. 9)**	**Retrofitting cost**	**Benefit-Cost ratio Eq. (8)**
a_1	150,000	247.86	6,196.50	-	3.54
$^*a_3$	151,500	35.14	878.50	1,500	
a_2	300,000	509.94	12,748.50	-	0.79
$^*a_4$	301,500	462.50	11,563.50	1,500	

*Alternatives a_3 and a_4 are after implementing the mitigation measures.

4. Conclusions

A cost-benefit analysis of seismic mitigation measures for wine barrel stacks is presented. The risk parameters are evaluated in an event-based probabilistic framework for a set of hazard events, and then all these results are integrated, including all the uncertainties related to each part of the process.

This methodology is used to carry out a case study. Twenty-five wineries located in seismic hazard zones in Chile were considered, where a decision between four alternatives is to be made: a_1 is all 3-level wine barrel stacks without mitigation measure, a_2 is all 6-level wine barrel stacks without mitigation measure, a_3 is all 3-level wine barrel stacks with mitigation measure, and a_4 is all 6-level wine barrel stacks with mitigation measure. It was observed that alternative 3, a_3, all 3-level wine barrel stacks with mitigation measure, avoids a large number of collapses of barrels and, thereby, significantly increase the benefit-cost ratio computed using Eq. (8). According to results, the benefit-cost ratio for alterative 4, a_4, in 6-level wine barrel stacks is less than 1, therefore, other alternatives must be proposed.

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