Cost-Benefit Analysis of Seismic Mitigation Measures for Wine Barrel Stacks

Miguel A. Jaimes,[a)] **Gabriel Candia,**[b),d)] **and Philomène Favier**[c),d)]

This study conducts a cost-benefit analysis of alternative seismic risk mitigation methods for 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 benefit-cost ratios, are computed for wineries at different locations. By computing seismic risk within a consistent framework, this study shows the value of cost-benefit simulations for defining the best mitigation strategies and allocating economic resources. Likewise, this approach helps communicate information to decision makers because it is presented in a simple and transparent way, even if they are not familiar with formal risk studies. For three-level wine barrel stacks, it was observed that the Cradle Extender® (MS1) prevents a large number of barrel collapses and provides the highest benefit-cost ratio. On the other hand, for six-level wine barrel stacks, the prestressed cable (MS2) is more effective than MS1 as it prevents the barrel stack from overturning. No significant loss reduction is apparent in four- and five-level wine barrel stacks with the use of mitigation strategies; indeed, the mitigation strategies could generate greater losses and, therefore, other alternatives must be proposed. [DOI: 10.1193/111516EQS196M]

INTRODUCTION

Losses of nonstructural components and contents due to earthquakes may be significant and even exceed the loss value of structural components, such as the facilities used for wine storage. For instance, the Mw 8.8 Chile earthquake of 27 February 2010 caused significant damage in wine storage containers and direct losses to the wine industry exceeding US$430 million in addition to long recovery periods (Zareian et al. 2012). Similar damage levels were observed after the 2014 Mw 6.0 Napa earthquake in California (EERI 2014, Galloway and Ingham 2015). In countries with robust seismic building codes, such as Chile or the United States, the seismic risk assessment for contents and nonstructural components, as well as the evaluation of mitigation measures based on cost-benefit analysis (e.g., seismic retrofitting for anchored tanks in Federal Emergency Management Agency, *FEMA E-74* 2011), has become customary in order to minimize the losses in future earthquakes.

Most Chilean wineries are located in the central valleys, with over 80% of the national wine production concentrated between the Maule Region in the south and the Metropolitan

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[a)] Instituto de Ingeniería, UNAM, Av. Universidad, No. 3000, CP 04510, Del. Coyoacán, CDMX – México
[b)] Facultad de Ingeniería, Universidad del Desarrollo, Av. Plaza 680 Las Condes, Santiago – Chile
[c)] Pontificia Universidad Católica de Chile Vicuña Mackenna 4860, Macul. Santiago – Chile
[d)] Centro Nacional de Investigación para la Gestión Integrada de Desastres Naturales CONICYT/FONDAP/15110017. Santiago-Chile

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Region in the north. According to the Instituto Nacional de Estadísticas Chile (INE 2012), Chile has 339 wineries with a capacity of at least 300,000 liters each. The added storage capacity of the wineries reached 1,286 million liters in 2015 Servicio Agrícola y Ganadero (SAG 2015), of which 38 million liters are kept in wooden barrels. To the authors' knowledge, none of these storage facilities for wooden barrels use seismic mitigation measures, which makes this industry highly vulnerable to suffer losses from future earthquakes.

Past earthquake evidence shows that wine storage container failure comes not only from structural damage to the warehouses, but also from an inadequate behavior of the wine storage equipment (Zareian et al. 2012), which includes the partial or total collapse of wine barrel stacks. Although much effort has been made in the past to gather this evidence, useful field data remains lacking. Indeed, the documented performance of wine storage containers during earthquakes is very scarce because major structural damage of buildings receives nearly all the attention; moreover, rescue and clean-up teams may modify the state of the containers before a survey is conducted (Zareian et al. 2012). In addition, access to damaged facilities may be restricted in order to comply with insurance policies or safety concerns, and even if earthquake reports refer to nonstructural damage, existing databases are hardly usable for deriving empirical fragility functions based on classical statistical methods (Rossetto et al. 2014). Databases suffer from technical problems as a result of the lack of standardization throughout the collection methods and the scarcity of complete data sets (*ATC-69* 2008).

An alternative to empirically derived fragility functions are judgmental methods based on expert opinions (e.g., FEMA 2003), numerical methods (e.g., Purvance et al. 2008), and hybrid simulations. Although mostly applicable to rectangular blocks, several authors have developed overturning functions considering the fragility for single rigid blocks with and without mitigation measures. For instance, Yim et al. (1980) studied the influence of the intensity of ground motions on the cumulative distribution functions for rectangular blocks, and Vassiliou and Makris (2012) analyzed the seismic response of base-isolated blocks. More recently, Kounadis et al. (2015) studied the complex dynamics of multispondyle columns and developed instability criteria for a system with two degrees of freedom (DOF). The author also showed the impracticality of deriving exact solutions for multiple DOF systems. To deal with the complex response of wine barrel stacks, which include sliding, rocking, and uplifting of nonrectangular blocks, the fragility functions used in the present study were obtained from a physical-based model for wine barrel stacks (Candia et al. 2016).

This study conducts a cost-benefit analysis of three risk mitigation strategies for wine barrel stacks subjected to strong ground motions. They consist of a barrel stack with Cradle Extenders at the top rack, a barrel stack equipped with a prestressed cable pinned to the top rack, and the use of a reduced friction interface between the lower rack and the ground. 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 benefit-cost ratios are computed for wineries at various locations.

METHODOLOGY

The cost-benefit analysis of seismic mitigation strategies for wine barrel stacks at a regional level consists of five steps.

STEP 1: CHARACTERIZATION OF SEISMIC HAZARD

The ground motion at the site of interest must be described in terms of an intensity parameter that adequately relates to the observed damage in wine barrel stacks. As discussed in the vulnerability section, because of its simplicity, the selected ground motion parameter is the peak ground acceleration (PGA). However, other parameters, such as the incremental ground velocity or the rocking spectra (Makris and Konstantinidis 2003), have been proposed to describe the dynamic response of rigid body assemblies. In this study, the ground motion intensity is a random variable defined by its first two probabilistic moments: the expected value and the variance. The spatial distribution of PGA, the expected value, and its variability must be described through a Probabilistic Seismic Hazard Analysis (PSHA), which consists of a set of possible earthquake events—collectively exhaustive and mutually exclusive—that represent the seismicity at the location of each winery. A thorough description of the PSHA implementation may be found in Ordaz et al. (2007).

STEP 2: IDENTIFICATION OF EXPOSURE MODEL OF WINE BARREL STACKS

A regional inventory of wineries and the use of wine barrel stacks is required, identifying the location, physical characteristics, and economic value for each asset. The replacement value of the asset may be given directly by the owner or estimated from secondary sources (e.g., INE 2011). The accuracy of the results depends on the scale and level of detail of the available information.

STEP 3: DEVELOPMENT OF VULNERABILITY FUNCTIONS FOR WINE BARREL STACKS

The vulnerability functions express the relationship between the ground motion intensity (in this case, PGA) and the expected losses as a percentage for a given wine barrel stack, or in monetary terms if the value of the wine barrel stack is known. The vulnerability functions can be obtained from numerical simulations or based on the actual field performance of barrel stacks, from empirical data, judgmental knowledge, or a hybrid approach. The vulnerability functions used here are based on numerical simulations previously presented by Candia et al. (2016) who proposed a functional relationship to fit the losses computed from a dynamic analysis of a physical model with various ground motion inputs. Further details can be read in Candia et al. (2016) and in the "Vulnerability functions" subsection of that article. The considered wine barrel stack configurations are the most common in Chile: three-level, four-level, five-level, and six-level, with the ground motion applied in the transverse direction (i.e., perpendicular to the barrel axis), as shown in Figure 1. The nonretrofitted condition (i.e., barrel stacks with no implemented mitigation strategies) is henceforth referred to as MS0. Likewise, three mitigation strategies, referred to as MS1, MS2, and MS3, were studied for each barrel stack configuration. The mitigation strategy MS1 consists of a Cradle Extender (Marrow 2002)—a bracket and pin attached to the sides of the top rack, as shown in Figure 2a. The main benefit of the Cradle Extender is to reduce failure by top barrel ejection, a collapse mechanism that affects mostly three- and four-level barrel stacks (Candia et al. 2016). MS2 consists of a "tension only" prestressed cable that connects the top rack to the ground, as shown in Figure 2b, thus limiting the horizontal drift of the barrel stack during earthquakes and significantly improving its stability. No experimental or numerical

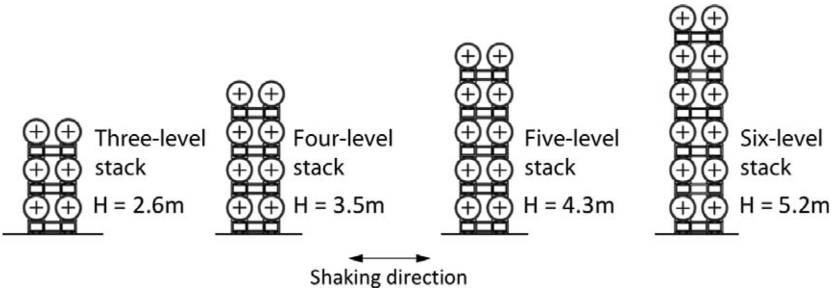


Figure 1. Barrel stack configurations used in the analysis.

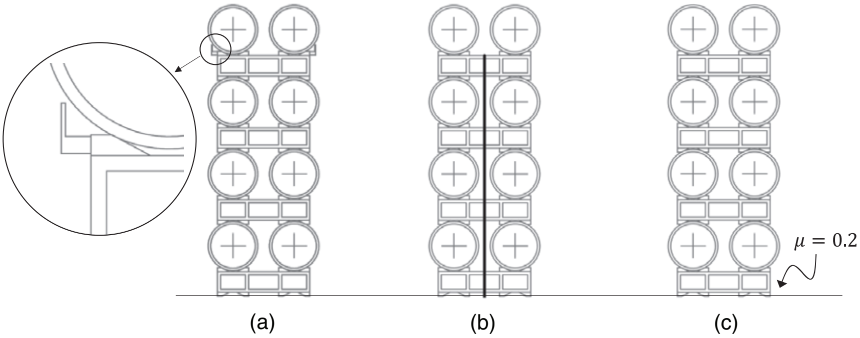


Figure 2. Risk mitigation strategies displayed on a four-level barrel stack: (a) Cradle Extender or MS1, (b) prestressed cable or MS2, and (c) reduced base friction or MS3.

simulations have been performed to date for this type of mitigation on wine barrel stacks. Finally, MS3 consists of a barrel stack with reduced base friction, in which the friction coefficient between the floor and the lower rack is set to $\mu = 0.2$. If the barrel stacks are allowed to displace freely on the floor, Candia et al. (2016) showed that MS3 is more effective in three-level barrel stacks than in six-level barrel stacks.

Using a two-dimensional physical model based on rigid body dynamics and contact elements (Candia et al. 2010), the seismic response was computed for the abovementioned configurations with and without mitigation measures. In the present study, the system of equations that describes the response of the barrel stack consisting of N_s bodies is written as:

$$\boldsymbol{M}\ddot{\boldsymbol{q}} = \boldsymbol{Q}_e + \boldsymbol{Q}_c + \boldsymbol{Q}_{ps} \tag{1}$$

where $\boldsymbol{q}$ is a vector of $3N_s$ generalized coordinates (DOF) that define the position and orientation of each body's reference frame, $\ddot{\boldsymbol{q}}$ denotes the second time derivative of $\boldsymbol{q}$, $\boldsymbol{M}$ is a diagonal the mass matrix, $\boldsymbol{Q}_e$ is a vector of external forces (e.g., self-weight), and $\boldsymbol{Q}_c$ is a vector of equipollent contact forces between bodies. The vector, $\boldsymbol{Q}_{ps}$, used only in MS2 models, accounts for the forces developed by the prestressed cable. Additionally, the Cradle Extender used in MS1 models is treated as a geometric feature of the top rack and is assumed infinitely rigid. In this formulation, the position and velocity of the ground are specified as boundary conditions. The solution of Equation 1 was implemented using a space-state explicit algorithm from which the number of collapsed barrels can be determined.

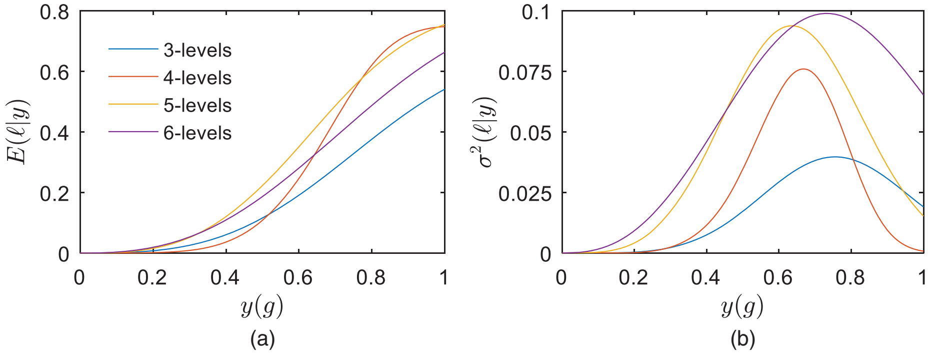
Candia et al. (2016) defined the loss ratio, ℓ, as the quotient of the expected seismically-induced dollar losses due to collapsed wine barrels to the cost of replacement of the wine barrel stacks, and proposed vulnerability functions that express the loss ratio conditioned on a PGA level. The expected loss, $E(\ell \mid y)$, and loss variance, $\sigma^2(\ell \mid y)$, for each wine barrel stack configuration can be approximated using continuous functions as:

$$E(\ell \mid y) = \ell_{N_s} - \ell_{N_s} exp(-y^a/b) \tag{2}$$

$$\sigma^2(\ell \mid y) = c \cdot (E(\ell \mid y))^d \cdot (\ell_{N_S} - E(\ell \mid y))^d \tag{3}$$

where y is the PGA, and the fitting parameters (a, b, c, and d) are specific to each barrel stack configuration and mitigation strategy. The term, ℓ_{N_s}, is the maximum loss ratio on a wine barrel stack composed of N_s barrels, which considers the fact that the lower barrels do not break upon impact with the ground, and, thus ℓ_{N_s} takes the values $\frac{4}{6}, \frac{6}{8}, \frac{8}{10}, \frac{10}{12}$ for barrel stacks of three, four, five, and six levels, respectively. Figure 3 presents an example of Equations 2 and 3 for barrel stacks without mitigation measures and ground motion acting along the transverse direction (Candia et al. 2016). Note that as the PGA increases, the expected loss approaches ℓ_{N_s} and the loss variance decreases.

As is commonly assumed (e.g., Jaimes et al. 2015) in the present study, the probability density function of the loss ratio is Beta, with mean and variance given by Equations 2 and 3, respectively.



(a)

(b)

Figure 3. Vulnerability functions for four wine barrel stack configurations in the transverse direction and no mitigation measures: (a) expected loss and (b) loss variance.

STEP 4: EVENT-BASED SEISMIC RISK ASSESSMENT

Loss ratios are evaluated in an event-based probabilistic framework, where losses are estimated for each hazard level. One of the most common ways to express risk is by means of the EAL. This risk assessment approach can be performed for either single or multiple wine barrel stacks.

For a single wine barrel stack, the evaluation of the EAL consists of computing the expected loss for all earthquake events that collectively describe the seismic hazard (i.e., all combinations of earthquake magnitude and location), and then integrating these results using the annual occurrence probability of each event as weight factors. Using total probabilities, the EAL for a single wine barrel stack, $E(\ell)$, can be expressed as:

$$E(\ell) = \sum_{i=1}^{\#Events} E(\ell \,|\, Event\, i) p_A(Event\, i) \tag{4}$$

where $E(\ell \,|\, Event\, i)$ is the expected loss that an i-th event causes to the exposed asset, and $p_A(Event\, i)$ is the annual occurrence probability of the i-th event. The risk due to seismic hazard is commonly expressed in terms of the exceedance rate of the loss or loss exceedance curve (LEC), defined by the following equation (Esteva 1967):

$$\nu(\ell) = \sum_{i=1}^{\#Events} P(L > l \,|\, Event\, i) p_A(Event\, i) \tag{5}$$

where $P(L > l \,|\, Event\, i)$ is the probability that the loss is greater than ℓ given that the i-th event has occurred. The sum in the previous equations is carried out for all potentially damaging events (i.e., the combination of all relevant events of earthquake magnitudes and locations). The probability of exceeding the loss, ℓ, conditioned on the occurrence of the i-th event is:

$$P(L > l \,|\, Event\, i) = \int_y P(L > l \,|\, y) f_A(y | Event\, i) dy \tag{6}$$

where $P(L > l \,|\, y)$ is the exceedance probability of the loss, ℓ, conditioned on intensity, y, and $f_A(y \,|\, Event\, i)$ is the probability density of the ground motion intensity, y, conditioned to the occurrence of the i-th event. This term takes into account the uncertainty of the ground motion intensity determined from standard PSHA procedures (Cornell 1968, Esteva 1967, McGuire 2008).

Similarly, for multiple wine barrel stacks, the total loss, C, is the sum of individual losses of N spatially distributed units given by Equation 4. Then, the mean total loss, $E(C)$, and the variance of the total loss $VAR(C)$ for all wine barrel stacks can be evaluated as

$$E(C) = \sum_{j=1}^{N} M_j E(\ell_j) \tag{7}$$

$$VAR(C) = \sum_{j=1}^{N} M_j \cdot VAR(\ell_j) + 2\sum_{j=1}^{N}\sum_{k=j}^{N} M_j \cdot M_k \cdot \rho_{jk}\sqrt{VAR(\ell_j) \cdot VAR(\ell_k)} \tag{8}$$

where ρ_{jk} is the correlation coefficient between the losses j and k, and M_j and M_k are the replacement values of the wine barrel stacks j and k, respectively. It is should be noted that Equation 7 is also the EAL for multiple wine barrel stacks. In general, Equations 7 and 8 are used in conjunction with an assumed Beta PDF. Therefore, the probability that the total loss, C, is larger than a loss, c, is computed from:

$$P(C > c) = 1 - F(C, \alpha, \beta) \tag{9}$$

where $F(C, \alpha, \beta)$ is the Beta CDF, and α and β are shape parameters that can be written in terms of the mean and variance of the total loss (Benjamin and Cornell 1970) as:

$$\alpha = \frac{1 - [1 + CV^2(C)]E(C)}{CV^2(C)} \tag{10.1}$$

$$\beta = \alpha \cdot \left[\frac{1 - E(C)}{E(C)}\right] \tag{10.2}$$

and the coefficient of variation $CV(C)$ is computed as:

$$CV(C) = \frac{\sqrt{VAR(C)}}{E(C)} \tag{11}$$

STEP 5: COST-BENEFIT ANALYSIS

The economic efficiency of pre-earthquake strengthening of wine barrel stacks can be estimated in terms of the net present value of the investment of the retrofit. If the expected benefits exceed the expected loss, the present value is positive (benefit/cost ratio greater than one), and the retrofit investment is economically justified (Kappos and Dimitrakopoulos 2008, Valcárcel et al. 2013). The benefit/cost ratio (due to the retrofit) is computed (Smyth et al. 2004, Kappos and Dimitrakopoulos 2008, Valcárcel et al. 2013) as:

$$B/C = \frac{L_U - L_R}{C_R} \tag{12}$$

where L_U is the total loss in terms of present worth due to all future earthquakes for the current condition; L_R is the total loss in terms of present worth due to all future earthquakes for the retrofitted case, and C_R is the retrofitting cost. In the long term, it is assumed that the expected losses L_U and L_R are equal to the mean total loss $E(C)$ as in Equation 7 (e.g., Valcárcel et al. 2013). Therefore, the expected value of L_U and L_R included in Equation 12 is calculated as:

$$L = \frac{E(C)}{\tau} \tag{13}$$

where τ is the discount rate. On other hand, to estimate the expected losses for a given lifespan, t_{life}, the expected loss and its time of occurrence are considered as random variables. Then, based on the LEC, stochastic loss events can be generated for a given lifespan t_{life}. On this basis, the present value of loss, L, can be obtained from (e.g., Valcárcel et al. 2013).

$$L = \sum_{i=1}^{t_{life}} L_i e^{-\tau t_i} \tag{14}$$

where L is the present value of losses, t_{life} is the lifespan of the barrel stacks under study and t_i is the time of occurrence of the loss event, L_i.

APPLYING THE METHODOLOGY TO CHILEAN WINERIES

STEP 1: CHARACTERIZATION OF CHILEAN SEISMIC HAZARD

For PSHA, the seismicity of the Pacific coast of Chile was divided into three groups: interface, intraslab, and shallow earthquakes. The first group was subdivided into 25 seismic sources, the second group was subdivided into 12 seismic sources, while the third group was divided into five seismic sources. It is considered that each seismic source is responsible for generating seismic events with magnitude exceedance rates that follow the modified Gutenberg-Richter model. The parameters of the seismicity models and the geometry of Chilean seismic sources were obtained from Martin (1990), Núñez (2014), and Núñez et al. (2015), which are based on statistical analyses of the available earthquake catalogues from 1906–1985 and 1973–2012. For each seismic source, a set of events with specific magnitude and hypocenter location were generated with their respective annual occurrence probability of the i-th event $p_A(Event\, i)$ using CRISIS software (Ordaz et al. 2007), so that the total number of events generated for each seismic source describes the magnitude exceedance rate. Once the seismicity has been determined for each seismic source, the intensities of events associated with seismic activity were estimated using ground motion prediction models. The attenuation of PGA resulting from interface/intraslab earthquakes was modeled using the ground motion prediction equation (GMPE) proposed by Boroschek et al. (2012) and Abrahamson et al. (2016). For shallow crustal earthquakes, the GMPE proposed by Sadigh et al. (1997) was used. These relations are probabilistic because the intensities are regarded as random variables whose probability distribution is fixed by the GMPE, for a given seismic event.

In this study, an individual seismic event is simply the probabilistic geocoded scenario of the ground motion associated an intensity measure (e.g., PGA) generated by this seismic event. Each scenario gives, in probabilistic terms, the geographical (spatial) distribution of the ground motion intensities produced by this event. For a given event, the scenario consists of a pair of grids of values associated to the intensity measure. The first one gives the geographical distribution of the median intensity and the second one gives the geographical distribution of the standard deviation of the natural logarithm of the intensity. Therefore, for each winery, it is possible to estimate the probability density of the ground motion intensity conditioned to the occurrence of the i-th event (see Equation 6). Thus, the ground motion individual intensities are correlated, because they are associated with the same i-th event; this implies that they are neither independent nor exclusive. A seismic hazard map for Central Chile is shown in Figure 4 for PGA with a 10% exceedance probability in 50 years.

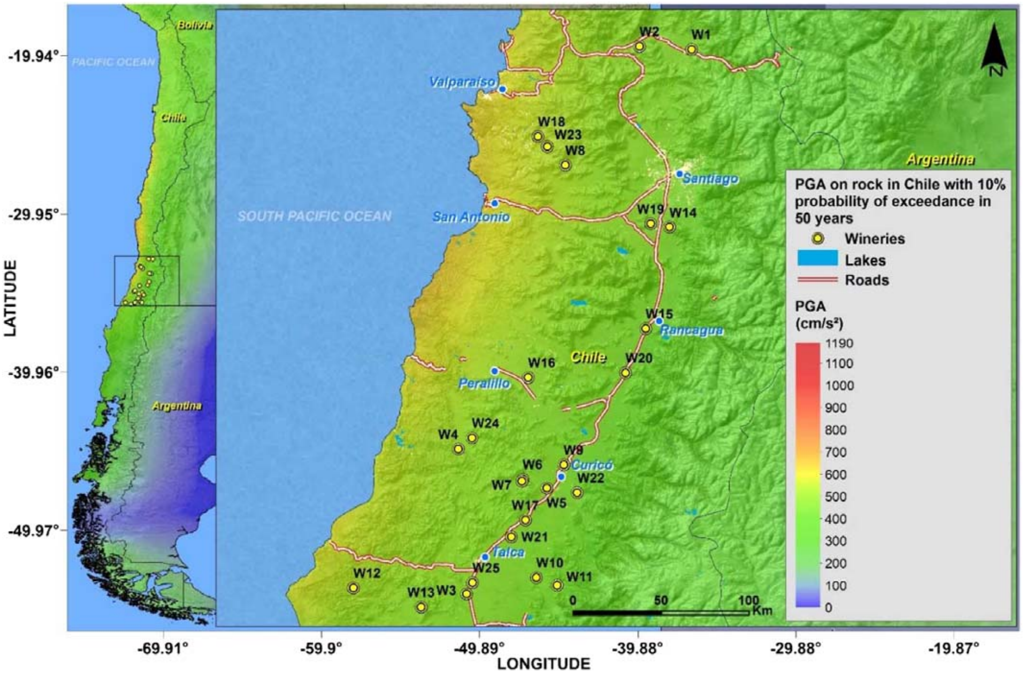


Figure 4. PGA on rock in Chile with 10% exceedance probability in 50 years and location of studied wineries.

STEP 2: IDENTIFICATION OF EXPOSURE MODEL OF WINE BARREL STACKS

The inventory of wine barrel stacks used in this study is distributed in 25 wineries located in South Central Chile, as shown in Figure 4. The cost-benefit analysis was performed for a total of 16 barrel stack configurations, as a result of combining barrel stacks with three, four, five, and six levels, and the mitigation strategies MS0, MS1, MS2, and MS3. It is assumed that the 25 wineries have identical barrel stack configurations. The decision maker is also assumed to be the owner of the 25 wineries, who is responsible not only for the cost of repair or replacement of the damaged wine barrels, but also for any loss of profit from any damaged winery. The economic value (standard replacement cost) for each wine barrel stack configurations is summarized in Table 1.

These values were obtained as follows: the replacement cost for a single wine barrel was assumed as US$1,000 and only one barrel stack per winery is considered in this study. Therefore, the cost of wine barrel stacks of three, four, five, and six levels without mitigation measures (MS0) is US$6,000, US$8,000, US$10,000, and US$12,000, respectively, which, multiplied by the number of wineries, provides the values given in the first column of Table 1. On the other hand, retrofitting costs are related to the mitigation measure adopted in order to increase the safety of wine barrel stacks. In this study, we estimated the retrofitting cost with Cradle Extender (MS1) as US$60 per wine barrel stack (Wine Business), and the retrofitting cost with prestressed cable (MS2) as US$400 per wine barrel stack. Finally,

Table 1. Replacement cost of wine barrel stacks with and without mitigation measures

Number of levels	Replacement cost (US$) MS0	MS1	MS2	MS3
3	150,000	151,500	160,000	200,000
4	200,000	201,500	210,000	250,000
5	250,000	251,500	260,000	300,000
6	300,000	301,500	310,000	350,000

the retrofitting cost of the reduced base friction isolation (MS3) was estimated at US$2,000 per wine barrel stack.

STEP 3: VULNERABILITY FUNCTIONS

The number of wine barrel collapses at different PGA levels was modeled using the vulnerability functions given by Equations 2 and 3, developed after Candia et al. (2016). The fitting parameters (a, b, c, and d) were computed for each wine barrel stack configuration through a nonlinear regression, and their values are presented in Table 2. To account for the ground motion variability, this study used a set of 30 synthetic acceleration records compatible with a Newmark Hall spectrum in medium dense to firm soil, as outlined in Candia et al. (2016). The records were further scaled to PGA values between 0.2–0.7 g in 0.1 g increments.

STEP 4: PROBABILISTIC SEISMIC RISK ANALYSIS

The seismic induced losses for the 25 wineries were evaluated by combining the seismic hazard with the loss vulnerability functions of the wine barrel stacks listed in the inventory. The computation was performed in the software CAPRA (ERN-AL 2010), a platform for probabilistic risk assessment of natural hazards. The results presented here are the potential economic consequences expressed in terms of EAL or pure premium for each exposed element, or in probabilistic terms, the EAL $E(\ell)$, given by Equation 4. Figures 5 and 6 show the distribution of the EAL on a three- and six-level barrel stack, respectively. In these figures,

Table 2. Parameter values of vulnerability functions for each wine barrel stack configuration studied

No. of levels	ℓ_{NS}	MS0 (no mitigation measures) a	b	c	d	MS1 (with Cradle Extender) a	b	c	d	MS2 (prestressed cable) a	b	c	d	MS3 (friction isolation) a	b	c	d
3	4/6	3.13	0.60	1.07	1.50	9.09	0.09	0.30	0.68	2.25	1.60	0.16	1.51	2.59	3.16	0.71	1.27
4	6/8	5.16	0.18	0.67	1.11	4.56	0.32	0.67	1.02	1.09	2.20	0.18	1.72	4.61	0.34	1.99	1.59
5	8/10	3.13	0.35	0.83	1.19	2.59	0.59	0.74	1.12	1.19	2.81	0.16	1.82	2.92	0.49	0.60	1.00
6	10/12	2.65	0.63	0.54	0.97	2.23	1.02	0.54	0.96	2.13	3.16	0.15	1.76	2.44	0.80	0.50	0.89

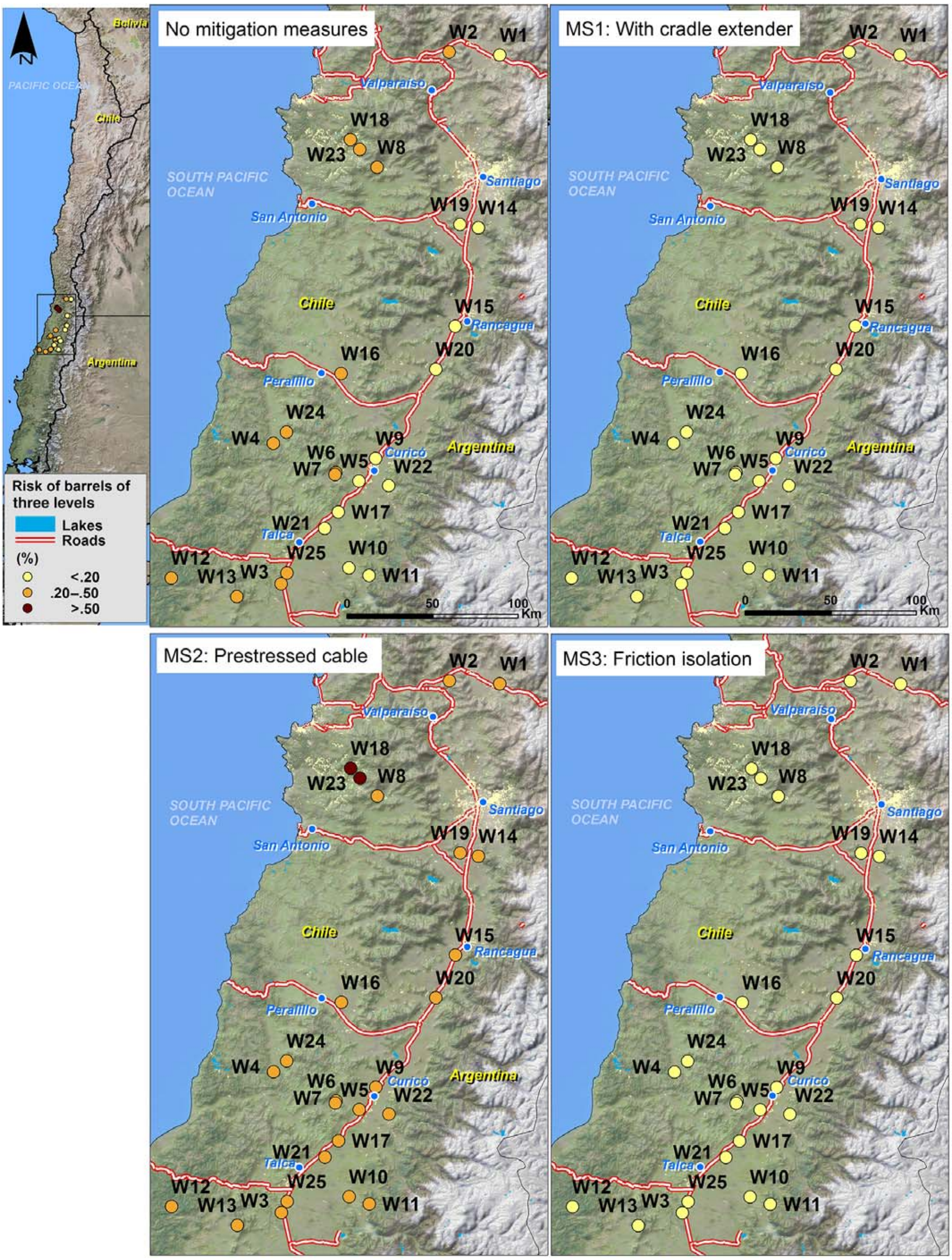


Figure 5. Distribution of the EAL due to earthquake for barrel-stack systems of three levels, without mitigation measures (left-top) and with mitigation strategies MS1 (right-top), MS2 (left-bottom), and MS3 (right-bottom). This seismic risk map for wine barrel stacks is a useful tool for developing appropriate strategies for regional planning. Notice that this map is easy to communicate to decision makers (i.e., winery owner), even if they are not familiar with formal risk results.

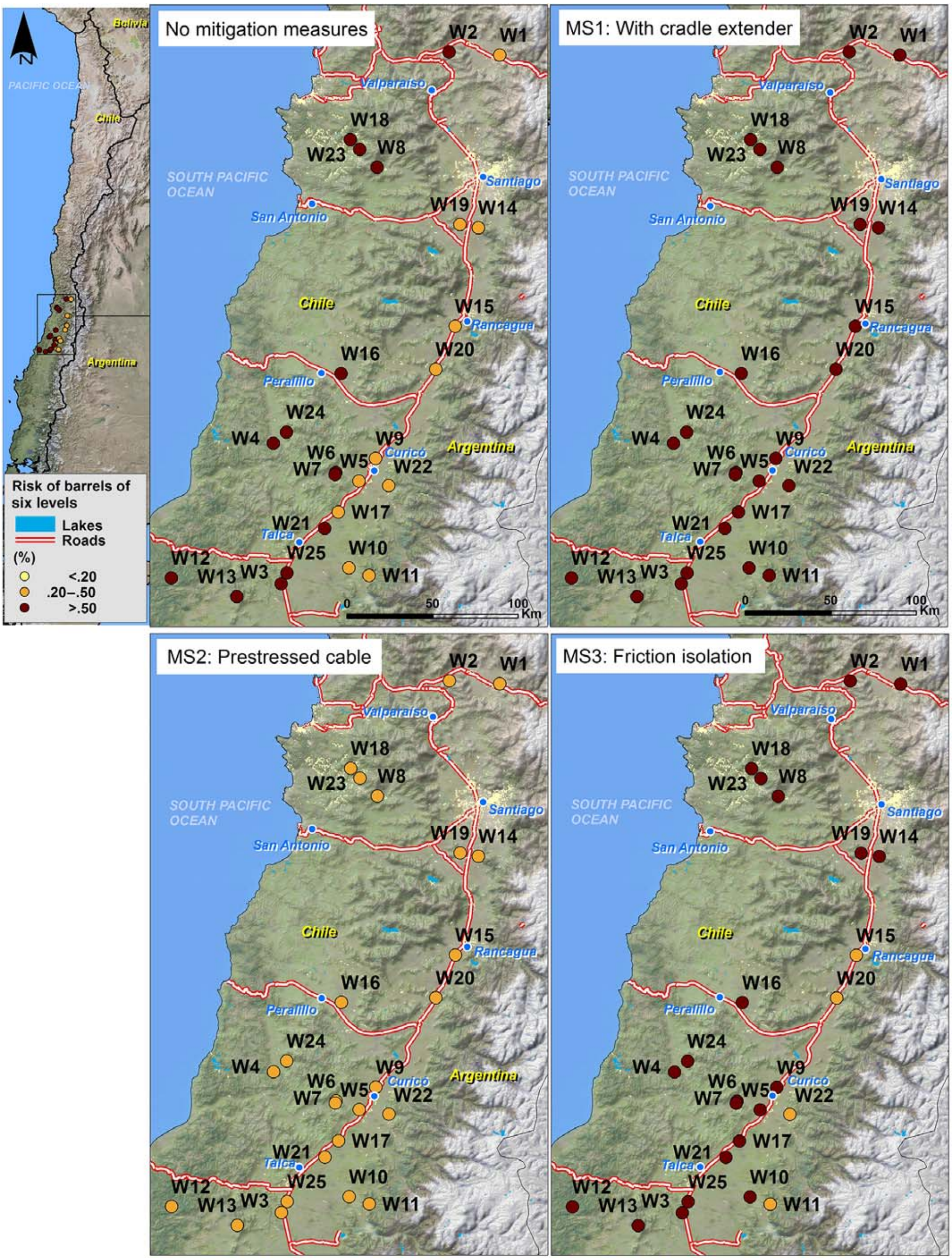


Figure 6. Distribution of the EAL due to earthquake for barrel-stack systems of six levels, without mitigation measures (left-top) and with mitigation strategies MS1 (right-top), MS2 (left-bottom), and MS3 (right-bottom).

the nonretrofitted condition MS0 is shown in the top-left corner, the mitigation strategy MS1 is shown in the top-right corner, MS2 in shown in the the bottom-left corner, and MS3 is shown in the bottom-right corner. Three intervals of the EAL values were considered: EAL less than 0.20%, EAL between 0.20% and 0.50%, and EAL greater than 0.50%.

For three-level barrel stacks (Figure 5), results show that 13 out of 25 (i.e., 52%) non-retrofitted barrel stacks have an EAL greater than 0.20%. If mitigation strategies MS1 and MS3 are implemented, all barrel stacks have an EAL less than 0.20%. However, the mitigation strategy MS2 (prestressed cable) has a detrimental effect on the losses computed on a regional level, with values above 0.20% on all 25 barrel stack systems (Figure 5, bottom-left).

On the other hand, the losses computed on a six-level barrel stack show some remarkable differences compared to losses with a three-level stack. Since the collapse on a six-level barrel sack is controlled by overturning modes rather than top barrel ejection (Candia et al. 2016), the Cradle Extender (MS1) and reduced base friction (MS3) are not effective loss mitigation strategies; indeed, the computed losses may even exceed those of the

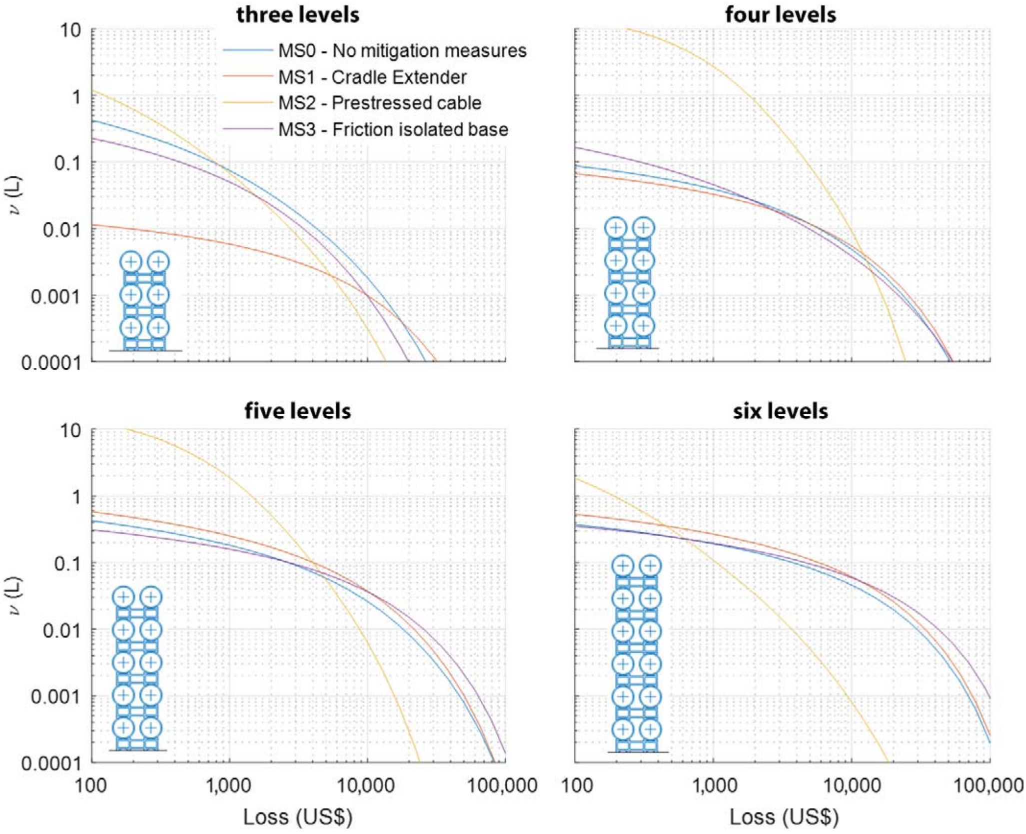


Figure 7. LECs for barrel stacks of three, four, five, and six levels with and without mitigation measures.

nonretrofitted condition (Figure 6, top-right and bottom-right). Instead, the prestressed cable (MS2) significantly reduces probability of failure by overturning, leading to a uniform loss ratio throughout the region.

Figure 7 shows the LEC for all wine barrel stacks computed from Equation 5; these curves represent the exceedance rate of the loss (or equivalently, the reciprocal of the return period, T_R). Based on the loss exceedance rates, a winery owner or decision maker can judge whether investing on a particular mitigation measure is justified or not. For instance, the losses for barrel stacks of the three, four, five, and six levels and MS0 (no mitigation strategies) associated with an annual exceedance frequency of 0.004 (i.e., TR = 250 years) are US$7,490, US$22,950, US$2,490 and US$19,900, respectively. Depending on the stakeholder's risk tolerance, the owner may decide to manage for losses up to a given return period.

STEP 5: COST-BENEFIT ANALYSIS

Table 3 shows a summary of the exposed values, expected total loss in terms of present worth, net present value, retrofitting cost, and calculated benefit-cost ratio (B/C). In order to reflect the preferences of the decision maker (i.e., the winery owner), the benefit-cost ratios were calculated using Equation 12, with a discount rate of 4% (e.g., usual values of τ are 2%–5% per year, Valcárcel et al. 2013). For three-level wine barrel stacks, the Cradle Extender (MS1) avoids a large number of barrel collapses, thereby significantly increasing the benefit-cost ratio (B/C = 5.05). The mitigation strategies MS2 and MS3 result in B/C values of −0.63 and 0.07, respectively, and therefore are not advised for three-level barrel stacks.

Table 3. Summary of results of cost-benefit analysis

No. of levels	Mitigation strategy	Exposed value US$	E(C) (Equation 7)	*L* (net present value) (Equation 13)	Retrofitting cost, C_R	B/C (Equation12)
3	MS0	150,000	341.59	8,539.75	–	–
	MS1	151,500	38.41	960.25	1,500	5.05
	MS2	160,000	595.36	14,884.00	10,000	−0.63
	MS3	200,000	203.75	5,093.75	50,000	0.07
4	MS0	200,000	224.17	5604.25	–	–
	MS1	201,500	214.64	5366.00	1,500	0.16
	MS2	210,000	10,042.92	251,073.00	10,000	−24.55
	MS3	250,000	241.92	6048.00	50,000	−0.01
5	MS0	250,000	1,130.19	28254.75	–	–
	MS1	251,500	1,579.72	39,493.00	1,500	−7.49
	MS2	260,000	7,901.19	197,529.75	10,000	−16.93
	MS3	300,000	1,334.14	33,353.50	50,000	−0.10
6	MS0	300,000	1667.01	41,675.25	–	–
	MS1	301,500	2260.90	56,522.50	1,500	−9.90
	MS2	310,000	945.94	23,648.50	10,000	1.80
	MS3	350,000	2,229.87	55,746.75	50,000	−0.28

For six-level wine barrel stacks, the mitigation strategies MS1 and MS3 result in negative benefit/cost ratios. However, the prestressed cable (MS2) yields B/C = 1.80, which economically justifies investing in this mitigation strategy.

For four-level barrel stacks, the mitigation strategy MS1 yields a ratio B/C = 0.16, and in five-level stacks, all computed ratios are negative. Therefore, the studied mitigation strategies for wine barrel stacks of intermediate height (i.e., four and five levels) did not translate into a significant loss reduction; indeed, the losses may even increase after implementation of the mitigation strategy.

CONCLUSIONS AND RECOMMENDATIONS

In this cost-benefit analysis of seismic mitigation measures for wine barrel stacks, the risk parameters were evaluated in an event-based probabilistic framework for seismic hazards. Results were integrated, including the uncertainties related to magnitude, size, and timing of earthquakes and the seismic-induced damage and losses to wine barrel stacks. The systematic procedure for evaluating decisions related to strategic risk management was divided into five steps: (1) to characterize the seismic hazard in terms of the annual rate of occurrence and the aleatory variability of ground motions at the sites of interest; (2) to describe the exposure of wine barrel stacks at risk; (3) to compute vulnerability functions of barrel stacks with and without seismic mitigation measures; (4) to conduct a probabilistic seismic risk analysis for selected Chilean wineries; and (5) to perform cost-benefit analyses for nonretrofitted conditions and alternative risk mitigation measures. This methodology was used to conduct a parametric analysis

Twenty-five wineries located in seismic hazard zones in Chile were considered, in which a decision between four alternatives would/could be made: (a) no mitigation measures; b) the use of Cradle Extenders (MS1); c) the use of a prestressed cable (MS2); and d) the use of reduced base friction (MS3). Results showed that mitigation measures resulting in positive benefit-cost ratios using Equation 12 can be achieved for three- and six-level wine barrel stacks using mitigation strategies MS1 and MS2, respectively. The mitigation strategies MS1 and MS2 help to prevent a large number of wine barrel stack collapses; therefore, the retrofit investment is economically justified. All of the three studied mitigation strategies provided a positive benefit-cost ratio for four- and five-level barrel stacks; however, the computed B/C ratios are considered to be insignificant (e.g., MS1 mitigation measure induced B/C = 0.16). Alternatives mitigation strategies should be proposed (e.g., mitigation measures with lower cost of implementation), or other mitigation measures that will more efficiently prevent the four- and five-level barrel stacks from collapsing.

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