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EVALUATION AND COMMUNICATION OF SEISMIC RISK BASED ON THE LONG-TERM AND SHORT-TERM RISK TOLERANCE

A. Babič(1), M. Dolšek(2)

(1) *Assistant, University of Ljubljana, Faculty of Civil and Geodetic Engineering, anze.babic@fgg.uni-lj.si*
(2) *Professor, University of Ljubljana, Faculty of Civil and Geodetic Engineering, matjaz.dolsek@fgg.uni-lj.si*

Abstract

An approach for the evaluation and communication of seismic risk is presented that is based on a five-grade grading system. Each of the grades (AA, A, B, C and D) indicates a level of long-term and short-term risk tolerance. Long-term risk tolerance is equivalent to the conventional concept of risk tolerance, while short-term risk tolerance corresponds to a specific period of time in which risk is allowed to be greater than in the long term. The grading process is performed in two steps. First, the initial grade is determined based on the comparison between the estimated risk and a set of risk boundaries. If the initial grade corresponds to long-term negligible or tolerable risk, the grading process is concluded. However, if risk is long-term intolerable, another step is performed, in which the initial grade is gradually reduced to the lowest grade (grade D). The time periods corresponding to the reduction of grades are determined by comparing the estimated cumulative risk to the cumulative risk boundaries. The grading system can be used for multiple purposes. As a communication tool, it can serve to enhance the public discussion about tolerable risk and to incorporate the aspect of seismic risk in self-regulating markets. However, it can also be used as the basis for disaster risk management by linking grades to specific sets of actions which are scheduled after the risk evaluation. The use of the grading system is demonstrated by performing a risk evaluation of a precast reinforced concrete building, which is exposed to long-term intolerable risk. It is shown that by using the grading system in risk evaluation, the period can be determined in which the owner is required to strengthen the building in order to avoid detrimental actions.

Keywords: risk evaluation; risk communication; grading system; short-term risk tolerance; long-term risk tolerance

1. Introduction

Although the built environment behaves as a system of systems, the measures to reduce the seismic risk are often applied arbitrarily at the facility level. This is reflected by several studies that define the tolerable or acceptable risk for individual facilities [1, 2, 3]. In the most straightforward approach, the tolerable risk can be considered as the threshold for the estimated risk. In such an approach, the tolerable risk and the estimated risk are effectively treated, respectively, as the capacity and demand. It is thus required that the demand is less than the capacity. Such a binary decision model is embedded in the current codes for the design of buildings, although the demand and the capacity are not related to risk measure. Although engineers are familiar with the binary decision model, its efficiency for decision making may be questionable, because the risk estimation is inherently associated with some level of uncertainty, which can lead to different experts producing different outcomes of the risk evaluation, thus jeopardizing the public's trust in the estimated risk and its communicators [4].

Another problem with the binary decision model is that it is unable to distinguish between facilities exposed to tolerable risk, and between facilities exposed to intolerable risk. In the case of evaluation of existing facilities, this shortcoming prevents the decision-maker from prioritizing which facilities to retrofit first, while giving more time to the owners of facilities which are associated with a lesser but still intolerable risk. In the case of a large-scale evaluation, such an approach would result in a situation where all facilities exposed to long-term intolerable risk would be confronted by actions at the same time. If these actions were of a restrictive nature (e.g. involving temporary or permanent suspension of the facility operation), their sudden effect could disrupt normal functioning of the community, which is contrary to their initial intent, i.e. the prevention of such disruptions.

In the paper, a different approach for the evaluation and communication of seismic risk is presented. It is based on a recently developed grading system [5], which consists of five grades (AA, A, B, C and D). The grades represent different levels of risk tolerance, which can be approximately related to terms used by Helm [6] (i.e. negligible risk, as low as reasonably practicable (ALARP) risk, possibly unjustifiable risk and intolerable risk). However, the novelty in the proposed grading system is that each grade indicates a level of long-term and short-term risk tolerance. Long-term risk tolerance is equivalent to the conventional concept of risk tolerance and is defined by several risk boundaries, while short-term risk tolerance corresponds to a specific finite period of time in which risk is allowed to be greater than the long-term tolerable risk. This approach makes it possible to define the time when the estimated risk, if greater than the long-term tolerable risk, becomes intolerable. Thus, the proposed grading system assists in designing and managing risk mitigation strategies over the long term. This could help to prevent situations where a great deal of facilities is confronted by actions simultaneously. Moreover, the grading system is formulated so that a small change in the risk estimate can only cause a small change in the consequences of the grading. In this way, the effect of uncertainties in risk estimation cannot significantly impact the outcome of the risk evaluation.

The grading system is intentionally introduced in two stages (Section 2). In the first stage, a two-grade grading system (consisting of grades A and B) is developed based on the binary decision model that is incorporated in the design codes of structures and most of other regulatory documents. In the second stage, the five-grade grading system is developed by expanding the two-grade system. After the presentation of the grading system, its advantages compared to the conventional binary decision model are discussed (Section 3). The use of the grading system is then demonstrated by performing a risk evaluation of a precast reinforced concrete building (Section 4). The conclusions are drawn in Section 5.

2. Formulation of the grading system

In this section, the grading criteria of the proposed grading system are first introduced (Section 2.1), followed by the formulation of the five-grade grading system. The latter is derived from a simplified two-grade grading system (Section 2.2), which reflects the decision model incorporated into the conventional codes for design of structures. The five-grade grading system is then developed by expanding the two-grade system (Section 2.3).

2.1 Grading criteria

The grading criteria contain the risk criterion and the cumulative risk criterion. The risk criterion is associated with the long-term risk tolerance and refers to a fixed period (e.g. one year), while the cumulative risk criterion is time-dependent, which allows introducing the concept of short-term risk tolerance into the proposed grading system.

The risk criterion is based on a comparison between the estimated risk P (where P stands for the *Performance* of the facility) and a set of risk boundaries R_{ug} (where R stands for the *Resistance*, and *ug* represents the *upper grade* of the two grades separated by R_{ug}). The risk boundaries R_{ug} have to be pre-defined by the legal entity that requires the risk evaluation (e.g. the regulator, an insurance company, or other stakeholders). Various risk measures can be used to express P and the corresponding R_{ug}. In this paper, risk measures are defined by the frequency of an event and the expected economic loss, which are commonly used for communicating risk in engineering problems. However, it should be noted that the grading system is not limited to the use of these risk measures, as shown in [5].

The cumulative risk criterion involves the evaluation of the cumulative risk $\widehat{P}(\Delta t)$ predicted for a period of Δt, which is counted from the time of the risk evaluation T_{eval}. In general, $\widehat{P}(\Delta t)$ is based on the estimated risk P and the assumed effect of discounting. However, if the discount rate is small and/or Δt is short, then the effect of the discount rate on the grading process may be disregarded. Then, $\widehat{P}(\Delta t)$ can be calculated as:

$$\widehat{P}\left(\Delta t\right)=\int_{T_{eval}}^{T_{eval}+\Delta t}P\left(\tau\right)d\tau\,. \tag{2.1}$$

If risk evaluation is foreseen as a one-time event and changes in risk cannot be reliably predicted in advance, it is reasonable to assume that P is constant over time. Under these assumptions, the calculation of the cumulative risk can be simplified:

$$\widehat{P}\left(\Delta t\right)=P\cdot\Delta t\,. \tag{2.2}$$

Hereinafter, Eq. (2.2) is used to define $\widehat{P}(\Delta t)$. Note, however, that the consideration of constant risk and insignificant effect of discount does not limit the generality of the proposed grading system.

The cumulative risk criterion is evaluated by comparing $\widehat{P}(\Delta t)$ to a set of cumulative risk boundaries $\widehat{R}_{ug}(\Delta t)$. Since $\widehat{R}_{ug}(\Delta t)$ are derived on the basis of the short- as well as the long-term tolerable risk (as explained in Section 2.3), the comparison between $\widehat{P}(\Delta t)$ and $\widehat{R}_{ug}(\Delta t)$ may result in a different grade over time. Thus, the grades may become time-dependent.

In general, more than one risk measure can be used in the risk evaluation. In such a grading process, a grade is assigned to each risk measure. Therefore, the grading criteria need to be specified for each risk measure separately. It is foreseen that each grade assigned has a particular pre-defined consequence, i.e. triggers a particular pre-defined action, which should be aimed at reducing risk. In the case when more than one risk measure is considered, it is foreseen that the envelope of grades (i.e. the lowest grade) is assigned to the facility because it is considered that all risk measures need to meet their objectives.

2.2 The two-grade grading system

A two-grade grading system was developed in order to reflect the philosophy embedded in the conventional design codes for structures (e.g. [7, 8]). These codes generally incorporate a binary decision model which divides facilities into those which are compliant and those which are non-compliant with the code. Compliance with the code is usually achieved by many different design checks, without requiring estimation of risk. Nevertheless, the decision as to whether a given facility is acceptable or not can also be made from the risk point of view. In this case, decision-making can be formulated by a grading system that foresees two grades (A and B), which correspond, respectively, to the long-term tolerable and the long-term intolerable risk (Fig. 1a). The grade is determined by utilizing the risk criterion, which means that the estimated risk P is compared to risk boundary R_B, which separates grades A and B (Fig. 1b).

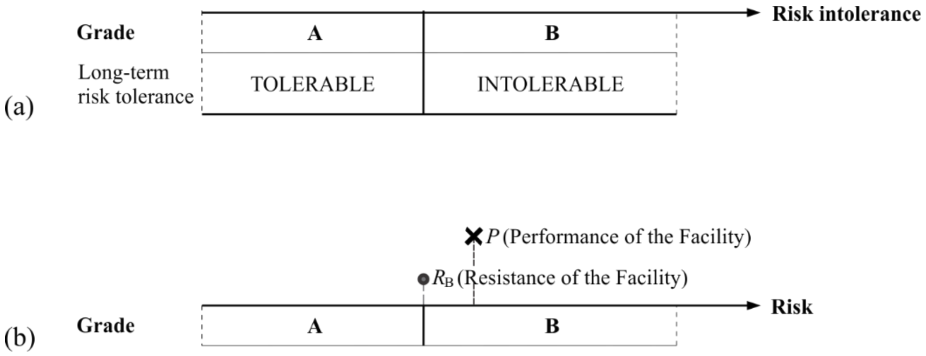


Fig. 1 – (a) The metric (grades and levels of long-term risk tolerance) of the two-grade grading system, and (b) the determination of the grade based on the risk criterion.

The two-grade grading system is simple and easy to understand. Effectively, grades A and B, respectively, imply the passing or failing of the risk evaluation. However, such a grading system does not allow differentiation to be made between facilities exposed to long-term tolerable risk, and those exposed to long-term intolerable risk. Additionally, the two-graded grading system does not reward stakeholders who are willing to invest more in order to improve the performance of new facilities.

2.3 The five-grade grading system

The five-grade grading system is derived from the two-grade grading system. In particular, grade A from the two-grade grading system is divided into grades AA and A, whereas grade B from the same system is divided into grades B, C and D. Grade AA is the most favorable, while grade D is the most unfavorable (Fig. 2a).

The grading process is performed in two steps. In the first step, the facility is evaluated with the initial grade based on the risk criterion. The estimated risk P is compared to the risk boundaries R_A, R_B and R_C, and the grade is assigned as is demonstrated in Fig. 2b. At this point, only grades AA, A, B or C are possible. Grades AA and A indicate long-term negligible and long-term tolerable risk, respectively (Fig. 2a). As explained in the following, the formulation of the grading system ensures that these grades, if assigned, remain unchanged until the next risk evaluation. It is expected that grade AA will be given to facilities where a level of design higher than that corresponding to the current codes has been considered. On the other hand, solely employing the current codes will presumably result in grade A.

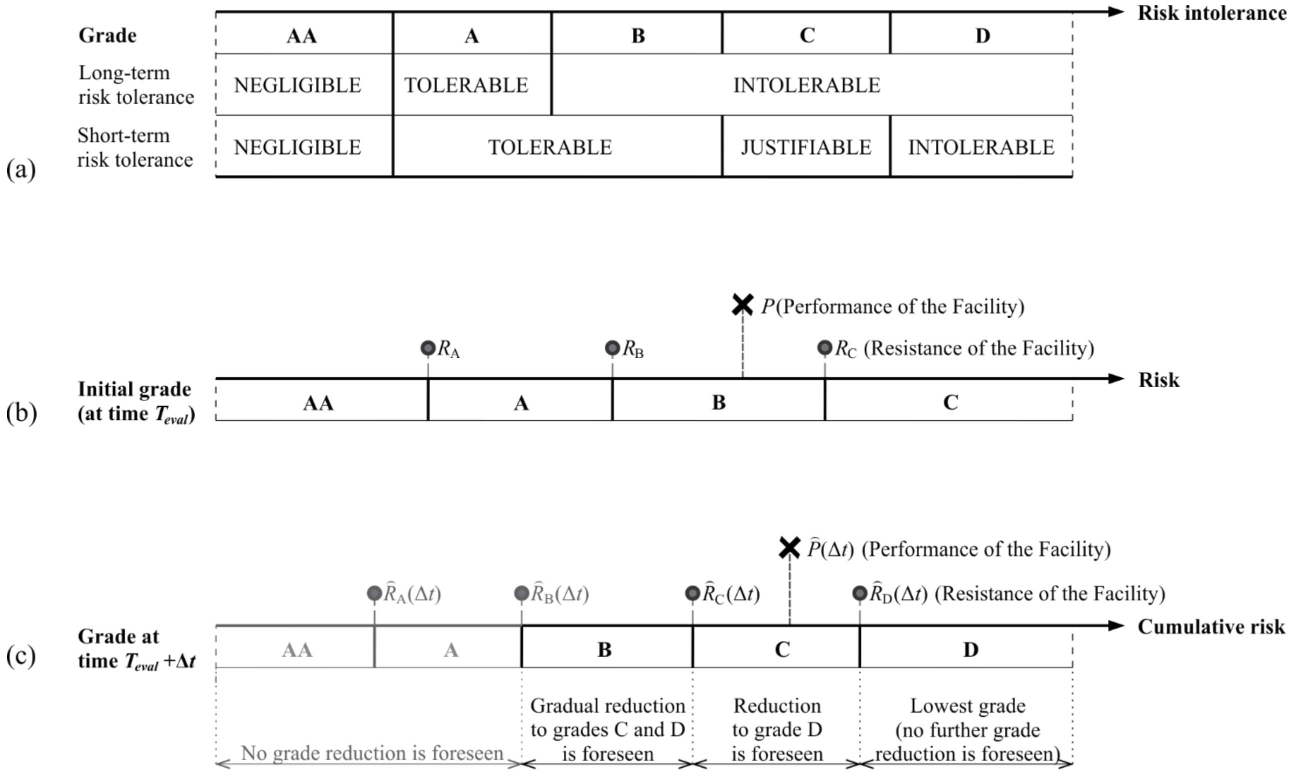


Fig. 2 – (a) The metric (grades, levels of long-term risk tolerance and levels of short-term risk tolerance) of the five-grade grading system, (b) determination of the initial grade based on the risk criterion, and (c) determination of grade at time $T_{eval} + \Delta t$ based on the cumulative risk criterion.

Other facilities, which were built when the design codes were not yet adequately developed are expected to obtain initial grade B or C. Both grades are related to a risk which is considered long-term intolerable. However, the grades differ from the perspective of short-term risk tolerance. Grade B indicates short-term tolerable risk, while grade C indicates short-term justifiable risk (Fig. 2a).

The concept of short-term risk tolerance assumes that the risk to which the facility may be exposed in the short term is greater than the risk to which the facility may be exposed in the long term. In order to incorporate short-term risk tolerance into the grading system, the grading system is integrated into the time domain. The time domain makes it possible to introduce the *reference short-term period* Δt_{ref}, which is defined as the maximum period in which risk that is equal to the risk boundary R_C is tolerated. Thus, the maximum cumulative risk that is tolerated in Δt_{ref} is equal to $R_\mathrm{C} \cdot \Delta t_{ref}$, which is more than the maximum long-term tolerable risk (R_B) accumulated in the same period of time, i.e. $R_\mathrm{B} \cdot \Delta t_{ref}$. The difference between the cumulative risk based on the short-term risk tolerance $R_\mathrm{C} \cdot \Delta t_{ref}$ and the cumulative risk based on long-term risk tolerance $R_\mathrm{B} \cdot \Delta t_{ref}$ is defined as the *additionally tolerated cumulative risk* $\Delta \widehat{R}_{tol}$:

$$\Delta \widehat{R}_{tol} = \left(R_\mathrm{C} - R_\mathrm{B}\right) \cdot \Delta t_{ref} \; . \tag{2.3}$$

Note that the additionally tolerated cumulative risk $\Delta \widehat{R}_{tol}$ controls the short-term risk tolerance. If $\Delta \widehat{R}_{tol}$ is low, the short-term tolerable risk is similar to the long-term tolerable risk. However, if $\Delta \widehat{R}_{tol}$ is high, the risk is allowed to be much greater in the short term than in the long term. Note also that $\Delta \widehat{R}_{tol}$ represents a finite amount of cumulative risk. Therefore, if the risk is long-term intolerable ($P > R_\mathrm{B}$), the estimated cumulative risk $\widehat{P}(\Delta t)$ quickly increases over time and exceeds the cumulative risk that additionally accounts for $\Delta \widehat{R}_{tol}$ (Figs. 2c and 3).

The concept of grade reduction foresees that the initial grade is gradually reduced until it reaches grade D, which is additionally introduced to indicate the long-term intolerable risk. The concept applies to initial grades B and C. For example, if grade C is initially assigned, it is reduced directly to grade D (Fig. 3d). However, if grade B is initially assigned, it is first reduced to grade C and then to grade D (Fig. 3c). The reductions to grades C and D are performed, respectively, at times when the estimated cumulative risk $\widehat{P}(\Delta t)$ (Eq. (2.2)) is equal to the cumulative risk boundaries $\widehat{R}_\mathrm{C}(\Delta t)$ and $\widehat{R}_\mathrm{D}(\Delta t)$. These times can be denoted as $T_{eval} + \Delta t_\mathrm{C}$ and $T_{eval} + \Delta t_\mathrm{D}$, where Δt_C and Δt_D represent the periods after which the grade will be reduced to C and D, respectively.

The boundary $\widehat{R}_\mathrm{D}(\Delta t)$ is defined as the cumulative risk that exceeds the maximum long-term tolerable cumulative risk for $\Delta \widehat{R}_{tol}$:

$$\widehat{R}_\mathrm{D}\left(\Delta t\right) = R_\mathrm{B} \cdot \Delta t + \Delta \widehat{R}_{tol} \; . \tag{2.4}$$

However, the boundary $\widehat{R}_\mathrm{C}(\Delta t)$ is defined by considering that all facilities with the initial grade before being assigned grade D, remain in the range of grade C for an equal period. Moreover, it is foreseen that this period is equal to Δt_{ref}. Such a definition of $\widehat{R}_\mathrm{C}(\Delta t)$ allows the grading system to be robust, which means that a small change in the estimated risk does not significantly change the consequences of the grading (for more discussion on robustness see Section 3). By considering this constraint, $\widehat{R}_\mathrm{C}(\Delta t)$ can be expressed as follows [5]:

$$\widehat{R}_\mathrm{C}(\Delta t) = \frac{R_\mathrm{B} \cdot \Delta t^2 + R_\mathrm{C} \cdot \Delta t_{ref} \cdot \Delta t}{\Delta t + \Delta t_{ref}} \; . \tag{2.5}$$

By now comparing $\widehat{P}(\Delta t)$ with $\widehat{R}_{\mathrm{C}}(\Delta t)$ and $\widehat{R}_{\mathrm{D}}(\Delta t)$, Δt_{C} and Δt_{D} can be calculated:

$$\Delta t_{\mathrm{C}} = \frac{R_{\mathrm{C}} - P}{P - R_{\mathrm{B}}} \cdot \Delta t_{ref}\,, \tag{2.6}$$

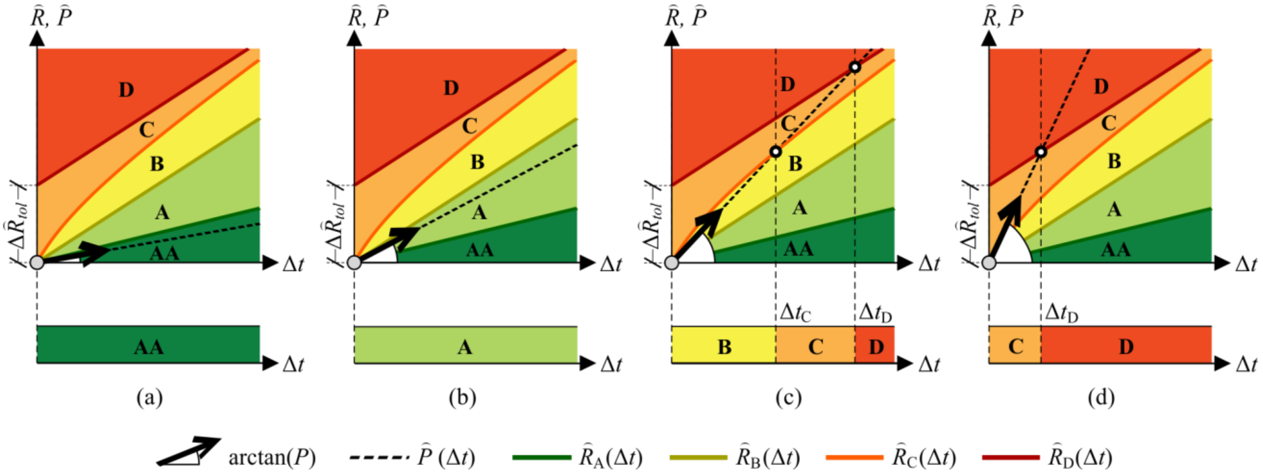
$$\Delta t_{\mathrm{D}} = \frac{R_{\mathrm{C}} - R_{\mathrm{B}}}{P - R_{\mathrm{B}}} \cdot \Delta t_{ref}\,. \tag{2.7}$$

Note that definition of the cumulative risk boundaries $\widehat{R}_{\mathrm{A}}(\Delta t)$ and $\widehat{R}_{\mathrm{B}}(\Delta t)$ is trivial because these boundaries are based only on the long-term risk tolerance, and are therefore linear functions of the corresponding risk boundary and period Δt:

$$\widehat{R}_{\mathrm{A}}(\Delta t) = R_{\mathrm{A}} \cdot \Delta t \tag{2.8}$$

$$\widehat{R}_{\mathrm{B}}(\Delta t) = R_{\mathrm{B}} \cdot \Delta t\,. \tag{2.9}$$

Based on such definitions, the estimated cumulative risk cannot exceed $\widehat{R}_{\mathrm{A}}(\Delta t)$ and $\widehat{R}_{\mathrm{B}}(\Delta t)$ (see Figs. 3a and 3b) if the estimated risk is long-term tolerable ($P < R_{\mathrm{B}}$). This explains why grades AA and A, if assigned, remain unchanged, until the next risk evaluation.



(a) (b) (c) (d)

Fig. 3 – The five-grade grading system in a time-cumulative risk space. The performance of the facility is presented by straight dashed line for the example of initial grades (a) AA (b) A, (c) B, and (d) C.

3. Discussion about the advantages of the five-grade grading systems

With the introduction of the grading system in two stages, it becomes possible to discuss the differences between the conventional grading as implicitly introduced in the codes (i.e. the two-grade grading system), and the proposed five-grade grading systems (Table 1).

The two-grade grading system reflects the current state-of-design of structures, where a given structure is considered either acceptable or not acceptable. It is unable to differentiate between levels of acceptable risk, or between levels of unacceptable risk. Therefore, it may be too rigid for the evaluation of existing facilities. However, the five-grade grading system foresees more grades (AA, A, B, C and D). It can be used to distinguish between facilities that are considered acceptable according to the two-grade grading system, and also to distinguish between facilities that are considered unacceptable from the perspective of the two-grade grading system.

It should be noted that the proposed grading system is not limited to the number of grades. In general, additional grades could be introduced. However, this would require the definition of additional risk boundaries, which is a challenging task. Each boundary should have a clear basis which is understandable to the public. For example, the risk boundaries proposed in the five-grade grading system reflect the following risk levels: a risk level representing the future goal for society (R_A), a risk level with a broad societal consensus on being tolerable in a long term (R_B), and a risk level with a broad societal consensus on being intolerable (R_C) over a given time period (Δt_{ref}).

Another advantage of the five-grade grading system is that it allows the grading process to be robust. Robustness implies that a small change in the estimated risk, which may occur due to epistemic uncertainties, does not significantly change the consequences of the grading. This is an important issue, because the epistemic uncertainties, which are inherent to the entire process of risk estimation, can jeopardize the public's trust in the estimated risk and its communicators [4]. The robustness depends on the type of transition between the implications of the different grades. It is enabled only if all such transitions are designed as "soft" (rather than "strict"), meaning that the change in grade that occurs at a small difference in risk does not imply significantly different actions.

In the case of the two-grade grading system, the different actions corresponding to grades A and B are inherently foreseen. Because a small difference in risk can change the grade from A to B (or vice versa), the transition between the implications of the two grades is characterized as “strict”. Thus, such a grading system is not robust. In the case of the five-grade grading system, robustness is not automatically guaranteed but can be achieved by appropriately selecting input parameters of the grading system and actions corresponding to certain grades. A "soft" transition is generally designed between the implications of grades C and D (regardless of the type of actions which are foreseen for these two grades) because a small change in risk can result in only a small change in Δt_D. Moreover, the transition between the implications of grades B and C can be characterized as "soft" if the time period from the point when the grade is reduced to C to the point when the grade is further reduced to D (i.e. $\Delta t_D - \Delta t_C$) is equal to Δt_{ref}. This constraint ensures that a facility with P just above R_C and a facility with P just below R_C will both obtain grade D approximately after the period of Δt_{ref}, even though the facilities will obtain different initial grades (i.e. B and C, respectively). Also, the accumulated consequences resulting from grade C will be approximately the same for both facilities, because they will both be in the range of grade C for approximately the period of Δt_{ref}. Furthermore, a "soft" transition between grades A and B may be achieved if both grades are associated with the same actions. Effectively, this means that the owners of facilities with the initial grade B are given some time to upgrade their facility, while, in the meantime, the facility remains functionally unaffected by the potential detrimental actions. Finally, the transition between the implications of grades AA and A can be characterized as "soft" if grade AA also corresponds to the same actions as grade A. Such a definition of actions implies that the owners of facilities that are exposed to long-term negligible risk are faced with the same actions as the owners of facilities exposed to long-term tolerable risk (the actions, in this case, should be neutral or favorable for the owners). However, this should not discourage the owners to obtain grade AA, especially when designing new facilities; firstly, because the grade communicates the facility's level of safety, and secondly because the objectives will likely be more and more strengthened as today's new facilities become tomorrow's existing facilities.

Table 1 – Comparison between the two-grade and the five-grade grading systems.

Feature	**Two-grade grading system**	**Five-grade grading system**
Required input	R_B	R_A, R_B, R_C, t_{ref}
Possible grades	A, B	AA, A, B, C, D
Differentiation between levels of acceptable/unacceptable risk	NO	YES
Grade reduction	NO	YES
Robustness	NO	YES *

* depending on the corresponding actions

4. Application of the grading system to a precast reinforced concrete building

In this section, the proposed five-grade grading system is demonstrated by evaluating the seismic risk of a single-story precast reinforced concrete building. The seismic risk is quantified by the annual frequency of collapse $\lambda(C)$ and the expected annual economic loss normalized to the expected reconstruction cost $E(L_{norm})$. It is assumed that the risk evaluation was required by the regulator, who associated the grades with potential actions for the owners. Grades AA, A and B are associated with neutral actions, grade C with lesser detrimental actions, and grade D with more detrimental actions (as proposed in the discussion given in Section 3).

In the following, the investigated building is first described (Section 4.1), and the grading system's input data is defined (Section 4.2). The risk of the building is then estimated and evaluated (Section 4.3).

4.1 Description of the investigated building

The example building (Fig. 4) is a commercial office building with a warehouse for cars and car equipment. The building is located in Ljubljana, Slovenia. It has a precast reinforced concrete structure designed [9] according to Eurocode 8 [7] for ductility class "High". At the building's perimeter, horizontal precast cladding panels are attached to the structure. The expected reconstruction cost of the building amounts to approximately 4.5 million euro.

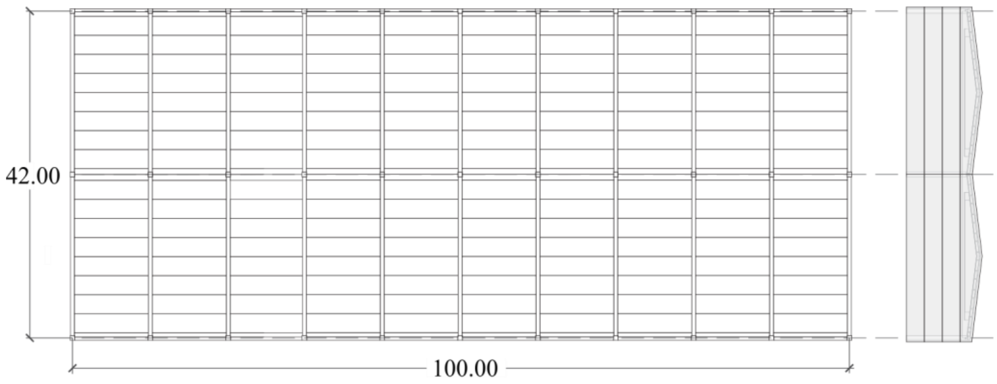


Fig. 4 – The plan view and the side view of the example building

4.2 Definition of risk boundaries and reference short-term period

The risk boundaries and the reference short-term period were defined for each risk measure considered. In the case of $\lambda(C)$, the boundary R_B was set to $2{\cdot}10^{-4}$ (Table 2), which is equal to the target collapse risk as considered in the USA [1]. The boundary R_A was set to 10^{-5}, which is approximately equal to the collapse risk acceptable to the general public in Slovenia [3], while R_C was set to 10^{-3}, which is five times the value of R_B. The resulting collapse frequency of 0.05 in 50 years is in the range of values corresponding to the buildings that were designed and constructed in the third quarter of the 20th century (e.g. [10]). It was considered that such risk is tolerated for no more than five years, i.e. Δt_{ref} = 5 years.

The definition of the risk boundaries in the case of $E(L_{norm})$ is not as straightforward due to the lack of standards which would explicitly prescribe tolerable economic losses. Because of this, the risk boundaries were determined based on the order of magnitude of the results in existing studies (Table 2). The boundary R_B was set to 0.1% of the reconstruction cost, which is somewhat higher than the risk of modern buildings reported in the literature [11, 12]. The boundaries R_A and R_C were determined by, respectively, decreasing and increasing R_B by a factor of five. As in the case of $\lambda(C)$, it was considered that R_C is tolerated for no more than five years, i.e. Δt_{ref} = 5 years.

Table 2 – The risk boundaries and the reference short-term period considered in the risk evaluation of the example building.

Risk measure	R_A	R_B	R_C	Δt_{ref}
$\lambda(C)$	$1{\cdot}10^{-5}$	$2{\cdot}10^{-4}$	$1{\cdot}10^{-3}$	5 years
$E(L_{norm})$	0.02%	0.1%	0.5%	5 years

4.3 Risk estimation and evaluation

Risk was estimated by using probabilistic methods [13]. The estimated annual frequency of collapse $\lambda(C)$ was equal to $5.4{\cdot}10^{-4}$, while the expected economic loss $E(L_{norm})$ was estimated at 0.072% of the expected reconstruction cost. A large part of $E(L_{norm})$ (about 75%) originates from the collapse cases.

Based on the estimated risk, initial grades were assigned (Fig. 5). Grade B was assigned for $\lambda(C)$, while grade A was assigned for $E(L_{norm})$. The latter grade indicates long-term tolerable risk. Therefore, no grade reduction is considered in this case. However, grade B, which was assigned for $\lambda(C)$, indicates that risk is tolerable only in the short term, but not in the long term. Therefore, the grade is scheduled to be reduced over time (Fig. 5a). The reduction to grades C and D is scheduled in 6.9 years and 11.9 years, respectively.

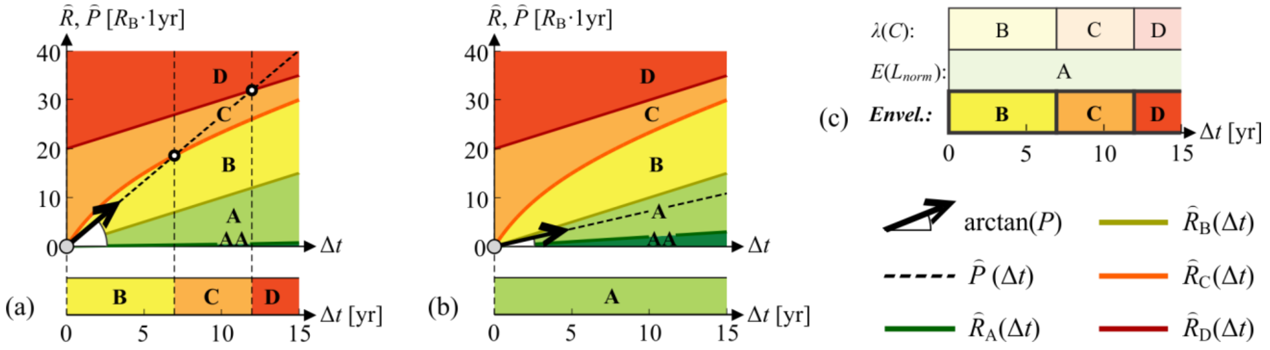


Fig. 5 – Risk evaluation of the example building: (a) the evaluation of $\lambda(C)$, (b) the evaluation of $E(L_{norm})$, and (c) the envelope of grades.

The grades assigned for $\lambda(C)$ and the corresponding periods also represent the global outcome of the risk evaluation, which was determined by enveloping the outcomes obtained for both risk measures (Fig. 5c). Based on the envelope of grades, only neutral actions are expected immediately after the risk evaluation. However, if the owner is unable to reduce risk, they will eventually be faced with detrimental actions. Less detrimental actions are scheduled in 6.9 years and more detrimental actions in 11.9 years. These periods are presumably long enough for the owner to strengthen the building, but not too long to motivate them to act quickly, and not to delay the risk mitigation.

5. Conclusions

A five-grade grading system for the communication and evaluation of seismic risk is presented. The grading system consists of grades AA, A, B, C and D, where grade AA is the most favorable and grade D is the most unfavorable. Each grade corresponds to a different combination of long-term and short-term risk tolerance. In the case of long-term intolerable risk, it is foreseen that grades are gradually reduced until reaching the most unfavorable grade, thus incentivizing the owners to strengthen their facilities in the shortest time possible.

The grading system can be used as a communication tool to enhance the public discussion about tolerable risk and to incorporate the aspect of seismic risk in self-regulating markets. Moreover, it can assist disaster risk management by linking grades to specific sets of actions which are scheduled after the risk evaluation. As a potential basis for disaster risk management, the grading system has two clear advantages. Firstly, because it allows a different period associated with imposing detrimental actions to be determined for each facility, it helps to avoid situations where many facilities would be confronted by actions simultaneously. Secondly, due to its robustness, the grading system decreases the sensitivity of the evaluation outcome to the uncertainties in risk estimation, and thus increases the public’s acceptance of seismic risk evaluations.

As an example, the grading system is applied in a risk evaluation of an existing precast reinforced concrete building, which is exposed to long-term intolerable risk. It is demonstrated that by using the grading system in risk evaluation, the periods can be determined in which the owner is required to strengthen the building in order to avoid detrimental actions. For the example building, it was determined that the owner would face less detrimental actions in 6.9 years and more detrimental actions in 11.9 years, if not reducing risk sufficiently.

The grading system was developed under the assumption of constant risk. However, seismic risk may change over time due to time-dependent hazard and/or time-dependent vulnerability. Additionally, the estimate of risk which is that actually considered by decision-makers can be impacted by newly-obtained evidence. Such changes in risk estimates cannot be predicted in advance but can be considered by performing risk evaluations periodically. An extension of the proposed grading system which would consider variations in risk over time, and thus make it applicable to periodical risk evaluations, is a good topic for future research.

6. Acknowledgements

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