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Structural assessment of existing bridges by using territorial scale analysis: some observations on the application of the Italian guidelines

Stefania Coccimiglio[1], Luca Mario Di Valentino[1], Erica Lenticchia[1],
Valerio Oliva[1], Linda Scussolini[1], Devid Falliano[1], Francesco Montagnoli[1],
Maria Romana Alvi[1], Marco Barla[1], Rosario Ceravolo[1], Mauro Corrado[1],
Giuseppe Andrea Ferro[1], Alessandra Insana[1], Stefano Invernizzi[1], Luciana Restuccia[1]
[1] Department of Structural, Building and Geotechnical Engineering, Politecnico di Torino, Turin, Italy.

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ABSTRACT
The recent bridge collapses in Italy (e.g., the Polcevera bridge in 2018 and the bridge on Magra river in 2020) highlighted the need for a systematic methodology to simplify and speed up maintenance of infrastructures. The management of existing bridges is a complex problem that must consider the technical aspects as well as the social and economical ones. The plurality of used materials, dimensions, construction periods, structural schemes makes the standardization of a procedure even more difficult. Moreover, the number of Italian bridges is currently uncertain, and often the related documentation is incomplete or does not correspond to the actual structure. Therefore, an accurate safety assessment for each bridge of the Italian territory can be therefore challenging. In this context, a multilevel approach is fundamental to optimize resources and costs. In this framework, guide lines for the classification and risk management, safety assessment, and monitoring of existing bridges have been developed. The main objective of the guidelines is to achieve homogeneity in classification, risk management and safety assessment. However, the analysis on a territorial scale can significantly affect the assessment of a single bridge, leading to similar results for different bridges on the same highway. For elaborating some first general observations on the application of the guidelines, a statistical analysis on a territorial scale of 251 bridges has been carried out. Eventually, the influence of the census characteristics on the assessment of the single bridge is validated by two case studies characterized by different environmental conditions.

1 INTRODUCTION

The management of existing infrastructures is becoming increasingly crucial, as highlighted by the recent collapses of the Polcevera bridge in 2018 (Bazzucchi et al. 2018) and the bridge on Magra river in 2020. However, the complexity of the great number of bridges characterizing the existing infrastructural heritage in Italy makes their management challenging.

By analyzing Italian bridges, several problems emerge due to the fragility of Italian territory from a hydrogeological and seismic point of view and to the lack, in the past, of a homogeneous and systematic maintenance program. Therefore, the need for a proper and uniform analysis of their health state arises. The Italian technical standards NTC 2018 (Consiglio Superiore dei Lavori Pubblici, 2018) suggest the extension of the safety assessment to all bridges, but the significant number of bridges, materials used, dimensions, construction periods, and static schemes make the application of a unique method of analysis difficult.

In this context, applying such a detailed level of analysis to all Italian bridges becomes demanding. For this reason, the new Guidelines (Ministero delle Infrastrutture e dei Trasporti Consiglio Superiore dei Lavori Pubblici, 2020) have defined a systematic and continuous method of analysis of bridges with the objective of simplifying their management: the so-called multilevel approach. This methodology allows to distinguish between a territorial scale analysis and a more accurate one, carried out only on a few bridges. However, the territorial scale can significantly affect the assessment of a single bridge. The main consequence is the difficulty to obtain properly diversified results for bridges belonging to the same highway and, therefore, prioritizing the interventions.

This paper aims to draw some first general observations on the application of the guidelines to a group of bridges located in two different Italian regions. One of the goals is to investigate how the territorial scale affects the evaluation of the health state of bridges. The paper is structured as follows: Section 1 provides an overview of the new guidelines. Section 2 reports some general considerations on the guidelines, resulting from statistical results of applying a territorial scale analysis on 251 bridges of two highways located in the Italian regions of Piemonte and Liguria. According to the procedure reported in the new guidelines, the seismic, hydraulic, and landslide hazards are considered. The first three levels of the multiscale approach are then applied to two case studies in Section 3. Conclusions are eventually drawn in Section 4.

2 THE MULTILEVEL APPROACH

The management of existing bridges is a complex issue with multiple variables. The plurality of materials, sizes, construction periods, and static schemes can generate many different combinations and cases of analysis. Moreover, the different hydrogeological contexts related to landslides and floods hazards, seismic zones, and traffic flows make the number of cases even higher. In this context, an accurate analysis as the one required by the NTC 2018 (suggested as the ideal approach) (Consiglio Superiore dei Lavori Pubblici, 2018) for every bridge becomes difficult, if not impossible, to perform. Therefore, it is necessary to proceed with a multi-level approach of analysis to optimize decision-making processes and concentrate resources only where necessary.

The multi-level approach proposed by the Guidelines (Ministero delle Infrastrutture e dei Trasporti Consiglio Superiore dei Lavori Pubblici, 2020) comprises six levels with increasing complexity and detail. Based on all the bridges under analysis, the first three levels consist of the census and geo-localization, the visual inspections and defect sheets, and the attention classes, respectively. This first level allows a more general overview of the dataset and permits drawing preliminary observations on a territorial scale analysis. On the other hand, the following three levels consist of applying a more accurate analysis on a limited number of bridges. The passage from a general to a more accurate analysis is done exploiting a classification system called attention classes, composed of bands going from low to high, useful for the next steps.

3 STATISTICAL ANALYSIS ON A TERRITORIAL SCALE

In this part of the study, a general first overview of the application of the guidelines is provided. A structural evaluation on the status of 251 bridges of highways located in the Italian regions Piemonte and Liguria (Figure 1) is carried out.

Figure 1. Overview showing the localization of the bridges considered for the territorial scale analysis.

The first step consists in identifying the used design guidelines, which are strictly correlated to the construction period. Approximately 85% of the bridges were built between 1962 and 1990 (Figure 2a). Therefore, the resulting design class is Class A (Figure 2b).

The considered bridges present some differences in the structural schemes, materials, and lengths. The most used construction material among the 251 bridges, that characterizes the 96% of the cases, is prestressed concrete, while only a mini-mum part has been built in reinforced concrete or has a mixed structure (Figure 2b).

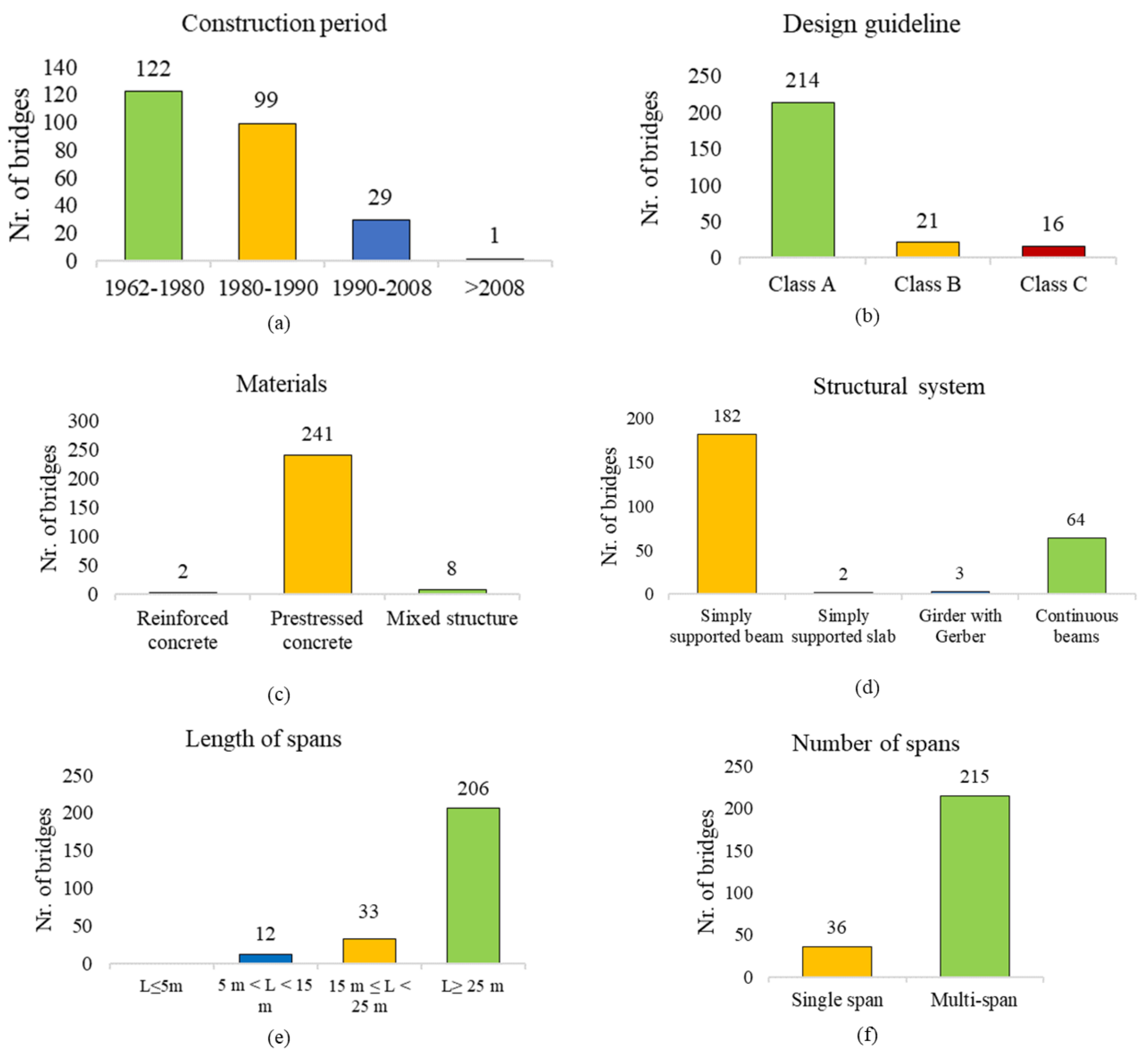


Figure 2. Statistical analysis results: (a) Construction period; (b) Design guidelines; (c) Materials; (d) Structural system (e) Length of spans; (f) Number of spans.

Concerning the structural scheme, the most used ones are the simply supported beam and the continuous beam, precisely for 182 and 64 bridges. A minimum part presents a simply supported slab or a girder with Gerber (Figure 2d). Moreover, the data present that most bridges are multi-span (Figure 2f) with a span length higher than 25 m (Figure 2e).

3.1 Defect Coefficient

Thanks to available inspection documents, it has been possible to obtain the current state of health of the structures. It is shown by the Defect Coefficient D_R that is calculated as follows:

$$D_R = \sum_i G_i \cdot K_{1,i} \cdot K_{2,i} \quad (1)$$

D_R is numerically calculated as a function of the weight associated to each defect G, the extension of defect K_1, and the severity of defect K_2. It represents a measure of the impact that the defect can have on the maintenance schedule.

The Guidelines then propose ranges to convert D_R to the new attention classes (Ministero delle Infrastrutture e dei Trasporti Consiglio Superiore dei Lavori Pubblici, 2020). The ranges are reported in Table 1. Exploiting the formula and the ranges provided in Table 1, the distribution of the coefficient D_R among the considered bridges can be calculated. Figure 3 shows that most of the bridges are in the medium and medium-high classes.

Table 1. Conversion table of D_R

D_R	Attention classes
$D_R > 25$	High

$19 < D_R < 25$	Medium - High
$12 < D_R < 19$	Medium
$5 < D_R < 12$	Medium – Low
$D_R < 5$	Low

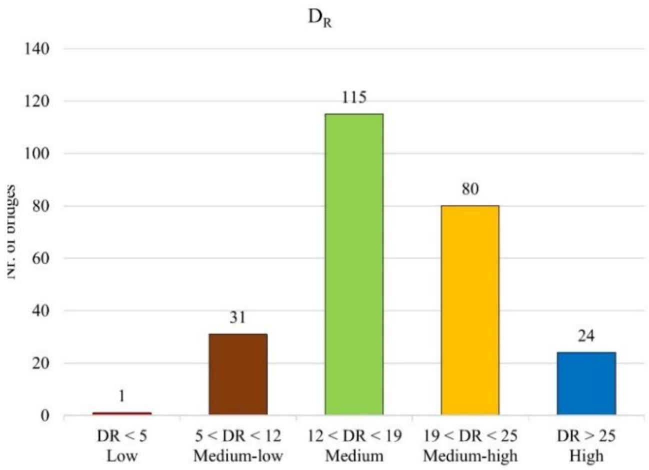


Figure 3. D_R distribution

3.2 *Defect Coefficient and hazard analysis*

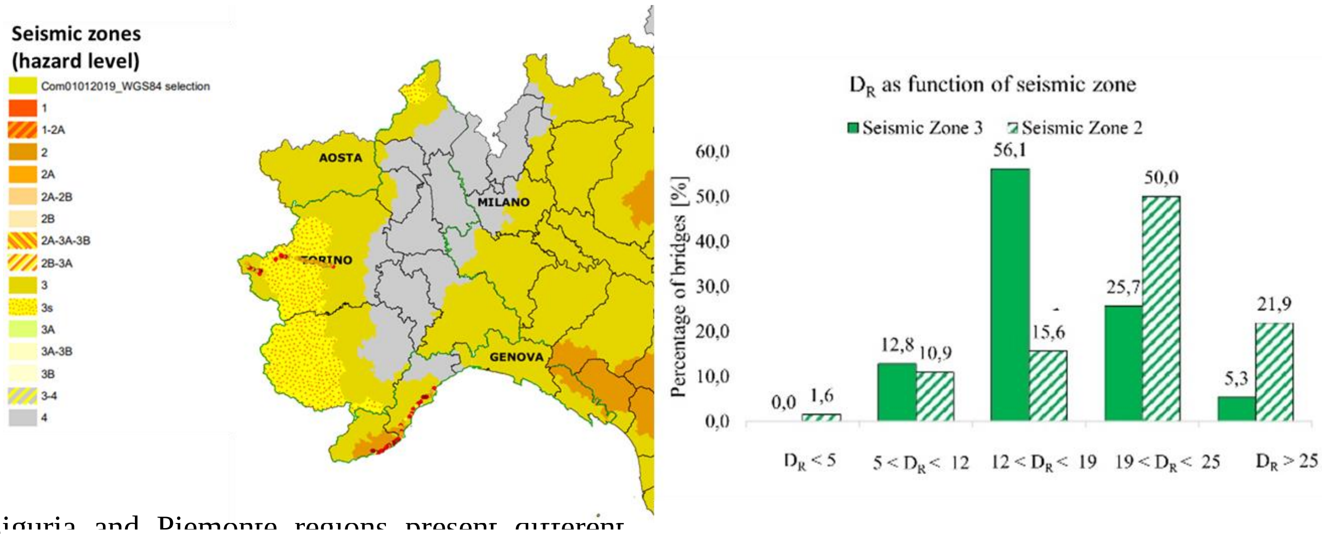
According to the attention classes, the bridges were analyzed considering the relationship between D_R and the seismic, hydraulic, and landslide hazards using the open-source software QGIS 3.20.1 version.

Each zone has a seismic action value useful for the design, which is given in terms of peak ground acceleration (PGA). The values for the four seismic zones are shown in Table 2.

Table 2. Definition of seismic zones

Zone	Acceleration having an exceedance probability of 10% in 50 years [a_g]	Maximum horizontal acceleration of the elastic response spectrum
1	$0.25 < a_g \leq 0.35g$	0.35g
2	$0.15 < a_g \leq 0.25g$	0.25g
3	$0.05 < a_g \leq 0.15g$	0.15g
4	$a_g \leq 0.05g$	0.05g

Increasing the seismic hazard from a low level to a medium level, D_R increases as well: in particular, the increment of bridges for $10 < D_R < 25$ is 17% and for $D_R > 25$ is 24% (Figure 4). Analogous results can be found when passing a low hydraulic hazard area to a very high hydraulic hazard area: in this case, the percentage of bridges having a high value of D_R increases (Figure 5). However, the landslide analysis does not highlight any correlation between the defects and the hazard (Figure 6).



Liguria and Piemonte regions present different

Figure 4. D_R as a function of seismic zones (Protezione Civile, 2021).

4, Figure 5 and Figure 6).

The first analysis highlights the relationship between the D_R coefficient and the seismic hazard level. The bridges under analysis are located in the so-called seismic zones 2 (medium risk) and 3 (low risk).

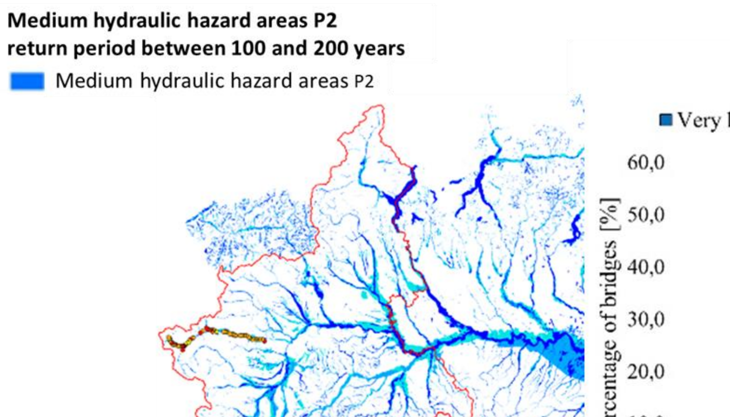


Figure 5. D_R as a function of the hydraulic hazard (Istituto Superiore per la Protezione e per la Ricerca Ambientale, 2021).

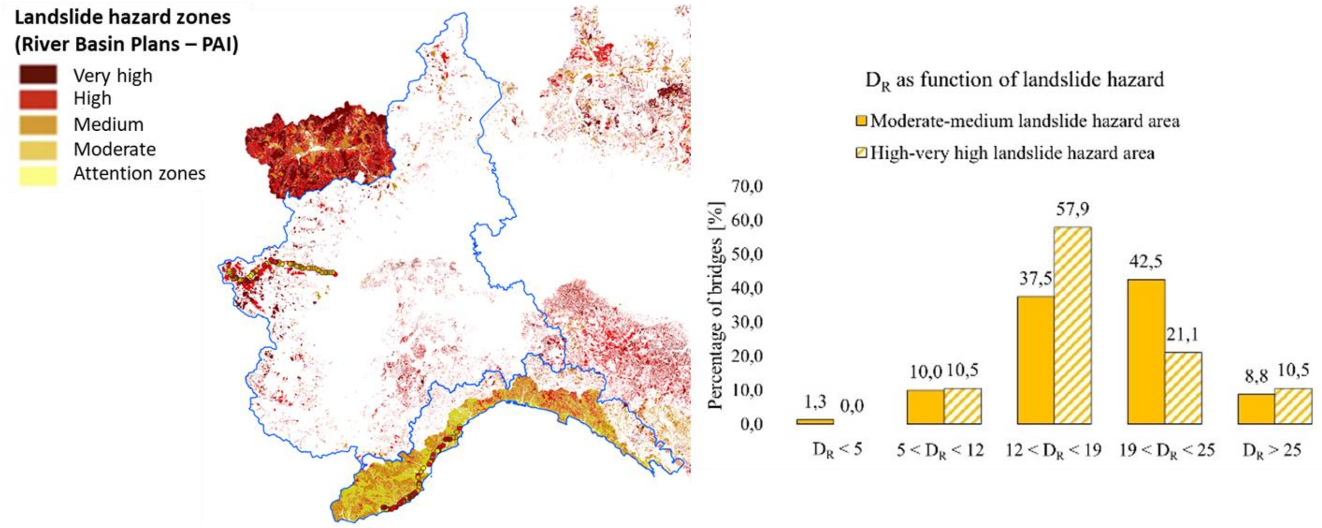


Figure 6. D_R as a function of the landslide hazard (Istituto Superiore per la Protezione e per la Ricerca Ambientale, 2021).

3.3 *Vulnerability analysis*

Exploiting the previously obtained results, the prevailing characteristics among the considered 251 bridges are considered, and a vulnerability analysis has been carried out, both from a structural/foundational and seismic point of view.

Starting from defect levels that are medium or medium-high, and considering the year of construction, the design class, and the geometrical characteristics that significantly affect this classification, the obtained vulnerability class is, in both cases, medium-high or high.

The vulnerability class in the case of structural/foundational hazard and in the case of seismic hazard are reported in Figure 7 and Figure 8.

4 DEFINITION OF CLASSES OF ATTENTION

Having established that the territorial scale can significantly affect the attention class from a first general analysis, the first three levels of multi-scale analysis are now applied to two case studies presenting different attention classes.

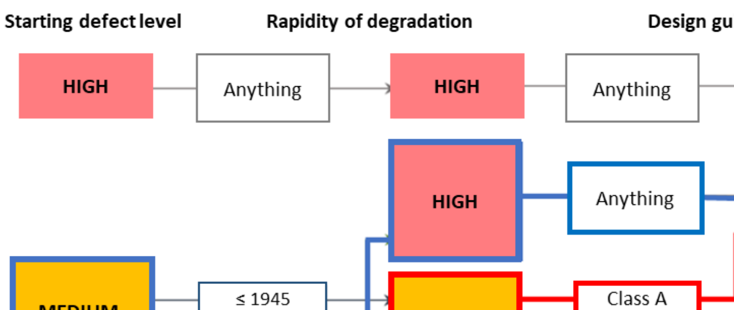


Figure 7. Structural/foundational vulnerability classes.

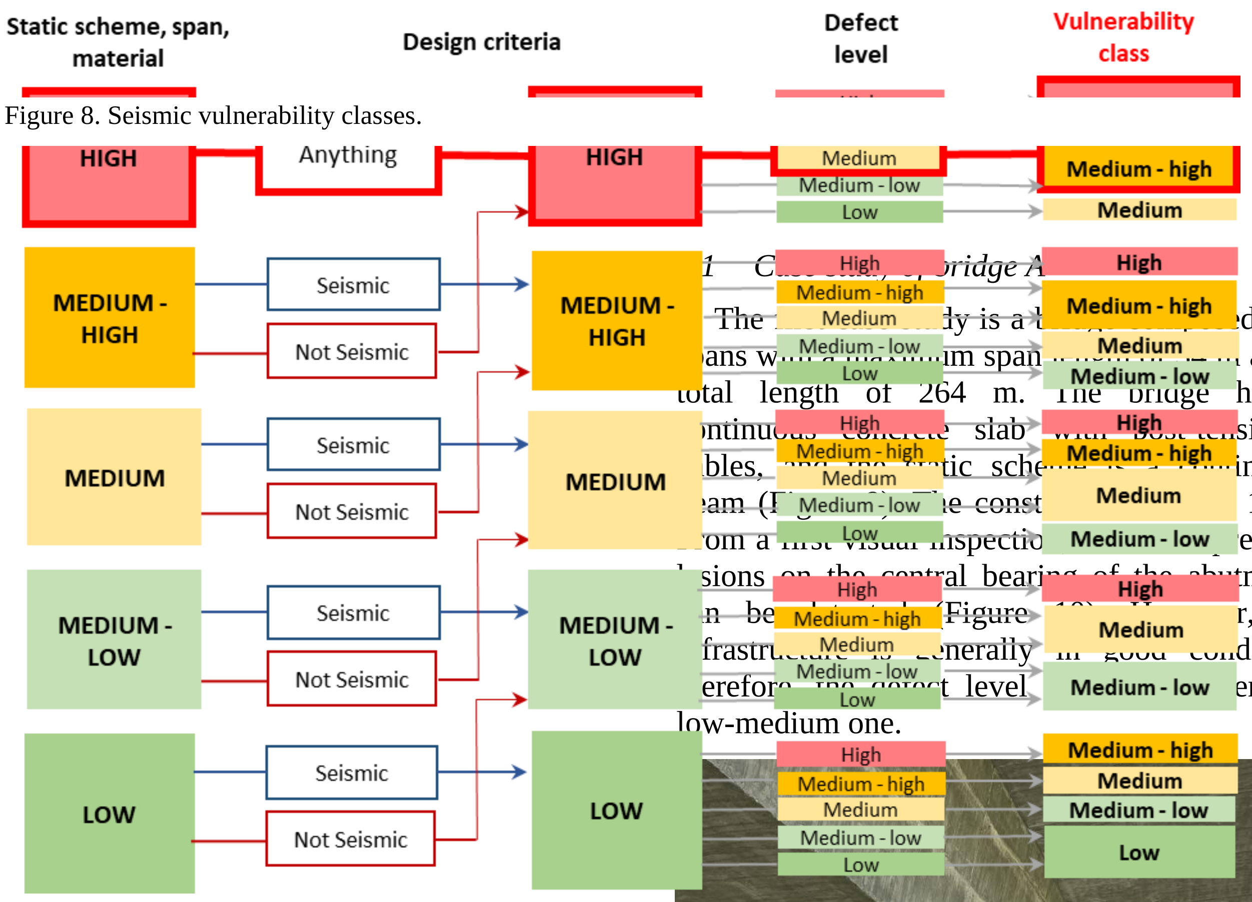


Figure 8. Seismic vulnerability classes.

4.1 C[illegible] Bridge A

The [illegible]dy is a [illegible]d of 8 spans w[illegible]m span [illegible] and a total length of 264 m. The bridge has a [illegible]ntinuous concrete slab [illegible]sioned cables, [illegible]tic sch[illegible]inuous beam (F[illegible]). The const[illegible] 1991. From a first visual inspectio[illegible]ession [illegible]sions on the central bearing of the abutments [illegible]n be [illegible] (Figure [illegible]r, the [illegible]frastructure is generally in good condition; [illegible]erefore the defect level [illegible]ered a low-medium one.

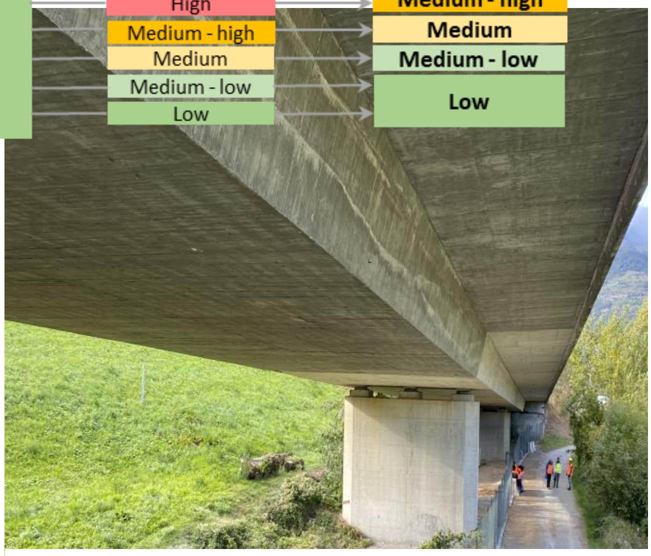


Figure 9. Bridge A: general view.

Considering that the bridge does not cross any river, which could affect the structure, and the visual inspections, the attention classes can be defined Table 3.

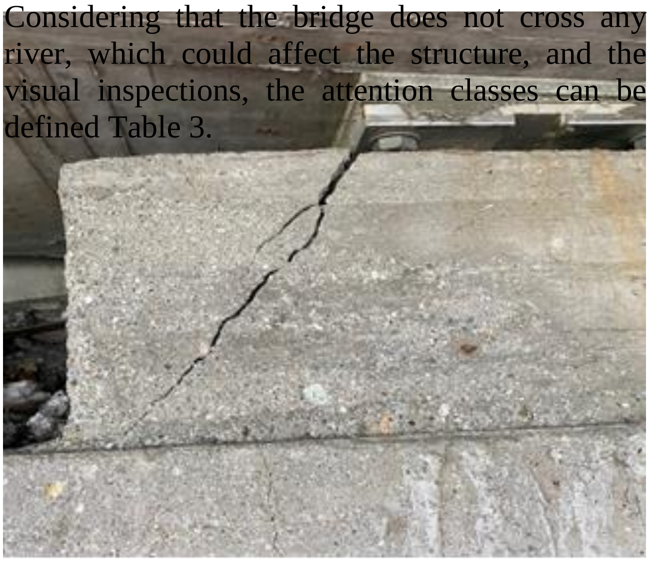


Figure 10. Bridge A: compression lesions on the central bearings of the abutments.

Table 3. Attention classes of Bridge A

Type of hazard	Attention class
Seismic	Medium
Structural/foundational	Medium - high
Hydraulic	Very low
Landslide	Medium - high
Overall	Medium - high

4.2 Case study of bridge B

The second case study is a bridge composed of 5 spans with a maximum span length of 38. The bridge is composed of pre-stressed concrete beams with post-tensioned cables (Figure 11). The construction year is 1990. From a first visual inspection, some parts of reinforcement cables show signs of oxidation, deformation, and rupture (Figure 12) and undermining of foundations (Figure 13) and oblique fractures been detected on some parts of the bridge. Consequently, the infrastructure is generally in bad conditions: the defect level can be considered a medium-high one.

After completing the visual inspections, the attention classes can be defined (Table 4).

Table 4. Attention classes of Bridge B

Type of hazard	Attention class
Seismic	High
Structural/foundational	High
Hydraulic	Medium - high
Landslide	Low
Overall	High

Figure 11. Bridge B: general view.

Figure 12. Bridge B: reinforcement oxidation.

Figure 13. Bridge B: undermining of foundations.

4.3 Discussion of the results

With the data coming from the visual inspections, together with the characteristics of the bridge and the attention classes, the overall attention class can now be determined according to the tables in the new guidelines.

In the case of bridge A, the starting classes are a medium-high structural/foundational one, a medium seismic and hydraulic/landslide one Figure 14.

On the other hand, in the case of bridge B, the starting classes are high structural/foundational and seismic ones and a medium-high hydraulic/landslide one Figure 15.

Applying the first three levels of multi-level analysis led to the individuation of similar attention classes for the two bridges: indeed, a medium-high class of attention was individuated for bridge A, while a high class of attention for bridge B. These results show that even changing the seismic, hydraulic, and landslide attention classes, the overall attention class would remain the same. Consequently, it can be said that the structural/foundational and the seismic attention classes significantly affected the overall attention class: the seismic and the structural-foundational attention classes were similar in both cases, and this led to similar results.

5 CONCLUSIONS AND FUTURE WORKS

The present paper provides a general view on the application of the multi-level approach proposed by the guidelines, exploiting a statistical analysis on the values of the Defect coefficient calculated on 251 bridges with respect to several types of hazards. As a result, the seismic and the hydraulic hazard affect the Defect coefficient, while the landslide hazard does not provide any correlation. The territorial scale analysis also allowed hypothesizing an influence of the territorial scale properties on the assessment of the bridges belonging to the same highway. This hypothesis has been validated by analyzing two case studies. As a main result, although the bridges have different health states, the resulting overall attention class is very similar.

In conclusion, it can be said that regardless of the health state of an infrastructure resulting from the in-situ inspections, the design class, the construction mate-rial, and the geometry have a preponderant weight in the resulting attention class. Indeed, infrastructures in different contexts are often located in similar attention classes. However, this could represent an issue in the definition of priority of infrastructures. Indeed, the guidelines require a more accurate analysis starting from a medium attention class, and, therefore, it could involve a large number of infra-structures. Therefore, the introduction of a quantitative approach could be helpful to evaluate the defect level; moreover, the definition of a priority criterion to apply to infrastructures belonging to the same attention class could optimize the whole process.

Structural/foundational attention class ***MEDIUM - HIGH***

		Hydraulic and landslide hazards attention class				
		High	Medium - high	Medium	Medium - high	Low
Seismic attention class	High	High		Medium - high		
	Medium - high	High	Medium - high			Medium
	Medium	Medium - high			Medium	
	Medium - low	Medium - high		Medium		
	Low	Medium - high	Medium			

Figure 14. Overall attention class of bridge A.

Structural/foundational attention class ***HIGH***

		Hydraulic and landslide hazards attention class				
		High	Medium-high	Medium	Medium-high	Low
Seismic attention class	High	High				
	Medium - high	High				
	Medium	High				
	Medium - low	High				
	Low	High				

Figure 155. Overall attention class of bridge B.

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