# Macroscale vulnerability and condition state assessment of bridges at municipality level

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ABSTRACT

Seismic assessment and retrofit interventions are required to enhance the reliability of strategic structures, since they are to be fully operational for post-event emergency activities. In this framework bridges play a crucial role as they are critical elements in several road networks. Thus, their condition state assessment is a theme of broad and current interest. Reliability of strategic structures is linked to seismic resistance, load carrying capacity for increased traffic loads and also to the damage state due to decay and environmental effects. The objective of this study is to provide the local authorities responsible for road networks, in this case the Municipality of Padua, with a combined assessment of the bridge stock reliability, considering both deterioration effects on efficiency and seismic vulnerability, in order to define priority lists for interventions on the network. The evaluation of bridge efficiency is carried out by means of visual inspection using a priority-ranking procedure that is able to quantify the health condition of the structure on standardized basis. The seismic vulnerability assessment is implemented using a set of fragility curves from literature to define the exceedance probability of the Limit State for each potential mechanism activated by seismic action. Both Damage and Life Safety Limit State are considered to be consistent with "*Sismabonus*" code setting. The procedure has been implemented to a bridge stock of more than 160 structures of various typologies. A significant number of the analyzed bridges presents a high or very high seismic vulnerability and/or degradation, needing an urgent or short-term intervention.

## 1 INTRODUCTION

Italian infrastructural network is dated (Del Grosso et al., 2002) and bridges are the most vulnerable elements in terms not only of seismic performance and load-bearing capacity to increased traffic load, but also due o degradation caused by environmental effects (Zanini et al. 2012) needing regular maintenance.

Most of Italy's infrastructures and road network was built in the 50s and 60s. The vast majority of the bridges stock on Italian highways was built during the two decades from 1955–1975 (Pinto and Franchin, 2010). According to the CNR, the National Council for Research, many of those structures are at risk today because of their age. (Occhiuzzi, 2018).

Thus, condition state assessment of bridges is a theme of broad and current interest, especially following tragic events that occurred in recent past (Calvi et al., 2019). Expeditious methodologies for bridge management systems are needed to support administrations in charge in decision-making processes for intervention and monitoring, and so ensure long service life and durability.

Various methods have been developed with the aim of assessing bridge performance in terms of either degradation effects (Gattulli and Chiaramonte, 2005; Wenzel, 2010) or seismic vulnerability (FEMA, 2003).

Recently, a new system accounting for multi-hazard interaction has been developed by Gehl and D'Ayala (2018).

This paper presents the application of a methodology for the combined assessment of the bridge stock reliability considering both deterioration effects on efficiency and seismic vulnerability. The evaluation aims to provide the local administration in charge for road network management, in this case the Municipality of Padova, with a priority lists for interventions on the network. The analysed stock is composed by 161 bridges of various typologies located in the territory of the municipality of Padova. The evaluation of bridge efficiency is carried out by means of visual inspection and the health condition of the structure is quantified on standardized basis.

## 2 METHODOLOGY

The proposed methodology is divided in five phases:

1. Knowledge process and data collection through archive documentation and identification of the structural typology and vulnerability class.
2. On site survey and visual inspection focusing on degradation.
3. Calculation of the efficiency level accounting for degradation based on the procedure developed by the University of Padova (Pellegrino et al. 2009).
4. Seismic vulnerability assessment through fragility curves from literature.
5. Summary of the results in the priority-ranking list.

### *2.1 Identification of typological and vulnerability classes*

Condition state assessment requires the identification of each bridge class due to both degradation and seismic vulnerability depends on its typological and structural characteristics.

Classification is primarily based on structural materials: masonry, reinforced concrete, prestressed reinforced concrete and steel bridges.

Most masonry bridges, in Italy, have more the one hundred years and the main damages caused by degradation are:

- Subsidence of the foundation.
- Dislocation, deterioration and efflorescence of bricks.
- Longitudinal and transversal cracking.
- Damage in the spandrel walls.
- Cracking and fractures of the piers and abutments.

Reinforced concrete bridges are subjected to the following degradation processes:

- Carbonation.
- Spalling of the concrete cover.
- Corrosion of reinforcing bars.
- Freeze-thaw cycles.
- Chloride action.
- Impact damages.

Whereas steel bridges are mainly subjected to:

- Corrosion.
- Delamination of the elements.
- Fatigue.

Each material macro-class is subdivided on the base of structural typology (Table 1) characterized by specific components subjected to damage and degradation. For seismic vulnerability assessment typologies are further subdivided so as to identify homogenous vulnerability classes and the related collapse mechanisms, as shown in Table 2.

Table 1. Subclasses of bridges based on typology.

| Material Classification | Typology |
|---|---|
| *Masonry bridge* | Arch |
| *Reinforced concrete bridge* | Arch<br>Girder |
| *Steel bridge* | Arch<br>Girder<br>Reticular<br>Cable-stayed<br>Suspended |

Table 2. Collapse mechanisms and relative elements.

| Collapse mechanisms | Element |
|---|---|
| ***Single span masonry arch*** | |
| *Longitudinal mechanisms* | Arch |
| *Spandrel wall overturning* | Spandrel wall |
| ***Multi span masonry arch*** | |
| *Longitudinal mechanisms* | Arch - Pier |
| *Transversal mechanisms* | Arch - Pier |
| *Spandrel wall overturning* | Spander wall |
| ***Single span reinforced concrete/steel bridge*** | |
| *Support failure* | Support |
| *Loss of support of deck* | Support |
| *Shear/Sliding* | Abutment |
| *Bending w/ axial force* | Abutment |
| ***Multi span reinforced concrete/steel bridge*** | |
| *Support failure* | Support |
| *Loss of support of deck* | Support |
| *Shear/Sliding* | Abutment |
| *Bending w/ axial force* | Abutment |
| *Shear* | Pier |
| *Bending w/ axial force* | Pier |
| ***Reinforced concrete arch*** | |
| *Support failure* | Support |
| *Loss of support of deck* | Support |
| *Shear/Sliding* | Abutment |
| *Bending w/ axial force* | Abutment |
| *Longitudinal mechanisms* | Arch |

A fragility curves from literature has been associated with each collapse mechanism.

### *2.2 Seismic risk classification assessment*

Seismic assessment is carried out by means of fragility curves from literature for each potential mechanism (Tecchio, 2013; Tecchio et al. 2016).

Fragility curves are defined for various range of geometrical and structural parameters (e.g. the ratio between the thickness of the arch and span length for masonry arched bridges) so as to choose the most suitable curve for the analysed bridge.

For each mechanism the probability of exceeding both Life Safety Limit State (LSLS) and Damage Limit State (DLS) are obtained using curves associated to different levels of damage. For each structural element the probability of exceeding the LSs is assumed to be the maximum of all the potential component mechanism (Eq. 1).

$$P(F_i) = \max\left[P\left(F_{mech,i}\right)\right] \tag{1}$$

The entire system exceeding probability is defined by means of a combination of the probabilities related to its components. In particular it was used a upper-lower bound approach (Choi et al. 2004) to define a probability range, in which the upper and lower bounds are defined as shown in equation (Eq. 2).

$$\max_{i=1}^{m}\left[P(F_i)\right] \le P\left(F_{sys}\right) \le 1 - \prod_{i=1}^{m}\left[1 - P(F_i)\right] \tag{2}$$

The lower bound represents the probability of failure for a system whose components are all fully stochastically dependent and provides an unconservative estimate of the bridge fragility. The upper bound assumes that the components are all statistically independent and provides a conservative estimate of the overall bridge fragility. Thus, Condition Factor (CF) (Pellegrino et al. 2009) is related to cumulative probability of exceeding the analysed LSs (Table 3) and it is cautiously evaluated considering the upper bound.

In order to quantify the exposure with a simplified approach, a Penalty Factor (PF) is introduced according to Pellegrino et al. (2009). PF is calculated as a combination of coefficients considering the age of the structure, road type and traffic intensity, and the importance of the bridge in the network.

Finally, the seismic Total Sufficiency Rating (TSR), defined as a grade of the overall general state of the bridge by Pellegrino et al (2009) is calculated as follows (Eq. 3).

$$TSR = 10 \cdot PF \cdot CF \tag{3}$$

TSR value is a natural entire number between 1 and 100 which assumes lower values for higher vulnerability. Table 4 shows TSR intervals for seismic risk classification and relative urgency of intervention. Seismic class is assigned to each bridge part of the stock considering the minimum resulting TSR between DLS and LSLS assessment. This is consistent with Italian Seismic Classification (DM 65/2017) which provides for the minimum class between the two deriving from PAM (accounting for damage) and IS-V (accounting for life safety), respectively.

Table 3. Condition Factor (CF) and relative probability ranges.

| Exceeding Probability | Condition Factor |
|---|---|
| $0 < P \le 10^{-2}$ | 10 |
| $10^{-2} < P \le 10^{-1}$ | 6 |
| $10^{-1} < P \le 0.5$ | 4 |
| $0.5 < P \le 1$ | 1 |

Table 4. Seismic risk classes and urgency of intervention.

| Seismic risk classes | Urgency of intervention | TSR |
|---|---|---|
| A | Long term intervention | 76-100 |
| B | Medium term intervention | 51-75 |
| C | Short term intervention | 26-50 |
| D | Urgent intervention | 1-25 |

## 3 CASE STUDY

### *3.1 Typological and structural classification*

The proposed methodology has been applied to a bridge stock of 161 structures of various typologies in the Municipality of Padova.

Structural and typological characteristics have been identified and aggregated data about the composition of the stock are presented as follows.

Typological characteristic, i.e. type of traffic load and year of construction, are shown in Figure 1 and 2 respectively. These parameters are used for a simplified accounting for exposition in both efficiency and seismic assessment, by means of coefficients, as indicated in Pellegrino et al. 2009. The majority of the observed structures are road bridges. It is possible to observe that the age of the stock is quite heterogeneous.

Classification parameters which affects the structural behaviour have been presented as follows. Figure 3 shows the distribution of deck material while Figure 9 shows the distribution of building materials over the years. About 26% of the stock bridges were built before 1920s, an amount that includes most of the masonry arched bridges but also steel and RC deck arch bridges and a first example of RC girder bridge. Starting from 1940s. RC girder bridges have been largely built.

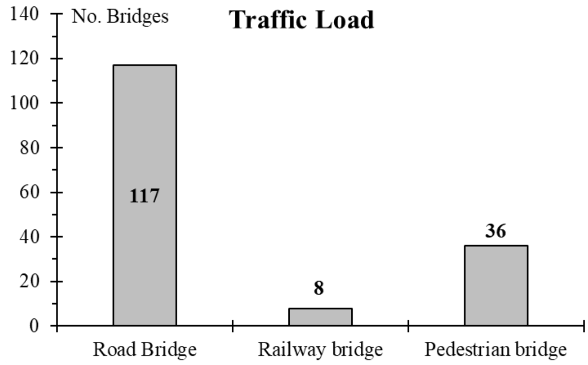


Figure 1. Statistical distribution of the traffic loads.

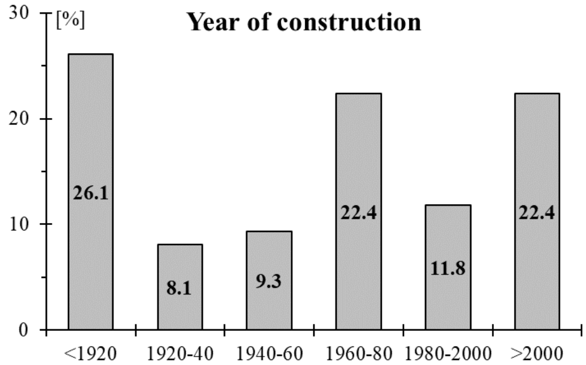


Figure 2. Statistical distribution of the years of construction.

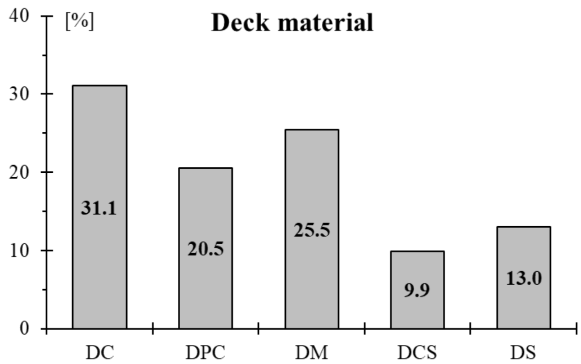


Figure 3. Statistical distribution of the deck materials. [Reinforced Concrete (DC), Prestressed Reinforced Concrete (DPC), Masonry (DM), Composite steel (DCS) and Steel (DS)]

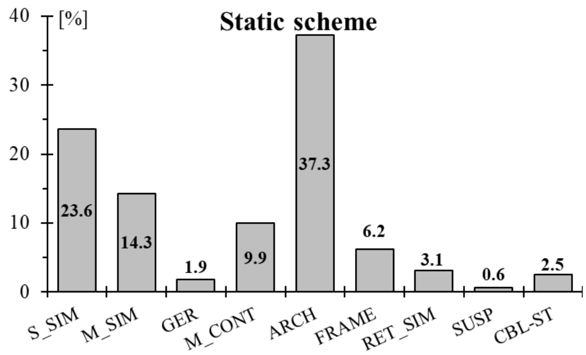


Figure 4. Statistical distribution of the static schemes. [single span simply (S_SIM), multi-span simply (M_SIM), multi-span Gerber scheme (M_GER), multi-span continuous (M_CONT), arch (ARCH), frame (FRAME) reticular simply supported (RET_SIM), suspended (SUSP) and cable-stayed (CBL-ST)]

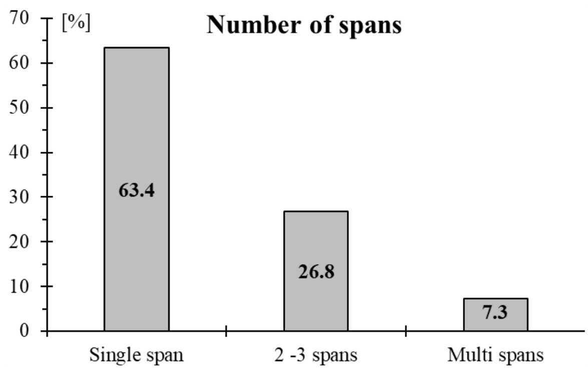


Figure 5. Statistical distribution of the number of spans.

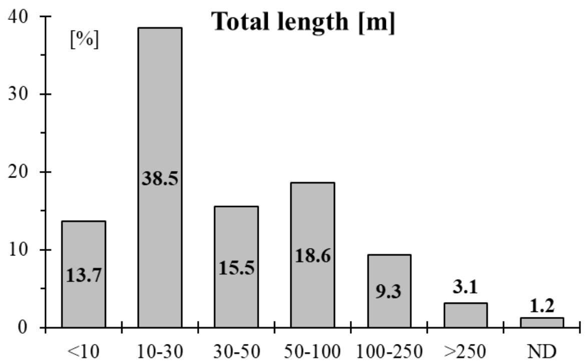


Figure 6. Statistical distribution of the total length.

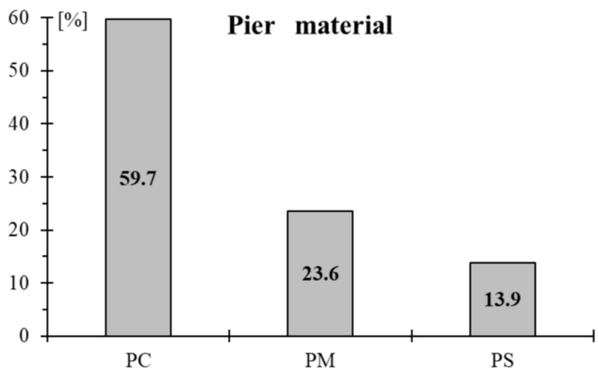


Figure 7. Statistical distribution of the pier material. [Reinforced Concrete Piers (PC), Masonry Piers (PM) and Steel Piers (PS)]

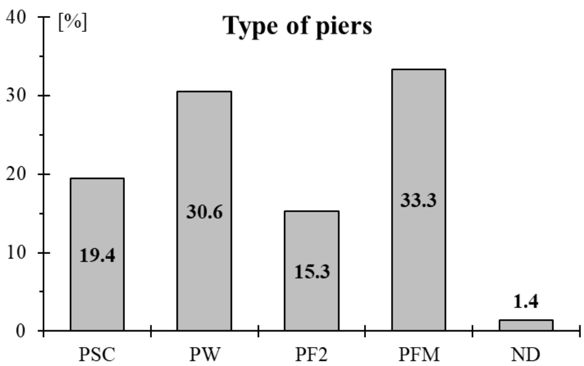


Figure 8. Statistical distribution of the type of piers. [Single Column (PSC), Wall (PW), Frame - Double (PF2), Frame – Multi (PFM) and Not available (ND)]

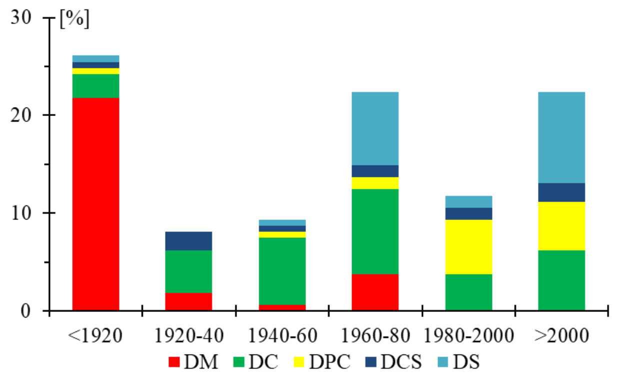


Figure 9. Distribution of structural materials over the years [Masonry (DM); Reinforced Concrete (DC); Prestressed Reinforced Concrete (DPC); Composite steel (DCS) and Steel (DS)].

The distribution of static scheme systems is shown in Figure 4, while Figure 5 and 6 show the number of spans and total length, respectively. It is possible to observe, from these two last figures, that the bridge stock presents mainly small to medium structures, as it is commonly perceived for quite small cities with densely populated historical centre and flat topography.

Finally, Figure 7 and 8 shows material and type distribution for piers. Reinforced concrete appears to be the most used material for piers.

### *3.2 Level of efficiency accounting for degradation*

The distribution of the efficiency level, accounting for damage and degradation, for the bridge stock is shown in Figure 10. About 8% of bridges (13 out of 161) requires urgent intervention and about 22% requires a short term intervention; therefore, about 30% of bridges shows a state of significant degradation.

Table 5 shows efficiency levels for bridges subdivided by year of construction. Aged structures are obviously the most subjected to degradation with a greater number of them requiring urgent or short-term interventions. The efficiency level mode for bridges built after 2000s is level 1, but it has to be observed that a number of structures has already shown a lower efficiency level 2. Levels of efficiency for bridges subdivided by deck material are shown in Table 6. Most of the bridges classified level 4 are RC structures affected by concrete degradation, loss of cover and corrosion of reinforcing bars. Masonry bridges, which were mostly built before 1920s, are mainly classified level 2 and 3. Steel and composite steel bridges, for the most part built recently, mostly belong to efficiency level 1.

### *3.3 Seismic risk classification*

Seismic risk classification has been implemented by means of fragility curves for almost the 90% of the bridge stock. For the remaining part, consisting of steel arch, suspended and stayed-cable bridges, it was not possible to find fragility curves from literature, yet. Moreover, the above mentioned steel bridges are usually light and flexible structures and thus less affected by seismic actions. The most frequent seismic risk class for the bridge stock is class C. Only 5% of the stock is classified D (Figure 11).

Figure 12 shows the distribution of seismic classification for the analysed bridges subdivided by deck material. Almost all masonry arch bridges are classified C, due to the out-of-plane spandrel wall mechanism.

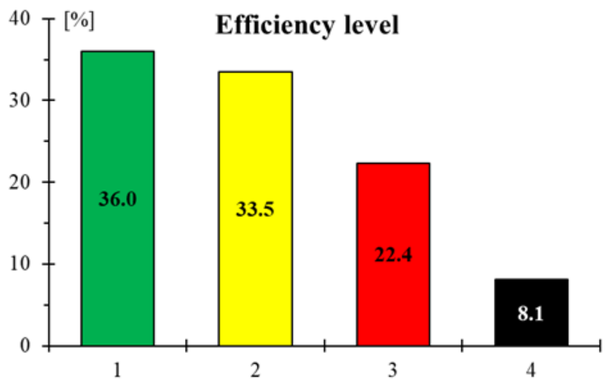


Figure 10. Distribution of the level of efficiency accounting for degradation. [1 – long term intervention; 2 – medium term intervention, 3 – short term intervention and 4 – urgent intervention]

Table 5. Level of efficiency by year of construction. The efficiency level mode for each year range is bolded.

| | | Efficiency level | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 |
| Year of construction | <1920 | 4.4% | 8.9% | **10.8%** | 2.5% |
| | 1920-1940 | 1.9% | **3.8%** | 0% | 0.6% |
| | 1940-1960 | 1.9% | 1.9% | **3.2%** | 2.5% |
| | 1960-1980 | 4.4% | **10.8%** | 5.7% | 1.9% |
| | 1980-2000 | **7.0%** | 3.2% | 1.9% | 0% |
| | >2000 | **17.1%** | 5.7% | 0% | 0% |

Table 6. Level of efficiency by deck material. The efficiency level mode for each deck material is bolded.

| | | Efficiency level | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 |
| Deck material | DC | 8.1% | **11.8%** | 6.8% | 4.3% |
| | DPC | **8.1%** | 7.5% | 5.0% | 0% |
| | DM | 4.3% | 9.3% | **9.9%** | 1.9% |
| | **DCS** | **5.0%** | 3.1% | 0.6% | 1.2% |
| | **DS** | **10.6%** | 1.9% | 0% | 0.6% |

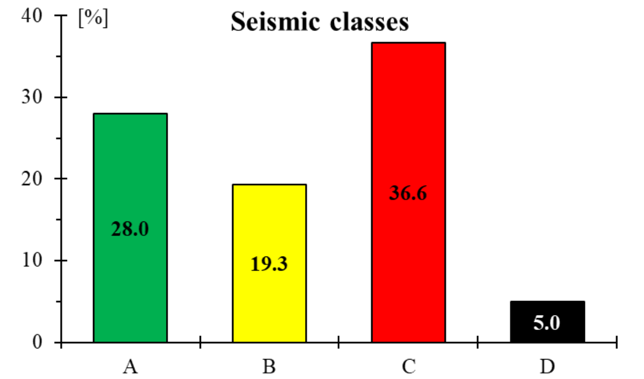


Figure 11. Seismic classes distribution for the analysed bridges.

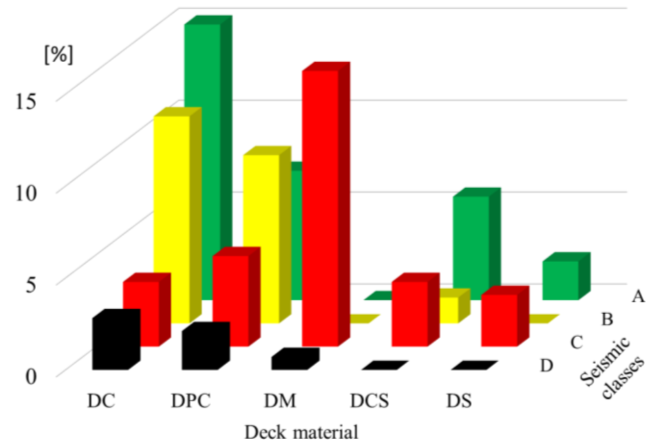


Figure 12. Seismic classification by deck material.

It has been observed that an intervention aimed to prevent spandrel wall failure, such as adding ties, significantly reduces seismic risk up to class A with a contained cost of intervention.

### 3.4 *Combined assessment and prioritization*

Bridge condition state assessment is greatly affected by degradation and reduced load-bearing capacity. Hence, the resulting priority-ranking list is obtained primarily sorting the analysed structures by decreasing efficiency TSR values. Then, for the same efficiency TSR value, structures are ranked by decreasing seismic classes. The results of the above-mentioned combined approach are shown in the following Table 7. Percentage are referred to the total number of bridges analysed in terms of both efficiency and seismic vulnerability, corresponding to 141 structures. About 14% of bridges belongs to efficiency level 1 and seismic class A which combination represents the best condition, while just one bridge (0,7% of the analysed bridges) presents efficiency level 4 and seismic class D, needing urgent retrofit and restoring intervention.

Table 7. Combination of seismic class and efficiency level for the bridge stock.

| | | Efficiency level | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 |
| Seismic class | A | 14.1% | 13.4% | 3.5% | 0.7% |
| | B | 5.6% | 6.3% | 5.6% | 4.2% |
| | C | 11.3% | 14.1% | 12.7% | 2.8% |
| | D | 0.7% | 1.4% | 2.8% | 0.7% |

Bridges at top of priority list belonging to efficiency level 4 urgently requires budgeting further investigations and interventions. Then, a mid-term and log-term intervention plan is required for the most part of the stock bridges, which belong to halfway conditions (i.e. about 60%)

## 4 CONCLUSIONS

The expeditious procedure presented in this paper, which is an enlargement of a method from literature, allowed evaluating both the efficiency level accounting for degradation and seismic vulnerability for a stock of 161 bridges of various typologies located in the Municipality of Padova. The methodology aims to provide local administration in charge for roadway network management with a priority list for further on site and numerical investigations, and interventions.

The evaluation is carried out by means of data collection through archive documentation and visual inspections.

The efficiency level appears to be linked with the bridge age, as expected. Furthermore, a significant influence is given by the deck material, with particular reference to RC structures, due to the poor quality of the material, inadequate design and construction methods. For this typology, further attention has to be paid to maintenance.

## ACKOWLEDGEMENT

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