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# Statistical analysis of risk assessment of bridges and viaducts according to recent Italian guidelines

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## Abstract

The safety assessment of existing bridges and viaducts is nowadays a critical task. Several works have been published in recent years relying on multi-risk based approaches, then aiming to properly evaluate the various risk sources involved in the identification and evaluation processes of existing infrastructures. In Italy, after some significant collapses (the most famous case is certainly the Polcevera viaduct, also known as the Morandi's bridge, collapsed in 2018), the Italian Higher Council of Public Works provides specific regulations, the 2020 Guidelines (updated in 2022), intended to standardize the entire risk classification procedures and monitoring activities of existing bridges and viaducts for the whole Italian road network.

This work proposes two main contributions. The first concerns a conceptual analysis of the logical path that leads from the considered parameters to the risk classification (class of attention, according to the cited Guidelines). The aim is to enucleate the total amount of parameters, their role and the possible combinations. The second contribution concerns an extensive investigation on the statistics of the class of attention. Such statistics represent the "a priori" distributions of the multi-risk procedure indicated by the regulation.

*Keywords:* road bridges; multi-risk assessment; 2020 Italian Guidelines; statistical analyses; machine learning.

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## 1. Introduction

Risk assessment of bridges and viaducts is crucial in order to preserve road networks functionality and to appropriately prioritize the maintenance interventions. According to the international technical literature, see for instance Allah Bukhsh *et al.* (2017) and Whelan *et al.* (2019), risk assessment procedures must rely on multi-risk approaches. In the Italian framework, some valuable bridges collapsed in recent years; for a comprehensive explanation see the work by Bazzucchi *et al.* (2018). After these failures, particularly after the sadly famous collapse of the Polcevera viaduct (also known as the Morandi's bridge, fell down on 14 August, 2018) the Italian Government decided to adopt specific regulations for the multi-risk evaluation of existing bridges and viaducts . These regulations will be published two years later by the Italian Higher Council of Public Works as "Guidelines 2020".

The 2020 Italian regulation, together with the relevant 2022 updating and operational instructions (CSLLPP (2020), CSLLPP (2022) and ANSFISA (2022), respectively), address the multi-risk evaluation and classification for bridges and viaducts with spans over six meters. The adopted approach is based on a multi-level scheme, consisting a six levels called Level 0-5, see Buratti *et al.* (2022). Level 0 involves a comprehensive inventory of the infrastructures, in order to provide a thorough database for the further stages; the data quality achieved here greatly affects the next judgements. Level 1 adds a visual inspection, aimed to confirm previous data and to observe the infrastructure actual conditions. Structural details, geometry, material degradation and other signs related to landslides and hydrodynamic actions must be carefully examined and annotated (on specific forms attached to the Guidelines) at this stage. Certainly, this level might miss non-visible defects. Level 2 increases in complexity, determining each bridge "Class of Attention" (CoA) combining hazard (H), vulnerability (V), and exposure (E) linked to four risk types: structural/foundational, seismic, landslide, and hydraulic; this latter is further subdivided into three entries: generalized erosion, localized erosion, and overtopping risks. Adopting the specific indications provided by the Guidelines, each risk gets a specific CoA, from low to high, with 5 possible results: low, medium-low, medium, medium-high or high. Then, Guidelines indicated how to combine the four individual risks into one overall CoA. This one provides a first risk estimation for bridges and viaducts, allowing to prioritize further studies, namely Level 3 and Level 4, where detailed risk assessment are considered involving tools and analyses more detailed than ones scheduled in Level 2. The last level, Level 5, not detailed in the Guidelines, focuses on bridges and viaducts considered crucial for socio-economic reasons and/or with reference to the resilience of the network.

Some very recent articles have been published regarding the guidelines, to follow their theoretical and applicative developments, Cosenza and Losanno (2021) and Cutrone *et al.* (2023). This study focuses on the analysis leading to Level 2 classification, emphasizing risk evaluation and management from a logical viewpoint and providing statistical investigations. Whitin this framework, a paper published by Santarsiero *et al.* (2021) proposes a statistical research on a real Italian road, showing some significant observations on the risk classification in terms of clustering of the collected results. The main novel contribution provided in the paper is the numerical evaluation of the "a priori" probability to get a low, medium-low, medium, medium-high or high risk. The paper is organized as follows: § 2 concerns the conceptual analysis of the Italian Guidelines, where ruling (both primary and secondary) parameters are enucleated and possible combinations are evaluated; § 3 provides new statistical findings on CoA outcomes; § 4 draws the conclusions of the paper.

**Nomenclature**

| | |
|---|---|
| CoA | Class of Attention |
| CoA-S&F | Class of Attention for Structural and Foundational risk |
| CoA-S | Class of Attention for Seismic risk |
| CoA-L | Class of Attention for Landslides risk |
| CoA-H | Class of Attention for Hydraulic risk |
| CoA-Le/Ge/E | Class of Attention for Localized Erosion/Generalized Erosion/Erosion risk |
| CoA-Ot | Class of Attention for OverTopping risk |
| H, V, E | Hazard, Vulnerability, Exposure |
| $L_{1,2,3}/L_m$ | Different max span length categorization/Mean span length |

## 2. Conceptual analysis of the Italian Guidelines

The evaluation of CoAs according to the Italian Guidelines represents a complex and stratified operation, which is based on a structured path of “classes and logical operators”. The methodology requires the categorization and evaluation of various parameters, all closely linked to the three pivotal components of any risk assessment: hazard (the probability of a harmful event occurring), vulnerability (the susceptibility of a structure or geographical area to suffer damages), and exposure (the magnitude of elements at risk). When all parameters, whether primary or secondary, have been examined, the classes of attention are determined for the individual risk categories: structural and foundational (CoA-S&F), seismic (CoA-S), landslides (CoA-L), localized erosion (CoA-Le), generalized erosion (CoA-Ge), and overtopping (CoA-Ot) risks. After these specific attention classes have been evaluated, the process requires additional combinations: CoA-Le and CoA-Ge are first merged to give the erosion class of attention (CoA-E); then, this class of attention is combined with the CoA-Ot, producing the hydraulic attention class (CoA- H); subsequently, the CoA-H class is combined with the landslide one, CoA-L, providing the hydrogeological attention class (CoA-H&L); finally, this hydrogeological class is combined with the CoA-S&F and CoA-S, providing the overall class of attention. All the involved steps determine how the classes interact with each other and how, collectively, they influence the final evaluation of the CoA (Fig. 1).

### *2.1. Ruling parameters and possible combinations*

The specific parameters required for the **CoA- S&F** are first analyzed:

- for the hazard parameters: the “extent of expected loads” describes the load capacity, ranging from Class A, as required by Technical Standards, to Class E, which has a limit of 3.5 tons; the “frequency of commercial vehicle passages” measures the frequency of commercial vehicles on the bridge, categorized as high, medium, or low;
- for the vulnerability parameters: the “level of degradation” specifies the bridge degradation level, which can be high, medium-high, medium, medium-low or low.; the “static scheme” details the structural design scheme, such as supported beams, thin arch, or Gerber beams; bridges are also categorized by their “max span length” ($L_1$), with four distinct ranges; the “material” refers to construction materials like reinforced concrete, steel, and masonry; the “number of spans potentially involved in collapse” indicates if a bridge has up to 3 spans or more involved by a collapse; “degradation speed” indicates the time since the bridge last significant maintenance; the bridge “exposure to sea currents or antifreeze salts”; bridges are also categorized as “I” or “II” category bridges whether military vehicles are allowed or not; there’s an additional “max span length” ($L_2$) categorization, which is combined with the “design code” to describe the design standards;
- for the exposure parameters: the “average daily traffic” gives the typical vehicle count, ranging from high to low; the “mean span length” ($L_m$) is divided into three categories; “road alternatives” states whether alternative routes are available; “public and social functions”, “consequences of interruptions”, “crowding”, “naturalistic, economic, and social values”, and “pedestrian traffic” reflects the significance of the eventual crossed structure; “transport of dangerous goods” designates if hazardous materials cross the bridge.

In total, there are therefore 21 parameter, 8 primary and 13 secondary according to the Guidelines, which provides **24’494’400 possible scenarios**.

Regarding the **CoA-S**:

- for the hazard parameters: the “expected peak ground acceleration” based on a return period of 475 years; the “topographical category”, which plays a primary role and includes classifications such as T1, T2, T3, and T4; the “subsoil category”, a secondary factor, distinguishing areas such as A-B from C-D-E;

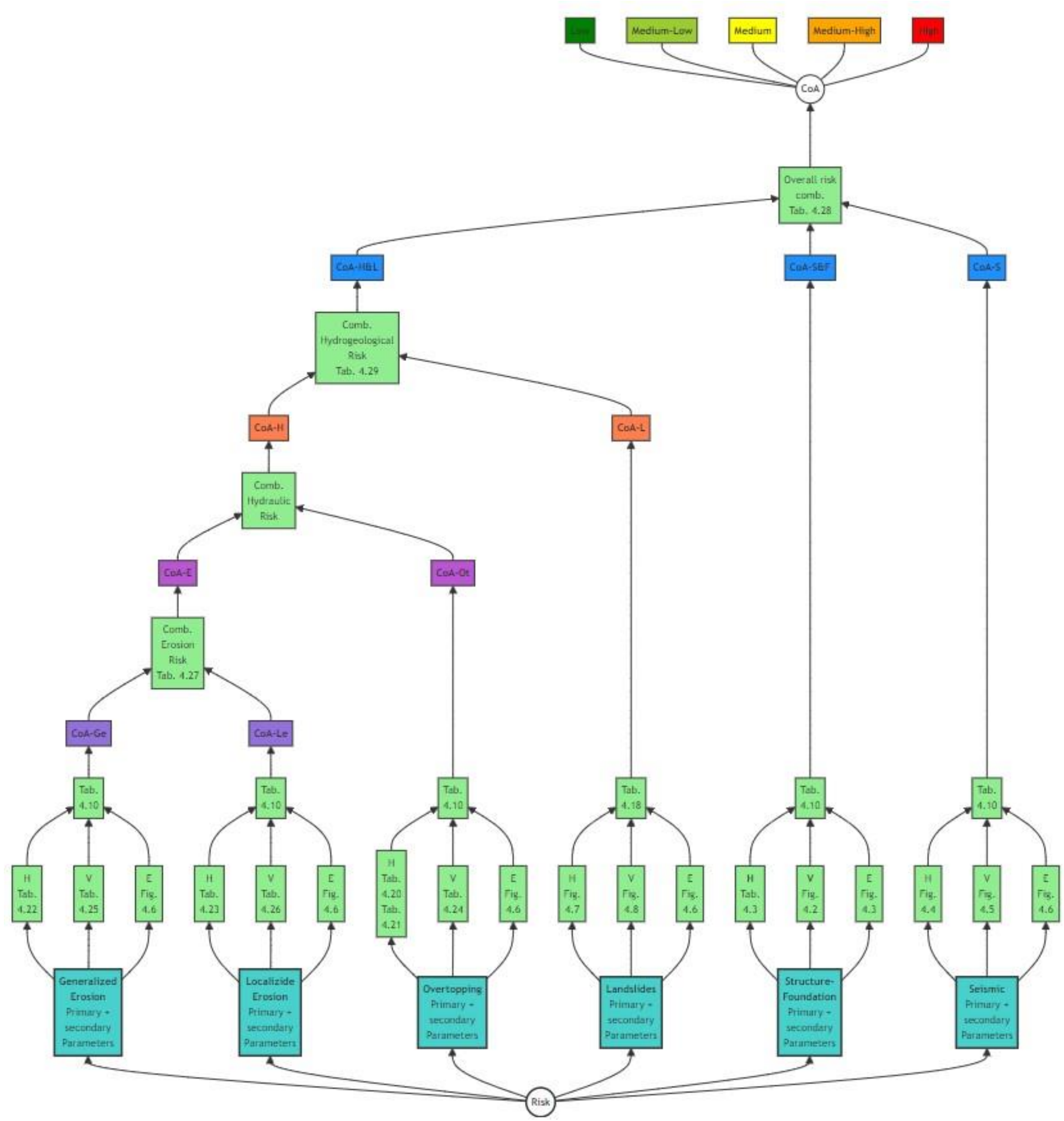

Fig. 1. Flow chart for CoA assessment.

- for the vulnerability parameters: the “static scheme”, which classifies bridges as isostatic or hyperstatic; the “max span length” ($L_3$) is another primary factor, indicating whether the bridge has a span length that’s medium-low (up to 20m) or high (more than 20m); the “bridge construction material” is crucial here, with options like reinforced concrete, prestressed reinforced concrete, steel, and masonry; the “number of spans”, categorized by whether the bridge is a single span or has multiple spans; the “level of degradation”, ranging from high to low; the "seismic vulnerability factors"; the "seismic criteria design" indicates if seismic rules have been adopted or not during the design;

- for the exposure parameters: the same listed for the CoA-S&F, plus the "strategic function of the structure".

For the CoA-S, there are then 20 individual parameters; among these, 10 are primary, and 10 are secondary. Considering all the potential combinations, **2'246'400 scenarios** can be obtained.

Considering the **CoA-L**:

- for the hazard parameters: the "activity status", which includes options highly critical, critical, and scarcely critical; another primary parameter is the "maximum expected speed", with various speed ranges; the "magnitude of slope instability", which is quantified through volume ranges; the "model uncertainty" is classified as good or limited; the "mitigation measures" are also considered, where the result can be absentees, monitored, or stabilized;
- for the vulnerability parameters: a significant parameter is the "bridge and foundation type"; a secondary parameter here is the "interference extension" with options including total, partial, and approach zone;
- for the exposure parameters: the same listed for the CoA-S.

In total, considering all the 17 parameters and their potential combinations, the CoA-L shows **7'581'600 possible scenarios**.

Regarding the **CoA-H**:

- for the hazard parameters: for overtopping, parameters such as the "minimum bridge clearance" and the "freeboard level" are considered primary; for generalized erosion, the "upstream riverbed width", the "width of the riverbed occupied by piers and abutments", the "upstream floodplain width" and the "floodplain width occupied by piers and abutments" play a crucial role, since they characterize how erosion might affect the overall stability of the bridge structure; for localized erosion, the "depth of foundation" and the "maximum depth of excavation" are the primary parameters;
- for the vulnerability parameters: in the case of overtopping, primary parameters are the "evidence of sediment deposition or riverbed erosion" and the "evidence of transport of large-sized vegetal material", which can be both categorized as prominent, significant, or absent; additionally, the "dimension of the watershed" are considered, specifying if it's less than or equal to 100 km², between 100 km² and 500 km², or greater than 500 km²; for generalized erosion, parameters are the "evidence of widespread riverbed lowering" (which can be prominent, significant, or absent), the "curvature of the riverbed" and the "foundation types for piers and abutments" (either shallow or deep); for localized erosion, parameters are the "presence or absence of debris accumulations" upstream of the piers, the "riverbeds tendency for planimetric meandering", the "evidence of pier and abutment protection works", and the "presence or absence of a downstream protection weir".
- for the exposure parameters: the same listed for the CoA-S.

Regarding the CoA-H, there are then 28 parameters; among them, 21 are identified as primary and 7 as secondary. Considering all these factors, the **total possible combinations are 186'624'000**.

The total number of parameters for the classification of a bridge is then equal to **86 (21+20+17+28) parameters**. However, considering that 9 exposure parameters are common for the CoA-S&F and CoA-S, and that the CoA-L and CoA-H have the same 10 exposure parameters of the seismic attention class, the number of parameters decreases to**57 (21+11+7+18)**.

### *2.2. Constrained combinations*

In the previous section 2.1, all the parameters associated with each attention class have been listed; then the relevant combinations have been evaluated. To recognize the overall magnitude of the possible combinations, it is sufficient to multiply the obtained values. Carrying out this calculation, the **impressive total amount of $7.79 \cdot 10^{28}$ combinations for the overall CoA** is gathered. It must be noted, however, that the bulk of the combinations reside in CoA-H and CoA-S&F. Nevertheless, not all these combinations are fully realistic, since interactions and constraints between different parameters must be considered. These relationships can exist both within the same class of attention and between different classes. Hereafter, the paper will focus on the constraints inside the individual CoA.

Considering the **CoA-S&F**, a specific correlation is identified between two length parameters: $L_1$, the max span length, and $L_m$, the average one. Since the average span length cannot exceed the maximum, the ranges indicated in the Guidelines must respect the constraints:

- if $L_1 \leq 5$ m or 5 m $< L_1 <$ 15 m, $L_m$ will certainly be less than 20 m;
- if 15 m $\leq L_1 <$ 25 m, $L_m$ may be less than or at most equal to 20 m or between 20 m and 50 m;
- if $L_1 \geq 25$ m, there are no constraints on $L_m$.

This constraint has a direct impact on the possible combinations. In detail, the original amount see a reduction of 41.67%, **from 24’494’400 to 14’288’400 combinations**.

Also with regard to the **CoA-S** there is an interdependence between the parameter referring to the maximum span length ($L_3$) and the average value $L_m$. This can be expressed as:

- if $L_3 \leq 20$ m, $L_m$ will be surely less than or equal to 20 m;
- if $L_3 > 20$ m, $L_m$ is not constrained.

By applying this constraint, the number of combinations is reduced by 33.33%, **from 2’246’400 to 1’497’600 possible scenarios**.

Considering the landslide class **CoA-L**, there is the same interdependence already described among $L_3$ and $L_m$. By applying this constraint, the number of combinations is reduced by 33.33% **from 7’581’600 to 5’054’400 possible scenarios**.

**CoA-H is not subject to interdependence** between its parameters; consequently, the number of possible combinations does not change.

At the same time, there are dependencies between parameters belonging to different classes. For CoA-S&F and CoA-S:

- the seismic exposure class is obtained by combining the structural and foundational exposure class with the “strategic function” parameter;
- the types of structural material are summarized in tables 4.6 and 4.13 of the Guidelines for CoA-S&F and CoA-S, respectively. Even if the number of possible choices changes between the two classes, there is interdependence among the options;
- a further interconnection concerns the parameters relating to the static scheme: as regards the CoA-S&F there are seven possible choices, whereas for the CoA-S only two (isostatic or hyperstatic);
- also the number of spans and the number of spans potentially involved are linked; in the case of an isostatic scheme, both in the case of a single span and in the case of a multiple span, the number of spans potentially involved in a collapse is less than or at most equal to three; in the case of hyperstatic schemes, this number is certainly less than or at most equal to three in the case of a single span, whereas there may be ambiguity in the case of a multiple span;
- considering the spans lengths $L_1$, $L_m$ and $L_3$ cited above, the constraint is:
  - if $L_1 \leq 5$ m or 5 m $< L_1 <$ 15 m, then $L_3$ and $L_m$ will certainly be less than or at most equal to 20 m;
  - if 15 m $\leq$ L1 $<$ 25 m, $L_3$ can be either less than or at most equal to 20 m or greater than 20 m, whereas $L_m$ can be less than or at most equal to 20 m or between 20 m and 50 m;
  - if $L_1 \geq 25$, $L_3$ will certainly be greater than 20 m and $L_m$ can take on all the allowed values.

By applying all these constraints between **CoA-S&F and CoA-S**, **44’556’480’000 possible combinations** survive for the two classes.

Further considerations on the interconnection of the parameters between the different attention classes must be made regarding CoA-S, CoA-L and CoA-H:

- the parameter “bridge and foundation type” determined for CoA-S is the same required for CoA-L;
- the exposure class assessed for CoA-S is the same required for CoA-L and CoA-H.

Considering these two constraints, the number of possible combinations for **CoA-L** is further reduced **from 5’054’400 to 1’350** (99.97% reduction), whereas the combinations for **CoA-H** are reduced **from 186’624’000 to 864’000** (99.54% reduction).

As a consequence, the number of realistically possible combinations, i.e. **possible bridges and viaducts**, obtained by constraining the parameters inside the individual classes and between the different CoAs is drastically reduced **from $7.79 \cdot 10^{28}$ to 51’970’678’272’000’000’000**. Table 1 summarizes the results obtained for the possible scenarios.

Table 1. Summary of possible combinations.

| CoA | N° free combination | N° constrained combination (considering only constraints inside of the considered class) | N° constrained combination (all constraints) |
|---|---:|---:|---:|
| Structural and Foundation (CoA-S&F) | $24.49 \cdot 10^{6}$ | $14.29 \cdot 10^{6}$ | $4.46 \cdot 10^{10}$ |
| Seismic (CoA-S) | $2.25 \cdot 10^{6}$ | $1.50 \cdot 10^{6}$ | |
| Landslides (CoA-L) | $7.58 \cdot 10^{6}$ | $5.05 \cdot 10^{6}$ | $1.35 \cdot 10^{3}$ |
| Hydraulic (CoA-H) | $186.62 \cdot 10^{6}$ | $186.62 \cdot 10^{6}$ | $864 \cdot 10^{3}$ |
| Overall | $7.79 \cdot 10^{28}$ | $2.02 \cdot 10^{28}$ | $5.20 \cdot 10^{19}$ |

## 3. Statistical analyses

This section shows the statistical analyses related to the possible combinations of bridges and viaducts. Each individual risk is considered in the evaluation: by applying the constraints between the parameters belonging to the same class, all the samples listed in the second column of Table 1 (“N° constrained combination (considering only constraints inside of the considered class)”) were performed and all the relevant CoAs were then collected. Clustering all the results, the “a priori” distribution for the various risk have been obtained.

The results are summarized as histograms in Fig. 2. Examining the plots, several observations can be drawn:

- distribution of CoA-S&F, see Fig. 2(a), indicates a predominance of combinations falling within the “High” risk category. If the iso-probabilistic case is considered as expected, this finding suggests that the Guidelines are particularly cautious (in the terms of potentially overestimated risk) or that there are several parameters leading to high-risk conditions;
- Figure 2 (b) illustrates the seismic analysis, showing again a significant number of combinations in the “High” risk class. As for CoA-S&F, this might reflect an inherent prudence in the Guidelines when addressing seismic risks, or that several parameters lead to high-risk conditions;
- for the landslides risk, Fig. 2(c), there’s a notable predominance in the “Medium-High” category (close to 50%). The second class in terms of occurrence is the “Medium”. This suggests a less prudent approach than the two previous CoAs, or a set of parameters less prone to lead to high-risk conditions;
- regarding the hydraulic risk, as observed in Fig. 2(d), the Guidelines behaves as for the landslide one (although the first class in order of importance is here the “Medium”, then follows the “Medium-High” one). Moreover, in this case, the distribution is more uniform.

## 4. Conclusion

The multi-risk analysis of bridges and viaducts according to the recent Italian Guidelines has been investigated in this paper. The focus was the Level 2 evaluation, i.e., the evaluation of the classes of attention.

Two main contributions were provided: a deep conceptual analysis of the path connecting parameters to attention classes and an extensive investigation of the statistics of these classes. Concerning the first contribution, the ruling parameters were analyzed and the possible scenarios were counted for each of the four risk classes. Introducing the proper constraints inside the individual classes and among the four classes, the number of possible scenarios were then reduced, providing the number of realistic possible scenarios. Moving towards the second contribution, the histograms showing the probability to get a low, medium-low, medium, medium-high or high class of attention have been provided for each of the four risk. These histograms are the clustering of the results obtained running all the realist cases ($208.46 \cdot 10^{6}$ evaluations of the attention classes). Significant insights into the risk class distributions have been obtained. First of all, none of the cases is iso-probabilistic: for structural and foundational risk, as well as for the seismic risk, the “High” risk class is dominant; for the landslide risk the dominant class is the “Medium-High”; in the case of hydraulic risk the distribution is more uniform, with a peak for the “Medium” class. Based on these results, predictive algorithms are also under investigations; these could be useful both for bridges and viaducts not yet inspected (to depict a first rough classification) and for the structures already classified (to quickly check the obtained classes of attention).

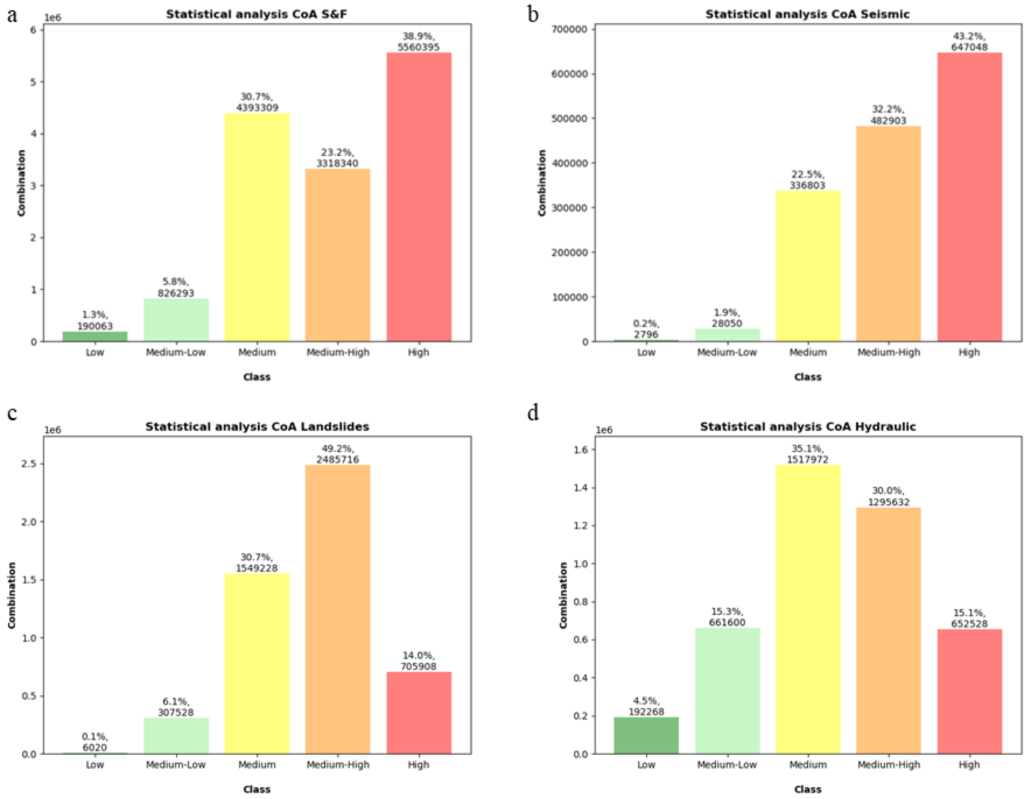

Fig. 2. Histogram of: (a) CoA-S&F, (b) CoA-S, (c) CoA-L, CoA-H.
N.B.: for CoA-L and CoA-H, the basic assumption is that the respective risks are actually present (i.e., a landslide or a river affects the structure).

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