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Human Errors induced risk in reinforced concrete bridge engineering

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Abstract:

Throughout the last century and in recent years, several bridge failures have taken place worldwide. Recent studies uncovered that the primary cause of these collapses were human errors in design, construction and operation phases. Regardless of this finding, there is still a considerable gap between this information and the known errors and the risk they represent for structural safety. Aiming for a better understanding of human errors, an identification procedure and a qualitative assessment of such errors considering risk-based indicators (probability of occurrence and consequence) was performed. Several brainstorming meetings with design and construction experts led to the identification of 49 relevant human errors, which were listed for further evaluation on a survey. Much more important than identifying and assessing these errors is identifying those that pose a greater threat to safety. Using a decision-making tool (Analytical Hierarchy Process) to process all the information collected in the survey, the errors were ranked according to risk indicators. Furthermore, a qualitative risk assessment is performed, allowing the identification of the errors denoting higher risk for structural safety, according to experts' opinions.

Keywords: Human error, Bridge Failure, Reinforced Concrete Bridges, Risk Analysis, Analytic Hierarchy Process (AHP)

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Introduction

As one of the key elements for economic growth and citizens' well-being, the transportation sector has always been a valuable asset for societies. Nevertheless, the transportation system depends very often on connections provided by roadway, railway, and footway bridges. Thus, these infrastructures play a crucial role in the transportation network, being responsible for tremendous consequences when wrongly managed. Several examples can be found in the literature (Cavaco, 2013; Imhof, 2004; Scheer, 2010). According to design standards (CEN, 2005; ISO, 2015; JCSS, 2001), a structure shall be designed and executed in such a way, with an appropriate degree of reliability and robustness, that it will not be damaged to an extent disproportionate to triggering events such as explosion, impact and consequence of human errors. Aiming at the reduction of occurrence rate and consequence of bridge collapse, the reliability and robustness of these structures should be increased (Starossek and Haberland 2010), as well as the identification of the sources of uncertainties and triggering events that may lead to their failure.

Relying on the work developed by (Syrkov, 2017) and further developed within task group 1.5 of the International Association for Bridge and Structural Engineering (IABSE), statistics in bridges failure will be briefly discussed. Such a database is probably the most relevant bridge failure database available with more than 700 bridge failure incidents worldwide from 1966 to 2018 and covering the leading causes of failure. Examining the information provided by the database, it is concluded that the main source of uncertainties triggering bridges collapse is human errors (see Fig. 1). The design and construction errors are responsible for 31.8% of the collapses, while the operation errors are responsible for 32.2%.

Several definitions have been given to human errors in the literature. Nevertheless, due to its broad scope, a formal definition is required, leaning toward its boundaries definition to prevent misunderstandings with other works definitions. Within the scope of this paper, human errors are any Procurement, Design, Construction and Operation errors (deviations out of the acceptable margins) that do not exceed the currently available engineering knowledge and have taken place due to poor work condition, lack of knowledge, negligence, miss instruction and communication, greed, calculation errors, time and budget constraints, inadequate construction methods, lack of surveillance, among others. Such errors or uncertainties are not covered by the partial safety factors given in present-day semi-probabilistic standards. A similar understanding of what is understood by human errors is shared by (Stewart & Melchers, 1988; Tylek, Kuchta, Rawska-Skotniczny, 2017, Brehm & Hertle, 2017). Also, aiming the explanation of human errors boundaries, its clusters are schematically presented in Fig. 2. Human errors and human-made hazards are two major components of human factors field, being the former the interaction of humans with a system as a technician, and the later the interaction of humans with the system as a user.

By performing a more exhaustive analysis over the database, aiming at a more detailed analysis of the causes of failure of reinforced concrete bridges, some relevant specific failure causes are presented in Fig. 3. Each of these specific failures causes are linked to the main ones as follow: (a) Natural hazards (floods and wind effects); (b) Human-made hazards (ship collision, explosion, vehicle collisions, vandalism, and overloading by live load); (c) Design and construction errors (design defect, construction defect, design and construction defects and construction negligence); (d) Operation errors (corrosion, deterioration of reinforced concrete, and overloading by the live load (during maintenance works)). A similar classification of the causes of the collapse of bridges can be found in (Deng et al. 2016; Imhof, 2004). Some specific causes of failure such as debris in the water, creep and shrinkage, temperature, normal corrosion, and freeze-thaw cycles with small percentage were gathered into the group named Others. One can observe from Fig. 3 that flood is responsible for a considerable number of failures, and due to climate change, its influence is likely to increase due to increasing rainfall intensity (Chen 2017). More detailed research on flooding effects (namely scour) uncertainties can be found in (Johnson et al. 2015; Manfreda et al. 2018).

Procurement errors

The procurement phase is defined by the explanation of the overall idea of an undertaking, definition of execution deadlines suitable for the owner, forecast of the overall cost of the project and selection of the technical team (designer and contractor). The incorrect management of the procurement phase very often leads to poor decision making from the owner, creating and stimulating several sources of the errors taking place in the design, construction and operation phase.

Given the highly aggressive labour market, companies from the construction industry sometimes face decisions where they are forced to assume execution time and financial costs beneath the needs for the proper fulfilment of the durability, safety or serviceability requirements. Hence, the technical expertise and technology required for successful design and execution are not always the key factor for the contractor or the designer eligibility. The restricted execution time and limited resources usually lead to simplification of complex tasks that typically require expertise and detailed approach, leading very often to assumptions that do not correspond to the reality nor reliable execution strategies. Therefore, many of the errors that might occur in the later stages of a project are often the consequence of the procurement phase's primary mistakes. Quality control strategies are also features of the procurement phases that can greatly impact the identification and mitigation process of potential sources of errors. Thus, a balance between reasonable execution time, cost, quality control strategies and the selection of a qualified technical team (enough experience) should be set as a strategy for human error mitigation in the long term.

Design errors

Conceptual errors

The conceptual stage considers several essential aspects required for a successful design. Aspects such as the contextualization of the design project in time and space, considering the available engineering technology, adequate base material at disposal, maximum concrete strength manufactured with local raw materials, reachable technical and non-technical support, suitable structural system and construction procedure (according to geotechnical constraints) and required geotechnical characteristics. All these aspects influence the cost of the project and the complexity of execution, consequently providing a greater or lesser environment for human errors occurrence (Fröderberg, 2015). Hence, a well-achieved conceptual design is also a mitigation strategy of human errors induced risk. Such considerations should demand an even greater consideration when the project is of non-local or international nature since the designer and the contractor must get familiar with local needs and safety requirements.

A well achieved conceptual design pays off in the long run, by a good structural performance during its operation, minimization of the structure life cycle costs and robust performance under expected or even unexpected single or multiple hazards. Projects with a daring conceptual design with large spans, uncommon column and deck shapes, and other unique characteristics are more vulnerable to human errors, requiring utmost attention and mitigation measures. For conventional bridges though, the conceptual design is a more standardized procedure since agencies already established internal specifications dictate the material, span, structural systems, among other features of the structure. Thus, a less error-prone design is to be expected. A good example of a well-achieved conceptual design, leading to the reduction of a human-made hazard probability of occurrence, is the consideration of an arch bridge instead of a common girder bridge with several piers to avoid vessels collisions on the piers. This example is given in a context where the bridge would span over a river/narrow sea with high traffic. The definition of a structural system compatible with construction procedure or technique usually employed by contractors is also a good conceptual strategy aiming to reduce execution difficulties.

Structural analysis and design errors

Nowadays, international demand over the construction industry requires design corporations to be involved in numerous projects worldwide. Under this scenario, local standards must be used during the design very often, and the philosophy behind them may be varying from one to another. The same standards can be occasionally incomplete, leading to the need for the combination of different standards. Errors scenarios are drawn, mostly when the quantification of design loads is completed using a given standard where safety factors are less strict in the quantification of the design loads than in the resistance computation. Simultaneously, the resistance computation is performed according to a different standard where the philosophy behind it is the opposite. Consequently, the structural reliability due to these standards' combination will be below the target values established initially by both standards. Non-coherence between several international design codes was reported by (Sykora et al. 2017), where different target reliability values are recommended for the same case study.

Another common source of error is in the definition of the structure boundary conditions or the soil-structure interaction due to high uncertainties linked to soil behaviour when wrongly addressed. Foundation rotations, differential settlements, support condition stiffness and geotechnical failure, are issues that require careful evaluation from experts, but sometimes neglected, even though they are responsible for tremendous consequences. Other issues, such as mistaken allocation of the bearing devices and lack of maintenance leading to support condition different from the initially designed, can lead to a severe structural system malfunctioning. A common example used to demonstrate the importance of the previously mentioned matter is the development of second-order effects in bridges with long piers due to the development of friction forces between the deck and the malfunctioning bearing devices, caused by the deck thermal expansion or shrinkage. As the bearing device allows the deck to deform freely at the design stage, the second-order effects are typically not considered for strength computation.

During the construction and transportation of structural components, a structural element or the structural system itself goes through different static conditions that are often different from the final ones considered in the design. Therefore, the structural system or the element resistance might be tested in certain cross-sections not designed to support unexpected stresses. Precast and prestressed elements are often damaged by the failure of decompression limit state caused by this error, leading to premature cracks. Nevertheless, more severe consequences such as element yielding or system collapse may also occur, especially when the construction technique demands static conditions changings during different assemble steps.

Detailing errors

All the information gathered and created by the designer is transferred to the main contractor through detailed drawings. Through the detailing phase, two stakeholders with different mindset are deeply connected; hence, the information conveyance must be clear to avoid any misinterpretation of the high volume of information being transferred. These are common characteristics of all linking and interface activities. As an interface or linking activity, detailing is considered a potential source of errors since it is susceptible to a mistaken interpretation of the given information, absence of specific information, drawings mistakes, among other errors. As such, the detailing phase should be carefully managed, especially when the information being transferred is of great importance for structural safety.

During the structural analysis and design, several assumptions are made, and very often, these assumptions play a crucial role in the successful performance of a system. It is not uncommon to find detailing drawings where the detailing strategy does not agree with the standard recommendations for the previously considered design assumptions, leading to unpredicted behaviours. For instance, systems with some redistribution capabilities are usually proposed in seismic design. Thus, the connection between different structural elements is expected to have improved ductile behaviour; hence, specific detailing strategies should be used, so the structural analysis correspond to the structure performance as built.

Construction errors

Falsework execution errors

Falsework or scaffold execution errors are referred to as being the most commons errors and responsible for the worst consequences in the execution phase. They often lead to complete demolition of concrete elements and a high number of fatalities and injuries. A flawed assessment of the falsework foundation, or no assessment at all going beyond the visual inspection, is a common problem. It is not unusual to find an execution plan where the collected data from piers or abutments foundation location are used to check the falsework foundation resistance. This procedure may fail when the falseworks are needed in extended lengths, because the foundation's geotechnical properties may vary along its length, especially if the given soil is heterogeneous, leading to soil properties assumptions entirely dissimilar to the real one. This mistaken assumption may well end up in substantial settlements, converted into large deflections, or even structural collapse. Another likely scenario of failure is the non-consideration of the reduction of soil resistance due to rainfall conditions. For this auxiliary structure, the area through which the load is transferred to the ground is usually small; thus, the soil stress limits should be carefully controlled. A common mistake here is the use of soil maximum load capacity as its resistance performance indicator, neglecting the importance of the area through which the load is transferred.

Movable falseworks require utmost attention when changing them from their current position to a new one since a constant change in its support condition is necessary. As such, no room for mistakes is allowed given severe consequences that might take place. Collapses have taken place in several constructions using this technic due to miss coordination between the different involved parts and lack of proper surveillance and effective communication.

Material quality control errors

Nowadays, material quality control errors are becoming a less concerning issue due to the industry's rigorous standards adopted to avoid former misfortunes and for quality assurance purposes. Nevertheless, this was not a certainty during the last century. The exceptional registered occurrences are related to concrete quality specifications due to a mistaken evaluation of aggregates water content, alkali-aggregate reaction, wrongful quantification of the required admixtures, and miscalculations to fulfil specific concrete requirements (e.g. concrete strength, elasticity modulus, among others). It is also worth mentioning the deficient vibration of concrete in areas of difficult access, due to high density of passive and active reinforcement allowing the formation of voids, or excessive vibration leading to segregation of concrete constituents. Additional deformation of concrete due to non-agreement between creep properties of employed concrete with those assumed in the design, is an error to bear in mind. Concerning the durability, it has been reported that the usage of the right or favourable use of the cement type can double the service life of the structure (Zambon et al., 2019). In construction sites where more than one reinforcement class is available, it is vital to take these classes' incorrect usage as a potential risk. Additionally, proper storage condition of reinforcement to avoid early corrosion and ductility reduction is an important consideration to keep in mind, especially when a long-stored period is concerned. Also, a non-controlled concreting of mass concrete components leading to high temperature is an error that leads to deficient concrete with severe strength reduction.

Logistics errors

The construction phase requires massive management of human, equipment, and material resources. Thus, logistic errors are part of companies' daily work, and they must not be neglected. Some examples are here presented:

- Adoption of a concrete resistance class or other specification that is not available at an affordable distance from the construction site;
- Air pollution, underground water or soil contamination, due to inadequate eco-friendly safety measures;
- Functional capabilities limitations of movable and fixed cranes in the construction site due to errors related to insufficient foundation preparation, limited action radius, allowed movable distance, maximum transportation weight, among others;
- Absence of special licences for transportation of big precast elements through public roads or physical restrictions to transportation can be a drawback that usually turns into large delays;
- Inadequacy of the launching girders to the pier's geometry is a logistic error to keep in mind;

Bridges collapse

Particular major bridges collapse were recorded due to some of the errors highlighted in the previous section. Given their technical relevance, they are shortly described and discussed.

In early 2018, one of the towers of a reinforced concrete cable-stayed bridge under construction in Colombia (Chirajara) collapsed due to a design error. The same error also led to the demolition of the still-standing tower since it was also about to collapse, making any attempt for its strengthening or rehabilitation very problematic. Ten workers lost their lives during the incident, and another five injured required some medical support. An investigation about the incident headed by Modjeski & Masters concluded that the bridge collapse was caused by the failure of the prestressed transversal girder and the failure of the diamond tower lower diaphragm. The influence of the tower diaphragm, in its overall resistance, was overestimated at the design stage (Bridge Design Engineering, 2018). Other sources state that the prestressed transversal girder was insufficiently prestressed and that the main reinforcements of the tower diaphragm were placed in the wrong direction (Pujol et al. 2019).

On March 2018, a pedestrian bridge under construction in the USA (Miami) collapsed due to a design error causing six deaths and eight injuries. It was reported by the Federal Highway Administration Office of Bridges and Structure that a design error led to the overestimation of the stresses that could be taken by the bridge. The cracks observed before the collapse were consistent with the design error. Lab tests were performed over the concrete samples to check its quality, proving that the concrete met the standard's requirements (NTSB, 2018). The bridge had structural design deficiencies that contributed to the collapse during one of the construction stages. The consultant hired by FIGG Bridge Engineers (the engineer of record) to conduct an independent peer review of its design did not check the structural integrity of the bridge for different construction stages. Consequently, the review was performed only under the final design stage, where all segments of the bridge were already in place and completed (Ayub, 2019).

On August 2018, a cable-stayed bridge from the sixties, designed by Ricardo Morandi, collapsed in Italy (Genoa) during a heavy traffic day causing 43 deaths. The collapse was mainly triggered due to structural deterioration caused by advanced corrosion in one of the four cables. Despite this fact, the structure had an initial deficiency related to lack of structural redundancy (absence of multiple load paths) or, consequently, lack of robustness because it had few crucial supports (four cables on each tower supporting the deck). The structure had another initial flaw that led to the crack of the protective concrete coat surrounding the stayed steel cable that left it unprotected, unchaining a premature corrosion process. An unneglectable piece of the puzzle is also the consequence of political decisions regarding public infrastructures when maintenance and restrictions applied to the structure are concerned. A good example of this last statement is the Morandi bridge since a political or owner decision neglecting the information given by experts also contributed to the bridge collapse (The New York Times, 2018). The lack of structural robustness (disproportionate outcome due to any support failure) is here highlighted as a conceptual structural error once a different cable-stayed structural system with multiple load paths would avoid such a terrific ending. The high rate degradation of the southern cable is here seen as an error of operation since no maintenance action on the structure was taken, before an obvious indication of high degradation that was prompted by a design error (protective concrete coat surrounding a highly tensioned element) from the early ages of the structures (Morgese et al. 2020). Three main groups of human errors led to this catastrophic ending: the conceptual error, the design error and the operation error. The occurrence of multiple errors, creating a sequence of events leading to bridges collapse, is the typical scenario.

Despite today's efforts and the new standards for quality control that implicitly deals with human errors, these errors are still a major concern. It is also known that bridge quality control standards were less strict during the sixties, seventies and eighties, where a high volume of bridges was built. Therefore, in the present days, it is important to consider human errors in infrastructure management procedures, in particular, when the error is expected to increase the deterioration rate of the structure since maintenance strategies and interventions are supported by predefined degradation rates (predictive models).

Design and Construction Errors Investigation

The risk management process aims at the systematic use of available information, within a carefully established and clearly defined context, to identify hazards and estimate the risk they pose to human beings, property, and environment. Hence, three steps are initially required (i) Hazard identification, (ii) Probability of occurrence analysis, and (iii) Consequence analysis. The combination of the last two provides the risk measure. Probability of occurrence and consequence analysis can be performed using a qualitative or a quantitative approach, yet the later is more complex and usually employed after the first one. A hazard is defined as any condition, circumstance or action that can undermine the structural system resistance features and may lead to malfunctioning or failure of the structure (Canisius et al. 2011; Faber, 2008; Rausand, 2011). Within the scope of this paper, human errors are the leading hazard under assessment, being design and construction errors in reinforced concrete bridges the focus subject. Therefore, the novelty of this research lies in the identification of design and construction errors that are carefully addressed according to expert judgement.

Delphi technique and survey

For hazard identification purposes the Delphi technique is here employed. The Delphi technique is defined in ISO 31010 (ISO, 2009a) as "a procedure to obtain a reliable consensus of opinion from a group of experts through a standardized procedure". Experts are expected to express their opinions independently and anonymously while having access to the other expert's views as the procedure goes on. Accordingly, six experts (20 years of average work experience) were selected and questioned about the most common and troubling design and construction errors in reinforced concrete bridge engineering that they have faced during their professional career. The experts were asked to keep in mind a standard roadway overpass with three spans of 68 *m* (18 *m* + 27.8 *m* + 18 *m*, which is the most common type in the Portuguese road transportation network). This request aimed to narrow the discussion around conventional bridges, avoiding particular structural types as suspension, cable-stayed and large span arch bridges. Nevertheless, the content of the information provided by the experts exceeded, to a small extent, such expectation. The expert views converged to a group of 20 design and 29 construction errors, see Table 1 and Table 2, respectively, clustered according to Fig. 4. The concerns expressed in the preceding chapters are also a summary of the expert's thoughts.

Following the detailed discussion around design and construction errors and listing of such errors by experts (i.e. hazard Identification), the second and third steps of the risk analysis are achieved through a survey addressed to experts aiming the qualitative assessment of the probability of occurrence and consequence of such errors according to five categorical levels. The experts were also encouraged to suggest additional errors important to be considered. The survey was carried out by e-mail through the COST Action TU 1406 network and to additional Portuguese civil engineers. The answers provided by the participants were analysed using a multi-criteria decision-making tool named the analytic hierarchy process (AHP) and a risk matrix. Twenty-four participants, with professional experience ranging between 5 and 40 years, answered the survey call. Half were from Portugal and the other half from other European countries. Half of them were design engineers, and the other half were construction site engineers, but some of them had experience in both fields.

Analytic hierarchy process

The AHP is a multi-criteria decision-making tool (Saaty & Vargas, 2013) that considers pair-wise comparisons of alternatives and criteria to prioritize such alternatives or criteria. It is supported by qualitative or quantitative inputs comparing different objects/subjects. Such comparison is numerically represented by a matrix comparing the alternative *i* with alternative *j*. The AHP is typically implemented in three main steps: (i) decomposition; (ii) comparative judgment; (iii) synthesis of priorities (Thompson et al. 2006). The decomposition is the particularization of the problem into different choices or possible solutions, which in this paper are the design and construction errors listed in the survey. The comparative judgment is performed by the survey participants where the probability of occurrence (PO) and consequence (CO) of each of the errors are categorized into five levels (see Fig. 5 and Fig. 6). The comparative judgement is then transformed into a comparison matrix that will allow the synthesis of priorities through the matrix eigenvectors, leading to the ranking of the errors according to their probability of occurrence and consequence, given the survey participants inputs.

The AHP is implemented through a MATLAB script developed according to Goepel's methodology (Goepel, 2013, 2018), aiming at a more automatized procedure to analyse the information collected through the survey. Such methodology is being widely used by the research community (e.g. Kifokeris et al. 2018) given its simplicity, straightforward tutorials and Excel templates available in (Goepel, 2013). The methodology is summarized here into the following consecutive steps:

1. The pair-wise comparison is summarized in a square comparison matrix, rating the probability of occurrence and consequence of each error using a qualitative typical 5-point Likert scale ranging from one to nine or from one to the inverse of 9 (i.e. 1-3-5-7-9 and 1-1/3-1/5-1/7-1/9). One is used when errors are similarly likely to occur, or similar consequences are to be expected, and nine is used when an error is much more likely to occur than another one, or a much greater consequence is expected from one error to the other. The inverse numbers are used when the error is less likely to occur, or minor consequence should be expected when compared to another error. The comparison matrices of each participant were all considered consistent.

2. The consolidation of each expert input is achieved by an aggregated square comparison matrix, considering the weighted geometric mean method according to equation (1), where: $a_{ij(k)}$ is the comparison performed according to Likert scale comparing error i to error j by expert k; and w_k is the expert weighting factor defined according to its years of experience as follow i) 1.0 for 5 to 10 years of experience; ii) 1.5 for 10 to 20 years; iii) 1.75 for 20 to 30 years; iv) 2.0 for 30 to 40 years.

$$C_{ij} = exp\frac{\sum_{k=1}^{K} w_k \ln a_{ij(k)}}{\sum_{k=1}^{K} w_k} \tag{1}$$

3. In order to quantify the agreement or homogeneity between different experts input, a consensus index is computed, ranging the consensus between expert's opinions from 0% (no agreement) to 100% (perfect agreement). Finding a reasonable rate of this index is crucial to support the claim of a satisfactory convergence in the identification of relative priorities of the errors. The consensus or group judgement dispersion is derived from the consensus index S^*, computed according to equation (2).

$$S^* = \frac{\left[\frac{M - \exp(H_{\alpha\, min})}{\exp(H_{\gamma\, max})}\right]}{\left[\frac{1 - \exp(H_{\alpha\, min})}{exp\left(H_{\gamma\, max}\right)}\right]} \quad where \quad M = \frac{1}{exp(H_\beta)} \tag{2}$$

Where: H_β Shannon entropy beta measures the variations of priorities distribution among experts, given by equation (3). Which is dependent on Shannon entropy alpha H_α and gamma H_γ. The first one measures the average individual expert priority distribution among the errors, computed for all K experts and the second one measures the group aggregated priorities. The Shannon entropy alpha and gamma are computed according to equation (4), where p_{ik} is the normalized priority value of the ith error according to the kth expert, given by equation (5). The absolute priority values r_i are computed according to the row geometric mean method, as shown in equation (6) where N is the total number of errors.

$$H_\beta = H_\alpha - H_\gamma \tag{3}$$

$$H_\alpha = \frac{1}{K}\sum_{k=1}^{K}\sum_{i=1}^{N} -p_{ik} \ln p_{ik} \quad \& \quad H_\gamma = \sum_{k=1}^{K} -\bar{p}_k \, ln\, \bar{p}_k \quad where \quad \bar{p}_k = \frac{1}{N}\sum_{i=1}^{N} p_{ik} \tag{4}$$

$$p_i = \frac{r_i}{\sum_{i=1}^{N} r_i} \tag{5}$$

$$r_i = \exp\left[\frac{1}{N}\sum_{j=1}^{N} ln\left(a_{ij}\right)\right] \tag{6}$$

Subsequently, the minimum Shannon alpha entropy $H_{\alpha min}$ and the maximum Shannon gamma entropy $H_{\gamma max}$ must be computed applying the equation (7) and equation (8), respectively. Where $c_{max} = 9$ is the maximum value of importance rating used according to 5-point Likert scale to build the pair-wise comparison matrix in step 1.

$$H_{\alpha min} = -\frac{c_{max}}{z} ln\left(\frac{c_{max}}{z}\right) - (N-1)\frac{1}{z} ln\left(\frac{1}{z}\right) \quad with \; z = N + c_{max} - 1 \qquad (7)$$

$$H_{\gamma max} = (N-K)\left(-\frac{1}{z}\right) ln\left(\frac{1}{z}\right) - \frac{u}{z} ln\left(\frac{1}{K}\frac{u}{z}\right) \quad with \;\; u = K + \, c_{max} - 1 \qquad (8)$$

4. Priority values are obtained by computing the eigenvector of the pair-wise comparison square matrix. The prioritization or ranking of the errors is displayed in Table 1 and Table 2, last two columns, for each risk indicator, that is, the probability of occurrence (PO) and consequence (CO). Relative ranking position numbers are used, where the number one is attributed to the error that is more likely to occur or the error expected to have the highest consequences, while the maximum number is assigned to the error that represents the lowest probability of occurrence or the lowest consequence.

The consensus index obtained according to the AHP was 87% among the design engineers, and 73% among the construction site engineers. Thus, expert opinions did not disperse too much. The awareness and resemblance of the design engineer's assessment, of the design errors, are higher than those provided for the construction site engineers for the construction errors. Given that the designer's daily activities go through a more standardized procedure, a higher consensus index for the design engineers is a reasonable observation.

The input of each expert was weighted according to their years of experience. For instance, the input of a structural engineer with additional professional experience should have more influence on the outcome than the contribution of a junior engineer. As it is very difficult to quantify the influence of professional experience in this matter, there is no way to validate the weighting factors adopted in equation (1) without performing a major study of the topic. However, it is known that a senior engineer is more likely to make a better decision than a junior engineer due to the accumulated expertise; therefore, the weighting factor was increased with the years of experience.

Qualitative risk analysis

Once the design and construction errors rankings are established according to the probability of occurrence and consequence, it is of paramount importance the characterization of the relationship between these two for qualitative estimation of the risk. Hence, the risk matrix approach is employed (Rausand, 2011). It is commonly used to rank hazardous events according to their significance, to screen out insignificant events, or to evaluate the need for risk reduction of some events".

The loss of the information, concerning the qualitative levels assigned to the errors by the experts, is one the AHP handicap. In other words, the priority list or ranking is set with a great cost since the qualitative level of each one of the errors becomes unknown during the AHP procedure. The loss of such information renders difficult the qualitative assessment of the error with a risk matrix. To overcome this drawback, and accomplish a broader analysis of the information provided by the survey participants, the qualitative levels assigned to each risk indicator are obtained for each error using a weighted geometric mean method to aggregate the participant's inputs. Fig. 5 and Fig. 6 show the qualitative risk matrices of the design and construction errors, respectively, and their distribution according to their likelihood and expected consequences, using their identification number (ID) provided in Table 1 and Table 2. The prioritization information obtained by the AHP is also considered inside each matrix cell.

Making use of the information provided by the AHP and risk matrix, comprehensive risk classification of the errors was achieved. For exemplification purposes, let one take the errors with ID7 ($\mathrm{PO}_{\mathrm{Ranking}} \rightarrow 7$ and $\mathrm{CO}_{\mathrm{Ranking}} \rightarrow 18$) and ID8 ($\mathrm{PO}_{\mathrm{Ranking}} \rightarrow 1$ and $\mathrm{CO}_{\mathrm{Ranking}} \rightarrow 16$) from the design risk matrix. They are both within the high-risk group ($40 \geq Risk \geq 25$), but if the AHP ranking information is taken into account, the error with ID8 can be highlighted as the one representing greater risk, since it has a higher ranking position than the error with ID7. Therefore, the wrong definition of a cross-section shear centre (design error ID7) represents a lower risk than a wrong quantification of the effects of deck deformation due to creep, shrinkage and temperature variation, in columns leading to unexpected second-order effects (design error ID8). Using this same procedure, a further distinction between the risk of the different errors within the same cell is possible. Nonetheless, the risk of errors can be easily categorised into five different risk levels.

Based on Epaarachchi (Epaarachchi & Stewart, 2004), the error magnitude is the size of the error as a percentage of the correct outcome or in other words; it is the parameter that describes the severity of the error. It is a vital characteristic of an error, here neglected. The severity of an error is always associated with its consequence but is not the ultimate factor. For instance, the consequence of error with ID8 increases with the slenderness of the column, thereby, the same error with the same magnitude (equal relative deviation from its correct value) might have entirely different consequences for different structural systems or components. Subsequently, it is important to consider the magnitude of the error in a detailed structural analysis, mainly if the error is understood as being of paramount importance for risk management. Some research work addressing error magnitude can be found in the literature (Epaarachchi & Stewart, 2004; Fröderberg, 2014; Galvão et al. 2019; Nowak & Collins, 2000). Nevertheless, such analysis is beyond the scope of this paper, which addresses a general approach for categorization of errors according to five risk levels considering their probability of occurrence and expected consequences.

An essential characteristic of the risk matrix here used is that it enhances the influence of the consequence over the probability of occurrence, in terms of risk rating. Such a risk matrix was chosen for this research because it is directly connected with risk management of civil engineering activities. Dissimilar risk matrices can be found in the literature (Rausand, 2011). However, in civil engineering, the consequence should be enhanced over the probability of occurrence an event in risk quantification.

Additional errors collected within the survey

Besides the errors listed above, the inquired experts reported a series of other errors (see Table 3 and Table 4). They were not considered in the risk analysis since different experts independently reported them; thus, insufficient information for the analysis was available. Nevertheless, it is important to make them available in the literature for further research.

Investigation remarks

Looking at the risk matrices (see Fig. 5 and Fig. 6), three errors stand out in the critical zone ($Risk \geq 50$), one in design errors risk matrix (ID 14) and two in the construction errors risk matrix (ID 19 & 21). The error with ID 14, described as the lack of consideration of different support conditions through which the element or the structural system will be subjected during the construction procedure for validation of the design calculation, is identified as the error that might represent the highest risk in the design phase, within the context described in this paper. Coincidently, it is the main cause of the Miami bridge collapse described in “Bridges collapse” section that took place in March 2018. The construction errors found in the critical zone are both concerning the falseworks. One is related to continuous bracing required for the global stability of the falsework. The other is associated with the poor assessment of the foundation soil properties supporting the falsework, neglecting water influence in such properties. Such negligence is common since the falsework is just a temporary structure and further investigation addressing such an issue is usually not performed.

For summary purposes, the top five design and construction errors are listed in Table 5, according to the investigation described in this paper (AHP and Qualitative risk analysis). Many errors related to falsework/scaffolding take the lead in the risk analysis, along with the soil properties and support conditions. During the brainstorming meetings, the malfunctioning of structures was primarily linked to these errors, since they bear support to whatever is going to be built up, hence of remarkable consequences. Detailing of reinforcement and lack of consistency between the design assumptions and detailing rules are two detailing errors that are among the ones representing the highest risk.

The design error identified as the most frequent error is the incorrect quantification of the effects of deck deformation due to creep, shrinkage and temperature variation in columns, causing and amplifying second-order effects (ID 8). On the other hand, the least frequent error is the mistaken dead load quantification (ID 4). Within the construction phase, reinforcement covering errors (ID 13) are the second most frequent errors followed by expansion joints deficiency (ID 9).

Human error mitigation

Mitigation measures against human errors control exhibit a vast scope due to the multidisciplinary partners playing different roles in this matter. From the political decision, economic constraints, cultural and environmental influences, missing technological advancements of the sector, the engineers' qualification, the type of structural systems and geometric shapes used, makes very difficult any attempt to provide specific mitigation measures without bringing forth a long discussion that goes beyond the scope of this work.

The increase of the awareness of design and construction errors and the discussion around the subject and their risks is a mitigation strategy itself since the mitigation of known potential hazards, and their risks are part of engineers' daily challenges.

A few common mitigation measures were pointed out by the experts consulted within the scope of this research, namely the use of different design software for outputs validation, critical interpretation of the outputs by expert engineers, self-made computation sheets for validation of the software outputs, the careful appointment of the project surveillance team and serious investigation of the geological and geotechnical properties of the foundation soil.

In civil engineering, the uniqueness of each construction and its details render challenging to approach the problem in terms of production automation. However, with artificial intelligence, there might be a greater influence of technology in the construction sector for human errors mitigation. Nowadays, contractors are continuously gathering data on accidents taking place in the construction site, so machine learning can be used to find underlying patterns in the collected data and prevent accidents (engineering .com, 2019; Kifokeris & Xenidis, 2019; Maskin entreprenoren, 2020). Nevertheless, other technological advancements are already playing an important role in this matter these days, through technologies such as Building Information Modelling Technology, 3D printing, Virtual Reality and Augmented reality (Qeshmy, Makdisi, Ribeiro da Silva, & Angelis, 2019). From the economic point of view, investments in such innovative technologies are compensated because a problem found during the design phase that cost 1$ to fix, will cost 20$ to fix during the construction phase and 60$ to fix during the operation phase (engineering .com, 2019).

Quality management measures

Basic design, execution and maintainability requirements are the foundation of design codes such as the Eurocodes. Accordingly, the fulfilment of requirements such as structural safety, serviceability, traffic safety and durability, must be assured by the designer and the contractor, for all relevant load cases and traffic demands for an indicative design working life of 100 years, according to the current codes. Therefore, quality management strategies for quality control and quality assurance should be employed to reduce or avoid design and construction errors, so the newly constructed bridges are handed over to the owner fulfiling the code's requirements. Such codes are (CEN, 2003, 2005 & 2009), (ISO, 2009b), among others whose the main goal is standardization for quality assurance in bridge design and execution.

The Eurocode 0 (CEN, 2005) provides quality management measures aiming at the reduction of errors during the design and execution of structures so that the structures can meet certain reliability levels. For quality management purpose, three design supervision levels and three inspection levels for construction works are proposed according to the reliability classes and consequence classes defined in Eurocode 0 (CEN, 2005) (see Table 6). Similar measures are proposed by (Melchers & Beck, 2018). The (FIB, 2010) proposed as-built documentation that describes the actually constructed structure, including results of the initial inspection and direct input parameters required for maintainability purposes. The recommended structural reliability classes, measured by a target reliability index (β_T), are defined according to the expected consequence (life loss, material damage, functionality losses, among others) of failure of a structure. Hence, three consequence classes are correlated to three reliability classes. The target reliability index stands for the minimum nominal probability of failure that should be assured by the employed design and construction procedures. Nevertheless, Eurocode 0 (CEN, 2005) states that "the actual frequency of failure is significantly dependent upon human errors, which are not considered in partial factor design". Thus, the target reliability index does not necessarily provide an indication of the actual frequency of structural failure since they stand for reliability classes of structures designed and built according to the codes, not necessarily as built.

As stated above, the design codes do not take into account human errors in the definition of the threshold value provided for reliability classes since such errors are expected to be eliminated by design supervision and construction inspection, even though this is not always the case. Nonetheless, several attempts in the literature targeting the numerical quantification of human errors impact in structural safety can be found, namely, sensitivity analysis aiming to quantify the impact of different errors in structural safety reduction (Galvão et al. 2019; Nowak & Collins, 2000). Further research, seeking the probabilistic characterization of errors magnitude through probability distribution functions is also available (Haan, 2012; Melchers & Beck, 2018; Qeshmy et al. 2019). Nevertheless, additional investigation is required.

On the organization level (Terwel & Jansen, 2015) reported that internal factors regarding interactions between project partners (e.g. agencies, contractors, consultants, designers, owners, reviewers and inspection team) were the ones with the greatest impact on structural safety. Such factors are (i) allocation of responsibility, (ii) coordination, control mechanisms, (iii) communication and collaboration, (iv) safety culture, (v) risk management, among others. External factors such as the economic and political landscape are also important factors to keep in mind. Each organization manages each of these factors according to their internal specification standards and code procedure to tackle human interaction, which is the weakest link in structural design and construction process.

Risk mitigation

The risk analysis is usually followed by a risk evaluation, where the risk of the assessed hazard is compared with acceptance criteria, which sometimes are hard to define and can vary for different industries and societies. The establishment of such acceptance criteria aims to direct proper mitigation actions, to specific hazards, seeking its risk reduction as low as reasonably practicable (ALARP) (Jones-Lee & Aven, 2011). The ALARP concept is directly related to the acceptance criteria; thus, it groups the risk of a hazard into three categories, the critical region, the ALARP region and the acceptable region. A hazard event considered to be present in the critical region cannot be accepted, so it must be reduced at all cost. The ALARP region is characterized by a risk reduction principle targeting the avoidance of a gross disproportion between the risk reduction costs and the obtained risk reduction. Thus, a risk reduction measure must be efficiently employed, so the costs are minimized, and the risk reduction is maximized. (Aven, 2016). For risks within the acceptable region, mitigation is unnecessary, but it is worth mentioning that many of these hazards can lead to unexpected accidents due to their accumulation or long term effect. In this paper, according to the qualitative analysis performed, the critical, ALARP and acceptable regions are identified respectively by the "$Risk \geq 50$", "$40 \geq Risk \geq 5$" and " $Risk \leq 4$", respectively, see also Fig. 5 and Fig. 6.

As discussed above, the critical zone of the risk matrix usually encompasses risks that must be mitigated at all cost. Consequently, two mitigation actions were suggested by experts for "error due to poor evaluation of the falsework foundation soil properties, and variation of these properties with rainfall", ID 19, see also Fig. 6:

> **Mitigation Action 1:** Quantification of the soil plastic properties in order to consider further resistance reduction due to rainfall conditions and to better predict the soil maximum bearing capacity.
>
> **Mitigation Action 2:** Adoption of a new construction technique (i.e. launching girder) to avoid continuous loading of the soil by the falsework structure.

A theoretical curve for the risk reduction and its cost is depicted in Fig. 7. However, for more precise results, a quantitative risk analysis should be performed. With the first mitigation action, the uncertainty concerning the soil properties is decreased; therefore, a risk reduction at a reduced cost can be achieved'. A significant risk reduction can be achieved by the mitigation action two since the adoption of a new construction technique would significantly reduce the error probability of occurrence. However, this mitigation action demands a higher cost than the previous one, since the acquisition or renting cost of a launching girder is considerable.

Conclusion

The design and construction errors are responsible for about 32% of bridges collapse recorded worldwide; hence, they must be carefully addressed. Given the numerous multidisciplinary activities required for the materialization of any idealized engineering structure into its physical equivalent and the human uncertainties in executing such activities, a screening procedure and assessment of the most important sources of errors are demanded. This work provides a framework for such investigation with conclusive outcomes that allow, the design and the construction engineers conceiving the structure to focus their attention on the most relevant errors, and the inspection and the design supervision team to perform enhanced surveillance of the required activities. The framework for the management of human errors risks implement in this research work is summarized according to the following consecutive steps:

a) An initial screening procedure aiming at the identification of most concerning errors threatening the structural safety of similar structures according to recorded and well-documented failure or collapse cases;

b) Brainstorming meeting with experts aiming at the identification of errors concerning the on-going project or any other structural system under assessment;

c) Qualitative risk assessment of the initially identified errors by a carefully selected group of experts;

d) Prioritization of the errors according to their expected probability of occurrence and consequence leading to the identification of the risk they represent, according to expert's judgement;

e) Definition of mitigation strategies for errors denoting greater risk and benchmark of their benefits with their costs aiming at the implementation of the most efficient ones;

A qualitative categorization of design and construction errors has been performed considering a qualitative risk assessment of such errors by experts through a survey. Different errors risk groups are defined, employing risk matrix and AHP, allowing the prioritization or errors according to their probability of occurrence, consequence and risk. Therefore, a more efficient risk mitigation strategy can be implemented for errors that denote a higher risk for structural safety or construction works, besides overall supervision of the errors that denote lower risks according to standards recommendations. Focusing on the most relevant errors, risk reduction techniques should be effectively implemented, and the structural safety easily assured. Errors concerning geotechnical and falsework malfunctioning, and the system supporting condition changes throughout different construction stages, as well as reinforcement detailing, are highlighted as the errors of highest risk.

Furthermore, the impact of three design errors (ID = 4, 13, 17) was numerically assessed in (Galvão et al. 2019) considering a prestressed reinforced concrete overpass. Their impact on structural safety reduction was in accordance with the results obtained with the Analytic Hierarchy Process. Their relative consequence, as ranked in Table 1, was confirmed. Nevertheless, this was not the case for the consequence of two construction errors (ID = 4, 27) also numerically assessed in the same paper.

Some design and construction errors go undetected or not reported due to legal implications, but they are usually uncovered after failure. Some errors are detected in existing structures given the structural system underperformance, visible deterioration and deficiencies, non-destructive tests and monitoring systems, but still, many of them go undetected. Thus, the assessment of existing structures should employ strategies for the identification of design and construction errors that are likely to lead to the underperformance of the structural system, service life reduction or even structural collapse.

Data availability statements

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions. That is **1.** Bridge failure database (IABSE's Task Group 1.5 proprietary). **2.** Matlab script implementing the Analytic Hierarchy Process (authors proprietary). **3.** Information collected with the survey (authors proprietary). Requests for the first item must be directed to IABSE. The last two items are meant to be kept confidential for further research work, publications and surveyed experts data protection.

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Table 1 – List of design errors identified and analysed

Errors Cluster	ID	List of Errors	Rankings	
			PO	CO
Structural Analysis and Design Errors	1	Error due to a non-conservative arrangement between design and load regulations with different backgrounds, leading to a less reliable structure	16	17
	2	Errors in regulations interpretation	9	20
	3	Error in live loads quantification due to lack of data	13	14
	4	Error in dead load quantification	20	1
	5	Error in the definition of the most significant load combinations	11	7
	6	Error in defining the gravity centre for highly compressed elements, or in defining load eccentricity	18	11
	7	Error in defining a cross-section shear centre (torsion effects)	7	18
	8	Error in the quantification of the effects of deck deformation due to creep, shrinkage and temperature variation, in columns (second-order effects)	1	16
	9	Error in defining the buckling length of an element	12	10
	10	Error in defining/describing the location of prestressing tendons	15	8
	11	Error in the decompression limit state calculation	14	19
	12	Error in defining the prestressing hyperstatic effects	3	15
	13	Error in defining the soil-structure interaction (boundary conditions and differential settlements)	2	12
	14	Error due to lack of consideration of different support conditions that a bridge or an element will be subjected through the construction process	5	2
	15	Error in modelling the connections between structural elements (e.g. deck, beams and columns)	8	5
Detailing Errors	16	Error due to the lack of consistency between the design assumptions and the detailing rules	4	9
	17	Error in reinforcement cross-section area	17	3
	18	Error in reinforcement spacing (flexural and shear reinforcement)	10	4
	19	Error in concrete and reinforcement classes indication	19	6
	20	Error in defining the quota of implantation	6	13

Table 2 – List of construction errors identified and analysed

Errors Cluster		ID	List of Errors	Rankings	
				PO	CO
Material Quality Control Errors	Concrete	1	Errors leading to alkali-aggregate reaction	19	15
		2	Error in the quantification of cement hydration heat	18	22
		3	Error in the evaluation of aggregates humidity	13	28
		4	Error due to poor concrete workmanship leading to concrete with characteristics and properties different from the requested	22	13
	Reinforcement	5	Errors leading to reinforcement corrosion	10	25
		6	Error using a wrong reinforcement class especially when different reinforcement classes are also used in construction	29	23
		7	Error in the production of reinforcement cross-section area	26	14
Execution Errors	Generic Errors	8	Error due to wrong positioning of supports	15	12
		9	Error due to expansion joints deficiency and wrongly positioned	3	19
		10	Error due to wrong interpretation of the design project	21	8
		11	Error in topographic implantation	14	16
		12	Error due to wrong concrete vibration	20	27
		13	Error in the reinforcement covering	2	18
		14	Error in the longitudinal shape due to shrinkage and creep effects not correctly computed in the design phase	9	26
		15	Error due to consideration of support conditions different from those defined in the design phase	23	24
		16	Error due to the establishment of wrong final boundary conditions	25	20
		17	Error due to wrong evaluation of the foundation soil properties	5	4
		18	Error due to geometric imperfections (inclination and cross-section imperfection)	11	29
	Falsework Execution Errors	19	Error due to poor evaluation of the falsework foundation soil properties, and variation of these properties after rainfall	1	3
		20	Error due to poor preparation of the falsework foundation using gravel material and/or poor positioning of the timber elements that support the falsework	8	10
		21	Error due to deficiency in the continuous falsework bracing, leading to global instability	4	1
		22	Error due to a deficient maintenance plan leading to poor falsework material quality	12	7
		23	Error in the falsework clamping elements (connectors and couplers)	6	6
		24	Error in movable falsework due to non-controlled hyperstaticity reduction to perform his movement	16	2
		25	Error in the assessment of the formwork and falsework deformability properties	7	17
		26	Error due to wrong positioning of formwork ties	17	21
	Prestressing Errors	27	Error due to insufficient prestressing	28	5
		28	Error due to over loss of prestressing	24	11
		29	Error due to insufficient curing of concrete subjected to prestressing forces leading to a deficient bond between the concrete and the prestressed cables	27	9

Table 3 – List of additional design errors collected within the survey

Errors Cluster	List of Errors
Structural Analysis and Design Errors	Error due to low design experience
	Error due to accelerated design programmes to meet deadlines and design budgets
	Error due to incorrect application and understanding of partial prestressing
	Error due to incorrect use of structural analysis software
	Errors of data entry in structural software's (e.g. material strength, boundary and nodal constraints, self-weight, elasticity modulus. etc.)
	Error due to non-validation of automatic computation of complex numerical models with simpler models
	Error due to hydrostatic effects negligence in the structural analysis
	Error due to the project non-verification by authorized and qualified design reviewers
Detailing Errors	Lack of experience with good detailing practices (mainly in steel structures)
	Error due to drawings misinterpretation due to lack of experience and awareness
	Error due to the use of general details drawings from existing projects
	Error due to lack of coherence between shear reinforcement detailing and different details

Table 4 – List of additional construction errors collected within the survey

Errors Cluster		List of Errors
Material Quality Control Errors	**Concrete**	Error due to non-attendance of quality control expert inspectors to the construction site
		Error due to lack of protective measures in very high and low-temperature work sites
	Reinforcement	Error due to non-attendance of quality control expert inspectors to the construction site
		Error due non-conformity of steel reinforcement bars with standards
Execution Errors	**Generic Errors**	Clashing of reinforcement (particularly for precast elements)
		Error in the execution of the abutment's embankments
		Error due to deficiency in the execution of the approach slabs
		Errors or deficiencies caused by interrupted concreting because of equipment malfunctioning or delays of the concreting mixer trucks
		Error due to non-controlled concreting of mass concrete elements leading to high temperatures in the concrete core (spread foot of abutments and piers, pile cap, among others)
	Falsework Execution Errors	Errors due to the inexistence of checklist or check procedures for execution quality control
		Errors caused by changes in the assembly technique and material concerning the execution project
		Errors due to the usage of uncertified materials
		Errors caused by the absence of the rainwater drainage system or any other protective measure

Table 5 – Top five design and construction errors with the highest risk

Design Errors	Construction Errors
Error due to lack of consideration of different support conditions that a bridge or an element will be subjected through the construction process; (ID 14)	Error due to deficiency in the continuous falsework bracing leading to global instability (ID 21)
Error in reinforcement cross-section area detailing; (ID 17)	Error due to poor evaluation of the falsework foundation soil properties, and variation of these properties after rainfall (ID 19)
Error due to lack of consistency between the design assumptions and the detailing rules; (ID 16)	Error in movable falseworks due to non-controlled hyperstaticity reduction needed to perform his movement (ID 24)
Error in the definition of the soil-structure interaction (e.g. boundary conditions and differential settlements); (ID 13)	Error due to wrong evaluation of the foundation soil properties (ID 17)
Error in modelling the connections between structural elements (e.g. deck, beams and columns); (ID 15)	Error in the falsework clamping elements (connectors and couplers) (ID 23)

Table 6 – Design supervision and construction works inspection levels according to Eurocode 0 (CEN, 2005)

Reliability Class (RC)*	Examples of buildings and civil engineering works (ISO, 2015)	Design supervision levels	Inspection Levels
RC3 ($\boldsymbol{\beta_T} = 4.3$)	Major bridges and public buildings where consequences of failure are high (e.g. fewer than 500 fatalities)	Third-party checking: Checking performed by an organizational different from that which has prepared the design	Third-party inspection
RC 2 ($\boldsymbol{\beta_T} = 3.8$)	Typical bridges, residential, office buildings and public buildings where consequences of failure are medium (e.g. fewer than 50 fatalities)	Checking by different persons than those originally responsible and in accordance with the procedure of the organization	Inspection in accordance with the procedures of the organisation
RC 1 ($\boldsymbol{\beta_T} = 3.3$)	Agricultural buildings where people do not normally enter (e.g. storage buildings), greenhouse	Self-checking: Checking performed by the person who has prepared the design	Self-inspection

*Target reliability levels established for ultimate limit states for 50 years reference period.

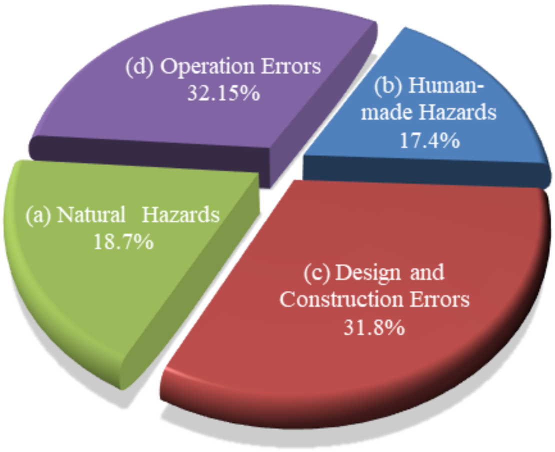


Fig. 1 – Main causes of failure of reinforced concrete bridges (Syrkov, 2017)

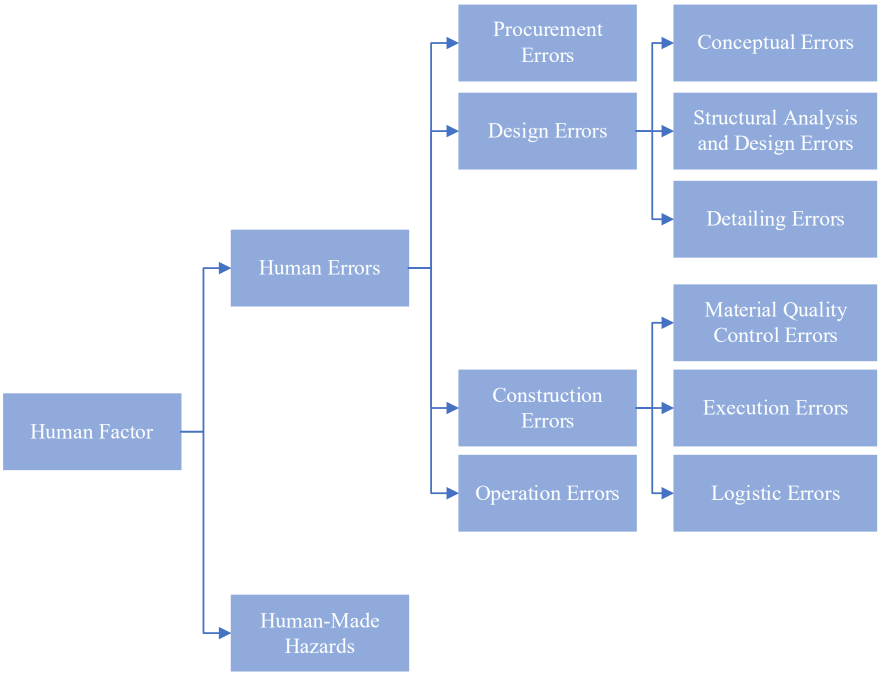


Fig. 2 – Human error clusters

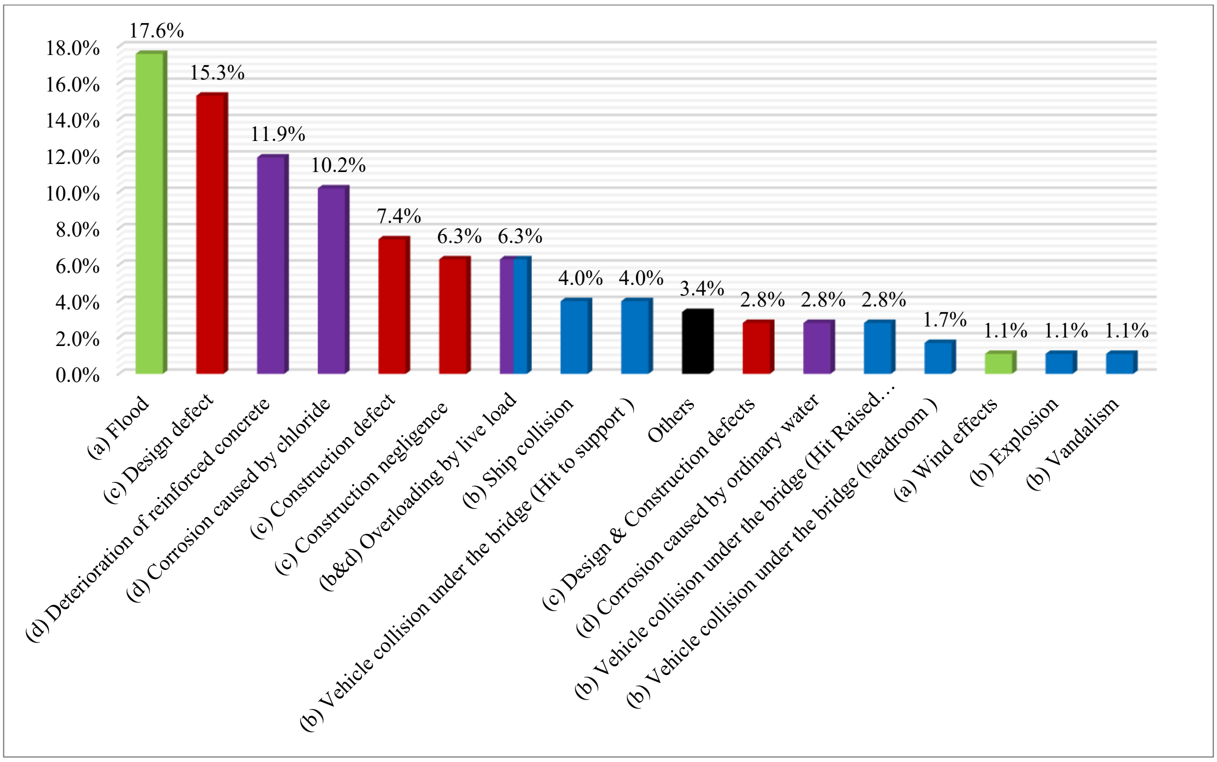


Fig. 3 – Specific causes of failure for reinforced concrete bridges

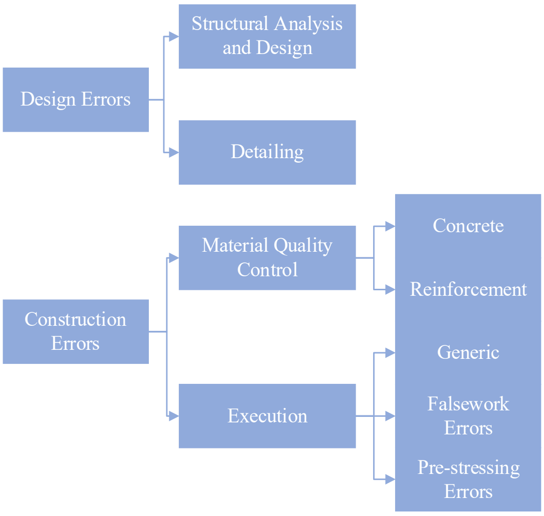
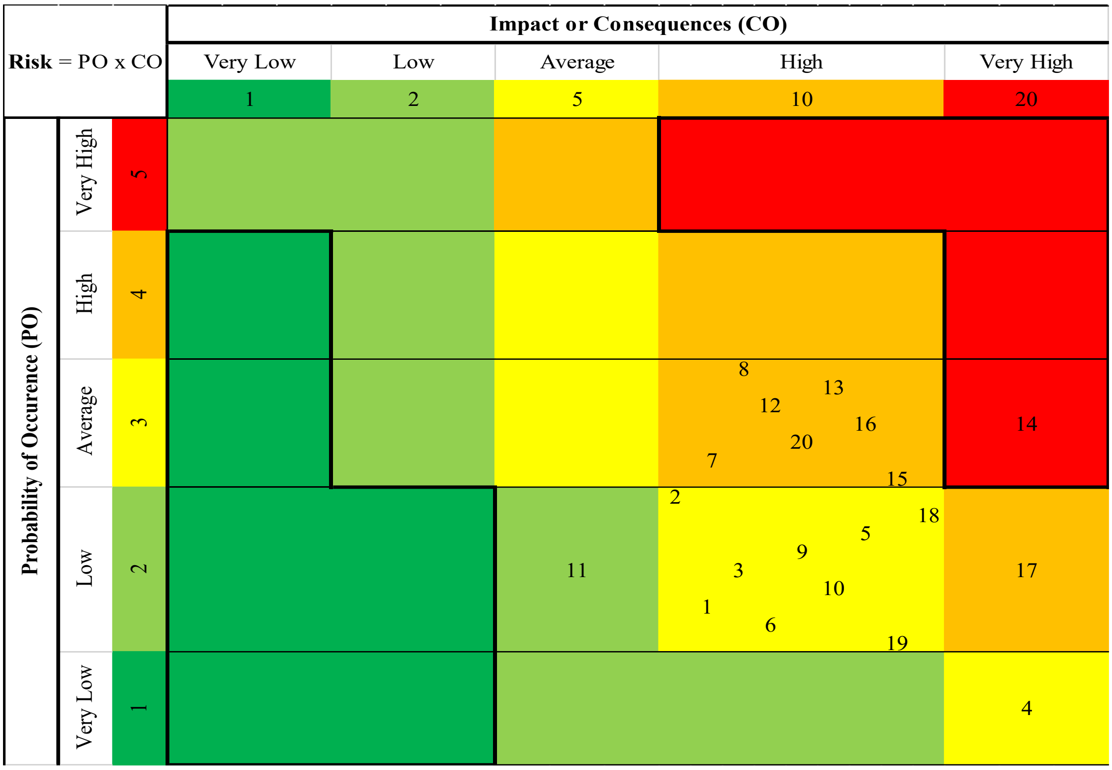
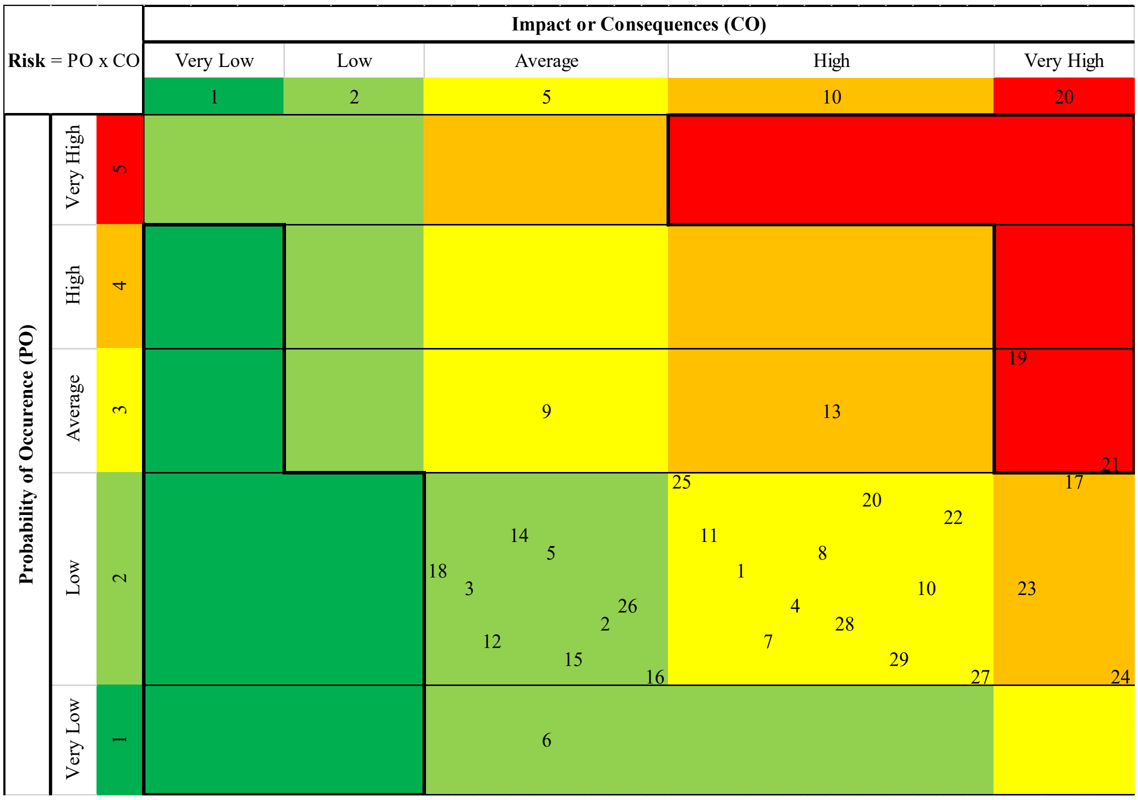


Fig. 4 – Design and construction error clusters



Risk = PO x CO			**Impact or Consequences (CO)**				
			Very Low	Low	Average	High	Very High
			1	2	5	10	20
Probability of Occurence (PO)	Very High	5					
	High	4					
	Average	3				8 12 13 16 20 7 15	14
	Low	2			11	2 18 5 9 3 10 1 6 19	17
	Very Low	1					4

Fig. 5 - Risk matrix of design errors



Risk = PO x CO			**Impact or Consequences (CO)**				
			Very Low	Low	Average	High	Very High
			1	2	5	10	20
Probability of Occurence (PO)	Very High	5					
	High	4					
	Average	3			9	13	19 21
	Low	2			14 5 18 3 26 2 12 15 16	25 20 22 11 8 1 10 4 28 7 29 27	17 23 24
	Very Low	1			6		

Fig. 6 - Risk matrix of construction errors

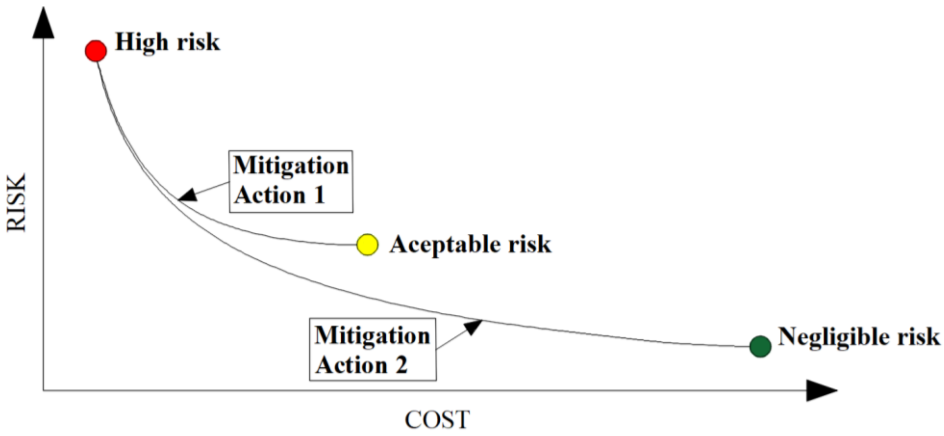


Fig. 7 – Risk reduction due to the mitigation actions