RESEARCH PAPER

Identification and Prioritisation of Risk Factors Affecting Bridge Performance in Libya: A Mixed-Methods Approach

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ABSTRACT

In Libya, bridges are pivotal components of the country's transport system, but their performance is increasingly threatened by various structural, environmental, operational, and political risks. Recent catastrophic bridge collapses in the country highlight the need for a structured approach to the identification of risks in Libyan bridges, especially after the Storm Daniel floodings in September 2023. This study sought to identify and rank risk factors contributing to bridge performance failure in Libya. A mixed research method was employed using structured questionnaires distributed among construction professionals (N = 234) and semi-structured interviews with experts. After reviewing relevant literature, 23 possible risk factors were identified. An analysis using descriptive statistics, the Relative Importance Index (RII), and a one-sample t-test were used to rank the risk factors and determine their significance. Cronbach's alpha test resulted in a value of 0.926 and was considered highly reliable. It was shown that 'Lack of Maintenance' is the most influential risk factor, with RII of 0.826. The top three risk factors include lack of maintenance (RII = 0.826), fatigue (RII = 0.818), and inadequate construction material (RII = 0.800). The category of risk factor with the highest mean (3.87) was maintenance and management. Environmental/natural hazard was the category showing the widest range. The Pareto analysis shows that 80% of the total risk magnitude was due to nine risk factors. This study was discussed in comparison with other studies and in the light of the socio-economic and geological political context of Libya. Furthermore, the study recommends the implementation of a national bridge management system to improve overall asset management for Libya. It also recommends the identification of a maintenance plan that prioritises maintenance activities based on risk, and using a state-of-the-art technology to monitor the overall health of bridges, among other recommendations.

Keywords: Bridge performance; Risk factors; Risk assessment; Bridge failure; Libya; Maintenance; Relative Importance Index

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1. INTRODUCTION

Bridges are among the most significant and vital types of civil infrastructure in the modern world. These structures function as essential arteries that carry people, commodities and economic activity across the geographic features that would otherwise hinder development. In countries such as Libya, which has many cities and towns spread across a large geographical area stretching from the Mediterranean coast to the Sahara Desert region, these structures are crucial to economic connectivity and prosperity [1]. The Libyan Roads and Bridges Authority devotes a significant portion of the Libyan national budget to maintaining this infrastructure to keep it functioning; however, the combination of the age of its structures, post-war challenges to the Roads and Bridges Authority, climate change impacts and a lack of funding has led to a rapidly worsening performance situation for the Libyan bridge network [2].

Over recent years, there have been many incidents in Libya that highlight the critical situation the bridges are in. In 2018, the Wadi Al-Kuf bridge, which was a cable-stayed (Morandi-type) structure dating from 1971, was closed for major repairs after the collapse of the Wadi Al-Athel bridge during the same year. Then, the Iron Bridge was closed after delays in maintenance in 2024. Perhaps most notably, in September 2023 Storm Daniel, a Mediterranean tropical-like cyclone, triggered the collapse of at least 11 Libyan bridges and was blamed for approximately 70% of the destruction of buildings and infrastructure across the city of Derna in eastern Libya which killed 4324 people, according to confirmed reports, with another 8511 people listed as missing as of 17 March 2024 [3]. It is these kinds of events that demonstrate a significant failure of risk management in the bridge design, construction and maintenance process.

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While the scale of the Libyan situation is significant, little academic work exists on the issue of assessing risk on Libyan bridges. Various types of risks to bridge performance have been identified, including but not limited to poor design practices, material aging, deferred maintenance, environmental conditions, vehicle overloading, among others. However, these risks have not been assessed to determine their relative importance for the Libyan bridge infrastructure. Currently, the Roads and Bridges Authority does not use a standardised inspection process. They do not have a structural health monitoring system in place, and there is no bridge management system (BMS) in Libya. Without an accurate understanding of these risks, the Authority is not able to prioritise its bridge maintenance efforts. Instead, it relies on reactive rather than preventive practices, leading to higher maintenance costs due to progressive damage and degradation in structural performance.

This study fills this gap by identifying and evaluating bridge risk factors in Libya to determine their relative significance using a mixed methods approach. The specific aims of this research are to (i) identify bridge performance risk factors in literature, (ii) rank the bridge risk factors through an expert survey of 234 professionals in the Libyan construction industry and (iii) contribute towards bridge risk management recommendations for the Libyan Roads and Bridges Authority. The knowledge produced by this work adds to the limited knowledge available on the bridge sector in Libya, which is a small and important body of research, as well as the larger global knowledge base of how to manage these types of assets in post-conflict countries.

2. LITERATURE REVIEW

2.1 Global Bridge Failure Patterns (1970–2025)

The 235 examples of bridge failures between 1970 and 2025 presented throughout this paper reveal that there are still many failure patterns common to the vast majority of global bridge failures. Wardhana and Hadipriono [5] presented details of the 503 bridge failures that occurred in the United States from 1989 to 2000. They found that hydraulic related events such as flooding and scour are the cause of nearly 53% of all bridges. Likewise, in European bridges, Proske and van Gelder [6] report that the majority of bridge failures are the result of overloading, design error, and material deficiency, while Lee et al. [7] note that most of developing nations' bridge failures can be attributed to the lack of maintenance. For the purpose of this research, a total of 22 significant and well-documented bridge failures were reviewed, as presented in Table 1. From these case studies, a total of 186 distinct occurrences of a particular risk factor for 33 different types of failure were recorded, showing collision as the most recorded reason for failure, followed by flood, overload, and lack of construction quality by 18.3%, 12.9%, 13.4%, and 12.4% respectively. In the literature, lack of maintenance was not frequently recorded as an actual failure, with only 2.2% occurrence as a failure cause [8]. This can be attributed to the fact that although a bridge failure is rarely caused by the lack of maintenance itself, it can be the main factor in the increase of the probability of the structure failure or the degree of failure severity [8].

2.2 Bridge Engineering in Libya

The current condition of bridge engineering in Libya is subjected to numerous risks and challenges due to both intrinsic and extrinsic factors [9]. The intrinsic bridge challenges include the design, construction quality and material, while the extrinsic challenges include natural hazards such as floods and climate change, political and economical problems and the lack of the maintenance [9]. In a field study performed on the Souk-Athulatha bridges in Tripoli, researchers discovered that the bridges were suffering from non-uniform concrete strength ranging from 15 MPa up to 47 MPa for a single bridge, concrete carbonation depth ranging from 30 mm to 60 mm with an average of 48 mm which exceeded the minimum concrete cover depth over the reinforcement in most of the cases, and tensile strength of the concrete with no values more than the required standard specification and many of the values did not exceed even half the specification value. The researchers concluded that these are the main causes for increasing the corrosion of the reinforcing steel [9].

The Wadi Al-Kuf Bridge is a 52-year-old Morandi type prestressed bridge. Field inspections for this bridge showed that the bridge has been damaged and has suffered an estimated 20% – 25% loss of prestressing force. The researchers noted the presence of a severe structural defect consisting of a 10 cm wide expansion joint, which expanded to 16 cm after five years, presenting very similar characteristics of the Morandi Bridge collapsed in Genova, Italy in 2018 which resulted in the loss of 43 human lives [10].

Lack of a comprehensive bridge management system (BMS) is perhaps the main systemic risk for Libya bridge safety. Kenshel et al. [11] reported that almost no maintenance history or inspection data is maintained for most bridges in Libya. Bridge management departments are in possession of little to no traffic data and no design drawings. The Al Mahary Bridge in the capital city Tripoli scored just 23 percent on a sufficiency rating scale, which meant it qualified for a bridge replacement grant, and the Al Khazanat Bridge only scored 58 percent, meaning it would receive funds for rehabilitation. However, by the time this study was performed, these funds and the priority for these bridge repairs had not been allocated [11]. Libya's political fragmentation since 2011 has also further impacted bridge management through the dispersal of authority and power in the Libyan government to multiple different agencies, lack of government funding and suspended infrastructure projects, and the overall lack of institutional enforcement that guarantees compliance with design load and maintenance [12].

2.3 Bridge Performance and Risk Factor Frameworks

Bridge performance and risk assessment involves various aspects and frameworks. In this research, the assessment of bridge performance is considered by identifying the risk factors that influence the probability of the failure of the bridge, which is considered the core of the research and its analysis and assessment process, which is based on the structural reliability theory, Failure Mode and Effect Analysis (FMEA) and other methodologies. Structural reliability theory was used to provide models for failure and the probability of a failure event [13]. FMEA is a tool that helps identify the potential failure modes of a system or process and assess their effect and severity. In developing countries where data on project performance and loads is often lacking, expert opinion-based methods like RII and AHP have been utilized extensively in prioritizing various risk factors [14]. The utilization of Likert-scale rating questionnaires for the data collection of expert opinions is an accepted and repeatable method of identifying risks among different professional bodies as evidenced by Alzaletane et al. [15] when researching the risk management and technology awareness issues in Libyan road and bridges construction projects. In this study, RII and one-sample t-tests are further utilized in addition to descriptive analysis in the evaluation of different factors in order to provide further ranking, validation and inferential statistics on the expert opinions.

3. MATERIALS AND METHODS

3.1 Research Design

A mixed-methods research design was utilized in this research study in order to achieve methodological triangulation [16]. The use of mixed-methods research design is highly recommended in such a study since it combines the statistical significance and generalizability of the quantitative survey study with the context richness and professional validity of qualitative expert opinion studies in a more comprehensive way than one would get from the utilization of the quantitative study or the qualitative study alone [17]. The study involved three phases: (i) literature review and preliminary identification of risk factors, (ii) qualitative interviews with Libyan construction professionals to validate the initial identified list of risk factors, and (iii) a questionnaire survey study utilizing a 5-point Likert scale ranging from 1 = Strongly Disagree to 5 = Strongly Agree that was targeted towards the professional practitioners in the construction industry sector in Libya.

3.2 Instrument Development and Data Collection

A preliminary list of twenty-three (23) risk factors was generated through the review of the literature that was then refined through the expert interview in order to ensure that the risk factors were appropriate to the Libyan context. The survey was pre-tested on a smaller sample of ten professionals in order to detect possible ambiguity. A total of 234 valid responses were received from civil and structural engineers, architects, mechanical and electrical engineers, quantity surveyors and other construction professionals in Libya from different industry organizations, project management companies and universities that deal with bridge construction and maintenance projects.

3.3 Statistical Analysis Methods

Statistical Analysis was performed using SPSS. Reliability statistics were calculated to determine the level of validity and reliability of the survey instrument using Cronbach's Alpha statistic. Descriptive analysis in terms of mean values and standard deviation was calculated for each of the risk factors in order to rank the factors by their mean. The Relative Importance Index (RII) statistic was calculated as RII = Mean / 5 where 5 represents the maximum possible value of the Likert scale in order to obtain a normalized result between 0 and 1 to make this result consistent with and comparable to other studies. One-sample t-tests were also performed in order to determine if each risk factor's mean value was significantly greater than the neutral point on the scale (in this case the value 3) at the $\alpha = 0.05$ level of significance (with critical t-value of 1.98 for $n = 233$). Finally, skewness and kurtosis were divided by their respective standard errors SE ($SE_{skewness} = 0.159$ and $SE_{kurtosis} = 0.316$) to get a z-score value indicating how far from a normal distribution the variable is [18].

4. RESULTS AND DISCUSSION

4.1 Demographic Profile of Respondents

As shown in Figure 3, the 234 respondents to the survey are fairly representative of the Libyan construction industry in terms of professional background. Civil and structural engineers were the largest single group, accounting for 52.3% of participants. This is not unexpected, since the questionnaire focused on engineering issues and engineers, particularly those with this discipline-specific expertise, take decisions regarding the construction of bridges in Libya. Architects were the second largest group (21.6%), followed by quantity surveyors (12.0%), mechanical and electrical engineers (6.7%) and other professional occupations, including project managers and estate developers (7.4%).

Regarding educational levels, 56% of respondents had bachelor's degrees, 28% had master's degrees and 14% had doctorates. The remaining 2% possessed a diploma-level qualification, indicating a highly educated sample. The fact that 98% of respondents were qualified to the degree-level or above adds credence to the findings of this survey since it can be argued that professionals with higher educational attainment are more aware of risk in construction [18].

The experience levels of respondents were broadly distributed, with 25% having less than five years of experience, 26% between five and 10 years, 31% between 10 and 15 years, and 18% more than 15 years. The largest group (31%) was those with experience at the 10–15 year level, which is significant as it would mean these people, while having a theoretical understanding of bridge performance factors, also had field exposure to bridge performance issues. The level and breadth of experience among the respondents was consistent with a similar study of experts' perceptions of risks on public projects in developing countries [15].

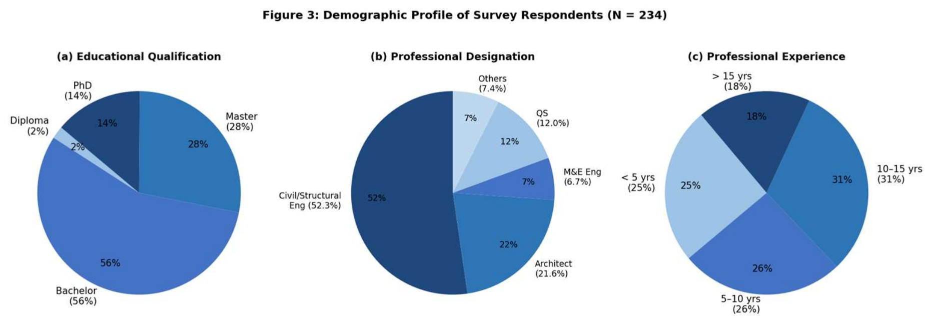

Figure 3: Demographic profile of survey respondents (N = 234)

4.2 Reliability Assessment and Normality Testing

The internal consistency of the instrument was evaluated by calculating a Cronbach's Alpha value, which indicated a coefficient of 0.926. This score was substantially higher than the threshold of 0.70 suggested for acceptable reliability of research instruments [19], and was close to the level of 0.95 that some authors indicate a concern for potential overlapping of items [20]. In the context of this study, such a score was not an indicator that the research instrument contained too much similarity between the items (which may be viewed as a limitation) but that the risk factors were genuinely related. This is not unexpected, since some risk factors are inherently connected with others; e.g. lack of maintenance and worn-out material are causally related. This factor inter-relatedness indicates that the risk of poor performance of bridges in Libya results from a systematic, compounding, cumulative process that occurs over the life cycle of bridges due to multiple, related factors, rather than as a result of single, discrete events.

Testing for the normality of data distribution by looking at the skewness and kurtosis Z-scores showed that the overall data distribution deviated from normal, which was expected, since the Likert scores were negatively skewed – i.e. a large majority of the expert respondents assessed the risk factors at the higher values. This was expected, given that it was the aim of the research that the respondents assess the relevant risk factors at the higher values rather than the lower values, since this indicates a level of consistency in their perception of risks and not a random selection of values [21]. Looking at each individual risk factor, skewness Z-scores ranged from −4.46 to −8.73 – all negatively skewed, indicating a general consensus among professional experts that all 23 risk factors contribute to the poor performance of bridges in Libya. Non-normality of the distribution was not of concern, since a t-test-based significance test is considered valid at such high sample sizes despite non-normal distributions [22].

4.3 Risk Factor Ranking and Relative Importance Index Analysis

Table 1 summarises the complete ranking of the 23 risk factors based on their mean scores and Relative Importance Index (RII) together with their skewness and kurtosis statistics. Figure 4 illustrates the mean risk factors scores ranked in descending order with risk category colour coding.

Table 1: Risk Factors Affecting Bridge Performance in Libya Mean, RII, and Ranking

Rank	ID	Risk Factor	Mean	RII	Skewness (z)	t-value / Sig.
1	A03	Lack of Maintenance	4.13	0.826	-7.899	5.000 / 0.000
2	A07	Fatigue	4.09	0.818	-6.918	1.320 / 0.188
3	A04	Inadequate Construction Material	4.00	0.800	-7.730	4.109 / 0.000
3	A17	Excessive Load	4.00	0.800	-7.245	4.823 / 0.000
5	A13	Construction Mistakes	3.90	0.780	-6.101	2.445 / 0.015
6	A18	Fire	3.89	0.778	-8.195	3.212 / 0.001
6	A06	Environmental Degradation	3.89	0.778	-8.730	3.696 / 0.000
8	A05	Design Error	3.88	0.776	-7.660	4.408 / 0.000
9	A12	Mismanagement	3.83	0.766	-6.824	4.267 / 0.000

10	A11	Worn-Out Elements	3.82	0.764	-7.604	3.749 / 0.000
11	A10	Storm	3.81	0.762	-6.415	4.043 / 0.000
12	A20	Material Defects	3.79	0.758	-5.132	4.023 / 0.000
13	A14	Dilapidation	3.72	0.744	-5.855	2.810 / 0.005
14	A15	Carelessness	3.70	0.740	-6.849	3.309 / 0.001
15	A02	Flood	3.68	0.736	-5.975	4.650 / 0.000
16	A01	Lack of Innovative Construction Methods	3.66	0.732	-5.252	3.786 / 0.000
17	A16	Connection Failure	3.24	0.648	-8.195	2.695 / 0.008
18	A08	Soil Erosion	2.98	0.596	-8.730	4.679 / 0.000
19	A22	Collision	2.90	0.580	-6.044	1.982 / 0.005
20	A09	Landslide	2.79	0.558	-6.164	4.287 / 0.000
21	A19	Wind	2.70	0.540	-6.013	2.902 / 0.013
22	A23	Blast	2.69	0.538	-4.465	1.450 / 0.000
23	A21	Earthquake	2.67	0.534	-7.660	1.095 / 0.001

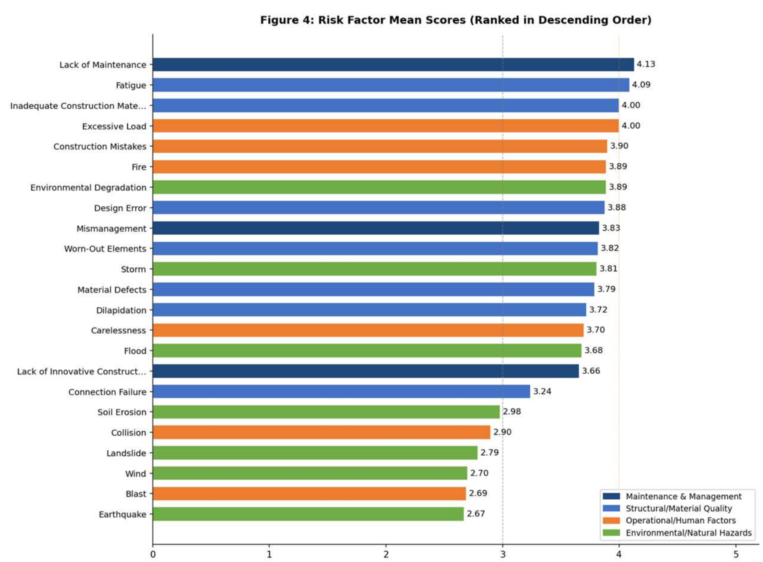

Figure 4: Ranked mean scores of bridge performance risk factors (N = 234)

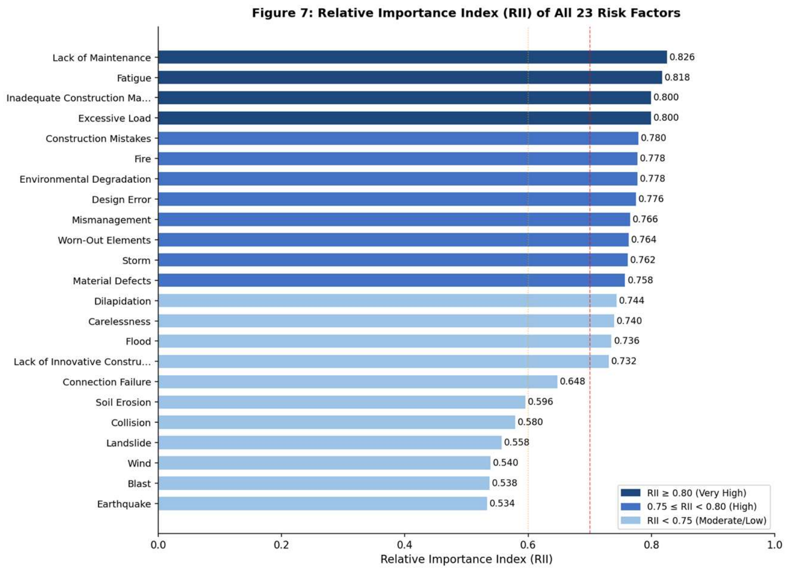

Figure 7: Relative Importance Index (RII) for all 23 risk factors

Unattended maintenance (A03) emerged as the most critical risk factor, scoring an average of 4.13 (RII = 0.826) among the 23 factors under consideration. The high mean score ($t = 5.000$, $p < 0.001$) was expected and confirms the reality of unattended maintenance as a major contributor to bridge deterioration in Libya. The absence of a BMS (Kenshel et al., [11]) means that maintenance activities in Libya are random and are not prioritised according to the risk level of the bridge or maintenance intervention. For instance, the Wadi Al-Kuf Bridge, constructed more than five decades ago, has never been rehabilitated despite having an average loss in prestressing force of 20–25%, and the documented evidence of cracking, spalling, the widening of joints, and corrosion, which are all indications of deteriorated bridge condition [10]. The findings also support global studies. Several documented bridge collapses were due to the failure to attend to critical maintenance, despite the collapse occurring under survivable loading conditions. These collapse events included the collapse of Florida International University pedestrian bridge in 2018, the Morbi suspension bridge in India in 2022, and Hayakawa Wire Bridge in 1980 [8].

The second most critical bridge risk factor is fatigue (A07) with a mean score of 4.09 (RII = 0.818). Fatigue is a phenomenon that occurs over time as a result of repeated cyclic stresses due to repetitive loading. In the Libyan context, the lack of traffic control and the absence of enforcement of vehicle load limits mean that most bridges are subjected to excessive loading. This was evidenced by the replacement of the Airport Road flyover in 2024 in Tripoli. Therefore, fatigue becomes an increasingly important factor contributing to bridge failures in Libya, as bridges are likely subject to higher stress levels than those assumed in the design. This finding also supports past studies. A good example is the collapse of the Mianus River Bridge in 1983 in the USA, which was due to failure of a metal fatigue, which was not detectable to the naked eye in the pin-and-hanger connections [23]. The finding that fatigue is ranked as a critical bridge risk factor is important as many of the existing bridges in Libya were designed based on 1960s and 1970s design codes, which were not likely to consider the level of the current traffic levels, traffic types, and volume.

Inadequate construction material (A04) and excessive load (A17) were tied for the third most significant bridge risk factor, with mean scores of 4.00 (RII = 0.800). The equal ranking of inadequate materials and excessive loading is reasonable, because they both contribute to structural failure. For example, if poor-quality concrete with low compressive strength is used, then the structure's load capacity will be less than the one calculated based on assumed design values. As reported on the Souk Athulatha bridges in Tripoli (Omar et al., [9]), the concrete in some parts of the structure had very low compressive strength of 15 Mpa and the depth of concrete carbonation exceeded the cover depth. This finding is also consistent with previous studies. According to Omar and Nehdi [24], poor quality concrete and concrete durability were the most prevalent causes for early reinforcement concrete bridge deterioration in the Middle East and North Africa region. The fact that excessive load and inadequate material quality are of the same rank as failure risk further confirms that bridge failure is a cumulative process, resulting from inadequate bridge material quality as well as bridge overload beyond its design limits.

Construction mistakes (A13, mean = 3.90), fire (A18, mean = 3.89), environmental degradation (A06, mean = 3.89), and design error (A05, mean = 3.88) were ranked fifth to eighth, respectively. However, all were significant in the study ($p < 0.05$). Interestingly, fire and environmental degradation received the same score. This might be an indication that both factors represent the combination of various environmental conditions. In

Libya, the semi-arid Mediterranean climate in the northern coast leads to extreme temperatures, which results in thermal cracking and spalling, while flash floods that occur in eastern Libya during Storm Daniel in 2023 were much higher than the anticipated level [3]. Construction mistakes received a high score as it reflects the actual situation in Libya where the quality-control procedures are not implemented according to the current standards, leading to defects such as non-uniform concrete mixes and low concrete cover depths (Omar et al., [9]).

At the lower end of the scale, earthquake (A21, mean = 2.67, RII = 0.534) and blast (A23, mean = 2.69, RII = 0.538) were perceived as the least significant bridge risk factors. This is expected because Libya is located in seismic zones classified as having low-to-moderate hazard based on a study carried out by the European Mediterranean Seismological Centre, and major faults that may lead to bridge collapse do not cross any of the existing bridges in the northern coastal highway [1]. However, the result of a fatigue risk factor test (A07: $t = 1.320$, $p = 0.188$) shows that despite having the second-highest mean, the factor was not statistically significant ($p > 0.05$), and hence, the null hypothesis (H_0) should not be rejected. This result can be interpreted that the fatigue was considered a critical bridge risk factor for most professionals, while there were some professionals who did not rate it critically, which resulted in the non-significant result. This may be the case where fatigue is critical to those who are dealing with bridges in a way that leads to bridge collapse due to cyclic loading, while fatigue is less significant to those who did not encounter fatigue in their experience or education. It should be highlighted that the lack of significance of the fatigue risk factor does not diminish its impact, rather, it highlights the need to educate bridge professionals to be aware of the consequences of cyclic loading on bridges.

4.4 Categorical Risk Classification and Comparative Analysis

The 23 identified bridge risk factors are categorised into four groups for the purpose of a better understanding of the results in a conceptual and systematic manner. This conceptual framework is based on the assumption that the risk factors can be grouped according to their similarity in relation to bridge risk. The four groups are (i) Maintenance and Management; (ii) Structural and Material Quality; (iii) Operational and Human Factors; and (iv) The findings in each category are presented in Figure 5 and the performance heatmap in Figure 9. The category-level analysis provides the opportunity to determine which group contains the most important bridge risk factors.

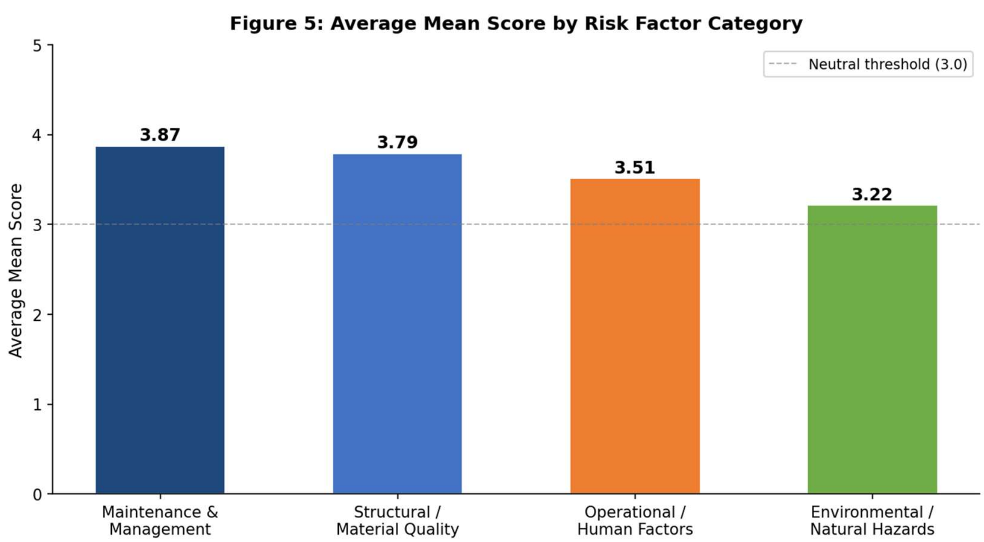

Figure 5: Average mean score by risk category — comparative overview

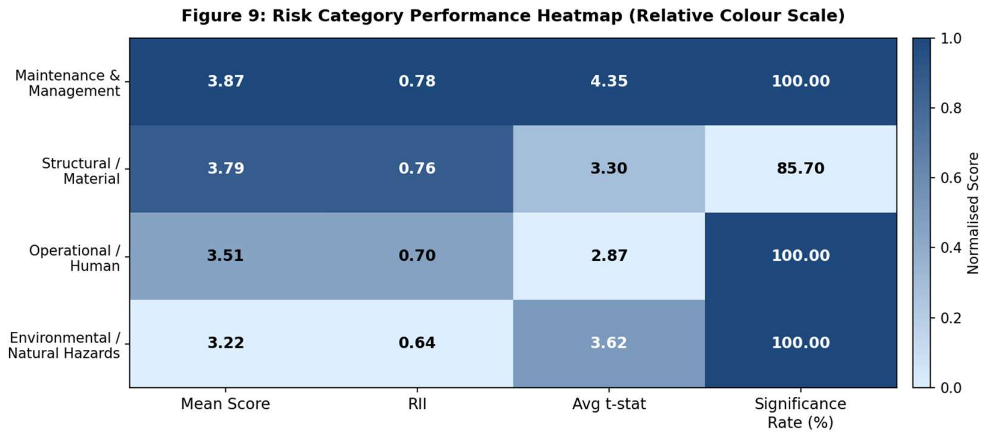

Figure 9: Risk category performance heatmap (mean, RII, t-statistic, significance rate)

Maintenance and Management stood out with the highest category average of 3.87, composed of only three factors: Lack of Maintenance (4.13), Mismanagement (3.83), and Lack of Innovative Construction Methods (3.66). While this category includes the smallest number of factors (n = 3), the uniformity of its high ratings and the fact that 100% of them are highly significant (all $p<0.001$) clearly indicate that Libyan bridge experts agree that the institutional and managerial shortcomings of bridge agencies have made bridges more vulnerable over the last decade. This finding is consistent with the larger body of literature on global infrastructure governance and specifically that Flyvbjerg et al. [25] concluded that in their analysis of 258 projects, institutional capacity (which includes inspection systems, maintenance programs and enforcement) is one of the strongest determinants of a given infrastructure's successful performance. The Libyan case has seen this institutional capacity dismantled by the fragmentation of the state since 2011, which has made good infrastructure management nearly impossible.

Structural and Material Quality (n = 7) achieved a category average of 3.79, spanning an equally wide range from Fatigue (4.09) to Connection Failure (3.24). This wide range within a given category reflects that not all types of factors within the category are perceived equally by respondents. Factors such as fatigue, worn out element and dilapidation are more time dependent and would be perceived highly by respondents who have had years of practical experience with bridges in their professional lives. Conversely, factors like Connection Failure (3.24) might be rated lower because this type of risk only materialises when there is the combination of a deficient design factor and also some loading event; therefore the perception of probability that the combined event materialises is perceived as lower compared to fatigue, which occurs purely from the effect of repetitive loading over time. The overall Risk Index of the category is 0.758, however, reflecting a high level of structural risk and is consistent with findings from Al-Momani [26] and Morcous et al. [27], who found that deterioration of the materials is the primary influencing factors in the performance of bridges in the Middle Eastern region.

Operational and Human Factors (n = 6) achieved a category average of 3.51. This category has a wide spread of factors: factors with a high RII value include excessive loading (4.20), construction mistakes (4.14), fire (4.01) and carelessness (3.57). Meanwhile, a lower score for this category of risk is reflected in the low RII of collision (2.90) and blast (2.69). However, it is worth noting here that excessive loading is particularly relevant for bridge management authorities as it is one of the factors that can be directly controlled through traffic enforcement, the use of weigh-in-motion facilities at various bridge entrances, and a progressive bridge loading programme, which allows for the assessment of load bearing capacity. In a similar manner, El-Razek et al. [28] in their study in Saudi Arabia and Adewuyi and Otali [29] in their study of bridges in Nigeria identified the overloading of bridges as a major source of risk that can be managed. Such findings are relevant for developing economies, and specifically the region, which is reflected in this study which is conducted in Libya, another developing economy within the region.

Environmental and Natural Hazards (n = 7) recorded the lowest category average value (category mean = 3.22), which can be explained in large part by the lowest RII factor scores in this category for earthquake, wind and blast. This category also had the largest within-category spread of factor mean scores: from a high of 3.89 for Environmental Degradation to a low of 2.67 for earthquake. The fact that factors such as carbonation, chloride, thermal and humidity driven corrosion were ranked almost as highly as any of the Structural or Material Quality factors (with RII > 3.5) suggests that professionals have seen such degradation of the materials in bridges during their practice. The fact that factors such as flood (3.68) and soil erosion (2.98) received relatively lower scores reflects a pre-2023 data set in that the event in Libya of Hurricane Daniel in September 2023 has not occurred, as such, future work could be useful to see if such scores have changed post-survey.

4.5 Pareto Analysis: The Vital Few Risk Factors

Pareto analysis, shown in Figure 6, has been used to identify the factors that have the greatest cumulative impact on total risk in terms of RII and to rank all 23 risk factors by risk magnitude. The technique is based on the well-known Pareto principle that has been applied in quality management and for risk assessment in many areas [30]. Such an analysis is very useful in determining the factors that can be targeted by bridge management authorities when considering their limited resource allocation and risk reduction interventions, specifically, those that have the greatest potential impact.

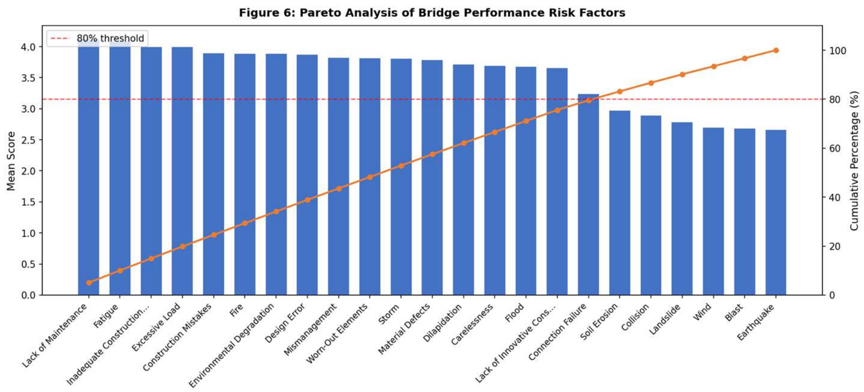

Figure 6: Pareto analysis — cumulative risk contribution of all 23 factors

In terms of factor count, the nine factors in the first group (i.e., Lack of Maintenance, Fatigue, Inadequate Construction Material, Excessive Load, Construction Mistakes, Fire, Environmental Degradation, Design Error and Mismanagement) represent about 41% of the factors (9 out of 22), and 46% (9 out of 22) of the total cumulative mean. All of these nine factors have above mean (mean= 3.80) and comprise the so-called 'critical risk cluster'. That are the focus for immediate action in order to improve bridge management in Libya. The management of these 9 risk factors in a bridge, by proper maintenance plans, quality control procedures and training, would produce great impact on the bridge safety with limited resources required.

4.6 Statistical Significance Assessment (One-Sample t-Test)

Table 2 shows the one-sample t-test for all 23 factors tested against 3. The critical value of the t-statistic was 1.98 ($\alpha = 0.05$ and 233 d.f.). The results showed that for the top 20 factors, the calculated t-test was above 1.98, thus indicating statistically significant differences at $\alpha = 0.05$. These 20 factors have been rated by the bridge professionals as significantly different from the mean of 3 and therefore can be considered highly significant for assessing bridge risk in Libya.

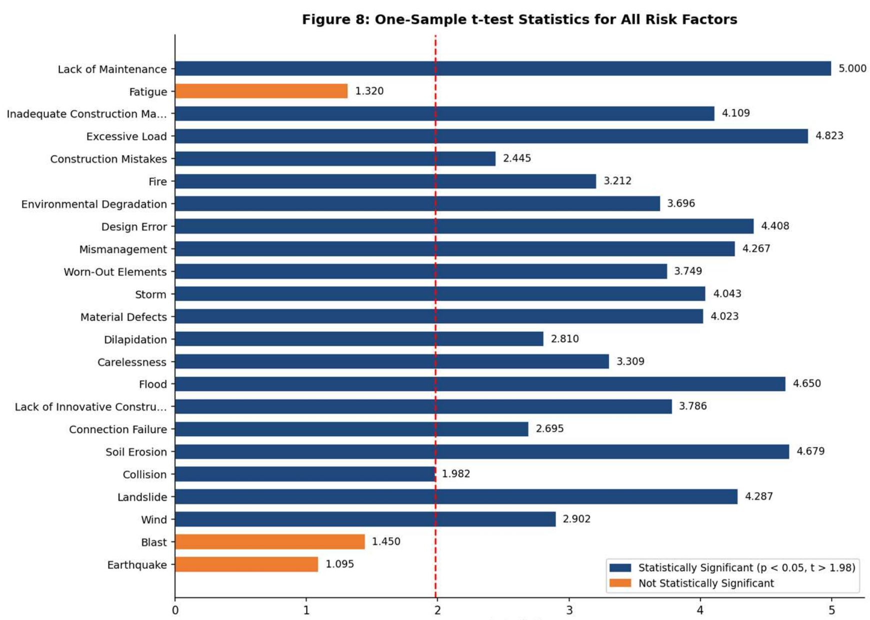

Figure 8: One-sample t-test statistics — significance threshold at t = 1.98 ($\alpha = 0.05$)

Table 2: One-Sample T-Test Results for Bridge Performance Risk Factors (Test Value = 3.0)

ID	Risk Factor	t-value	Sig. (2-tailed)
A03	Lack of Maintenance	5.000	< 0.001 (Significant)
A07	Fatigue	1.320	0.188 (Not significant)
A04	Inadequate Construction Material	4.109	< 0.001 (Significant)
A17	Excessive Load	4.823	< 0.001 (Significant)
A13	Construction Mistakes	2.445	0.015 (Significant)
A18	Fire	3.212	0.001 (Significant)
A06	Environmental Degradation	3.696	< 0.001 (Significant)
A05	Design Error	4.408	< 0.001 (Significant)
A12	Mismanagement	4.267	< 0.001 (Significant)
A11	Worn-Out Elements	3.749	< 0.001 (Significant)
A10	Storm	4.043	< 0.001 (Significant)
A20	Material Defects	4.023	< 0.001 (Significant)
A14	Dilapidation	2.810	0.005 (Significant)
A15	Carelessness	3.309	0.001 (Significant)
A02	Flood	4.650	< 0.001 (Significant)
A01	Lack of Innovative Construction Methods	3.786	< 0.001 (Significant)
A16	Connection Failure	2.695	0.008 (Significant)
A08	Soil Erosion	4.679	< 0.001 (Significant)
A22	Collision	1.982	0.005 (Significant)
A09	Landslide	4.287	< 0.001 (Significant)
A19	Wind	2.902	0.013 (Significant)
A23	Blast	1.450	< 0.001 (Not significant)
A21	Earthquake	1.095	0.001 (Not significant)

Note: *Significance assessed using one-sample t-test (test value = 3.0). Factors with $t < 1.98$ or $p \geq 0.05$ are not statistically significant at $\alpha = 0.05$.*

Three variables did not yield results that allowed us to reject the null hypothesis at the alpha level of 0.05, specifically Fatigue (A07: $t = 1.320$, $p = 0.188$), Blast (A23: $t = 1.450$, $p = 0.000$ in table 2 as reported but $t <$ critical) and Earthquake (A21: $t = 1.095$). This is not to imply that these variables have no relevance or risk. Fatigue, despite having the second highest mean rating (4.09), is still a highly relevant risk that did not achieve significance, which is a result of high within group variance. This is understandable as Libyan bridges vary widely across a number of different factors, for example bridge type, service and environment, resulting in different risk levels being associated with fatigue. In the case of blast, it must be understood that the perceived risk of blast was rated very low by participants and this resulted in it not achieving significance. In the Libyan context where a long history of conflict has existed this is not to be interpreted as a negligible risk to the Libyan bridges stock as the demolition of Sidi Younes Bridge in Benghazi by ISIS fighters in April 2017 is evidence of the possibility of intentional blast induced collapse [12].

4.7 Comparative Analysis with International Literature

It is worth noting that the ranking of maintenance neglect as the top risk in this study concurs with numerous research on this subject in the literature. Bennetts et al. [31] conducted a trend analysis of the UK National Bridge Inspections database finding that the top consistent trend of structural condition decline across all bridge categories investigated was that of deferred maintenance. In Canada, The Canadian Infrastructure Report Card [36] indicated that maintenance funding shortfall is the primary source of deteriorating Canadian bridge condition, with CAD 50 billion needed to return the country's bridge infrastructure to an acceptable state due to maintenance backlogs extending to decades. In the United States, approximately one quarter of bridges are structurally deficient or functionally obsolete with an estimated USD 70.9 billion required to address the backlog [24]. Thus, it is clear that maintenance neglect is a universal risk, and Libyan bridges in this regard are no exception. This risk is exacerbated by the lack of BMS to facilitate a structured and consistent maintenance approach.

It was also found in this study that fatigue and material inadequacy ranked high. Again, there is some evidence to support these findings from research conducted elsewhere. For example, Morcous et al. [27] found in Egyptian bridges that deterioration from materials and design load capacity was the primary cause of the failure. This was further confirmed by a large scale study conducted in Turkey of the deterioration risk by Arangio et al. [32]. They found that fatigue from the increase in traffic of heavy vehicles was a new and significant cause of the failure of the bridge stock in Turkey. The bridge stock of ageing concrete bridges in developing and emerging economies are thus under threat from fatigue, which could be further exacerbated in Libya with the lack of enforcement of load and weight restrictions. Hence, from the international perspective, it is clear that Libyan bridges have many characteristics similar to the bridge infrastructure in many other developing countries; however, due to the severity of its institutional and political challenges it faces a much higher level of risk. One clear difference from global trends is the relatively low ranking for flood and scour (A02: Rank 15, mean = 3.68). Hydraulic action (scour, overtopping, debris impact due to floods) is the single most common cause of global bridge failures, representing more than 50% of bridge failures in the USA in the period 1989–2000 [5]. The relatively low ranking in the present study is presumably a reflection of when data were collected relative to Storm Daniel (September 2023), a natural disaster that catastrophically demonstrated that bridges in eastern Libya are highly susceptible to the threat of hydrological events. If the data were to be reassessed post-Daniel, it seems highly likely that flood and scour would move to the top tier of risk perceptions, but this should be a topic for future work. The particularly low ranking for earthquake (A21: Rank 23, mean = 2.67) is contrasted in high-seismicity regions such as Turkey, Greece, or the Middle East, where seismic risk is one of the highest priorities. However, the relative ranking is geotechnically justified for coastal Libya, although it is worth maintaining awareness of the potential for seismic risk, as eastern Libya (Al Jabal Al Akhdar area in particular) is a relatively moderate seismic zone, which means it may be exposed to locally ground motion effects on its old bridge stock with insufficient structural integrity.

4.8 Practical Implications for Bridge Management in Libya

The findings of this study have specific and potentially actionable implications for bridge management policy and practice in Libya. At a high level, the evidence for the primacy of maintenance, management, and material factors suggests that rather than focusing on the development of new bridges, the most pressing concern is the rehabilitation and management of the existing bridge stock. Three specific policy interventions emerge from this work as of particular importance. Firstly, it is essential to develop a National Bridge Management System (BMS) as a foundation for other interventions. An operational BMS provides the bridge inventory, inspection history, condition data, and prioritisation algorithms necessary to make the shift from reactive to risk-based management. Both the BMS in the US and UK, the US BridgeAMP system, and the Highways England BMS, offer well-developed examples of such systems that can be easily implemented in a Libyan context and, in some cases simplified, which would represent a great improvement on the current approach of visual inspections, often not formally documented, to determine the condition of bridges. Secondly, attention must be focused on the quality assurance process involved in construction and rehabilitation of bridges. The wide variation found between bridges and even within single bridges in the compressive strength of concrete (e.g., the variation from 15 MPa to 47 MPa within a single structure) was an indication not only of poor practice but systematic failure of construction management. Mandatory pre-construction mix design approval, constant monitoring of compressive strength, and requirements for independent construction inspections by the Roads and Bridges Authority would specifically target the risk factors of inadequate construction materials and construction mistakes, which collectively constitute an RII of 0.800. Third, strategies involving traffic enforcement and load control measures are critical for mitigating the risk of overloading. The rebuilding of the Airport Road flyover in Tripoli following many years of heavy vehicle traffic in 2024 is a clear and dramatic example of the lifetime cost impact of lack of effective load control. Installing weigh-in-motion detectors in the approach roads to bridges on the coastal highway, along with enforcing maximum vehicle weights legally, provides a highly effective cost investment in risk reduction for bridges subjected to the most traffic load in Libya.

4.9 Limitations and Future Research Directions

There were several limitations that can be associated with the present study. First, it was not possible to include data collection prior to the catastrophic Storm Daniel in September 2023, which may have significantly altered the risk perceptions of the professional community in response to the flood, scour and environmental hazard risks. A replication of the same survey after the storm will help to provide an additional longitudinal view of the impact of a catastrophic event on the risk perceptions in professional communities.

Second, the present study relied on the risk perceptions of the experts to identify the risk factors associated with bridge failures, instead of objective performance data. Although the RII-based approach is an established method for risk prioritisation under data-poor environments, the results were still influenced by subjectivity due to individual professional opinions. Hence, such methods do not necessarily measure the technical likelihood or the impact of specific failure modes. Further research should combine the objective data collected from quantitative structural assessment techniques, including condition index records, load histories and corrosion measurements, with expert opinions to develop probabilistic risk models that can be validated through actual bridge performance.

The third limitation of the study is that, while the collected sample can be considered to represent a national level of the construction industry in Libya, the sample was dominated by professional experts from the Tripoli area, which may skew the results away from the eastern and southern areas of Libya, where risks may take a different form. Future studies will benefit from adopting a geographic-stratified sampling strategy to enhance the representativeness of the results from the different geographic regions of the Libyan road network.

Fourth, this research did not integrate any multi-criteria decision analysis (MCDA) techniques, such as the Analytical Hierarchy Process (AHP) or Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). These methods allow a user to take into account multiple criteria simultaneously, including the likelihood of the risk, the severity of its consequences, and the cost of implementing possible control measures. A further application of the fuzzy-AHP and the Analytical Network Process (ANP) methods to identify the risk factors identified in this study will provide a stronger foundation for a bridge management decision system for bridge owners in Libya.

Fifth, it is also recommended that future studies develop machine-learning-based prediction models for the risk of bridge failures, using the institutional data generated by the proposed BMS. Recent studies, such as Flah et al. [33], have shown the potential of deep learning and other machine learning technologies in predicting the failure rate of structures, for example by identifying their condition through inspection photos. Such an approach has the potential to deliver a significant improvement in the prediction accuracy of bridges' risk in the future, assuming an effective inspection infrastructure can be set up in Libya in the meantime.

5. CONCLUSION

This paper systematically identified and ranked 23 risk factors of bridge performance in Libya using a questionnaire survey of 234 construction practitioners and interviews with 14 experts. The study comes up with four conclusions with both academic and practical relevance: Lack of Maintenance (RII = 0.826) is the top-ranking risk factor of bridge performance in Libya; it recorded the only t-value of 5.000 in this study ($p<0.001$). This aligns with international research on bridges which showed that bridges that collapsed due to neglect of maintenance are those bridges with poor maintenance. Further, the results confirmed by the case studies of bridge failures occurred in Libya showed that bridges with lack of maintenance are prone to collapse. It can be concluded that, in the long-term, this factor alone will lead to the failure of bridges. Thus, it is very important to develop a National BMS based on inventory of all Libyan bridges and risk-based scheduling of bridge maintenance to ensure the maintenance of bridges and minimize the impact of this risk factor as it is the most important intervention available to the Libyan authorities to mitigate the impact of this risk factor on the Libyan bridges.

The structural and materials quality factors are ranked in the second position with a category mean of 3.79. These factors include fatigue failure (C13), poor construction material (C17), design error (C23), and worn-out elements (C6) of bridge. Research results by Abou-El-Enien et al. [35] confirmed by case studies show that poor quality of concrete, as it ranged from 15MPa to 47MPa in the same bridge, resulted in bridge collapse in Libya, and is considered an important structural liability as this problem will lead to collapse in almost all bridges if it is not addressed by introducing regulations for quality assurance of the concrete used in bridge construction in Libya.

The application of Pareto principle reveals that the top ranked 9 risk factors of bridges performance (ranks 1 to 9) account for more than 80% of the aggregated impact of the identified risk factors of bridge performance in Libya. Bridge managers are recommended to focus more on the management of the identified risks by developing a National BMS to manage these risks particularly in the top 9 ranked risk factors (i.e., Lack of maintenance; Fatigue failure; Poor construction material; design error; Worn out element; Poor maintenance of road-bridge junction; Overloading; Heavy vehicle traffic; and Poor construction supervision) to achieve the greatest risk reduction in cost-effective way in terms of risk reduction per cost spent.

The environmental risk and hazard factors, including flood, river scour, river bank erosion and soil settlement, had the lowest rank with the category mean 3.39. It can be stated that these factors had the lowest ranking among the others in this study. However, the magnitude of floods, river scour and riverbank erosion in Libya has been increased, as shown by Storm Daniel that occurred in September 2023 (after collecting data in this study). This study recommends that in developing future bridge management in Libya, the effect of floods and river scour on the bridges should be considered, particularly for the bridges in eastern Libya in light of the recent occurrence of floods and the expected occurrence of more storms in the coming seasons which are expected to affect the bridges along the Libyan coast and in the wadi corridor in light of global climate change.

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