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Energy-Based Reliability Analysis against Progressive Collapse of a Multi-Span Bridge under Dual Risks of Vessel Impact and Scour

Wen-Jun Lu[1], Li-Min Zhang[2] and Shu-Wen Cai[3]

[1]Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology,
Hong Kong SRA, China.
E-mail: wenjunlu@ust.hk
[2]Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology,
Hong Kong SRA, China; HKUST Shenzhen-Hong Kong Collaborative Innovation Research Institute, Futian,
Shenzhen, China.
E-mail: cezhangl@ust.hk
[3]Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology,
Hong Kong SRA, China.
E-mail: cecswaa@gmail.com

Abstract: Bridges spanning busy coastal or inland waterways are exposed to high risks of accidental vessel collisions. When a multi-span bridge is impacted, progressive collapses may develop within the bridge system, which can be aggravated by the decrease of pile embedment depth due to riverbed scour. Yet the system responses of a multi-span bridge supported on pile foundations under vessel collisions are not well addressed. In this study, a series of advanced centrifuge model tests on vessel-bridge collision under the normal and scoured condition was performed and interpreted from an energy perspective. Based on centrifuge tests results, an innovative energy-based limit state function is proposed and applied to the system reliability analysis of a multi-span bridge subjected to dual risks of vessel impact and scour. The reliability analyses show that, when the vessel energy is 3 times of the energy consumption capacity of the bridge, the probabilities of 3-span progressive failure with scour depths of 1, 3 and 5 times the pile diameter are 0.38, 0.94 and 1, respectively.

Keywords: Vessel-bridge collision; Progressive collapse; System reliability; Energy analysis; Centrifuge modelling

1 Introduction

Coastal bridges spanning busy navigation channels are exposed to two major hazardous effects: accidental vessel impact and local riverbed scour (Guo et al. 2022). The wave-induced scour or dredging around pile foundations has been shown to weaken the lateral capacity of pile foundations (Qi et al. 2016), which may aggravate the failure of bridges under vessel collision. The dynamic response and failure of individual pier-pile foundations of a bridge subjected to vessel collision have been investigated through physical and numerical simulations (Consolazio and Cowan 2005; Gholipour et al. 2019). However, knowledge gaps exist towards understanding the systematic response of a multi-span bridge subjected to dual risks of vessel impact and scour. The role of scour-induced decrease of pile embedment depth in the progressive failure of offshore bridges remains unclear.

Centrifuge modeling utilizes a high centrifugal acceleration to reproduce the prototype stress condition in a scaled-down model, which has been applied to investigate pile responses under impact loading (Grundhoff and Laue 1998; Xiao 2019; Chu et al. 2021). However, the previous centrifuge tests are limited to a single pile or a pile group, without considering the system response of a multi-span bridge. On the other hand, advanced numerical analyses have been conducted to simulate the complete dynamic process of progressive collapses of a stone arch bridge and multi-span beam bridges (Lu and Zhang 2013; Xu et al. 2013; Jiang et al. 2017), which are efficient but require validation by physical evidence. Detailed stress-strain and material failure analysis of soil-structure systems under different boundary conditions are essential. An alternative is to use a vigorous energy analysis. Gholipour et al. (2021) conducted pilot studies on energy components of vessel-bridge collisions through numerical simulations. Additional effort is required to investigate the energy transfer, distribution, and dissipation in a multi-span bridge under vessel collision.

The system reliability of a bridge subject to dual risks of vessel impact and scour is essential for risk management, which has not been well addressed. In structure engineering, the system reliabilities of intact and damaged frames are calculated based on two limit state functions using the Alternate Load Path method (Zhou et al. 2022). The system robustness is derived based on the intact and damaged reliability indices (Feng et al. 2020), which quantifies the probability of the progressive collapse of the frame after a certain structural component fails. In contrast, when analyzing the progressive failure of a multi-span bridge under vessel collision, the transversal impulse should be considered as a supplement to the vertical inertia effect of the collapse of one pier. The scour-induced decrease of pile embedment depth may weaken the structural resistance, leading to more complicated limit state functions compared with those of building structures. Therefore, a new analysis method is required to assess the system reliability of multi-span bridges under various actions. The motivation of this study is to investigate the extent of failure, the severity of failure consequences and the economic loss of a multi-span bridge subjected to dual risks of vessel impact and scour.

In this study, a series of advanced centrifuge model tests on vessel-bridge collision under the normal and scoured condition are interpreted from an energy perspective. The energy transfer pattern between the vessel and bridge, and energy distribution patterns among adjacent spans are revealed. Considering the uncertainty of scour depth and its effect on the vessel-bridge interactions, the system reliability of a multi-span bridge subjected to dual risks of vessel impact and scour is quantified using an innovative energy-based limit state function.

2 Centrifuge Modelling

The centrifuge tests in this study were performed at 100g in the Geotechnical Centrifuge Facility of the Hong Kong University of Science and Technology (Figure 1(a)). A 100-time scale-down bridge model with two spans and three piers was prepared, and each pier was supported by a four-pile group (Figure 1(b)). A movable model vessel attached to an inclined track was installed in front of one pier to realize the in-flight collision between the vessel and the bridge system (Figure 1(c)). The time history of impact load was recorded in each test through a load cell. The lateral displacements of pile caps were measured using laser sensors. The model piles were instrumented with strain gauges near the pile top to monitor the shear force and bending moment. The design pile embedment depth (L_0) is 30 m at the prototype scale. Two series of tests with the normal riverbed and a scour depth (ΔL) of 10 m were designed, respectively. Three different vessel tonnages (190, 490 and 790 tons) and nine different vessel speeds varying from 3.3 to 11.1 m/s were combined in nine tests to reveal the mechanisms of system failure of the multi-span bridge. Test configuration details are reported in Cai (2011).

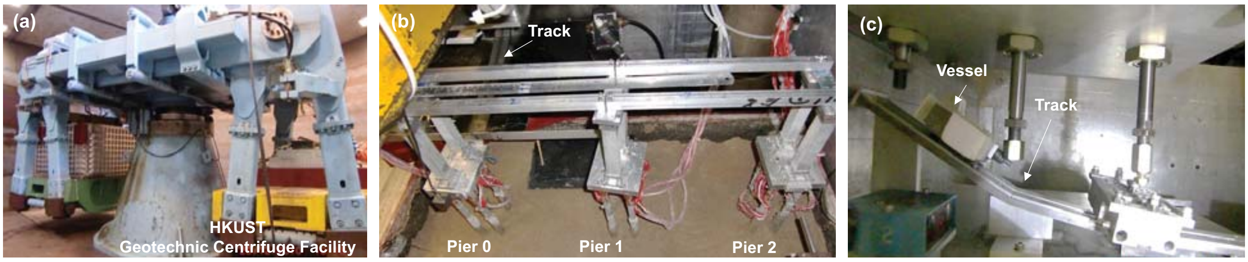

Figure 1. Photos of (a) HKUST geotechnic centrifuge facility, (b) model bridge with three piers, and (c) movable model vessel on an inclined track.

3 Energy Analysis of the Multi-Span Bridge

Vessel-bridge collision can be considered as a process of energy transfer and dissipation. During the vessel-bridge interaction, part of the initial energy transforms to the strain energy of the bow, another part transfers to the bridge through the work done by the impact force, and the rest remains as the residual kinetic energy of the vessel. The energy transferred to each pier is consumed by different structural components, in the form of kinetic, strain, damping and thermal energy. The kinetic energy component and the elastic strain energy component are reversible, while the plastic strain energy component, damping energy component and thermal energy are irreversible. Using the measured time histories of the impact force, pier deflections, pile strains, and accelerations, different energy components of the system have been derived based on the momentum theorem, energy conservation, Euler–Bernoulli beam theory and a linear lateral pile solution (Lu et al 2022).

The total energy transferred from the vessel to the bridge-soil system, E_{transf}, in different tests are summarized in Figure 3(a). In general, the energy transferred to the bridge-soil system varies in a range of 8% - 40%. As the initial energy increases due to either increased velocity or tonnage of the vessel, the energy proportion transferred to the bridge increases, and the corresponding residual energy proportion in the vessel decreases. Comparison of energy transfer with the normal and scoured conditions suggests that more energy is transferred to the bridge when scour occurs (scour depth ΔL=10m). The energy amounts dissipated in Piers 0, 1 and 2 under different initial conditions are compared in Figs. 3(b-c). The proportions of the three piers hardly change with different energy inputs but are greatly affected by the pile embedment depth. It indicates that the energy distribution among piers is exclusively related to structural characteristics. Pier 0, which is directly struck by the vessel, takes the majority of the transferred energy, which is around 80% with a larger pile embedment and 60% with a smaller pile embedment. The energy dissipated in Pier 1 accounts for 20% and 40% in the normal condition and scoured condition, respectively. Only 2% - 16% of the transferred energy is consumed in Pier 2. Under the same initial impact energy, both the deformation and internal forces of the structure are larger under the scoured condition (ΔL=10m), resulting in more energy transmission from Pier 0 to Piers 1 and 2.

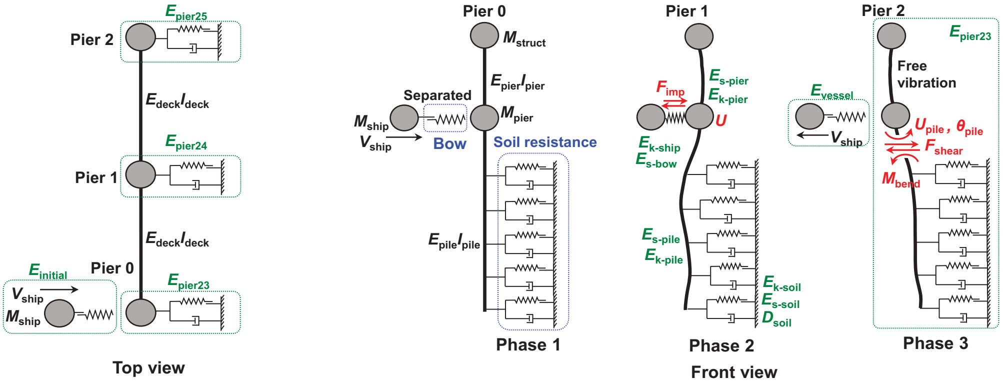

Figure 2. Energy analysis model during the vessel-bridge collision.

From the view of energy, the structure or a component fails when the input energy exceeds its energy dissipation capacity. After failure, the redundant energy is redistributed to the adjacent structural components, which may lead to additional failures in the adjacent components subsequently. This is the basic concept of progressive collapse of multi-span girder bridges.

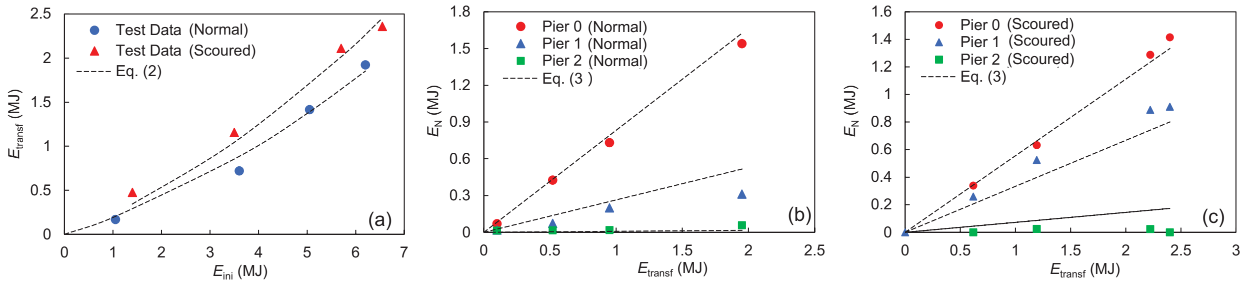

Figure 3. Energy transfer patterns: (a) between the vessel and bridge, and (b-c) among piers. E_{ini}, the initial energy of the impacting vessel; E_{transf}, the total energy transferred to three bridge piers; E_N, the energy dissipated by the N-th pier.

4 System Reliability of Bridge against Progressive Collapse

4.1 Energy limit state function of multi-span bridge

When determining whether progressive collapses will happen from the view of energy, the total input energy to each pier during initial distribution and redistribution of energy, and the energy dissipation capacity of each pier must be determined to establish an energy limit state function for the bridge. By ignoring other influencing factors, the input energy and dissipation capacity of piers could be assumed as exclusively related to the scour depth, ΔL. Through regression analysis on the centrifuge test data, estimated expressions of the energy transferred from the vessel to the bridge, E_{transf}, the energy amount distributed to the N-th pier adjacent to the impacted one, E_N, and the energy dissipation capacity of each pier, E_R, are derived as follows:

$$L = L_0 - \Delta L \tag{1}$$

$$E_{transf} = \left(0.1118E_{ini}^2 + 0.9416E_{ini}\right)\left(L_0\text{-}\Delta L\right)^{-0.5} \tag{2}$$

$$E_N = \begin{cases} \left(0.1118E_{ini}^2 + 0.9416E_{ini}\right)\dfrac{\left(L_0\text{-}\Delta L\right)^{0.5}}{36} \le E_R & (N{=}0) \\ \left(0.1118E_{ini}^2 + 0.9416E_{ini}\right)\dfrac{\left(L_0\text{-}\Delta L\right)^{0.5}}{36} e^{-(NL/28)^2} \le E_R & (N \ge 1,\ E_{N\text{-}1} \le E_R) \\ \left(0.1118E_{ini}^2 + 0.9416E_{ini}\right)\dfrac{\left(L_0\text{-}\Delta L\right)^{0.5}}{36} \displaystyle\sum_{k=1}^{N} e^{-(kL/28)^2} - NE_R \le E_R & (N \ge 1,\ E_{N\text{-}1} > E_R) \end{cases} \tag{3}$$

$$E_R = E_{R0} e^{-\left(\frac{\Delta L}{3D}\right)^2} \tag{4}$$

where L and L_0 are the current and initial pile embedment depths, respectively; ΔL is the scour depth; E_{ini} is the initial energy of the vessel; E_{R0} is the original capacity of energy consumption of each pier. The subscript N=0 denotes the directly stricken pier. The comparison between the proposed functions and centrifuge test data are shown in Figure 3. With an increasing initial energy of the vessel, the transferred energy amounts to Piers 0, 1 and 2 using Eq. (3) in a normal condition and scoured condition are presented in Figure 4.

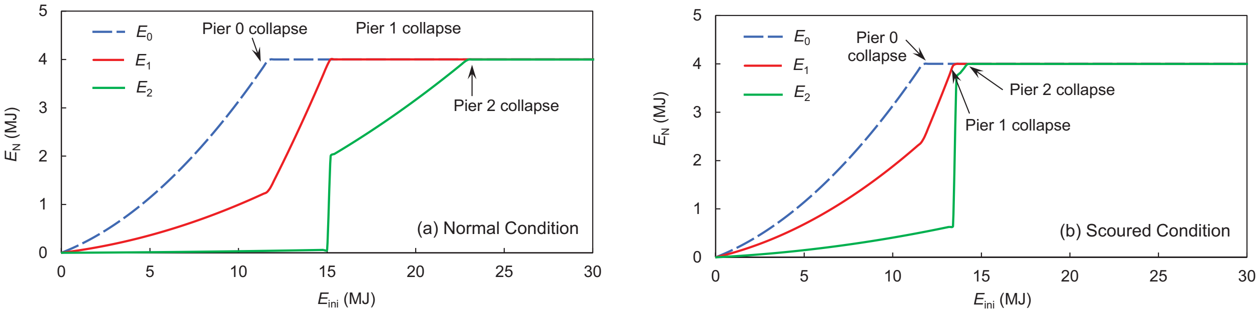

Figure 4. The input energy components to three adjacent piers with increasing initial vessel energy in the (a) normal condition and (b) scoured condition. E_{ini}, the initial energy of the vessel; E_{transf}, the total energy transferred to three bridge piers; E_N, the energy dissipated by the N-th pier.

For each individual pier, the energy-based limit state occurs when E_R-E_N=0. However, the pier failures are not independent events: each subsequent pier collapses in the condition that the adjacent pier has collapsed. Therefore, the probability of an N-span progressive failure equals to the probability of the failure of the N-th pier. As a result, the energy limit state function of a multi-span bridge under vessel impact can be established as follows:

$$Z(L)=\begin{cases} E_R-E_N=E_{R0}e^{-\left(\frac{\Delta L}{3D}\right)^2}-\left(0.1118E_{ini}^2+0.9416E_{ini}\right)\dfrac{\left(L_0-\Delta L\right)^{0.5}}{36} & (N=0) \\ E_R-E_{N|\left(E_{N-1}>E_R\right)}=(N+1)E_{R0}e^{-\left(\frac{\Delta L}{3D}\right)^2}-\left(0.1118E_{ini}^2+0.9416E_{ini}\right)\dfrac{\left(L_0-\Delta L\right)^{0.5}}{36}\sum_{k=1}^{N}e^{-(kL/28)^2} & (N\geq 1) \end{cases} \tag{6}$$

In the centrifuge models, the initial full-scale pile embedment depth and diameter were L_0=30 m and D=1.7 m, respectively. The original capacity of energy consumption of each pier, E_{R0}, is estimated as 4 MJ based on the centrifuge test data.

4.2 Reliability analysis

The uncertainty of scour depth and its effect on the progressive failure of the bridge are investigated using reliability analysis. Due to the lack of field monitored scour data, the scour depth, Δ*L*, is assumed to follow a normal distribution. Three mean values (1D, 3D, and 3D) and two standard deviations (0.25D and 1D) of the scour depth distribution are considered for a sensitivity analysis, where *D* is the pile diameter. Monte Carlo method is employed to calculate the probability of progressive failure of multi-span bridges, with the explicit limit state function (Eq. (6)). A total of 20,000 random samples of the scour depth following the above-mentioned normal distributions are generated. Then each number is substituted to Eq. (6) to obtain a corresponding value of *Z*. It should be noted that as Z(*L*) depends on the pier number, *N*, the Z value for each pier is derived separately. By calculating the proportion of the negative *Z* number to the total sample number, the probability of failure at the *N*-th pier under a certain initial energy can be obtained, which also represents different modes or degrees of the progressive failure of the multi-span bridge.

The cumulative probabilities of four progressive failure modes of the multi-span bridge along with the increasing vessel initial energy are presented in Figure 5. In the first three graphs, the 1-span collapse is most likely to occur when the vessel energy is no more than 2.5 times of the energy consumption capacity of one pier, which means no progressive failure happens after the directly stricken pier collapses in this condition. After the first pier fails, redundant energy is redistributed to the adjacent pier, leading to an increase of the probability of 2-span failure. The 3- and 4-span failures require much more energy input and are more difficult to trigger. The difference among Figs. 5 (a-c) is due to the different mean scour depths, varying from 1*D* to 5*D*. The comparisons show the larger the scour depth, the more the failed spans. For example, when the vessel energy is 3 times of the energy consumption capacity, the probability of 3-span failure with a 1*D* scour depth is 0.38, while those for the 3*D* and 5*D* scour depths are 0.94 and 1, respectively. This is because the increasing scour depth weakens the energy consumption capacity of the piers, increases the energy transferred from the vessel to the bridge, and changes the energy transmission among the piers to a more distributed pattern. As a result, the progressive collapse with a larger scour depth is more likely to happen. The comparison between Figs. 5 (b) and (d) indicates the influence of standard deviation of the scour depth. The less scatter the scour depth, the more concentrated the progressive failure modes. For instance, when the dimensionless ratio, E_{ini}/E_{R0}, increases from 1 to 2, the bridge experiences from 40% confidence of 1-span failure to 55% confidence of 3-span failure with

σ=1D. By contrast, the failure mode evolutes from the 20% confidence of 1-span failure to 90% confidence of 3-span failure under the same increment of energy input when σ=0.25D.

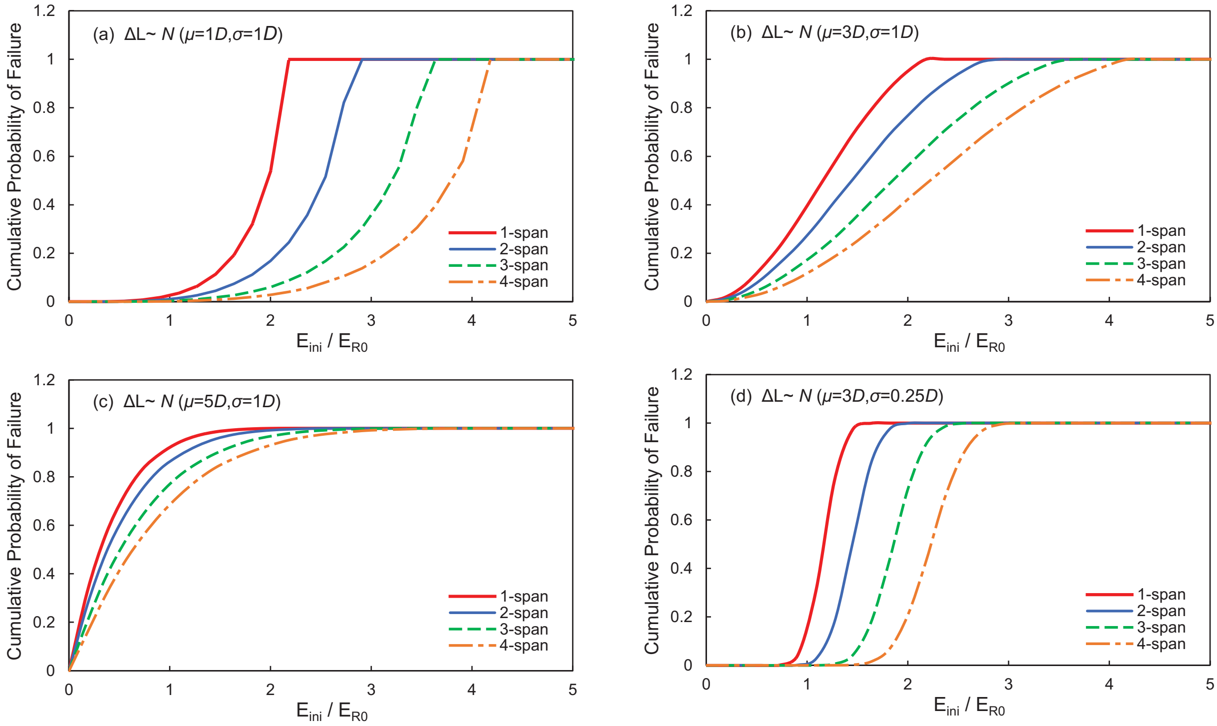

Figure 5. Cumulative probabilities of four progressive failure modes of the multi-span bridge with different distributions of the scoured depths. E_{ini}, the initial energy of the vessel; E_{R0} is the original capacity of energy consumption of each pier.

5 Summary

In this study, a series of advanced centrifuge model tests on vessel-bridge collision under the normal and scoured condition was conducted and interpreted from an energy perspective. Based on centrifuge tests results, an energy-based limit state function is proposed and applied to the system reliability analysis of a multi-span bridge subjected to dual risks of vessel impact and scour. It should be noted that there are some assumptions during the derivation of the energy limit state functions, which may induce errors in the calculated probability curves. This study aims to propose a feasible framework for the system reliability analysis of multi-span bridges subjected to vessel impact from an energy perspective. Further research is required to refine the study in the proposed framework. The influence of the load and energy transfer capacities of the connection joints on the progressive failure and system reliability of the multi-span bridge require clarification in the future.

Acknowledgments

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