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Understanding the response of masonry arch bridges under different scour scenarios

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Abstract

In the last decades, several flood-induced bridge collapses have been registered all over the world, in particular related to local scour phenomenon. Masonry bridges, which constitute the most of the existing infrastructure heritage worldwide, are significantly sensitive to this problem because of their high stiffness and typically shallow foundations. With the aim of helping to understand the response of masonry arch bridges under scour actions, this paper proposes a numerical study on a real case study. A 3D finite element model of the bridge is developed in Abaqus accounting for both mechanical and geometrical nonlinearities, then two possible scour scenarios are simulated by following a consolidated procedure proposed in previous works and the damage mechanisms activated at different scour levels are analyzed and discussed.

Keywords: masonry bridges; scour; monitoring; response parameters; damage states; failure; Abaqus FEM.

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1. Introduction

Scour represents one of the main causes of bridge collapse all over the world (Pizarro et al. 2020; Tubaldi et al. 2022a; Eidsvig et al. 2021; Malena 2021; Tubaldi et al. 2020). Masonry arch bridges are a widespread typology characterizing a large part of the existing infrastructural networks (Borlenghi et al. 2021a; Leoni et al. 2021;

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Zampieri et al. 2021; De Matteis et al. 2021) and they have proved to be very vulnerable to flood-induced scour actions, due to their high stiff-ness and the usually shallow foundations (Zampieri et al. 2017; Ragni et al. 2019; Solan et al. 2020).

The relevance of the problem is substantiated by the large number of scour-induced collapses registered in the last decades, as well as by the always increasing number of scientific studies on the topic. Indeed, according to the most recent scientific literature in the field, several works have been dedicated to the development of numerical modelling strategies able to describe the evolution of damage (Tubaldi et al. 2020; Pantò et al. 2022; Cannizzaro et al. 2018; Pepi et al. 2021). Numerical analysis have been performed on masonry arche bridges subjected to scour (Cabanzo et al. 2022; Tecchio et al. 2022; Scozzese et al. 2021, Scozzese et al. 2023).

Other studies have been oriented towards the assessment and development of techniques for scour detection, based for instance on dynamic identification via operational modal analysis or similar continuous monitoring strategies (Scozzese et al. 2023; Civera et al. 2022; Borlenghi et al. 2021b; Scozzese et al. 2021; Rainieri et al. 2020; Malekjafarian et al. 2020; Scozzese et al. 2019); some authors (Zhang et al. 2022) have investigated scour detection methods exploiting the input provided by passing vehicles; experimental and full-scale studies have also been conducted on scoured bridge piers (Hamidifar et al. 2022; Tubaldi et al. 2022b).

In general, while the scientific literature is rich of studies on the bridges response under seismic hazard (e.g., Zampieri et al. 2021, Minnucci et al. 2022, Scozzese & Minnucci 2024), there is still work to do in the context of flood hazard, where proper performance-based flood engineering methods needs to be defined.

As a first step towards this direction, in this paper, the scour problem is examined from the point of view of the bridge response and relevant potential structural damage. To this aim, a multi-span masonry arch bridge, representative of many bridges built in Europe, is considered as case study, and the failure mechanisms and damage states developed during the scour process evolution are analyzed by considering two scour scenarios: 1) involving a single pier, and 2) involving two adjacent piers simultaneously.

2. Case study

A real case study is considered as benchmark, being a bridge typology widely representative of the existing bridge stock in Europe and also worldwide. It is a seven spans masonry arch bridge, 130 m long, with segmental brick vaults and shallow foundations of height h = 4.17 m. Further bridge structural details and material properties can be found in previous works by the authors, e.g. Ragni et al. (2019) and Scozzese et al. (2019).

A 3D model is developed in ABAQUS 2017 (Figure 1-a) following the strategy adopted by Scozzese et al. (2019) which exploits continuum solid elements with cohesive interfaces between the various components, and accounts for both geometrical and mechanical nonlinearities. The soil-foundation interaction is modelled through three sets of springs (oriented along the three spatial directions X, Y and Z) with equivalent soil stiffness constants. However, it is worth to note that more refined impedances formulations might also be used (e.g., Morici et al. 2019; Minnucci et al. 2022). Scour is simulated following the procedure outlined in previous works by the same authors of this study (Scozzese et al. (2019); Scozzese et al. (2023)), i.e., by considering increasing values of the scour depth y_s and by removing the springs (simulating the soil-foundation interaction) located into the scour hole (see the explicative scheme in Figure 1-b).

Two parameters can be adopted to quantify the evolution of the process: the ratio y_s/h (h being the height of the foundation, which coincides with the embedment level) and the ratio B_s/B (i.e., the ratio between the scoured width B_s and the total width B of the foundation).

3. Numerical analysis

Two alternative scour scenarios are considered: the first one (denoted as "1-Pier" scour scenario) represents the case of a flow impinging on one pier only, producing a localized scour. The second scenario (denoted as "2-Piers" scour scenario) represents the case a flow impinging with the same conditions two adjacent piers, thus simulating a more diffused erosion which might be seen as a combination of global, contraction and local scour. The piers involved by the two scenarios are highlighted in Figure 1-a.

The damage states identified for both the scour scenarios are described in the following Table 1, where the levels of scour (in terms of the ratio B_s/B) at which these are attained are also provided. It can be observed how the effects of the scour start to become noticeable only for $B_s/B > 0$, i.e., when the base of the foundation starts to loose support, and this result is in agreement with previous studies available in the scientific literature, e.g. Maroni et al. (2023), Scozzese et al. (2023). It is also worth to note how the damage evolution is faster in the case of "2-Piers" scour scenario; the limit states, indeed, are attained for levels of excavation slightly lower than those corresponding to the local scour scenario.

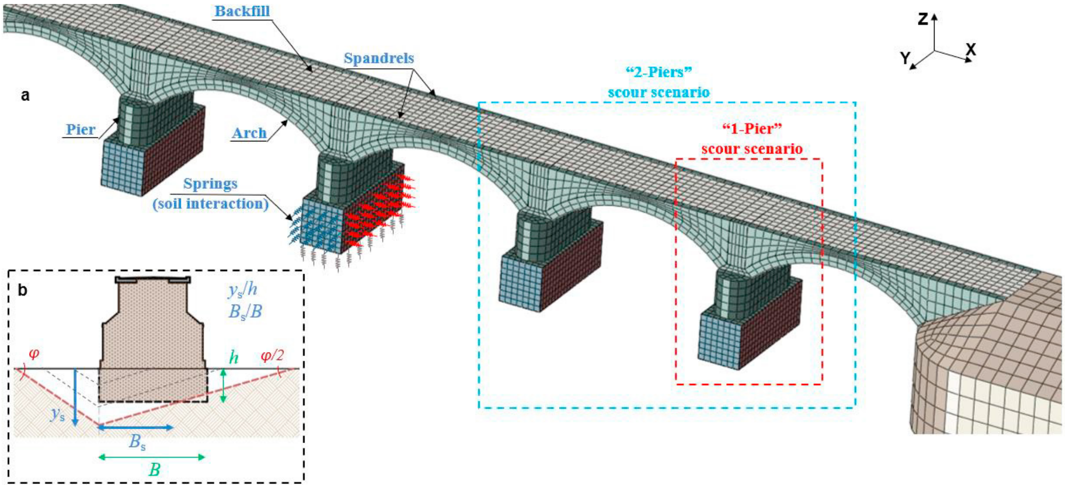


Fig. 1. (a) Abaqus 3D model with highlighted the Piers interested by the scour according to the two analyzed scenarios; (b) schematic representation of the scour hole and related parameters.

Plots of the bridge model with highlighted the elements experiencing a yielding state at the step of analysis corresponding to the three damage states are provided in Figure 2. It can also be observed how the simulated failure mechanisms are consistent with those observed on real bridges, see for instance the case of Samone Bridge on Panaro River (Italy) shown in Figure 3, reporting foundation pseudo-vertical crack and diagonal cracks on the arches (note that this condition is representative of a localized scour acting on a single pier).

Table 1. Damage states and levels of scour (Bs/B) at which they are attained.

Damage States	Local scour	Global scour
DS1 - Slight damage	$B_s/B = 0.30$. First plastic strains on spandrel walls and beginning of a kinematic mechanism; tension cracks of negligible amplitude.	$B_s/B = 0.27$. First plastic strains on piers and spandrel walls, and beginning of a kinematic mechanism; tension cracks of negligible amplitude.
DS2 - Severe damage	$B_s/B = 0.47$. Piers start developing slight pseudo-vertical cracks of width of about 2-3 mm and increment of spandrel walls damage (crack width higher than 3 mm).	$B_s/B = 0.40$. Widespread damage in piers and spandrel walls and first diagonal cracks (amplitude lower than 1 mm) developing on the side arches.
DS3 – Near collapse	$B_s/B = 0.63$. Damage spreading all over the structural elements, diagonal cracks of few millimetres appear on arches. Immediately after this condition the values of the response parameters start to increase in an uncontrolled manner for small increases of the scour depth (see Scozzese et al. 2023).	$B_s/B = 0.50$. Damage spreading all over the structural elements with estimated crack widths exceeding 10 mm; horizontal arch mechanism developing within the central arch. Immediately after this condition the values of the response parameters start to increase in an uncontrolled manner for small increases of the scour depth (see Scozzese et al. 2023).

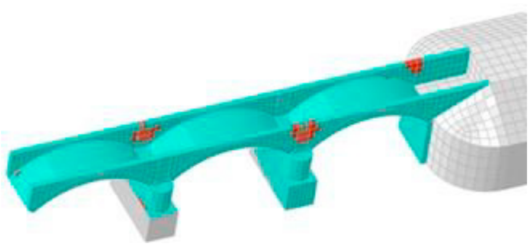
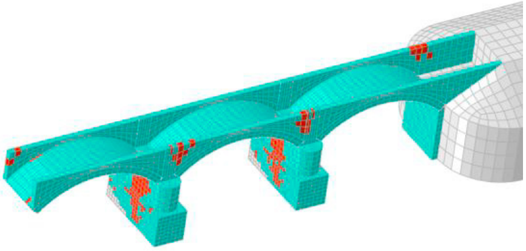
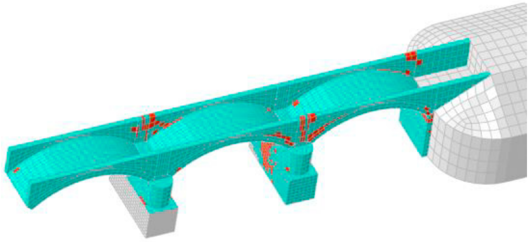
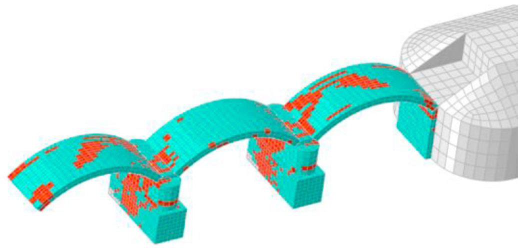
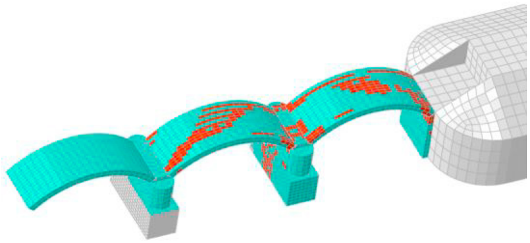
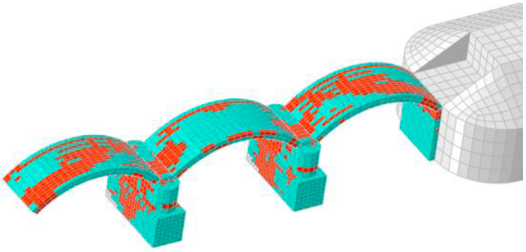
"1-Pier" scour scenario	**"2-Piers" scour scenario**
DS1 – Slight Damage	
 (y_s/h=1.26) (B_s/B=0.30)	 (y_s/h=1.22) (B_s/B=0.27)
DS2 – Severe Damage	
 (y_s/h=1.38) (B_s/B=0.47)	 (y_s/h=1.34) (B_s/B=0.40)
DS3 – Near Collapse	
 (y_s/h=1.52) (B_s/B=0.63)	 (y_s/h=1.41) (B_s/B=0.50)

Fig. 2. Damage states identified for the model, with solid elements currently yielding highlighted in red.

Fig. 3. Samone Bridge on Panaro River, Italy (photo courtesy of lapressa.it).

4. Conclusions

In this paper, the impact of scour on masonry arch bridges has been investigated. Extensive numerical analyses have been performed on a refined 3D model of a real multi-span masonry arch bridge, which is also representative of many bridges built in Europe.

Two scour scenario have been considered, a local one, involving a single pier, and a wider one, involving two piers simultaneously.

According to the outcomes presented for both the scour scenarios, it can be observed that a slight damage mechanism is triggered for values of Bs/B of around 30%, while the system failure is attained for levels of Bs/B around 50% or 60% for the “1-Pier” and “2-Piers” scour scenarios, respectively. Such high levels of scour required to lead the bridge to the collapse can be explained by the remarkable robustness characterizing this structural typology. Indeed, in witness of this, there are cases of real bridge failures with the pier base excavated up to the 80% of its width.

Furter details on the topic treated in this paper can be found in the work of Scozzese et. al (2023), where the interested reader can find insights on the most sensitive (both kinematic and modal) response parameters and suggestion about optimal sensor placements for bridge structural monitoring.

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References

Borlenghi, P., D’Angelo, M., Ballio, F., & Gentile, C. (2021b). Continuous monitoring of masonry arch bridges to evaluate the scour action. In International Conference of the European Association on Quality Control of Bridges and Structures (pp. 400-408). Springer, Cham.

Borlenghi, P., Saisi, A., & Gentile, C. (2021a). Determining and Tuning Models of a Masonry Bridge for Structural Assessment. In International Conference of the European Association on Quality Control of Bridges and Structures (pp. 409-417). Springer, Cham.

Cannizzaro, F., Pantò, B., Caddemi, S., & Caliò, I. (2018). A Discrete Macro-Element Method (DMEM) for the nonlinear structural assessment of masonry arches. Engineering Structures, 168, 243-256.

Civera, M., Mugnaini, V., & Zanotti Fragonara, L. (2022). Machine learning-based automatic operational modal analysis: A structural health monitoring application to masonry arch bridges. Structural Control and Health Monitoring, 29(10), e3028.

De Matteis, G., Bencivenga, P., Zizi, M., & Prete, A. D. (2021). Critical Issues of Typical Existing Masonry Road Bridges Handled by the Province of Caserta. In International Conference on Protection of Historical Constructions (pp. 1081-1092). Springer, Cham.

Eidsvig, U., Santamaría, M., Galvão, N., Tanasic, N., Piciullo, L., Hajdin, R., ... & Matos, J. (2021). Risk assessment of terrestrial transportation infrastructures exposed to extreme events. Infrastructures, 6(11), 163.

Hamidifar, H., Mohammad Ali Nezhadian, D., & Carnacina, I. (2022). Experimental study of debris-induced scour around a slotted bridge pier. Acta Geophysica, 1-15.

Leoni, G., Gara, F., & Morici, M. (2021). Evaluation of Seismic Vulnerability of the Historical SS Filippo e Giacomo Masonry Arch Bridge in Ascoli Piceno (Italy). In International Conference of the European Association on Quality Control of Bridges and Structures (pp. 613-622). Springer, Cham.

Li, Z., Tang, F., Chen, Y., Hu, X., Chen, G., & Tang, Y. (2021). Field experiment and numerical verification of the local scour depth of bridge pier with two smart rocks. Engineering Structures, 249, 113345.

Malekjafarian, A., Kim, C. W., OBrien, E. J., Prendergast, L. J., Fitzgerald, P. C., & Nakajima, S. (2020). Experimental demonstration of a mode shape-based scour-monitoring method for multispan bridges with shallow foundations. Journal of Bridge Engineering, 25(8), 04020050.

Malena, M., Angelillo, M., Fortunato, A., de Felice, G., & Mascolo, I. (2021). Arch bridges subject to pier settlements: Continuous vs. piecewise rigid displacement methods. Meccanica, 56(10), 2487-2505.

Maroni, A., Tubaldi, E., Ferguson, N., Tarantino, A., McDonald, H., & Zonta, D. (2020). Electromagnetic sensors for underwater scour monitoring. Sensors, 20(15), 4096.

Mendoza Cabanzo, C., Santamaría, M., Sousa, H. S., & Matos, J. C. (2022). In-Plane Fragility and Parametric Analyses of Masonry Arch Bridges Exposed to Flood Hazard Using Surrogate Modeling Techniques. Applied Sciences, 12(4), 1886.

Minnucci L, Scozzese F, Carbonari S, Gara F, Dall’Asta A. Innovative fragility-based method for failure mechanisms and damage extension analysis of bridges. Infrastructures 7(9) (2022) 122. https://doi.org/ 10.3390/infrastructures7090122.

Minnucci, L., Morici, M., Carbonari, S., Dezi, F., Gara, F., & Leoni, G. (2022). A probabilistic investigation on the dynamic behaviour of pile foundations in homogeneous soils. Bulletin of Earthquake Engineering, 20(7), 3329-3357.

Morici, M., Minnucci, L., Carbonari, S., Dezi, F., & Leoni, G. (2019). Simple formulas for estimating a lumped parameter model to reproduce impedances of end-bearing pile foundations. Soil Dynamics and Earthquake Engineering, 121, 341-355.

Pantò, B., Chisari, C., Macorini, L., & Izzuddin, B. A. (2022). A hybrid macro-modelling strategy with multi-objective calibration for accurate simulation of multi-ring masonry arches and bridges. Computers & Structures, 265, 106769.

Pepi, C., Cavalagli, N., Gusella, V., & Gioffrè, M. (2021). An integrated approach for the numerical modeling of severely damaged historic structures: Application to a masonry bridge. Advances in Engineering Software, 151, 102935.

Pizarro, A., Manfreda, S., & Tubaldi, E. (2020). The science behind scour at bridge foundations: A review. Water, 12(2), 374.

Ragni, L., Scozzese, F., Gara, F., & Tubaldi, E. (2019, March). Dynamic identification and collapse assessment of Rubbianello Bridge. In Towards a Resilient Built Environment Risk and Asset Management: IABSE Symposium Guimarães 2019 (pp. 619-626).

Rainieri, C., Notarangelo, M. A., & Fabbrocino, G. (2020). Experiences of dynamic identification and monitoring of bridges in serviceability conditions and after hazardous events. Infrastructures, 5(10), 86.

Scozzese F, Minnucci L. Seismic Risk Analysis of Existing Link Slab Bridges Using Novel Fragility Functions. *Applied Sciences*. 2024; 14(1):112. https://doi.org/10.3390/app14010112

Scozzese, F., Ragni, L., Tubaldi, E., & Gara, F. (2019). Modal properties variation and collapse assessment of masonry arch bridges under scour action. Engineering Structures, 199, 109665.

Scozzese, F., Ragni, L., Tubaldi, E., Gara, F. 2021. Scour-induced dynamic properties modification of masonry arch bridges with different geometry. COMPDYN Proceedings.

Scozzese, F., Tubaldi, E., & Dall'Asta, A. (2023). Damage metrics for masonry bridges under scour scenarios. Engineering Structures, 296, 116914.

Solan, B., Ettema, R., Ryan, D., & Hamill, G. A. (2020). Scour concerns for short-span masonry arch bridges. Journal of Hydraulic Engineering, 146(2), 06019019.

Tecchio, G., Donà, M., Saler, E., & da Porto, F. (2022). Fragility of single-span masonry arch bridges accounting for deterioration and damage effects. European Journal of Environmental and Civil Engineering, 1-22.

Tubaldi, E., Antonopoulos, C., Mitoulis, S. A., Argyroudis, S., Gara, F., Ragni, L., ... & Anastasiadis, A. (2022b). Field tests and numerical analysis of the effects of scour on a full-scale soil–foundation–structural system. Journal of Civil Structural Health Monitoring, 1-21.

Tubaldi, E., Minga, E., Macorini, L., & Izzuddin, B. A. (2020). Mesoscale analysis of multi-span masonry arch bridges. Engineering Structures, 225, 111137.

Tubaldi, E., White, C. J., Patelli, E., Mitoulis, S. A., De Almeida, G., Brown, J., ... & Zonta, D. (2022a). Invited perspectives: Challenges and future directions in improving bridge flood resilience. Natural hazards and earth system sciences, 22(3), 795-812.

Zampieri P, Tetougueni CD, Pellegrino C. Nonlinear seismic analysis of masonry bridges under multiple geometric and material considerations: application to an existing seven-span arch bridge. Structures 2021;34:78–94.

Zampieri, P., Zanini, M. A., Faleschini, F., Hofer, L., & Pellegrino, C. (2017). Failure analysis of masonry arch bridges subject to local pier scour. Engineering Failure Analysis, 79, 371-384.

Zhang, B., Zhao, H., Tan, C., OBrien, E. J., Fitzgerald, P. C., & Kim, C. W. (2022). Laboratory Investigation on Detecting Bridge Scour Using the Indirect Measurement from a Passing Vehicle. Remote Sensing, 14(13), 3106.