Review article: Physical Vulnerability Database for Critical Infrastructure Multi-Hazard Risk Assessments – A systematic review and data collection

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Response to Anonymous Referee #3

This is an invaluable study for those engaged in the risk analysis of critical infrastructure for natural hazards. The paper is very well organised and includes a systematic literature review and an extensive database of fragility and vulnerability models, and associated costs for various types of infrastructure, while bridges are excluded due to the excessive amount of bridge literature.

[Authors' reply] *We thank the reviewer for the encouraging words with regard scientific novelty and soundness. In the following sections, we address the two valuable comments of the reviewer.*

The following comments are provided:

1. It is suggested adding the parameters of the fragility functions when possible (e.g. median, standard deviation when a lognormal distribution is adopted).

   [Authors' reply] *Thank you for your suggestion. We have decided to not include the parameters of the curves to the database as they were used to reconstruct the curves if available in the original reference. Instead, we explicitly specify whether parameters are presented in the original reference for users seeking further consultation. Specifically, this information is summarized in the Database's 'Table D1 Summary CI Vulnerability Data' under the column 'Readily available'. Additionally, we use color codes throughout 'Table D2 Hazard Fragility and Vulnerability Curves', which contains the actual curves, to highlight for which curves no parameters were available for the reconstruction of the curves.*

2. It is suggested adding in the database the following fragility functions:

Fragility functions for tunnels (earthquakes, and ageing effects):

Argyroudis, S. A., Pitilakis, K. D. (2012). Seismic fragility curves of shallow tunnels in alluvial deposits. Soil Dynamics and Earthquake Engineering, 35, 1-12.

Huang, Z. K., Pitilakis, K., Tsinidis, G., Argyroudis, S., Zhang, D. M. (2020). Seismic vulnerability of circular tunnels in soft soil deposits: The case of Shanghai metropolitan system. Tunnelling and Underground Space Technology, 98, 103341.

Argyroudis, S., Tsinidis, G., Gatti, F., Pitilakis, K. (2017). Effects of SSI and lining corrosion on the seismic vulnerability of shallow circular tunnels. Soil Dynamics and Earthquake Engineering, 98, 244-256

Huang, Z., Argyroudis, S., Zhang, D., Pitilakis, K., Huang, H., Zhang, D. (2022). Time-dependent fragility functions for circular tunnels in soft soils. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, 8(3), 04022030.

Tsinidis, G., Karatzetzou, A., Stefanidou, S., Markogiannaki, O. (2022). Developments in seismic vulnerability assessment of tunnels and underground structures. Geotechnics, 2(1), 209-249.

Fragility functions for retaining walls/abutments (earthquakes):

Argyroudis, S., Kaynia, A. M., & Pitilakis, K. (2013). Development of fragility functions for geotechnical constructions: application to cantilever retaining walls. Soil Dynamics and Earthquake Engineering, 50, 106-116.

Fragility functions for embankments (flood, scour)

McKenna, G., Argyroudis, S. A., Winter, M. G., & Mitoulis, S. A. (2021). Multiple hazard fragility analysis for granular highway embankments: Moisture ingress and scour. Transportation Geotechnics, 26, 100431.

Tsubaki, R., Bricker, J. D., Ichii, K., Kawahara, Y. (2016). Development of fragility curves for railway embankment and ballast scour due to overtopping flood flow. Natural Hazards and Earth System Sciences, 16(12), 2455-2472.

[Authors' reply] *Thank you for sharing these valuable references. As our review also covers road and railway embankment curves, we have decided to add the flood fragility curves for embankments considering scour. Lines 268-274 now reads:*

> *'McKenna et al. (2021) provides analytically derived fragility and vulnerability curves [F7.14-15] for granular highway embankments. They use the Water Intensity Measure (WIM) as intensity measure, which describes the proportion of the embankment height that would be considered saturated if exposed to moisture ingress due to flooding. Additionally, they also assess the impact of scouring using a scouring depth of 0.5 and 3 m as lower and upper boundary, respectively, whilst the raised groundwater level was maintained. Their study shows that higher damages are expected with increasing moisture ingress and scour depths.'*

And lines 291-296 now read:

> *'Tsubaki et al. (2016) explains that railway damage commonly occurs due to floodwater overtopping leading to scouring of the ballast and embankment upon which the trail tracks are built. Railway overtopping damage begins with ballast scour and progresses to embankment scour. They therefore developed fragility curves for ballast scour damage, embankment fill scour damage and a combination of both damage conditions [F8.9-11] using damage records of flood events for single-track railways in Japan.'*

The curves presented by McKenna et al. (2021) and Tsubaki et al. (2016) have also been added to the database. Subsequently, we have updated figures 3 and 4 in the discussion sections 4.1 and 4.2, respectively, as well as the numbers in the main text in these sections. Furthermore, we have adjusted our statement saying that only inundation depth is used as intensity measure for the flood curves (lines 822-825):

> *'We encounter a range of ground shaking hazard intensity measures for earthquakes such as PGA, PGV and elastic spectral displacement. Conversely, flooding predominantly relies on a*

single intensity measure, inundation, although there is a rare instance where WIM is used. However, other intensity measures such as flow velocity (Kreibich et al., 2009; Koks et al., 2022) and salinity (Glas et al., 2017) also play an important role to infrastructure damage.'