ECEE2026
18th European Conference on Earthquake Engineering

Intensity measure conversion of seismic fragility and vulnerability models

Gerard J. O'Reilly[1,2], Volkan Ozsarac[1,2], Davit Shahnazaryan[1,2]
1- Scuola Universitaria Superiore IUSS di Pavia, Pavia 27100, Italy
2- Djura | Risk - Data – Engineering Srl, Pavia 27100, Italy

gerard.oreilly@iusspavia.it

Abstract

Fragility and vulnerability models are essential components of regional seismic risk assessment. They establish a link between earthquake ground motion, represented by an intensity measure (IM) such as spectral acceleration or peak ground velocity, and the probability of damage or expected loss. When assessing risk across a large portfolio of structures, fragility models are often based on different IM types for different taxonomies, which creates inconsistencies that can hinder comparison and collective application. Previous studies have suggested several methods for converting fragility functions to a common IM, including approaches based on uniform hazard and risk equivalence, total probability, and the use of proxy structures. Here, a case study is used to systematically assess these methods' ability to convert fragility and vulnerability functions developed with traditional IMs as well as next-generation IMs like average spectral acceleration. The results show that methods rooted in uniform hazard or uniform risk do not provide reliable performance across all cases, while approaches based on total probability perform better but with the penalty of requiring detailed hazard information. An important conclusion is that converting models developed from less effective IMs (e.g., peak ground acceleration) does not improve predictive performance when converting to more optimal IMs - in fact, it significantly worsens. However, when developing fragility and vulnerability models using next-generation IMs, a much improved level of flexibility when adapting to other IMs is observed, paving the way for them to be adopted in future risk models.

Keywords: Intensity measure, fragility function, vulnerability function, conversion, seismic risk.

1- INTRODUCTION

Seismic risk assessment relies on fragility and vulnerability functions to quantify the probability of damage or loss as a function of ground shaking intensity. A fragility function formally describes the probability that a structure exceeds a particular damage state (DS) for a given level of shaking, $P[DS > ds|IM=im]$, while a vulnerability function expresses the expected loss ratio for a given intensity, $E[L|IM = im]$. Both are conditioned on an intensity measure (IM), which may take various forms ranging from classic scalar quantities such as peak ground acceleration (PGA) or spectral acceleration $Sa(T)$ to more advanced next-generation IMs such as average spectral acceleration Sa_{avg}(T) [1] or filtered incremental velocity *FIV3*(T) [2].

In regional risk applications, where large portfolios of structures are geographically distributed, ground motion fields (GMFs) are simulated and combined with fragility or vulnerability models to estimate consequences such as economic loss. A fundamental challenge arises when different structural taxonomies are characterised using different IMs. If structures can be treated as independent, each can be evaluated using its own IM-specific GMF and the losses are simply summed; however, when structural interdependencies must be considered, such as in infrastructure networks [3] or when correlation in damage across different structures is considered [4], multiple cross-correlated GMFs are required. Generating such fields for a variety of IMs simultaneously is computationally demanding and relies on cross-IM spatial correlation models that are seldom available [5,6]. A secondary issue is that when total expected losses computed using two different vulnerability models are compared, it can be useful to directly compare the underlying vulnerability functions individually to better understand the sources of such difference, instead of examining the aggregated results.

A practical alternative is to define all fragility and vulnerability models in terms of a single common IM. This allows a single GMF to be simulated and all models to be evaluated collectively, while also enabling direct comparison across different sources. Historically, PGA has served as this common denominator, though its well-documented limitations in terms of efficiency and sufficiency have been widely reported [7]. More recent frameworks, including the GEM global model [8] and the European Seismic Risk Model (ESRM20) [9], employ spectral acceleration at specific periods, which partially mitigates some of these deficiencies.

When analysts wish to exploit the many detailed fragility or vulnerability models developed in the research community, each potentially using a different IM definition, three broad strategies are available:

1) adopt a single IM for all models and evaluate consequences from one GMF type;
2) retain individually optimised IMs and evaluate consequences from multiple cross-correlated GMFs;
3) convert all models to a common IM using an appropriate conversion methodology.

This paper focuses on the third strategy, reviewing existing conversion approaches, with the aim of providing practical guidance for regional risk modellers.

2- CONVERSION METHODS

Several methodologies have been proposed in the literature to convert fragility functions between IMs, while none of these directly address the issue of vulnerability function conversion. Four main categories are considered here, and are briefly described in the following subsections.

2-1- UNIFORM HAZARD AND UNIFORM RISK APPROACHES

Silva et al. [10] proposed a simple scaling factor derived from a design spectrum to convert the median of a fragility function from one IM to another, while preserving the dispersion. O'Reilly and Calvi [11] extended this concept using hazard curves from probabilistic seismic hazard analysis (PSHA) rather than a design spectrum, enabling the treatment of non-$Sa(T)$ IMs. Both approaches assume equal variability between the original and converted fragility functions, which in practice is rarely satisfied when converting between IMs of differing efficiency. A novel uniform risk equivalence approach was also trialled and evaluated by O'Reilly et al. [12]. It is grounded in the principle that the mean annual frequency of exceedance (MAFE) of a fragility function's DS is unique for a given structure and site regardless of the conditioning IM used, provided the IM is efficient, sufficient, and unbiased [13–15]. With the Cornell et al. [16] closed-form risk integral, equating the MAFE under IM_1 and IM_2 yielded an expression for the converted fragility median, assuming the target dispersion is fixed.

2-2- TOTAL PROBABILITY APPROACH

The most rigorous conversion strategy employs the total probability theorem to express the converted fragility function $P[DS|IM_2]$ by integrating the original fragility $P[DS|IM_1]$ over the conditional distribution of IM_1 given IM_2:

$$P[DS|IM_2] = \int_{IM_1} P[DS|IM_1] f_{IM_1|IM_2} dIM_1 \tag{1}$$

where $P[DS|IM_1]$ is the original fragility function based on IM_1, and $f_{IM1|IM2}$ is the conditional distribution of IM_1 given IM_2 to result in the converted fragility function.

This formulation was initially presented erroneously by Michel et al. [17] and later corrected and substantially expanded by Suzuki and Iervolino [18]. In recent work by O'Reilly et al. [12], which is discussed here, this was further extended to incorporate the full set of rupture scenario parameters and ground motion models (GMMs) available from the OpenQuake [19] PSHA disaggregation output, rather than being limited to magnitude and distance alone. For a given IM_2 level, the conditional distribution $f_{IM1|IM2}$ is computed using the GMM-based conditional spectrum formulation together with IM correlation models from Aristeidou et al. [20].

3- EXTENSION TO VULNERABILITY FUNCTIONS

Previous research had tended to address only the conversion of fragility functions, whereas O'Reilly et al. [12] extended the total probability framework to vulnerability functions, which describe expected loss ratios as a function of IM. Since vulnerability functions are generally expressed as a discrete distribution $E[L|IM]$ rather than a lognormal fragility, the conversion integral was written as:

$$E[L|IM_2] = \int_{IM_1}\int_{Rup} E[L|IM_1] f_{IM_1|IM_2,Rup} dIM_1 dRup \quad (2)$$

where all conditional distribution terms carry the same meaning as in the fragility conversion. This extension is motivated by the fact that many practical risk models operate directly in terms of vulnerability rather than fragility, and it is therefore of direct operational relevance to test and validate the conversion procedure at this level.

4- CASE STUDY

Each of the conversion strategies outlined previously was evaluated using non-linear single-degree-of-freedom (SDOF) models. The total probability approach is referred to herein as Method 1 and is anticipated to be the most accurate but also the most data intensive. Simplified variants (Methods 2a, 2b and 2c) employ progressively coarser disaggregation representations while retaining the probabilistic framework. In particular, Method 2a considers a subset of rupture scenarios sufficient to capture approximately 50% of the hazard contribution; Method 2b is based on the mean scenario parameters (e.g., magnitude, distance); and Method 2c employs the corresponding modal scenario. Methods 3 and 4 correspond to the uniform hazard approaches of Silva et al. [10] and O'Reilly and Calvi [11], respectively, while Method 5 is the uniform risk approach of O'Reilly et al. [12] that was trialled to investigate whether it could be a possible solution.

4-1- STRUCTURAL MODELLING AND HAZARD CHARACTERISATION

To give a brief illustration of the results obtained, a single SDOF system with fundamental period of 1.0 s was modelled in OpenSees [21] using a bilinear hysteretic material with pinching, a base shear coefficient of 0.05 and a ductility capacity of 6.0. In this illustrative scenario presented below, a single damage state DS5 corresponding to the displacement capacity was considered, and the damage-to-loss model from O'Reilly and Shahnazaryan [22] was adopted to translate DSs into expected loss ratios.

Seismic hazard characterisation was carried out using the OpenQuake engine [19] for the site of L'Aquila, Italy, adopting the ZS9 seismic source model and the GMM by Aristeidou et al. [23]. Hazard curves and PSHA disaggregation results were computed for several IMs, including *PGA*, *PGV*, *Sa*(*T*) at four periods, *FIV3*(*T*) at four periods, and two definitions of $Sa_{avg}(T)$, described in O'Reilly and Shahnazaryan [22], at four periods each. Sets of 40 ground motion records were selected at multiple hazard levels using the conditional spectrum method via the Djura Record Selector [24], and their hazard consistency was verified.

4-2- CONVERSION RESULTS

Multiple stripe analysis was performed to develop fragility functions for every IM and DS. These reference fragility functions were then converted between all IM pairs using each of the five methods, and the quality of conversion was quantified using the Hellinger distance [25], which ranges from 0 (identical) to 1 (completely disjoint). As an illustrative example, Figure 1 shows a single conversion case, where the fragility functions for a single structure's DS are converted from IM_1=*Sa*(1.0) to IM_2=PGA and then compared to the reference fragility function initially developed in terms of IM_1=PGA. **Error! Reference source not found.** shows the Hellinger distance for each conversion case analysed in O'Reilly et al. [12], to give a better idea of the overall quality of the fragility conversion results.

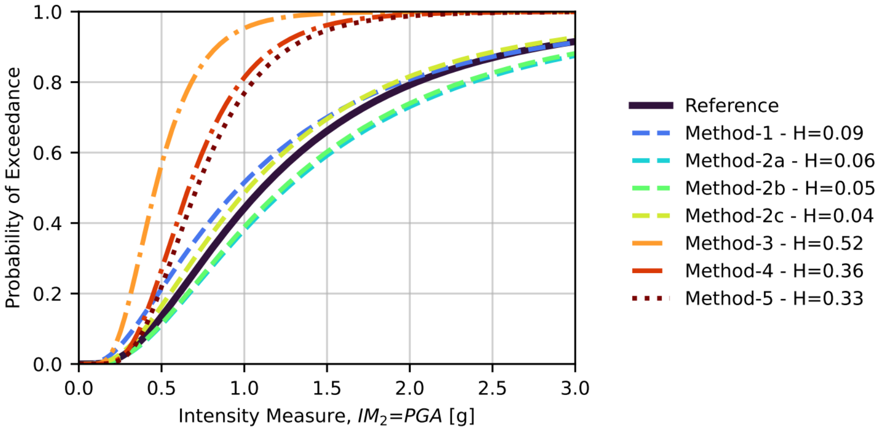

Figure 1- Comparison of reference (*IM_1*=PGA) and converted (from *IM_1*= *Sa*(1.0) to *IM_2*=PGA) fragility functions

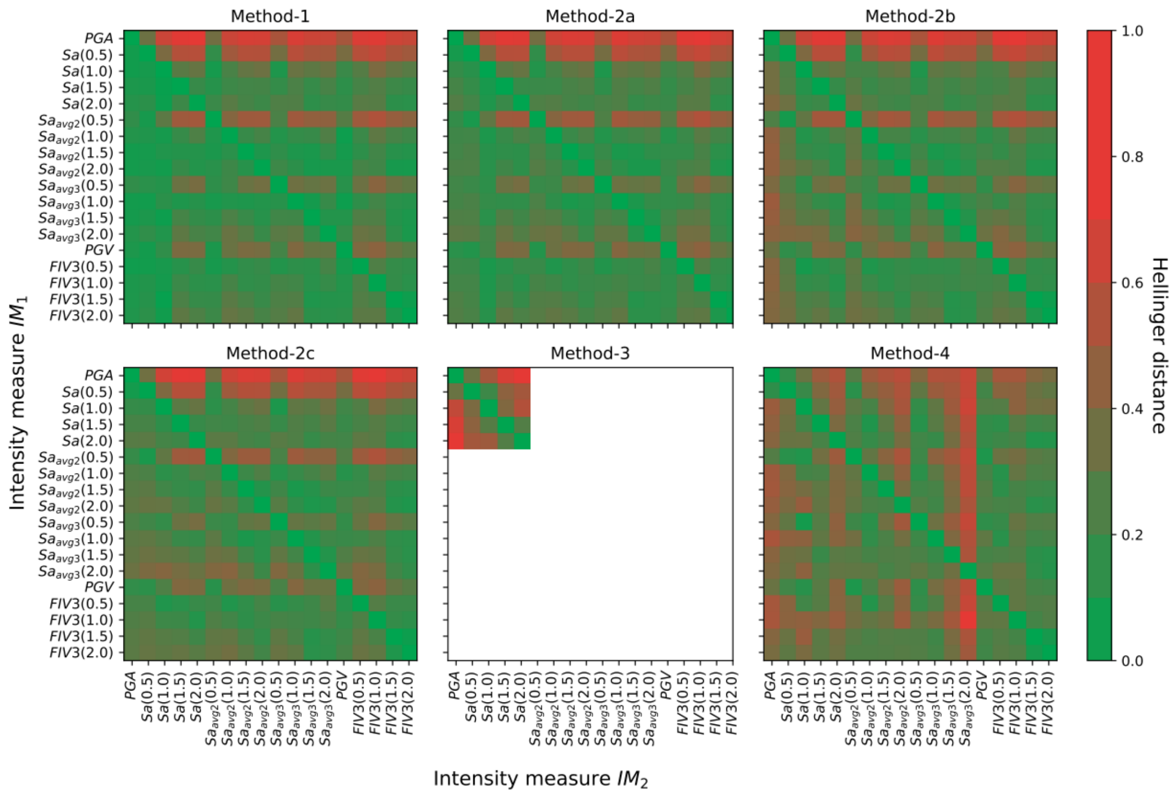

Figure 2- Average Hellinger distances between the reference and the converted fragility functions (from *IM_1* to *IM_2*), computed as the mean of distances across DSs

Overall, where results will be discussed in more detail during the presentation, for conversions between traditional *Sa*(*T*)-based IMs, the total probability-based Methods 1 and 2 consistently outperformed the simpler Methods 3–5. A key directional asymmetry was observed: converting from a longer-period IM to a shorter period (e.g., *Sa*(1.0s) to *Sa*(0.5s)) yielded accurate results across all methods, while converting in the reverse direction (shorter to longer period) was problematic for all approaches. This confirms earlier findings by Suzuki and Iervolino [18] and is attributed to the conditional distribution becoming wide and poorly constrained when extrapolating to longer periods, where scalar IMs fail to capture structural response adequately.

Conversions involving next-generation IMs displayed markedly different behaviour. Because *FIV3*(*T*) is highly correlated with itself across periods and exhibits near period-independence [20], conversions between *FIV3*(*T*) definitions were accurate with all methods. More strikingly, when *FIV3*(*T*) was used as the original *IM_1*, conversion to any target *IM_2* worked well regardless of method, in direct contrast to the PGA case. Using the analogy of blood transfusion types: PGA behaves as a universal receiver (other IMs can be converted to it with reasonable accuracy), whilst *FIV3*(*T*) acts as a universal donor, enabling flexible conversion in any direction. The vulnerability function conversion was evaluated in an analogous manner to the fragility conversion using the methodology presented in O'Reilly et al. [12]. The comparisons will be discussed in more detail during the presentation, but a notable finding was that differences between conversion methods were substantially smaller for vulnerability functions than for fragility functions, indicating that simpler hazard representations may suffice in practice when converting at the vulnerability level.

To assess risk-domain implications directly, average annual loss (AAL) values were computed by integrating each converted vulnerability function against the site hazard in L'Aquila, with Figure 3 showing the AAL ratio between the reference vulnerability model and the converted vulnerability model. This revealed an important subtlety: while converting various IMs to PGA produced apparently acceptable fragility function matches, the resulting vulnerability functions significantly overestimated AAL. This inflation is caused by the high dispersion inherent in PGA-based fragility functions, which inflates loss estimates at all intensity levels when integrated with the hazard. Conversely, conversions originating from or targeting *FIV3*(*T*) and $Sa_{\mathrm{avg}}(T)$ preserved AAL with good accuracy across virtually all method variants examined. Overall, the practical implication is clear: fragility and vulnerability models should ideally be developed using efficient next-generation IMs such as *FIV3*(*T*) or $Sa_{\mathrm{avg}}(T)$, which offer both high predictive accuracy and superior conversion flexibility.

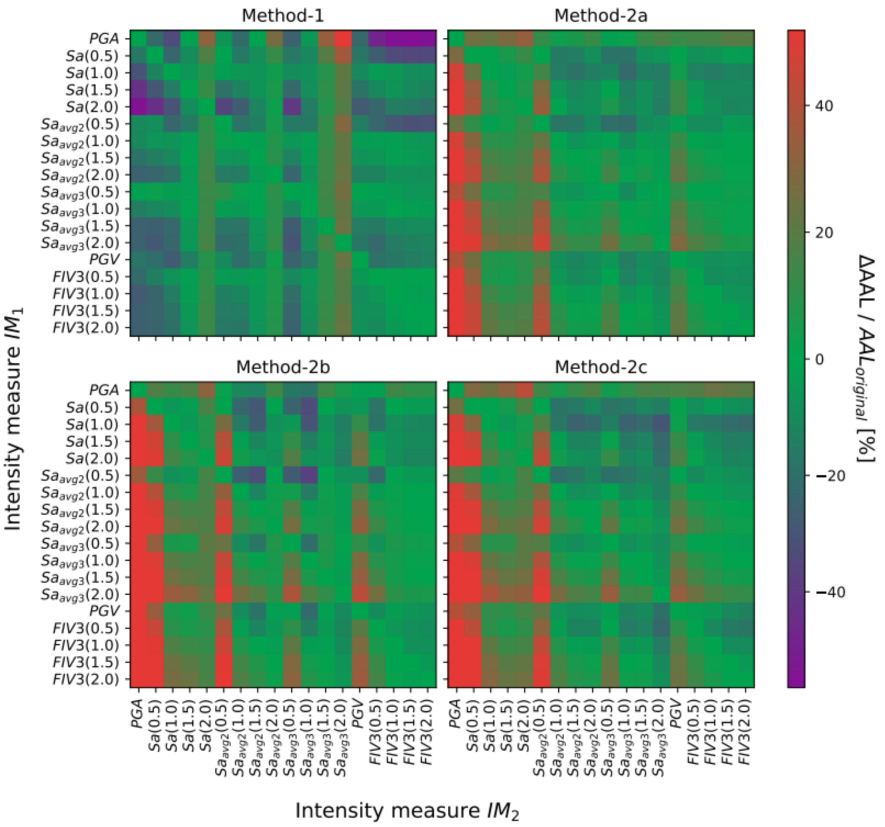

Figure 3- AAL ratio for vulnerability function conversions IM_1 to IM_2

5- CONCLUSIONS

This short paper examined the conversion of seismic fragility and vulnerability models between intensity measures, with the aim of providing practical guidance for regional risk modellers. The following main conclusions can be drawn:

- Total probability-based methods consistently outperformed simpler approaches. Simplified variants using mean or modal disaggregation scenarios achieve near-equivalent accuracy to the full method at reduced computational cost.
- For *Sa*(*T*)-based conversions, converting from longer to shorter periods works well, while the reverse direction tends to fail for all methods due to the poorly constrained conditional distribution.
- PGA acts as a universal receiver: most other IMs can be converted to PGA-based fragility functions, but the resulting high dispersion causes substantial overestimation of average annual loss. Developing fragility models in terms of PGA is therefore discouraged for future model development.

- *FIV3*(*T*) acts as a universal donor: its high efficiency, sufficiency, and near period-independence make it an excellent basis for fragility and vulnerability modelling, enabling reliable conversion to virtually any target IM.
- Vulnerability function conversion is less sensitive to the choice of method than fragility function conversion, and a simpler treatment of seismic hazard may suffice when converting at the vulnerability level.

6- ACKNOWLEDGEMENTS

Ground motion record selections were performed using an academic licence of the Djura online record selector (www.djura.it). This work was developed within the SONATA project, a Starting Grant awarded by the Italian Science Fund (Fondo Italiano per la Scienza) at IUSS Pavia, grant number FIS2023-03215.

7- REFERENCES

1. Cordova P, Deierlein GG, Mehanny S, Cornell CA. Development of a two-parameter seismic intensity measure and probabilistic assessment procedure. *Proceedings of the 2nd US–Japan Workshop on Performance-based Earth- quake Engineering Methodology for RC Building Structures*, Sapporo, Hokkaido, Japan: 2000.
2. Dávalos H, Miranda E. Filtered incremental velocity: A novel approach in intensity measures for seismic collapse estimation. *Earthquake Engineering & Structural Dynamics* 2019; **48**(12): 1384–1405. DOI: 10.1002/eqe.3205.
3. Monteiro VA, O'Reilly GJ. Notes on Spatial Correlation for Average Spectral Acceleration: Direct and Indirect Approaches. *Earthquake Spectra* 2026. DOI: 10.1002/esp4.70049.
4. Shome N, Cornell CA, Bazzurro P, Carballo JE. Earthquakes, Records, and Nonlinear Responses. *Earthquake Spectra* 1998; **14**(3): 469–500. DOI: 10.1193/1.1586011.
5. Martins L, Silva V. Development of a fragility and vulnerability model for global seismic risk analyses. *Bulletin of Earthquake Engineering* 2021; **19**(15): 6719–6745. DOI: 10.1007/s10518-020-00885-1.
6. Crowley H, Dabbeek J, Despotaki V, Rodrigues D, Martins L, Silva V, *et al.* European Seismic Risk Model (ESRM20). *EFEHR Technical Report 002 V100* 2021.
7. Silva V, Crowley H, Colombi M. Fragility Function Manager Tool, 2014. DOI: 10.1007/978-94-007-7872-6_13.
8. O'Reilly GJ, Calvi GM. Quantifying seismic risk in structures via simplified demand–intensity models. *Bulletin of Earthquake Engineering* 2020; **18**(5): 2003–2022. DOI: 10.1007/s10518-019-00776-0.
9. O'Reilly GJ, Ozsarac V, Shahnazaryan D. Conversion of seismic fragility and vulnerability models to alternative intensity measures for regional risk analysis. *Earthquake Spectra* 2026.
10. Bradley BA. The seismic demand hazard and importance of the conditioning intensity measure. *Earthquake Engineering & Structural Dynamics* 2012; **41**(11): 1417–1437. DOI: 10.1002/eqe.2221.
11. O'Reilly GJ. Limitations of Sa(T1) as an intensity measure when assessing non-ductile infilled RC frame structures. *Bulletin of Earthquake Engineering* 2021; **19**(6): 2389–2417. DOI: 10.1007/s10518-021-01071-7.
12. Cornell CA, Jalayer F, Hamburger RO, Foutch DA. Probabilistic Basis for 2000 SAC Federal Emergency Management Agency Steel Moment Frame Guidelines. *Journal of Structural Engineering* 2002; **128**(4): 526–533. DOI: 10.1061/(ASCE)0733-9445(2002)128:4(526).
13. Michel C, Crowley H, Hannewald P, Lestuzzi P, Fäh D. Deriving fragility functions from bilinearized capacity curves for earthquake scenario modelling using the conditional spectrum. *Bulletin of Earthquake Engineering* 2018; **16**(10): 4639–4660. DOI: 10.1007/s10518-018-0371-3.
14. Suzuki A, Iervolino I. Intensity measure conversion of fragility curves. *Earthquake Engineering & Structural Dynamics* 2020; **49**(6): 607–629. DOI: 10.1002/eqe.3256.
15. Aristeidou S, Shahnazaryan D, O'Reilly GJ. Correlation models for next-generation amplitude and cumulative intensity measures using artificial neural networks. *Earthquake Spectra* 2025; **41**(1): 851–875. DOI: 10.1177/87552930241270563.
16. McKenna F, Scott MH, Fenves GL. Nonlinear Finite-Element Analysis Software Architecture Using Object Composition. *Journal of Computing in Civil Engineering* 2010; **24**(1): 95–107. DOI: 10.1061/(ASCE)CP.1943-5487.0000002.
17. Shahnazaryan D, O'Reilly GJ. Next-generation non-linear and collapse prediction models for short- to long-period systems via machine learning methods. *Engineering Structures* 2024; **306**: 117801. DOI: 10.1016/j.engstruct.2024.117801.

18. Pagani M, Monelli D, Weatherill G, Danciu L, Crowley H, Silva V, *et al.* OpenQuake Engine: An Open Hazard (and Risk) Software for the Global Earthquake Model. *Seismological Research Letters* 2014; **85**(3): 692–702. DOI: 10.1785/0220130087.
19. Aristeidou S, Shahnazaryan D, O'Reilly GJ. Artificial neural network-based ground motion model for next-generation seismic intensity measures. *Soil Dynamics and Earthquake Engineering* 2024; **184**: 108851. DOI: 10.1016/j.soildyn.2024.108851.
20. Shahnazaryan D, Ozsarac V, O'Reilly GJ. Djura Ground Motion Record Selector: A Software Solution For Earthquake Engineering. *COMPDYN 2025- 10th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Rhodes, Greece: 2025. DOI: 10.7712/120125.12444.25126.
21. Hellinger E. Neue Begründung der Theorie quadratischer Formen von unendlichvielen Veränderlichen. *Journal Für Die Reine Und Angewandte Mathematik* 1909; **1909**(136): 210–271. DOI: 10.1515/crll.1909.136.210.