



## GROUND MOTION INTENSITY MEASURES, VARIABILITY AND SEISMIC LOSS METRICS, A CASE STUDY FOR HVERAGERDI, SOUTH ICELAND

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### Abstract

Iceland is the most seismically active country in northern Europe. The largest earthquakes take place in the two major transform zones of the country, one of which is the South Iceland Seismic Zone (SISZ), where earthquakes up to  $M_w7$  have occurred and caused damage in the predominantly flat rural agricultural region with a few small population centres/towns and all critical infrastructure and lifelines of modern-day society.

The most recent destructive earthquake in the SISZ was the  $M_w6.3$ , May 29, 2008 Ölfus earthquake close to the town of Hveragerði. The town experienced intense near-fault strong-motion, characterized by large high-frequency accelerations and large amplitude near-fault velocity pulses recorded on a small-aperture strong-motion array (ICEARRAY-I). Horizontal peak ground accelerations (PGA) in the range of 38 to 88%g were recorded on the array. Despite the Ölfus earthquake being the costliest natural disaster in Iceland to date and caused widespread damage, there were no collapsed residential buildings and no casualties. To fulfil insurance purposes, detailed building-to-building loss database was established immediately after the event. It was linked to an official property database ([www.skra.is](http://www.skra.is)) which stores key information for each building, e.g., construction year, building material, number of storeys, floor area, replacement value, etc. Having complete building characteristics, the key building typologies are identified according to the SERA classification (ESHM20 project).

The ICEARRAY-I high-quality waveform recordings give the opportunity to compute various intensity measures (IMs) in unusually high spatial resolution. To explore the spatial variability of the selected IMs across the study area, Kriging spatial interpolation is performed to generate shake maps for these IMs along with their corresponding uncertainties. The IMs considered are PGA, spectral acceleration response (SA) at short-to-long periods, and cumulative absolute velocity (CAV).

In the context of the TURNkey H2020 project ([www.earthquake-turnkey.eu](http://www.earthquake-turnkey.eu)), comprehensive building exposure data has been compiled and collocated with the Open Street Map buildings through validation and integration. From the loss database and the exposure data, the mean damage factors ( $DFs$ ) are determined for the identified building typologies in the town. Having detailed ground-motion (GM) data, complete building exposure database, and loss data in Hveragerði gives the unique opportunity to perform loss estimation associated with the higher level of detail building typologies on the contrary to the simple classification of concrete, masonry and timber buildings considered in previous studies in Iceland. Hence, we carry out a detailed probabilistic seismic loss estimation at Hveragerði using the most recent global fragility curves developed as part of the global seismic risk model. The predicted losses are compared with the observed losses in the damage database of the May 2008 earthquake in terms of mean  $DF$  and monetary loss across all identified building typologies in the study area. The simulated losses are far higher than the observed losses.

*Keywords:* loss estimation; seismic risk assessment; building exposure; intensity measure; south Iceland; Kriging interpolation



## 1. Introduction

In Iceland, the most significant earthquakes take place in the two major transform zones of the country, one is the South Iceland Seismic Zone (SISZ), where earthquakes up to  $M_w7.0$  have occurred. The SISZ is predominantly in flat rural agricultural region with a few small towns and all critical infrastructure and lifelines of modern-day society. On May 29, 2008, a  $M_w6.3$  earthquake occurred on two almost parallel north-south oriented faults with a right-lateral strike-slip mechanism in the Ölfus region in the central SISZ. Three towns, Hveragerði, Selfoss, and Eyrarbakki were strongly affected and around 2000 buildings were damaged to some extent (25 of them were uninhabitable after the earthquake). The macroseismic epicentre of the earthquake was located close to the small town of the Hveragerði. The town experienced intense near-fault strong-motion characterized by large high-frequency accelerations and large amplitude near-fault velocity pulses which was recorded on a small-aperture strong-motion array, ICEARRAY-I [1]. Permanent ground displacements were observed at almost all ICEARRAY-I stations that are depicted by pink circles in Fig. 1 [2]. The earthquake did not cause any collapse of residential buildings or other structures, but extensive damage was observed in many buildings [3]. Bessason *et al.* [4] studied observed losses of low-rise buildings subjected to the Ölfus earthquake and highlighted that the losses were dominated by damages of non-structural elements (flooring and partition walls) although some structural damages were registered as well. The buildings with the most severe damage were those built of concrete or masonry with little or no reinforcement [3, 5].

This study focuses on four subjects related to the town Hveragerði which is a testbed in the Horizon 2020 TURNkey project: 1) high-quality ground-motion data recorded in the Ölfus earthquake, 2) available building exposure data, 3) observed loss data collected after the May 2008 Ölfus earthquake, 4) prediction of losses using global vulnerability models for a scenario earthquake corresponding to the Ölfus earthquake, and comparison to the observed losses.

So far, a few numbers of studies have been carried out on GM characteristics of Ölfus earthquake that have merely been focusing on peak and spectral characteristics (e.g., [6–8]). The high-quality waveform recordings of the Ölfus event were recorded on ICEARRAY-I stations in high spatial resolution. Therefore, in this study, to better understand the earthquake's characteristics, we investigate a set of well-known IMs representing the intensity, energy, frequency content and amplitude of GM through records available from the Ölfus earthquake. More importantly, the GM records' dense spatial coverage across Hveragerði enables us to study the IMs spatially. To this end, the Kriging geostatistical method is applied to the selected IMs to account for spatial variability. Consequently, ground-motion IMs distribution maps are estimated for the Ölfus earthquake.

In Iceland, in the aftermath of strong earthquakes, such as the 2008 Ölfus event, the Natural Catastrophe Insurance of Iceland is required to estimate losses of all damaged buildings to fulfil insurance claims. This allows establishing a damage database for all building units in the affected region. Moreover, in Iceland, all properties are registered officially. As a part of the TURNkey Project, we constructed a detailed geographical information system (GIS)-based database by collating the real loss database registered after the May 2008 earthquake with the building exposure data of Hveragerði. It should be highlighted that such a complete loss database for a destructive earthquake is rare to find in post-earthquake related literature. Hence, having such a database gives us a unique opportunity to assess scenario-based loss estimation. The SERA taxonomy system [9] was used to classify the buildings into appropriate building typologies and to identify the most vulnerable building typologies.

SELENA is an earthquake loss estimation tool that provides the local, state and regional institutions with a state-of-the-art decision support tool for estimating possible losses caused by earthquakes [10]. In this study, the SELENA software was employed to perform a simulation of losses for a scenario event corresponding to the 2008 Ölfus earthquake and using a range of recorded PGA and SAs obtained across Hveragerði and by applying the recent global fragility functions for the identified building typologies [11, 12]. Finally, we compared the predicted and observed losses.

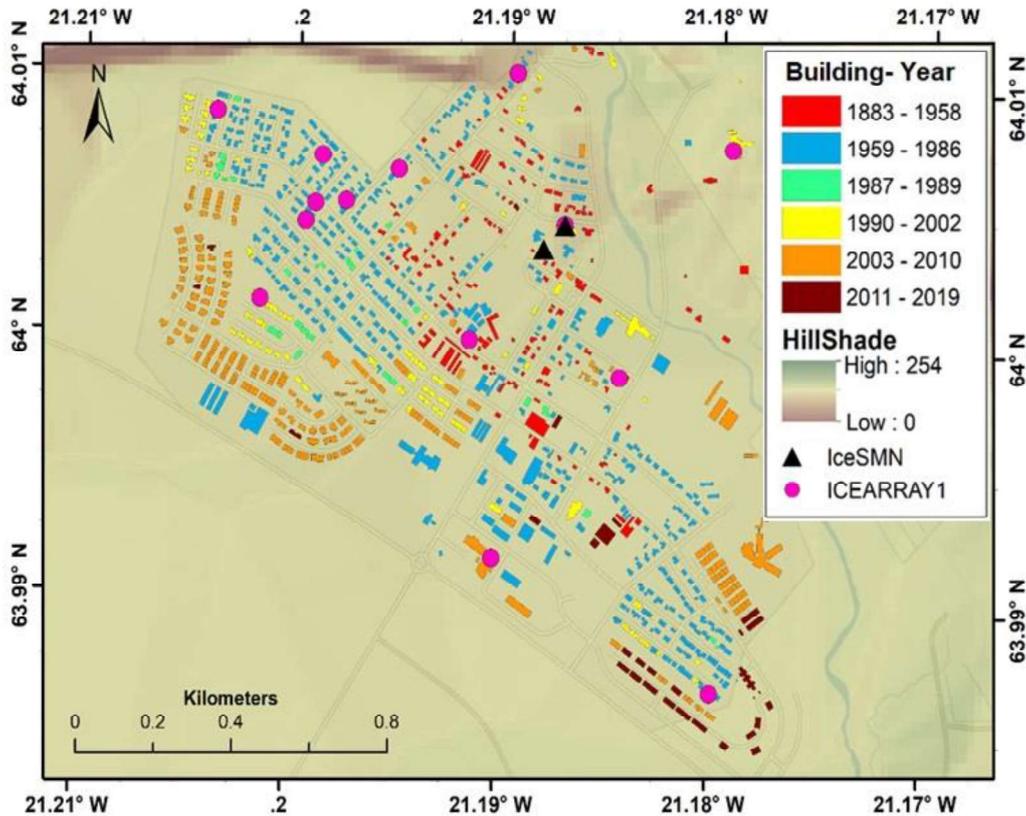


Fig. 1 –Spatial distribution of buildings classified by their construction year across Hveragerði town. The ICEARRAY-I stations are depicted by pink circles.

## 2. Building characteristic databank

In this study, the most recent building exposure database is provided for Hveragerði town. The building-by-building databank, including all unit's information, is assembled in various formats such as Excel spreadsheet, GIS-based shapefiles linked to the Open Street Map, and MATLAB structure for clear spatial visualization and convenient use of the units and buildings' characteristics in future research studies. Fig. 1 illustrates the distribution of buildings classified by their construction year across Hveragerði. In total, 1299 buildings are in the Hveragerði; of these 166 were constructed after 2008 when the Ölfus earthquake took place. 47.7% of buildings are built before 1976, when the first seismic code (i.e., ÍST 13) was implemented in Iceland. In 1989, the seismic code was upgraded and employed for building design until 2002 when Eurocode 8 and the corresponding National Application Documents were implemented in Iceland [13]. From the property database it can be seen that 30% of buildings in Hveragerði are constructed in the period 2002-2020 period. Notice that in an international context, the Icelandic building stock is relatively young, and for instance, in the SISZ region, no building in use was built before 1870 [14]. Almost all buildings are low-rise with less than two storeys (97.7%). Moreover, in Iceland, structural walls dominate the lateral load resisting system in nearly all buildings. It is worth noting that prescribed wind loads in Iceland are among the highest in Europe. Therefore, the Icelandic buildings are constructed to withstand substantial lateral loads imposed by winds, which especially affects the design of light weight structures like timber buildings. For all building typologies (RC, timber, masonry), the floor slabs and the building foundations are built using reinforced concrete that ties the foundations together and makes them more earthquake resistant.

The horizontal histogram in Fig. 2 indicates the number of buildings classified by detailed construction material in Hveragerði. The histogram illustrates that the critical construction materials are



reinforced concrete, timber (wood) and cinderblock, which is an unreinforced masonry comprised of hollow pumice blocks with a low weighted density of  $\sim 14 \text{ kN/m}^3$ . Therefore, to assign a specific building typology according to the SERA classification, the detailed material-based classes are simplified to three categories as follows: 1) reinforced concrete including concrete and precast concrete classes, RC, 2) wood, W, and 3) unreinforced masonry including cinderblock, bricks and concrete's combination with blocks/bricks, MUR. It should be noted that masonry buildings are no longer constructed in Iceland. Note that 16% of the building stock (residential, public, commercial, and industry) does not belong to any of these three classes, mainly due to their unknown construction material. Regarding the building occupancy classes in Hveragerði, the majority of buildings are residential (82%), whereas 14% of them are commercial/public and only 4% are industrial buildings, respectively (see the pie chart in Fig. 2). For the present study's scope, only residential buildings in Hveragerði constructed before 2008 (the May 2008 Ölfus earthquake) are selected. The selected building database includes  $\sim 500$ , 287 and 51 RC, W and MUR buildings.

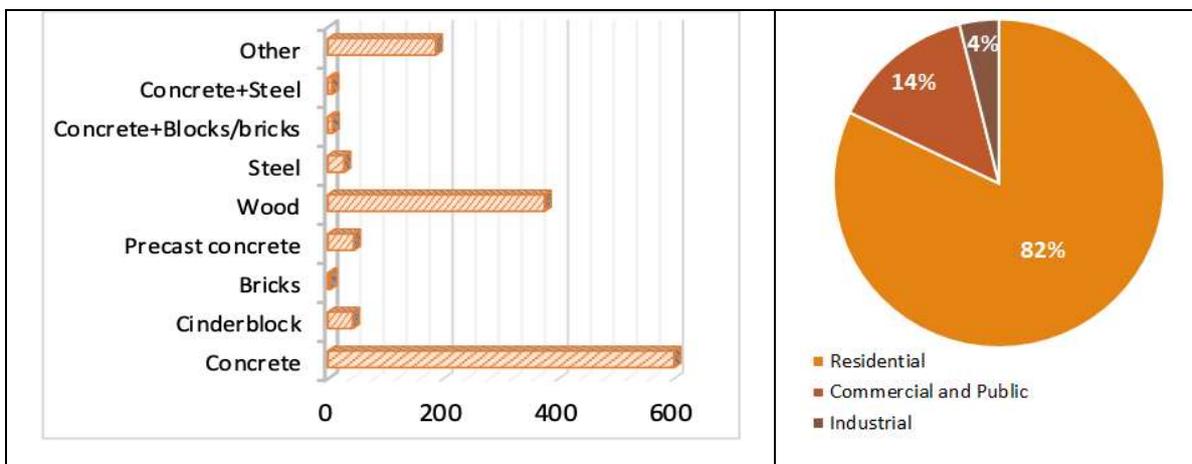


Fig. 2 – Left panel: Number of buildings in Hveragerði classified by their construction material. Right panel: percentages of buildings classified by their occupancy.

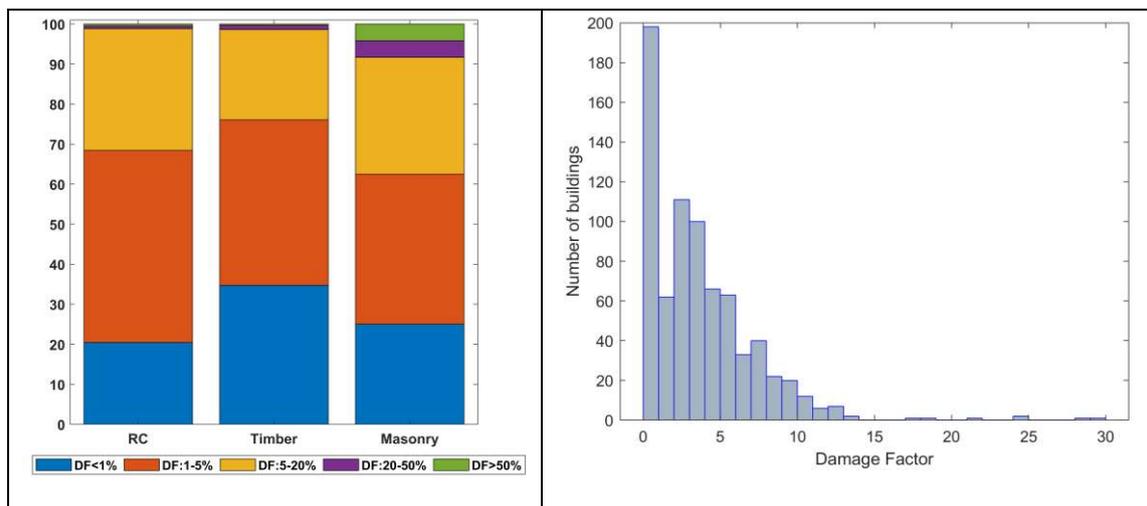


Fig. 3 – Left: classification of observed damage factor ( $DF$ ) as functions of material and damage states based on [15] definition. Right: histogram of number of buildings against observed damage factor (%).

### 3. Building damage database

In the present study, detailed empirical loss data for Hveragerði recorded after the May 2008 Ölfus  $M_w 6.3$  earthquake in SISZ was provided by the Natural Catastrophe Insurance of Iceland. The data contains the estimated repair cost of damaged units and the replacement value of each property from the assembled



exposure data. The repair cost for each unit was classified in number of subclasses of structural and non-structural losses (for details see [4]). Herein, the focus is on the total damage for each unit, defined with the damage factor variable,  $DF$ , which is the ratio of estimated repair cost (loss) to the replacement value of each building. The  $DF$  is in the range  $[0,1]$ , where 0 indicates no-loss, and 1 (100%) means total-loss. The loss data from these events are complete because they include all buildings in the study area, where PGAs ranging from 0.43g to 0.88g were recorded. In the loss database, the proportion of buildings with no loss is about 26%, i.e., where  $DF$  is equal to zero (see Fig. 3). The stacked histogram in Fig. 3 shows the number of buildings classified by key materials and damage states. As indicated in the legend, the five damage states are defined based on loss bins characterized by  $DF$  ranges [15]. The histogram indicates that about 20% of RC buildings, 35% of timber, and 25% of masonry buildings experienced no or negligible loss ( $DF < 1\%$ ).

## 4. Intensity measures variability across Hveragerði

### 4.1 Overall variability of IMs

In this section, a set of well-known IMs is computed from the processed waveforms of the Ölfus earthquake recorded by ICEARRAY-I stations. The near-fault seismic ground motion recordings were characterized by intense accelerations of a relatively short duration of 5-6 seconds and large amplitude near-fault velocity pulses. The variation of horizontal PGA in the area was considerable given the small area of the array, having a minimum between 0.43 to 0.53 g in the centre of Hveragerði to a maximum of 0.76 to 0.88 g in the eastern and western parts of the town, respectively. It should also be noted that the recording stations were located about 1-2 km from the vertical surface projection of one of the causative faults of this earthquake, a distance that can be considered to be negligible compared to the size of the fault.

Fig. 4 shows, for example, the statistics of horizontal components of the SAs obtained from Ölfus earthquake accelerograms recorded by ICEARRAY-I stations across Hveragerði, corresponding to N-S ( $x$ , red lines), E-W ( $y$ , blue lines) and the rotation-invariant average (ARI) of the components (black lines) [16]. The figure indicates the very high mean PGA values across the array and, importantly, their variability, along with that of SA at other periods where SA-ARI's mean values exceed 1.0g over  $0.08 < T < 0.38$  s. For comparison, in the current seismic hazard map for Iceland with a 475-year return period, given in the Icelandic National Annexes for Eurocode 8, the reference PGA on type A ground is given as  $a_{gR}=0,5g$  for the town [17] and therefore the elastic response spectra (5% damping ratio) as defined by the code is at 1.25g between the corner periods  $T_B$  and  $T_C$  (0.15s and 0.5s for soil class A, rock).

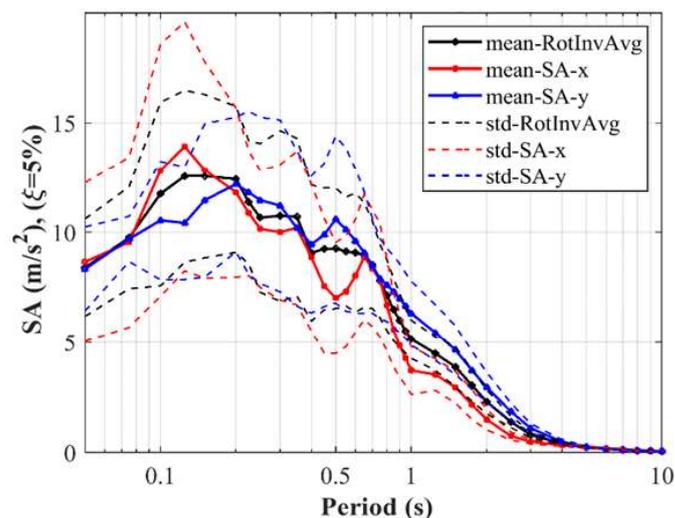


Fig. 4 – Mean and standard deviation (std) of horizontal spectral acceleration (SA) with 5% damping ratio obtained from Ölfus earthquake accelerograms corresponding to N-S component,  $x$  (red curves), E-W component,  $y$  (blue curves) and the rotation-invariant average (black curves) of the two components.



The high variability of PGA and SAs at periods shorter than  $T \sim 0.6$  s is much more apparent compared to that at longer periods. Since short-period motions are more susceptible to small-scale differences in source, path and site effects that are not modelled (i.e., effectively considered random), we propose to interpret the horizontal orthogonal components combined (e.g., using ARI [16]), but only for periods shorter than  $T \sim 0.4$  s. The reason is that clear near-fault forward directivity velocity pulses along the fault strike-normal direction (i.e.,  $y$ , E-W) were observed and dominated the motions in the  $y$  component above  $T \sim 0.4$ , having most energy at  $T \sim 0.5$  s. On the contrary, the strike-parallel ( $y$ , N-S) component of SA showed different characteristics, namely a narrow-band near-fault velocity pulse at  $T \sim 0.7$  s, associated with a permanent surface displacement along the fault [6]. In this study, other than PGA and SAs at short-to-long periods, CAV is also considered for investigation. The CAV is based on the integration of the characteristics of the entire GM time history, such as duration, frequency, and amplitudes, which renders them perhaps better suited to correlate with cumulative damage.

#### 4.2 Spatial variability of IMs through Kriging analyses

Interpolation methods estimate the values in unsampled locations to transform the observed data into a continuous form, such as raster data formats. Kriging spatial interpolation is one of the most frequently used optimal interpolator offering a minimum sampling error variance. In this section, the Kriging geostatistical analysis is carried out to generate shake maps (see Fig. 5) for the selected IMs over Hveragerði town and their corresponding uncertainty maps, which are essential for decision-making purposes. Kriging uses the variogram model to compute localized weighting parameter, in essence, the weights of neighbouring points based on the distribution of those values. To find the model that represents the slightest uncertainty, different semivariogram models are tested, and the sensitivity to the lag parameter is explored. For this reason, errors from Kriging were evaluated using fundamental statistical parameters such as root-mean-square-error, the variance of errors, and mean absolute error. For most IMs, an ordinary kriging method with a spherical semivariogram model is used.

Fig. 5 exhibits the Kriged shake maps (left panels) at short periods, i.e., for PGA, and SAs at  $T = 0.2$  s for the ARI horizontal component, i.e., the short-period ground motion intensity is interpreted using a measure that combines the two horizontal components, as mentioned above. The grey-scale maps indicate the uncertainty distributions at interpolated cells. The darker the colour, the smaller the standard deviation. We note that the comparison between different shake maps is relative, as the different ranges of IM-values are represented spatially by the same colour scheme and number of contours. Buildings are colour coded by construction year. Triangles depict the ICEARRAY-I stations, which are the observation points with inter-station distances of 50 to 1900 m over Hveragerði. The remarkably dense data provides the opportunity to construct detailed shake maps for a set of ground-motion IMs for the town and, consequently, explore the spatial correlation amongst a wide range of IMs. As expected, around ICEARRAY-I sites, the uncertainty is negligible. However, as the distance from the observation sites increases, the uncertainty increases as well. For all Kriged shake maps, the level of uncertainty is acceptable across the whole study area. Fig. 5 shows that a consistent spatial pattern emerges with largest values being recorded on the E-W outskirts of the town with the centre's motions being persistently lowest, a phenomenon most apparent at SA of 0.2 s. This pattern was consistently seen for IMs for peak parameters at short periods.

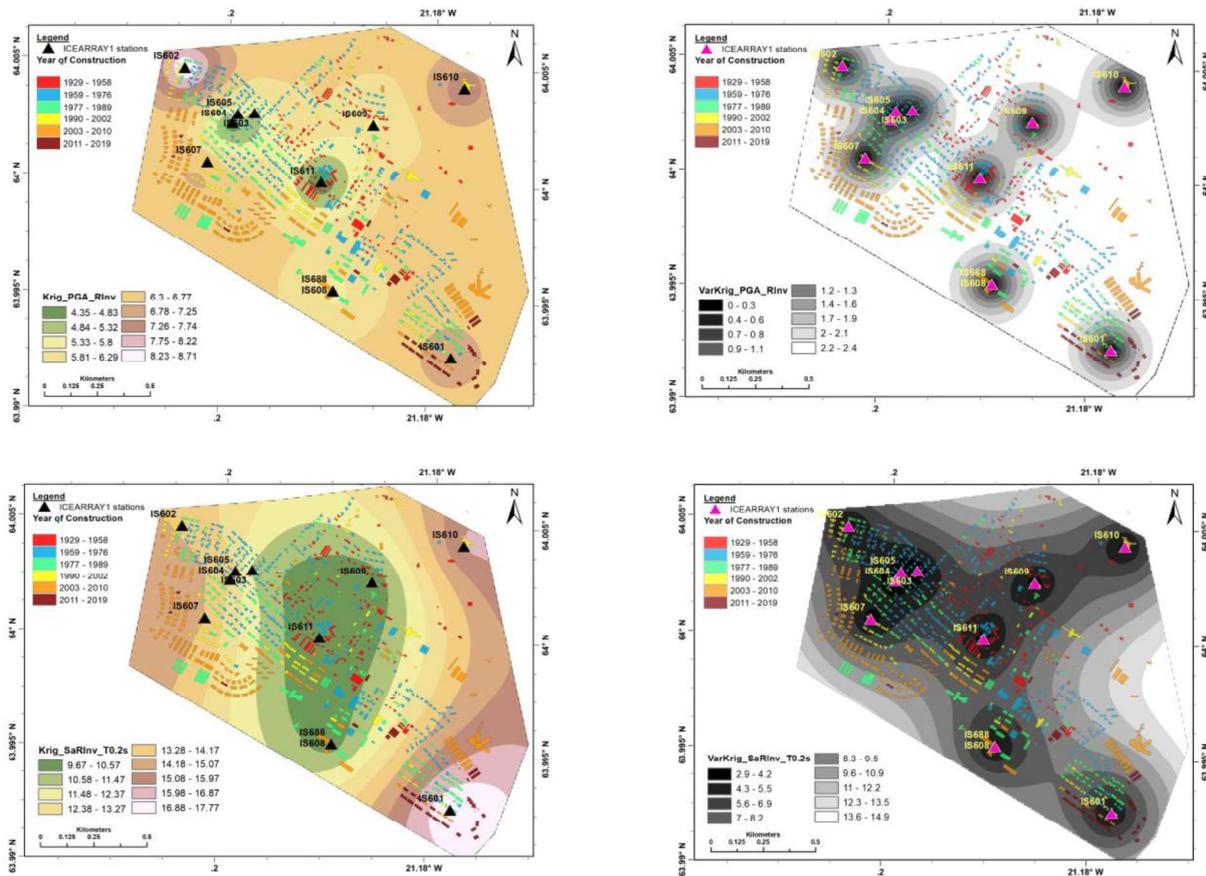


Fig. 5 – The Kriged IM shake maps, along with the uncertainty maps, for PGA, and SAs at  $T = 0.2$  s across Hveragerði. The rotation-invariant average (ARI) horizontal component is used for Kriging geostatistical analysis. Buildings are colour coded by their construction year. Triangles indicate the ICEARRAY-I stations.

Contrary to Fig. 5, Fig. 6 presents the Kriged shake maps for the  $x$  (N-S, left) and  $y$  (E-W, right) components separately and for SA at  $T = 0.65$  s and CAV. The central part of town (around IS608, IS611 and IS609 sites) persistently exhibits lower acceleration values, whereas higher SAs are indicated in the town's outskirts (except at longer periods, not shown). The SA 0.65 s along the  $x$ -direction, as seen in Fig. 4, is at the period of the narrow-band near-fault velocity pulse associated with permanent tectonic displacement in the fault direction. It shows very little spatial difference across the array. However, along the  $y$ -direction (E-W) the GM pattern of the forward directivity near-fault velocity pulse exhibits the previously described spatial pattern. Similar to the SA-shake maps at  $T = 0.65$  s, the CAV- $x$  and  $y$ -shake maps present smaller values centrally, and larger values are at the outskirts of the town. It is interesting to note that this is observed almost equally at both  $x$  and  $y$  components, presumably as near-fault velocity pulses are observed along both directions, even though they are of different physical origin and of different frequency extents.

Clues to the reasons why the central part of town exhibits lower motions can be found in the town's geology. A historical earthquake N-S fault has been mapped and lies directly through the centre of town (west of IS609, under IS611 and IS608 stations, and further south). Moreover, the fault serves as a conduit for geothermal water that reaches the surface, resulting in a geothermal area in the centre of town and a widespread geothermal anomaly around IS611 and towards the north [18, 19]. Then, underneath the surficial lava layer of several meters is a softer sedimentary layer, resulting not only in a velocity reversal [19], but has been affected by the geothermal activity. This area is therefore believed to attenuate higher-frequency motions more effectively than the outskirts of town, where this effect is not observed in data or in local



geology. These spatial differences in geology are also what is believed to contribute to the large scatter in the observed high-frequency motions, as exhibited in Fig. 4. However, the high-frequency motions were comparable. Finally, we note that at longer periods, the size of the small-aperture array becomes comparable in size or even small compared to the seismic wavelengths, and such small-spatial scale effects are less systematically observed.

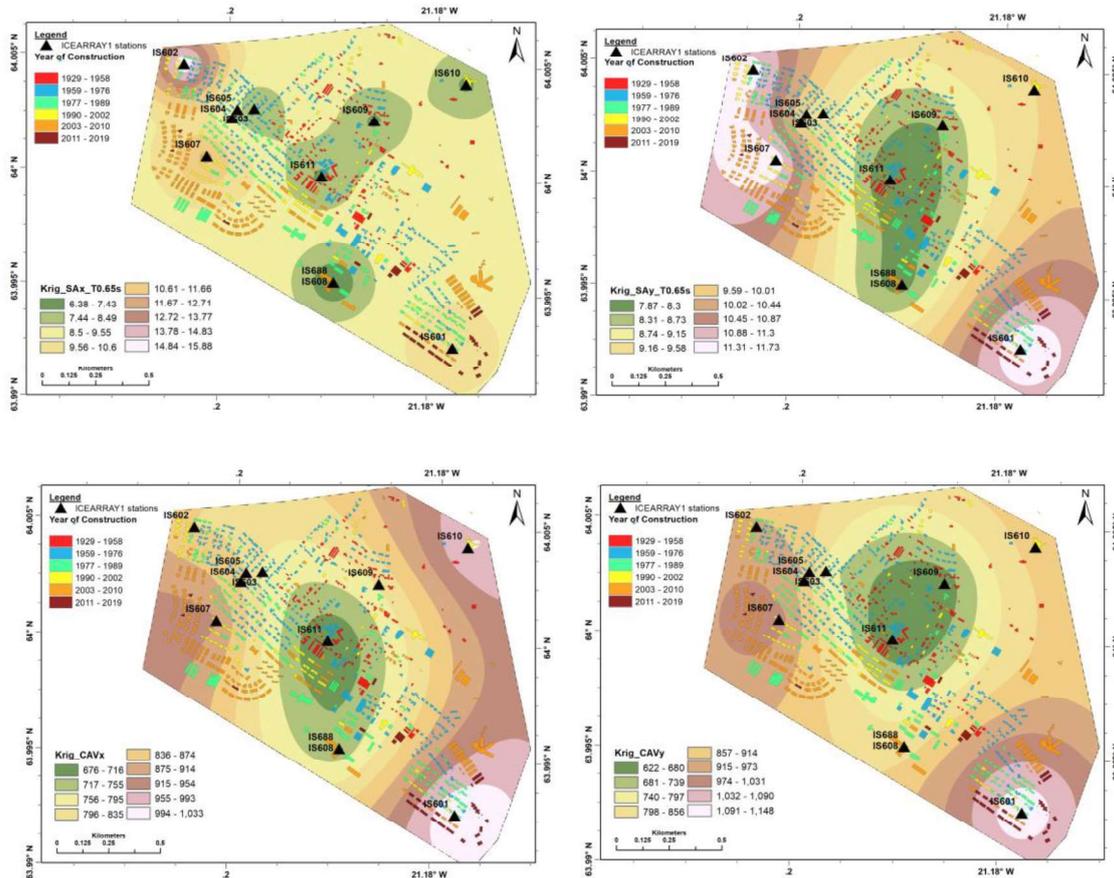


Fig. 6 – Kriged IM shake maps for SA at  $T = 0.65$  (top), and CAV (bottom) across Hveragerði obtained for two horizontal accelerograms of  $x$  (N-S direction, left-side panels) and  $y$  (E-W direction, right-side panels).

## 5. Seismic loss estimation

One of this study's main objectives is scenario-based risk assessment using the collated building database for detail building typologies, considering the most recent fragility functions. The scenario event tested in the study is defined as identical to the  $M_w 6.3$  Ölfus earthquake in May 2008. Using this scenario gives the opportunity to compare predicted losses to real observed losses. Moreover, in the present study, a logic tree scheme with weighted input of uncertain parameters (e.g., ground shaking values and economic loss values) is incorporated. The open-source algorithm, SELINA [10], has been adapted to estimate the seismic loss at Hveragerði town. The methodology is based on treating the whole town as one cell ( $2 \times 2$  km), i.e. all buildings' information is aggregated and IMs refer to centre point of the cell.

To this end, first, the key building typologies are identified according to the SERA classification ([9] ESHM20 project) with slight modification. For instance, a few numbers of existing 3-storey buildings are classified as 2-storey building class. Based on the local engineer's expert opinion in Iceland, structures built before 2008 are designed based on less rigorous regulations than modern seismic codes; thereby, no buildings are classified as high ductility. In total, buildings are classified into eight main typologies based on



their level of ductility, construction material, lateral load resisting system, and building's height. The ductility level reflects different levels of seismic design. Herein, the structures are divided into two ductility levels. Namely, low ductility structures were built before 1976 that incorporated minimal seismic provision and medium ductility structures that included some seismic design degree and made after 1976. Note that the first seismic code was implemented in 1976 in Iceland. The standard construction materials are CR, W and MUR+CB. Here is the list of identified model building typologies for Hveragerði building stock (short names are in parenthesis): *CR\_LWAL-DUL\_HI,2*, (CL1, CL2), *CR\_LWAL-DUM\_HI,2* (CM1, CM2), *W-WWD\_LWAL-DNO\_HI,2* (W1, W2), and *MUR-CB99\_LWAL-DNO\_HI,2* (M1, M2). The global fragility models developed by [11, 12] associated with the identified building typologies are employed. Considering the low-rise buildings in Hveragerði, the fragility models attributed to either PGA or SA at  $T = 0.3$  sec are utilized dependent on building height and availability of the fragility model. Fig. 7 exemplifies the fragility curves associated with the CR/LWAL-DUL-H1 typology against PGA and presented four damage states.

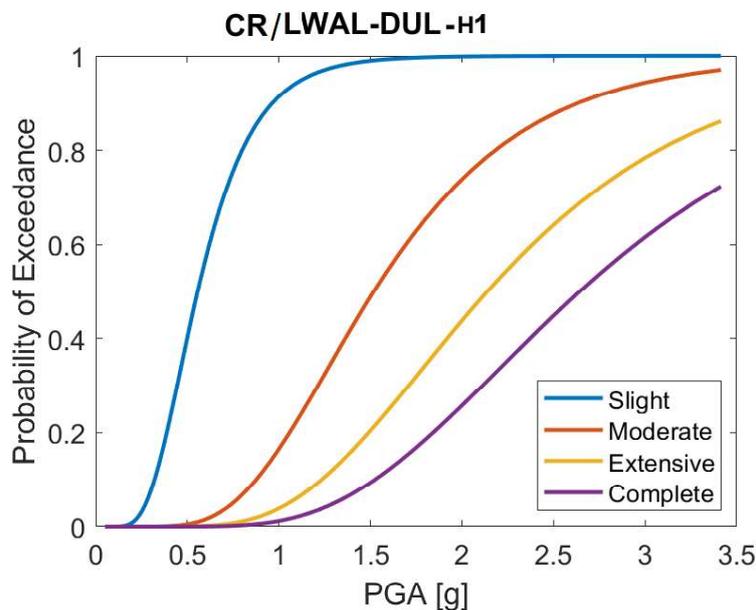


Fig. 7 – Fragility curves as a function of PGA for four damage states corresponding to CR/LWAL-DUL-H1 building typology extracted from the global fragility functions developed by [12].

To determine the economic value, first, the replacement value for each building (dwelling) is normalized by the floor area. The mean and standard deviation of the normalized monetary values are calculated for the whole Hveragerði, corresponding to each building typology. Having the statistic of the monetary values (known as economic values), three branches of the economic values are defined considering the mean, mean - standard deviation (lower bound of the economic value) and mean + standard deviation (upper bound of the economic values) and hence incorporated within the logic-tree framework with weights of 60%, 20% and 20%. Moreover, the mean loss value corresponding to the complete, extensive, moderate, and slight damage states are determined by 100%, 60%, 20% and 5% of the total normalized monetary values as recommended in HAZUS. We employ the average and standard deviation of the PGA and SAs at short-to-long periods obtained from the actual recordings of Ölfus earthquake across Hveragerði (one average PGA value and one standard deviation value used for the whole town). Therefore, ground shaking values are provided in three logic-tree branches: the mean IM, upper bound IM, and lower bound IM, which are calculated by mean  $\pm$  one standard deviation, with weights of 50%, 25%, and 25%.

The loss computation is performed in a  $2\text{ km} \times 2\text{ km}$  municipality level to compute the following risk metric: damage probabilities at four damage states (i.e., slight, moderate, extensive, and complete) and for each building typology, mean  $DF$  as per building typology, the median and 16<sup>th</sup> and 84<sup>th</sup> percentile of the damaged area are as per building typology and five damage states as well as the total economic loss.



The combined mean  $DF$ s are predicted as 3.45%, 16.5%, 1.4%, 7.75%, 34.1%, 32.2%, 32.3%, and 37.4%, respectively, for building typologies of CL1, CL2, CM1, CM2, W1, W2, M1 and M2 (see blue bars in Fig. 8). The total combined mean  $DF$ s in Hveragerði is estimated at 17%. The results show that the most vulnerable building typologies are masonry and then timber buildings, while the least vulnerable buildings are those made of concrete, even with low ductility. To compare with the actual damage database of Ölfus earthquake, out of seven highly damaged buildings with  $DF > 30\%$ , one is timber with 100%  $DF$ , four of them are masonry built in 1940- 1950, and the rest are concrete buildings constructed in 1974-1977.

Rupakhety *et al.* [20] computed a mean  $DF$  of 6.8%, 4% and 14.2% for concrete, timber and masonry buildings, respectively, for the three most affected towns (Hveragerði, Selfoss and Eyraðakki) after the May 2008 earthquake. The difference between the estimated damage ratio associated with timber and masonry buildings are much more significant than those predicted in this study. Moreover, they obtained a combined  $DF$  of 6.4%, assuming 61, 32 and 7% of the total buildings constructed using concrete, timber and masonry, respectively. Hence, much lower damage than the loss estimates of this study for Hveragerði (i.e., 17%). Furthermore, as per our expectation, building typologies associated with low ductility (e.g., CL1, CL2) results in higher loss than buildings with higher ductility (e.g., CM1, CM2) (see Fig. 8).

### 5.1 Comparison with actual damage values

Fig. 8 presents the comparison of observed and predicted mean  $DF$  values for the eight identified building typologies for Hveragerði. The mean  $DF$ s based on observed repair costs after the May 2008 earthquake are much lower than the predicted mean  $DF$ s. If the observed  $DF$ s are pooled for three main groups of RC, timber and masonry buildings, then the observed mean  $DF$ s for each group are 4.2%, 3.4% and 7.2%, respectively. Therefore, based on actual loss data, the timber buildings displayed the best performance during the earthquake. Finally, the observed combined mean  $DF$ s for all buildings in Hveragerði is 4.0 % which is less than  $\frac{1}{4}$  of the predicted mean  $DF$  (i.e. 17%) estimated based on the global fragility models.

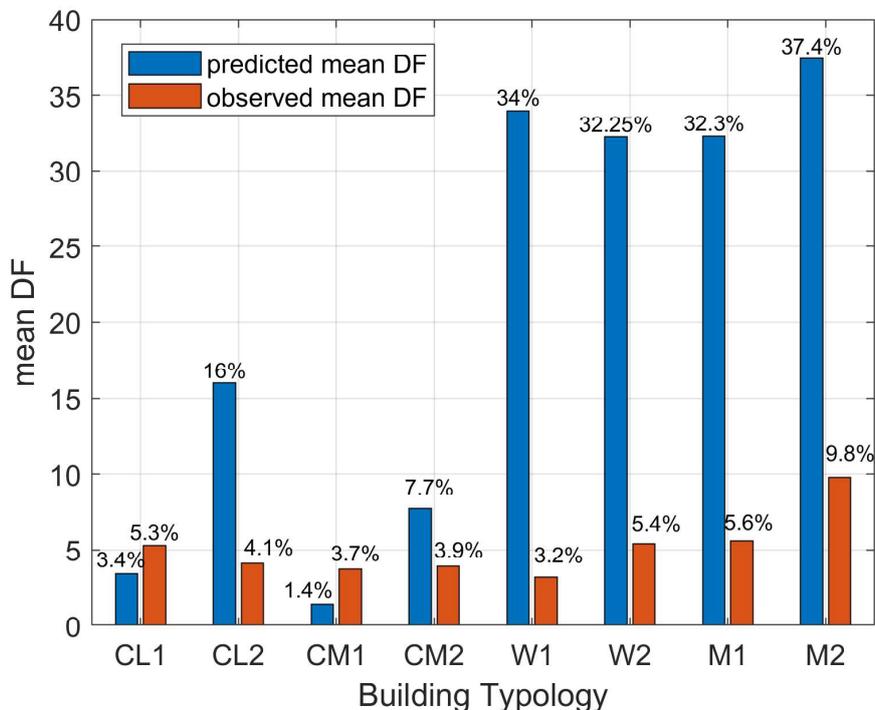


Fig. 8 – Comparison of observed mean  $DF$  based on this study's assembled loss database with predicted mean  $DF$  from the global vulnerability models.

Moreover, the economic loss value is estimated at 2,980 million Icelandic Krona (ISK) with 16<sup>th</sup> and 84<sup>th</sup> percentile of 2,693 and 3,267 million ISK. The actual repair cost paid by the insurance company to



building owners was about 750 million ISK, which is remarkably lower ( $\sim 1/4$ ) than the predicted values. The results suggest that the global vulnerability functions overestimate the damage in Iceland.

## 5. Summary and conclusion

In this study, we collated a comprehensive GIS-based building exposure database for the town of Hveragerði in SISZ and classified them as per the SERA classification scheme. Moreover, a detailed loss database on a dwelling-by-dwelling level was provided by the Natural Catastrophe Insurance of Iceland following the  $M_w 6.3$ , May 29, 2008, earthquake. The loss data was collected to fulfil insurance claims as insurance against earthquake disasters is obligatory in Iceland.

We adopted a pioneering tool to compute probabilistic seismic loss assessment rigorously in Hveragerði for a specific large earthquake scenario defined by the  $M_w 6.3$  Ölfus earthquake in May 2008. This study provided built areas and buildings in different building typologies, earthquake sources, ground shaking data recorded by ICEARRAY-I stations for the Ölfus event, monetary values and fragility curves corresponding to each of the building typologies, and finally, building repair and replacement values. To this end, the recent global fragility functions proposed by [11, 12] were employed. The predicted risk metrics obtained from the most recent global fragility models are compared with the observed loss data recorded following the May 2008 earthquake. To account for uncertainty, the logic-tree framework was incorporated. The results indicate that the global vulnerability functions tend to overestimate the damage in Iceland remarkably, and overall, the buildings in Iceland showed much better seismic performance than predicted with the global fragility curves. The study proves the necessity of using local vulnerability models when available in seismic risk analyses for reliable risk assessment, which are essential for emergency management planning and raising societal awareness of risk.

Moreover, we thoroughly studied the spatial and overall distribution of a set of well-known intensity measures, namely, PGA, SAs at short-to-long periods, and CAV. The selected IMs were calculated in high spatial resolution from the accelerograms of the May 2008 earthquake recorded by ICEARRAY-I stations across Hveragerði town. To explore IMs' spatial variability, the Kriging geostatistical analyses were exploited to build shake maps for these IMs while accounting for the uncertainties in the spatial interpolation process. The results indicate the significant variation of different IMs across a small study area ( $2 \times 2 \text{ km}^2$ ). Thus, although in seismic risk assessment studies, it is common practice to assign a single ground-motion IM to a small grid cell (e.g.,  $\sim 5 \times 5 \text{ km}^2$ ), we emphasize that assuming a uniform distribution of a single IM value is not acceptable, especially if the geology is non-uniform as in the Hveragerði which was a testbed in this study. In such cases, we stress the necessity of detail seismic risk assessment in seismic prone regions, either considering much smaller grid cells or in the building-by-building level in future studies.

## 6. Acknowledgements

This study was funded by the Horizon 2020 TURNkey project [<https://earthquake-turnkey.eu/>] under grant agreement No 821046. This work was facilitated by an Erasmus+ staff mobility grant No. IS-TS2020-87850 for the lead author to the University of Alicante, Spain. The authors are thankful to Sergio Molina Palacios for his guidance on applying SELENA on Iceland's earthquake and exposure data. This work was also partly supported by a Postdoctoral fellowship (No. 218255-051) from the Icelandic Research Fund of the Icelandic Centre for Research. The authors thank the Natural Catastrophe Insurance of Iceland for allowing access to their earthquake damage database.

## 7. References

- [1] Halldorsson B, Sigbjörnsson R, Schweitzer J. (2009): ICEARRAY: the first small-aperture, strong-motion array in Iceland. *Journal of Seismology*, 13(1), 173–178.
- [2] Rupakhety R, Halldorsson B, Sigbjörnsson R. (2010): Estimating coseismic deformations from near source strong motion records: methods and case studies. *Bulletin of Earthquake Engineering*, 8(4), 787–811.



- [3] Sigbjörnsson R, Snæbjörnsson JT, Higgins SM, Halldórsson B, Ólafsson S. (2009): A note on the Mw 6.3 earthquake in Iceland on 29 May 2008 at 15:45 UTC. *Bulletin of Earthquake Engineering*.
- [4] Bessason B, Bjarnason JÖ, Guðmundsson A, Sólnes J, Steedman S. (2014): Analysis of damage data of low-rise buildings subjected to a shallow Mw6.3 earthquake. *Soil Dynamics and Earthquake Engineering*, 66, 89–101.
- [5] Rupakhety R, Sigbjörnsson R, Ólafsson S. (2016): Damage to residential buildings in Hveragerði during the 2008 Ölfus Earthquake: simulated and surveyed results. *Bull Earthquake Eng*, 14(7), 1945–1955.
- [6] Halldórsson B, Sigbjörnsson R. (2009): The Mw6.3 Ölfus earthquake at 15:45 UTC on 29 May 2008 in South Iceland: ICEARRAY strong-motion recordings. *Soil Dynamics and Earthquake Engineering*, 29(6), 1073–1083.
- [7] Halldórsson B, Rupakhety R, Sigbjörnsson R, Chanerley AA. (2012): Permanent coseismic displacement across the ICEARRAY associated with the 29 May 2008 Mw6.3 earthquake in South Iceland. *Bulletin of Earthquake Engineering*.
- [8] Sigbjörnsson R, Rupakhety R, Halldórsson B, Snæbjörnsson JTh. (2014): On the modelling of incoherence of strong-motion: A study of the May 2008 Ölfus earthquake. In *Proceedings of the 2nd European Conference on Earthquake and Engineering Seismology (2ECEES)*, Istanbul, Turkey. p.
- [9] Crowley H, Despotaki V, Rodrigues D, Silva V, Toma-Danila D, Riga E, et al. (2020): Exposure model for European seismic risk assessment. *Earthquake Spectra*, 36, 252–273.
- [10] Molina S, Lang DH, Lindholm CD. (2010): SELENA - An open-source tool for seismic risk and loss assessment using a logic tree computation procedure. *Computers and Geosciences*, 36(3), 257–269. Elsevier.
- [11] Silva V, Amo-Oduro D, Calderon A, Costa C, Dabbeek J, Despotaki V, et al. (2020): Development of a global seismic risk model. *Earthquake Spectra*, 36, 372–394.
- [12] Martins L, Silva V. (2020): Development of a fragility and vulnerability model for global seismic risk analyses. *Bull Earthquake Eng*.
- [13] National Application Documents (NAD) for Iceland (2002): Standards Council of Iceland/ Staðlaráð Íslands (SI).
- [14] Bessason B, Bjarnason JÖ, Rupakhety R. (2020) Statistical modelling of seismic vulnerability of RC, timber and masonry buildings from complete empirical loss data. *Engineering Structures*, 209, 109969.
- [15] Dolce M, Kappos A, Masi A, Penelis G, Vona M. (2006): Vulnerability assessment and earthquake damage scenarios of the building stock of Potenza (Southern Italy) using Italian and Greek methodologies. *Engineering Structures*, 28(3), 357–371.
- [16] Rupakhety R, Sigbjörnsson R. (2013): Rotation-invariant measures of earthquake response spectra. *Bulletin of Earthquake Engineering*, 11(6), 1885–1893.
- [17] IST (2010): Icelandic National Annexes to EUROCODES, *Standard Council of Iceland /Staðlaráð Íslands*, Reykjavík.
- [18] Sæmundsson K, Kristinsson S. (2005): Hveragerði. Hitamælingar í jarðvegi og sprungur (Hveragerði: Soil temperature measurements and faults). Reykjavík, Iceland: Iceland GeoSurvey (ÍSOR). Geologic mapping ÍSOR-2005/041.
- [19] Rahpeyma S, Halldórsson B, Olivera C, Green RA, Jónsson S. (2016): Detailed site effect estimation in the presence of strong velocity reversals within a small-aperture strong-motion array in Iceland. *Soil Dynamics and Earthquake Engineering*, 89, 136–151.
- [20] Rupakhety R, Sigbjörnsson R, Ólafsson S. (2016): Damage to residential buildings in Hveragerði during the 2008 Ölfus Earthquake: simulated and surveyed results. *Bulletin of Earthquake Engineering*.