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haselREC: an automated open-source ground motion record selection and scaling tool

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Abstract

In this paper, we present an open-source end-to-end Python tool for ground motion record selection and scaling for non-linear dynamic analysis of structures. The tool, named haselREC (HAzard-based SELection of RECords), has been formulated to be executed after performing a probabilistic seismic hazard and disaggregation analysis with OpenQuake, an open-source hazard and risk calculation engine developed by the Global Earthquake Model (GEM) Foundation. In addition to common intensity measures, such as peak ground acceleration and spectral acceleration, haselREC can perform ground motion record selection using average spectral acceleration, which can be advantageous when assessing multiple structures and to account for uncertainty on the conditioning response period. Moreover, haselREC can be directly linked to the web services of the European Strong Motion database for automatic download and scaling of records. The Python tool was designed to be modular, which facilitates its integration in third party scripts for automated record selection and scaling in hazard analysis studies. Here, we describe the main features of the software package in detail and provide an application example for the regional assessment of existing bridge structures.

Keywords haselREC · Record selection · Accelerograms · Conditional spectrum · PSHA · *AvgSa*

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1 Introduction

Non-linear dynamic analyses require the definition of suitable acceleration time-histories for the structure under consideration. Since the results from the seismic assessment of structures are highly sensitive to the adopted ground motion input (see Kwon and Elnashai 2004; Douglas 2006, among others), the selection of appropriate seismic input is critical, having an impact on the final results sometimes larger than structural modelling itself (Iervolino and Manfredi 2009). The seismic signals (usually accelerograms) used for this purpose can be either artificial, synthetic or real recordings (Bommer and Acevedo 2004).

Artificial accelerograms are signals obtained after generating a power spectral density function compatible with a building code-based target response spectrum (Gasparini and Vanmarcke 1976). However, they typically have a frequency content incompatible with that of real recordings and they do not reflect the real phasing of seismic waves (e.g. Naeim and Lew 1995; Carballo and Cornell 2000). This category of ground motions also includes hybrid accelerograms, which are signals obtained by appropriately modifying real recordings in such a way so as to enforce compatibility with a target spectrum (e.g. Abrahamson 1992; Hancock et al. 2006). Synthetic accelerograms are signals generated through a numerical simulation of the seismic wave propagation in the Earth's crust, using a kinematic or dynamic source model (i.e. physics-based). They are capable of accounting for both path and site effects (e.g. Crempien and Archuleta 2014; Graves and Pitarka 2010, 2014) and they are particularly useful to obtain physically-based waveforms for any earthquake scenario and site condition. Yet, even if appealing, they require the use of complex computer programs, large computational resources, specific seismological skills and the availability of detailed input information. Moreover, synthetic accelerograms need to be preliminarily validated against ground motions generated by real earthquakes. An example of a comparison between recordings and physics-based ground motion simulations is provided in Zuccolo et al. (2020).

Real (or natural) accelerograms are actual signals recorded during past seismic events, made available by accredited strong-motion databases, such as the Engineering Strong-Motion database (ESM, http://esm.mi.ingv.it/, Luzi et al. 2016), the PEER (Pacific Earthquake Engineering Research Center) NGA-West2 Database (http://peer.berkeley.edu/ngawest2/, Ancheta et al. 2014) or the KiK-net (KibanKyoshin network) strong ground motion database (http://www.kyoshin.bosai.go.jp, National Research Institute for Earth Science and Disaster Resilience 2019) among others. These accelerograms are undoubtedly more suitable than simulated waveforms for dynamic analysis of structures since they have a realistic duration given the earthquake scenario, frequency content and correlation between the vertical and horizontal components of ground motion and also between the phase and the amplitude of the record. However, despite the increasing availability of real recordings covering a wide range of scenarios, they often need to be scaled to be compatible with a target hazard level being focused on in seismic assessment of structures. This alters the original characteristics of the accelerograms and introduces a non-negligible bias in response estimates especially when large scaling factors are employed, as recently shown by Dávalos and Miranda (2019a, b), for example. The bias introduced by amplitude scaling is greater when the spectral shape is not taken into account, but it is also observed even after carefully performing a ground motion record selection that considers target spectral shape and its variability.

A traditional approach to identify suitable ground motions is to select recordings based on seismological parameters, such as magnitude, source-to-site distance, the tectonic environment and, potentially, the earthquake focal mechanism. The soil category can also be considered as a seismological parameter, even if a common alternative to account for the site class variability is to select ground motions recorded on rock sites and then conduct site response analysis by applying site-specific seismic response, either from empirical observations (e.g. standard spectral ratios) or from numerical simulations, especially for those sites with a detailed velocity model from geophysical and geological characterization tests. However, a selection strategy based only on seismological parameters is affected by two major limitations: a) the number of available ground motions satisfying the prescribed criteria can be limited, especially at large magnitudes and short distances, and b) seismological parameters are fairly poor predictors of the resulting structural demands (e.g., Haselton et al. 2009; Shome et al. 1998).

To overcome these shortcomings, another strategy is usually applied. It is based on using seismological parameters, with relaxed constraints, to pre-select recordings, and then selecting ground motions based on their consistency with time series properties, which are stronger predictors of structural demand (Baker 2015). These properties may be the response spectrum, ground motion duration or energy content, for example. In this paper, we focus on the response spectrum.

Seismic codes (such as the Italian NTC18, NTC18 2018, and Eurocode 8, CEN European Committee for Standardisation 2004) prescribe spectrum compatibility with a code design spectrum (which is often an approximation of the Uniform Hazard Spectrum—UHS) for the selection of ground motion records. The UHS is obtained from Probabilistic Seismic Hazard Analysis (PSHA) and is characterized by spectral amplitudes at all periods with the same probability of being exceeded in a given observation time interval. A certain number of tools were developed in the literature to select recordings according to code design spectra, or UHS. This is the case of REXEL (Iervolino et al. 2010), along with the on-line version REXELite (Iervolino et al. 2011) and REXEL-DISP (Smerzini et al. 2014), based on displacement response spectra. A similar software is ASCONA (Corigliano et al. 2012), which has the characteristic of selecting only recordings on outcrop rock conditions to be used as input for site response analyses (e.g. Zuccolo et al. 2014; Rota et al. 2012), thus assuring hazard consistency at the bedrock, but not necessarily at the top of the soft sediment cover (Cramer 2003; Bazzurro and Cornell 2004).

The UHS comprises contributions from all possible earthquakes that can affect the hazard at a given site. It was observed (Bommer et al. 2000) that the short-period range of the UHS is dominated by small nearby earthquakes, while the long-period range is dominated by larger and more distant earthquakes. Therefore, the UHS is not representative of a single earthquake ground motion since real accelerograms do not usually have energy content as broad as that of the entire UHS, but rather an envelope of several contributions. As a consequence, when the accelerograms selected considering the UHS are used as input to structural analysis, they tend to produce probabilistically conservative estimates of structural response due to the overly aggressive nature of their spectral content (Baker and Cornell 2006).

An alternative to the UHS, the Conditional Mean Spectrum (CMS), was developed to use PSHA results to perform dynamic response analyses. The CMS represents the expected (i.e. mean) response spectrum conditioned on the exceedance or occurrence of a target spectral acceleration value at the period of vibration T^*, $Sa(T^*)$. It was introduced by Baker and Cornell (2006) and further background is provided in Baker (2011), which also demonstrated that the CMS is a more appropriate target spectrum when performing dynamic analysis of structures. Ground motions can be selected to match a target spectrum individually (e.g. Wang et al. 2015, whose tool has been adapted and incorporated in the PEER database website) or on average for a suite of recordings (as in the case of REXEL and ASCONA). In the former case, all the selected response spectra individually match the target mean response spectrum within a prescribed margin of error. In the latter case, it is the average spectrum that matches the target. This is for example the approach suggested by some seismic design codes, such as Eurocode 8 and NTC18.

An extension of the CMS, called Conditional Spectrum (CS), was then proposed by Atik and Abrahamson (2010), Jayaram et al. (2011a) and Lin et al. (2013a) to properly consider the aleatory variability in the response spectrum for the conditioning value *Sa(T*)*. In the CS approach, it is the distribution of candidate ground motion intensities that is chosen to match a target distribution.

In this paper, we briefly introduce the codes already available in the literature to perform CS-based record selection. We then present haselREC—HAzard-based SELection of RECords—a Python-based code for CS-based record selection and scaling, born from the need to have an end-to-end tool capable of communicating directly with hazard analysis outputs and directly provide the seismic input (natural scaled accelerograms) for non-linear dynamic analyses, without the need for the user to perform additional external operations. For this purpose, haselREC uses several state-of-art tools, resources and methodologies in a coherent and harmonized framework, thus minimizing the number of operations that a user has to perform manually. Finally, an application example of record selection for regional risk assessment of bridges is presented.

2 State of art on CS-based ground motion record selection tools

Only recently, the computation of the CS has been introduced in PSHA software (e.g. REASSESS V2.0, Chioccarelli et al. 2019) as an alternative to the UHS, which is the response spectrum traditionally computed by PSHA. For standard PSHA software (e.g. R-CRISIS, Ordaz et al. 2017, or OpenQuake, Pagani et al. 2014), the CS can be derived from classical PSHA outputs using additional ingredients (i.e. Ground Motion Models, GMMs, and correlation coefficients). Therefore, the computation of the CS generally requires external tools, which are available in the literature, to facilitate the selection of spectrum-compatible accelerograms. For instance, a widely used software package for computing the CS and to select ground motions accordingly is described in Jayaram et al. (2011a) (available for download at http://web.stanford.edu/~bakerjw/gm_selection.html, last accessed April 2021). The code consists of a set of MATLAB scripts that allows the definition of a CS-based on a four-step procedure, as outlined in Baker (2011). The main ingredients are the fundamental period of vibration of the structure, T^* (termed conditioning period), a dominant earthquake usually obtained from disaggregation of PSHA calculation (Bazzurro and Cornell 1999), which comprises the magnitude (*M*), source-to-site distance (*R*) and $\varepsilon(T^*)$ (the number of standard deviations by which the logarithmic spectral acceleration of interest deviates from the mean logarithmic spectral acceleration predicted by a GMM at the period of interest T^*), a selected GMM (ideally consistent with the dominant ground motion model of the PSHA logic tree) and the correlation coefficient between spectral ordinates. For this purpose, the GMM proposed in Campbell and Bozorgnia (2008) and the correlation coefficients suggested by Baker and Jayaram (2008) are implemented by default in the software, with the possibility to implement other models if preferred. A recent update by Baker and Lee (2018) allows the direct use of the target spectral acceleration at *T*, Sa(T*),* obtained from the PSHA, rather than having it computed from the GMM using the dominant earthquake scenario in the software. The selection algorithm stochastically generates a set of response spectra realizations by sampling the target CS distribution and then selects the suite of recorded ground motions (from the NGA-West1 database, Chiou et al. 2008) whose response spectra best match the simulated response spectra. The matching is evaluated individually, meaning that for each simulated response spectrum the best matching record is chosen. A greedy optimization technique is further used to improve the matching between the target and the sample mean and variance. This consists of replacing each selected ground motion, one at a time, with a record from the ground motion database that causes the best improvement in the matching between the target and the sample means and variances.

Recently, Baker and Lee (2018) included the screening of recordings (in terms of *M*, *R* and shear wave velocity in the uppermost 30 m, *Vs30,* ranges) in order to allow only a set of recordings to be considered for selection. The NGA-West2 database, along with three databases of numerically simulated ground motions produced by a Southern California Earthquake Center (SCEC) project to validate simulations (Goulet et al. 2014) were considered in addition to the NGA-West1 database. The software includes the GMM proposed in Boore et al. (2014) by default. Both GMM and the correlation coefficients between spectral ordinates can be replaced by the user with some coding. It is highlighted that the tool produces an output file that lists the selected ground motions and associated scaling factors (when scaling is required). The retrieval and scaling of recordings should then be performed externally by the user.

The approach suggested by Jayaram et al. (2011a) was also implemented in a web-based system (CGMapp) described in Klinc et al. (2019). The web application allows selecting ground motions based on a single arbitrary horizontal ground motion component from an internal database obtained combining the NGA-West1 and the RESORCE (Akkar et al. 2014a) databases. Only the Campbell and Bozorgnia (2008) GMM is implemented. The screening of records as introduced by Baker and Lee (2018) is also taken into account. A second-step selection procedure is further implemented by making use of nonlinear dynamic analyses of a single-degree-of-freedom (SDOF) model to lastly obtain seven risk-targeted, hazard-consistent, and structure-specific ground motions. The scaling of accelerograms is also performed.

Another recently proposed code for CS-based record selection is SelEQ (Macedo and Castro 2017), which is written in Python and includes a graphical user interface. It allows the 'exact' CS for European territory as proposed by Lin et al. (2013a), Lin et al. (2013b) and Lin et al. (2013c), to be obtained considering multiple causal earthquakes (not only the dominant earthquake) and multiple GMMs often included in the PSHA computation. For this purpose, SelEQ uses the open-source platform OpenQuake (Pagani et al. 2014), a widely-used free and open-source software for the assessment of earthquake hazard and risk, and the SHARE hazard model (Woessner et al. 2015). SelEQ has the advantage of linking the record selection to the hazard component (represented by the SHARE model) in a single package and consists of three integrated modules. The first module is the seismological module, powered by the OpenQuake engine, which requires the coordinates of the site under consideration, the EC8 soil classification, the conditioning period *T**, and the probability of exceedance in 50 years as input. The output of the seismological module consists of site-specific hazard curves, disaggregation matrices, uniform hazard spectra or conditional spectra (the latter computed according to the procedure outlined by Lin et al. 2013a, b, c). The second module is the pre-selection module, which performs the preliminary selection of ground motion records by screening the NGA-West2 ground motion database. The allowable pre-selection criteria are *M*, *R* and *Vs30* (as in the Baker and Lee 2018 code), along with peak ground acceleration (*PGA*), peak ground velocity (*PGV*) and lowest usable frequency. Finally, the third module performs the record selection for a given *T** based on the adaptive harmony search algorithm. Similarly to the code proposed by Baker and Lee (2018), SelEQ produces an output file listing the selected ground motions and their required scaling factors. Similarly, the retrieval and scaling of recordings should be performed externally by users.

Based on the Baker and Lee (2018) algorithm, our tool, haselREC, is designed to directly provide the seismic input for non-linear dynamic analyses without the need for the user to perform additional operations (e.g. computation of the dominant earthquake, computation of the extended-source parameters to be used as input for complex GMMs, implementation of required GMMs, scaling of accelerograms, etc.). The tool does not include an in-built seismological module like SelEQ, which is limited to the sole use of SHARE results (Woessner et al. 2015), but it is designed to be used with any output from an external PSHA and disaggregation analysis, for maximum flexibility. The software presently works with input in OpenQuake format, although extensions to other formats are possible. However, if hazard computations are performed, for whatever custom hazard model, with the OpenQuake platform, haselREC can be executed sequentially, without the need to manipulate the format of the hazard information.

In addition to most common intensity measures (IMs), such as peak ground acceleration and spectral acceleration at a given period, haselREC can perform ground motion record selection using average spectral acceleration, *AvgSa*, which is advantageous when assessing multiple structures and to account for the uncertainty of the conditioning period. Moreover, haselREC can be directly linked to the web services of the European Strong Motion database for automatic download and scaling of records.

3 Methodology

The architecture of haselREC is illustrated in Fig. 1. haselREC takes the results from a PSHA and disaggregation analysis performed externally by OpenQuake as input. It consists of two main modules, selection and scaling, along with an optional verification module. The selection module makes use of a database flatfile that includes the response spectra of the candidate GMMs and returns as output the IDs of the selected records. These are then used by the scaling module to scale the selected recordings, thus providing the required input for non-linear dynamic analysis. An optional module is also available to facilitate the identification of missing NGA-West2 selected records stored on the computer. The selection and scaling modules, which represents the core of haselREC, are described in the following paragraphs.

3.1 Record selection

Record selection is performed following the steps described in Baker and Lee (2018). In this section, we particularly focus on those methodological aspects of the record selection module that represent clear improvements to the existing available tools with special regard to the use of European data (Engineering Strong Motion database and European

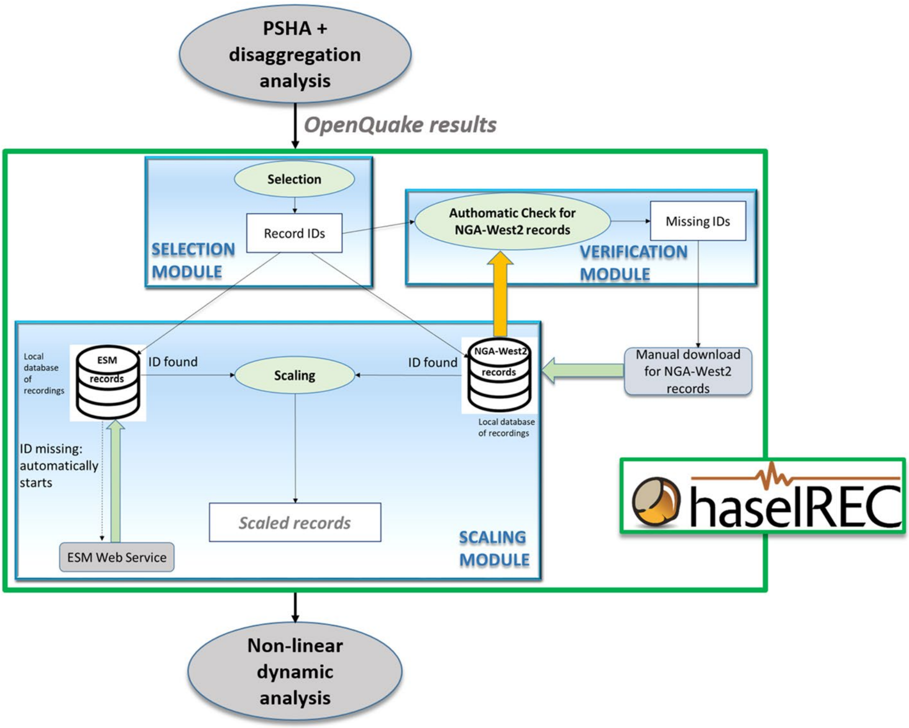

Fig. 1 Architecture of haselREC

correlation relationships between spectral accelerations at different periods) and the adoption of *AvgSa* as an IM.

3.1.1 Ground-motion database and screening criteria

haselREC uses a composite database made up of accredited databases. Its structure is modular so that each database can be used individually or as a unique composite database, without any double-counting of recordings. The current version of haselREC incorporates the PEER NGA-West2 and the ESM (Lanzano et al. 2019) database flatfiles. To avoid double-counting of the recordings of the European-Mediterranean and Middle-East regions, when both databases are considered, ground motions from the NGA-West2 database are retained only if recorded at stations located outside the geographical area covered by the ESM database. The modular structure also allows the easy inclusion of additional databases in the future. Being an open-source code, modules for accessing arbitrary external databases can be easily included by a user with little coding effort.

haselREC stores, in an internal database, the metadata and the response spectra (at 5% of critical damping) for all recordings, specified as *RotD50* components (the median value of spectral accelerations computed over all rotation angles for a given ground motion, Boore 2010). This choice relies on the availability of this component in both the considered databases (in fact, the NGA-West2 flatfile provides only the *RotD50* component of motion, not the individual components of motion). As a consequence, the selection performed by haselREC is a two-component record selection based on the *RotD50* spectra associated with the recordings.

Once the database is loaded, it is preliminarily screened so that only appropriate ground motions are considered for selection. Besides the screening criteria considered in Baker and Lee (2018), such as maximum scaling factor, *Vs30*, *M* and *R* ranges, we consider two additional criteria: the focal depth range and EC8 soil class (to be used in conjunction with the data from the ESM database). If both *Vs30* and EC8 soil class criteria are specified, priority is given to the *Vs30*. Moreover, the *M* and *R* ranges are defined as intervals centred on the mean values from the disaggregation analysis, respectively (the magnitude and distance radii are required as input parameters). As an additional constraint, only free-field ground motions are retained, to avoid the influence of the structure on the ground motion record.

3.1.2 Conditional spectrum computation

haselREC computes the CS according to the 'approximate' method described by (Baker and Lee 2018), which requires the target spectral acceleration (obtained from the result of the seismic hazard disaggregation in terms of mean magnitude and distance), a specific GMM (usually the one characterized by the highest weight in the logic tree scheme) and the correlation coefficients between spectral accelerations at different periods. As in Baker and Lee (2018), $\varepsilon(T^*)$ is not read as a disaggregation output, but is back-calculated by haselREC. This is done to exactly match the conditional spectrum at the target period, generally computed with mean magnitude and distance values, with the target $Sa(T^*)$, which is derived from the full distribution of possible ruptures considered in a seismic hazard calculation and the full logic tree.

haselREC incorporates several procedures available in the literature that facilitate the construction of the CS. First of all, haselREC relies on the GMM library included in OpenQuake, which is open-source, tested and continuously updated with newly published GMMs by the GEM Foundation. This enables the use of all suitable GMMs included in OpenQuake (presently more than 130 GMMs are implemented), thus ensuring full compatibility with the GMMs adopted for PSHA and disaggregation analysis and avoiding the need for users to manually implement commonly used GMMs. Due to the open-source nature of the project, new ad-hoc GMMs can still be implemented in the library, if needed.

In the case of complex GMMs, such as the NGA ones, which consider the finite representation of the fault rupture plane, missing user-defined input parameters are directly computed through the Kaklamanos et al. (2011) relationships, thus allowing non-expert users to handle these aspects appropriately also in case of little earthquake source information available. These relationships allow one to determine the rupture distance (R_{rup}) and the horizontal distance to the top edge of the rupture, measured perpendicular to the strike (R_X, site coordinate), from the moment magnitude (M_W) and Joyner–Boore distance (R_{JB}), source-to-site azimuth (assumed to be $\alpha = 50°$ if not known) and geometry of the fault plane. Kaklamanos et al. (2011) also suggest standard methods useful to estimate the parameters characterizing the fault plane (e.g. width, dip, depth of the top of the rupture plane Z_{TOR}), if not known, along with useful relationships to estimate the depth to the 1 km/s ($Z_{1.0}$) or 2.5 km/s ($Z_{2.5}$) velocity horizons, if needed.

As described previously, the composite database used by haselREC is expressed in terms of the *RotD50* component. Therefore, if the seismic hazard is expressed in terms of the *RotD50* component (as is the case of the NGA GMM models), the constructed CS turns out to be directly consistent with the metric in which the response spectra of the recorded accelerograms are specified. The same assumption can be made when the hazard is expressed in terms of the geometric mean of the two horizontal components of motion, due to the similarity between the geometric mean and *RotD50* (Beyer and Bommer 2006). Instead, if the hazard is expressed as the maximum of the horizontal components, the relationship proposed in Boore and Kishida (2016) is used to convert the maximum of the two horizontal components into *RotD50*, to assure compatibility with the composite database even in this case. Currently, this is available only for *PGA* and *Sa(T*)*.

Ideally, the CS computation requires the use of a correlation and GMM models derived jointly from the same ground motion database. Unfortunately, only a limited number of correlation models are available in the literature. The correlation model by Baker and Jayaram (2008) was developed based on the NGA-West1 ground motion database and can be adopted for any NGA ground motion model (as suggested by the authors themselves). A recent study for subduction zone ground motions from Japan suggests that this correlation model is also a reasonable representation for subduction earthquake sources (Jayaram et al. 2011b) and can be used without any significant bias. More recently, Akkar et al. (2014b) developed a correlation model based on the European RESORCE database, which is more suitable for use with European GMMs. As such, two alternative models are currently implemented in haselREC: Baker and Jayaram (2008) and Akkar et al. (2014b). The choice of the model is left to the user and should depend on the adopted GMM.

3.1.3 Ground motion intensity measure types

The CS, as described in Baker (2011), depends on the choice of the conditioning period, which in turn depends on the objective of the analysis. Typically, the period is defined in terms of the modal properties of the structure, with the spectral acceleration of the fundamental resonance mode, $Sa(T_1)$, being a popular choice in building assessment, since the building displacement response is generally dominated by this mode. This is, however, not strictly valid for every structure, as for the case of bridges, where most of the participating dynamic mass is not related to the first mode. In these cases, choosing a single period to characterize the IM in terms of $Sa(T_1)$ can be limiting. Furthermore, when dealing with the assessment of large numbers of structures, it is almost certain that each of them will possess a different first mode of vibration period, making the choice even more taxing. This is because the spectral acceleration at a single period may be efficient (i.e. a relatively accurate predictor of the structural response and subsequently, the damage) for some types of structures due to it being close to the conditioning period, but less favourable for others because it is far away from the conditioning period, resulting in increased dispersion and reduced IM efficiency. To avoid this issue in large-scale regional assessment, *PGA* has often been adopted, mainly due to its simplicity and independence from modal properties. While *PGA* is a simple and convenient solution, it is widely known to be a relatively poor predictor of structural response but has been shown (e.g. Monteiro et al. 2017) to be a fair performer when compared to other types of IMs, therefore still having some merit. It also correlates well with peak floor accelerations in low-rise buildings. A further aspect regarding the choice of the period is that it requires some knowledge of the structure's modal properties, which are typically not known before the construction of the numerical models. Hence, the adoption of an IM that does not require such specific information on modal properties is often a preferred route.

One candidate that has emerged as a potential solution to the aforementioned problems is the *AvgSa* (Vamvatsikos and Cornell 2005; Eads et al. 2015 and Kohrangi et al. 2017, among others). It has the advantage that its statistical distribution (logarithmic mean and variance) can be computed using existing GMMs and correlation coefficient models, without requiring new GMMs specific to *AvgSa* to be developed (Bianchini et al. 2009; Bojórquez and Iervolino 2011; Kohrangi et al. 2018). Alternatively, Davalos and Miranda (2018) presented a GMM that can be directly used for computing the median and the logarithmic standard deviation of *AvgSa* for NEHRP site class D. *AvgSa* works based on defining a period range of interest, rather than a single period, thus making the uncertainty in defining a precise T_1 less critical than in the case of $Sa(T_1)$. It also requires the use of correlation coefficients between the spectral acceleration at different periods for the computation of its standard deviation. Kohrangi et al. (2017) presented a recasting of conditional spectrum record selection based on *AvgSa*. This is advantageous when assessing multiple structures since the modal properties of neither are being focused on but an acceptable level of efficiency is still being maintained. For bridge-like structures, for instance, where there is no single dominant mode of vibration, the use of a period range also makes more sense since the entire response cannot be adequately linked to a single mode of vibration as in the case of buildings. For example, a study by O'Reilly and Monteiro (2019) and O'Reilly (2021a) showed that *AvgSa* tended to be a more accurate quantifier of bridge response than other IMs such as *PGA*, spectral acceleration and *PGV*; Abarca et al. (2021) further demonstrated the usefulness of *AvgSa* with respect to *PGA* when utilized for the regional loss assessment of different bridge taxonomy groups in Italy. Also with regards to infilled reinforced concrete frame structures, a common structural typology found in the Southern Mediterranean area, O'Reilly (2021b) noted how using *AvgSa* as the IM instead of the typically employed $Sa(T_1)$, provided several advantages in terms of both reduced dispersion and mitigation of unwanted bias. Heresi and Miranda (2021a) also noted the benefits of using *AvgSa* when assessing low-rise wood-frame residential housing in the US. It is noted that the above discussion regarding intensity measures is not intended to be an exhaustive discussion but rather to highlight some commonly encountered candidates. Interested readers may find further discussion and references on this topic in the studies mentioned above.

haselREC allows the user to choose between *PGA*, $Sa(T^*)$ and *AvgSa* as intensity measures on which to condition the response spectrum and therefore select earthquake recordings. To consider *AvgSa* as a conditioning IM, we have also updated the OpenQuake engine as described in Sect. 4.2 to perform the PSHA and subsequent disaggregation analysis in terms of *AvgSa*, which to our knowledge was an operation not previously possible in freely available tools.

3.2 Record scaling

Another capability of haselREC is that it allows the linear scaling of the selected records, as illustrated in Fig. 1. The scaling is possible only if all the necessary recordings are stored on the computer used for the analysis (i.e. local database of recordings). If a recording is not locally available, it has to be downloaded and stored. The download process is different in the case of ESM or NGA-West2 recordings. In the case of missing ESM recordings, haselREC starts the ESM Web Service to automatically download the selected recordings in batch mode (an internet connection is required). On the contrary, an automatic download of NGA-West2 recordings is not yet available; therefore, a manual download of recordings from the NGA-West2 online database is required. This can be performed by retrieving the IDs of the selected records and copying them into the online NGA-West2 search tool. The output of the selection module is a set of scaled records that can be directly used as input of non-linear dynamic analyses.

4 haselREC features

haselREC is a command-line application developed in the Python language, available on GitHub (https://github.com/elisa82/haselREC). It performs record selection and scaling for multiple IMs, sites and return periods. It has been designed in order to be compatible with OpenQuake for what concerns the seismic hazard and disaggregation inputs.

4.1 Execution modes

haselREC can be executed in four modes: 1) both record selection and scaling, 2) record selection only, 3) record scaling only, 4) verification (for NGA-West2 records). Except for mode 1, the remaining execution modes correspond to the modules illustrated in Fig. 1.

Mode 1 consists of a fully automatic workflow including both the selection and scaling of records. However, given that a fully automatic record scaling is not always possible, haselREC can split mode 1 into just the record selection (mode 2) and record scaling (mode 3) processes, allowing the user to run the two processes at different times. Since mode 3 takes the summary file created by mode 2 as input, containing information about the selected IDs and associated scaling factors, mode 2 must be executed in advance. Execution of mode 1 is therefore recommended when the ESM database is considered alone or when all NGA-West2 recordings are already locally stored. Otherwise, it is recommended to perform record selection at first (running haselREC in mode 2), to manually download the selected recordings and scale them by running haselREC in mode 3.

To facilitate the identification of missing NGA-West2 recordings, especially in case of a large number of record selections, haselREC can also be run in mode 4 (verification mode) to identify missing IDs (i.e. IDs of the records not already stored locally) from the list of selected IDs.

4.2 Integration with the OpenQuake engine

haselREC is strictly connected to OpenQuake since it relies on the OpenQuake GMM libraries and hazard calculation outputs. haselREC retrieves some input information from the hazard files created by OpenQuake, namely: a) the file with the target acceleration value computed for the selected site and return period (i.e. the output of a classical PSHA) and b) the file with the disaggregation results (i.e. the output of seismic hazard disaggregation analysis). Moreover, to enable the conditioning of the response spectrum to *AvgSa*, the possibility to analyse this IM has been added to the OpenQuake core library starting from Release 3.4.0 (https://github.com/gem/oq-engine/releases/tag/v3.4.0). In particular, a new GMM class has been developed and implemented to compute *AvgSa* from any arbitrary GMM available from the OpenQuake library. The mean and standard deviation are computed according to Kohrangi et al. (2018). Both the correlation models by Baker and Jayaram (2008) and Akkar et al. (2014b) have been implemented. Therefore, PSHA and hazard disaggregation can now be performed directly in terms of *AvgSA* without the need for additional posterior processing steps. This feature makes haselREC extremely useful for OpenQuake users interested in ground motion record selection. haselREC can be incorporated into bash scripts in order to automate the entire process from seismic hazard to record scaling. If the hazard is not assessed with OpenQuake, then a conversion format is required to assure compatibility with the input files required by haselREC.

5 Application example

We successfully used haselREC in the framework of a recent European-funded project (INFRA-NAT, www.infra-nat.eu), whose main purpose was to enable European and neighbouring countries to understand and manage their critical infrastructure exposed to natural and human-induced hazards. The project focused primarily on the seismic risk assessment of bridge infrastructure via three case studies that were developed within each country involved in the project: Italy, North Macedonia and Israel. Herein, an example of record selection for large-scale regional assessment of bridges, corresponding to the Italian

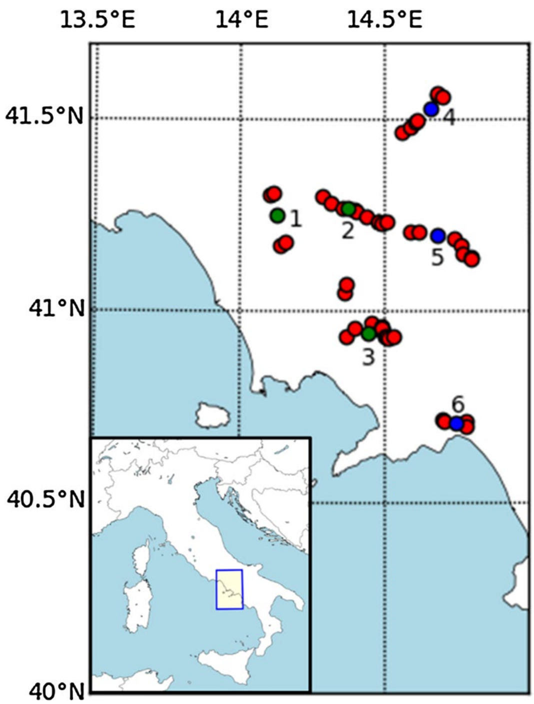

Fig. 2 Locations of the 47 Italian bridges (circles) analyzed during the INFRA-NAT Project. The green and blue circles represent the six sites, identified with a number located nearby the circle, selected for site-specific hazard analysis and record selection. The blue circles correspond to sites located on EC8 soil category B, while the green circles correspond to sites located on EC8 soil category C

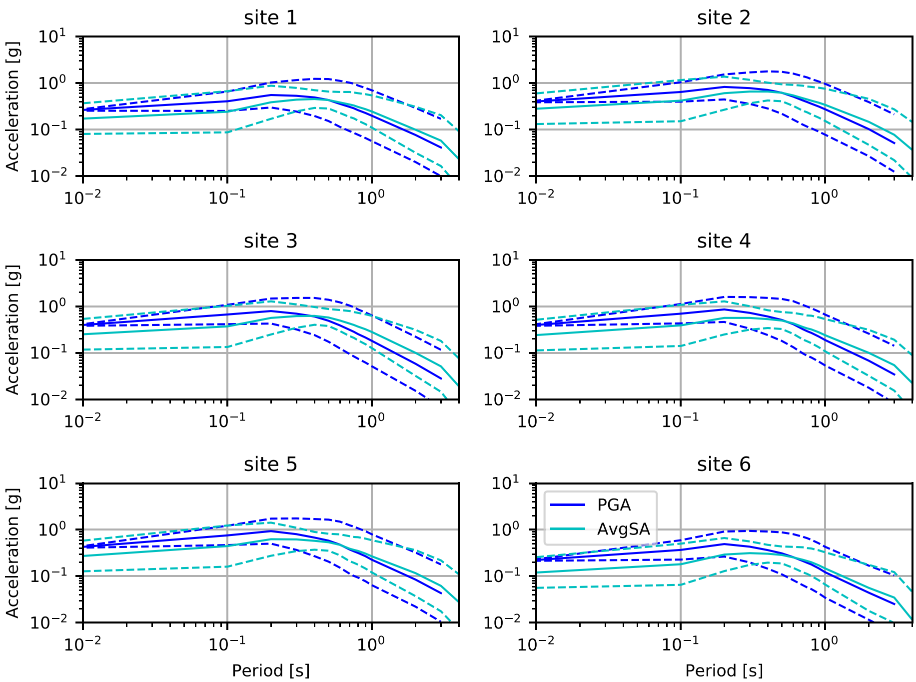

Fig. 3 Target spectra conditioned on the *PGA* (blue lines) and *AvgSa* in the period range [0.20 s ÷ 1.0 s] (cyan lines). Solid lines: average spectrum, dashed lines: average spectrum values ± 2 standard deviations. Each panel refers to one of the six sites

case study, is presented. It features a set of 47 bridges with a detailed level of knowledge, located in Southern Italy, for which dynamic analyses were performed.

5.1 Site-specific hazard computation and disaggregation analysis

To provide the hazard input for the selection of accelerograms, we used the OpenQuake engine to carry out site-specific hazard calculations for six representative bridge locations characterized by different hazard levels and soil conditions. The identified locations are shown in Fig. 2.

The 2013 Euro-Mediterranean Seismic Hazard Model (ESHM13) (Woessner et al. 2015) was adopted, while the soil category at the bridge locations was assigned based on the USGS topographic based *Vs30* dataset for active tectonic regions (Wald and Allen 2007), due to the lack of specific data on the subsoil. The hazard was then computed for seven return periods of interest, ranging from 98 to 9975 years, considering both *AvgSa* and *PGA* for comparative purposes as IMs.

According to the modal properties of the considered bridges, the period range necessary to compute the *AvgSa* was established as [0.20 s ÷ 1.0 s] following the rationale outlined in O'Reilly (2021a). To compute the *AvgSa* standard deviation, we adopted the correlation model by Baker and Jayaram (2008) for all the GMMs considered in the ESHM13 ground-motion logic tree, except for Akkar and Bommer (2010), for which we used the correlation model by Akkar et al. (2014b) to be consistent with the region for which it was developed (i.e. Europe and the Middle East region).

We performed the disaggregation of the seismic hazard using the most representative branch of the logic tree, corresponding to the area source model, which received the largest weight in the logic tree scheme, and the GMMs by Akkar and Bommer (2010) for active tectonic and stable continental regions, the one by Zhao et al. (2006) for subduction zones, and Faccioli et al. (2010) for volcanic regions.

5.2 Accelerograms selection

We performed the record selection with haselREC for the six sites shown in Fig. 2, the seven return periods of interest and the two considered IMs (*PGA* and *AvgSa*), for a total of 84 selections. The target CS obtained for the return period of 475 years are given in Fig. 3.

haselREC has the advantage of being able to handle different return periods and sites in a single run, with the possibility of defining the magnitude and distance radii adopted to screen recordings, as well as the maximum allowable scaling factors, as a function of the return period. The values adopted in the presented example are listed in Table 1. Accordingly, the allowed EC8 soil category and the allowed *Vs30* range were set consistent with the soil category of each considered site.

According to the prevalent tectonic regime of the area, we prescribed the computation of the CS using the GMM by Akkar and Bommer (2010) along with the correlation model by Akkar et al. (2014b). A set of 30 response spectra (corresponding to 30 two-component recordings) was then selected for each return period and site location. An example of record selection associated with the CS of Fig. 3 is shown in Fig. 4. It can be seen how for both IMs the target and selected CMS match quite well across all periods. For what concerns the distribution of the response spectra with respect to the target CS, the CMS plus and minus two standard deviations ($\pm 2\sigma$) is also plotted. It is seen how the dispersion of the *PGA* selected records matches the target quite well across all periods, starting from no dispersion at $T \approx 0$ s (i.e. *PGA*) and gradually growing for larger periods as it moves away from the conditioning value. For the *AvgSa* selection, the slight pinching in dispersion around the defined period range is evident and is matched well by the chosen records, although they tend to be characterized by a smaller dispersion with respect to the target one for lower periods but this is not deemed critical and could be improved with further refinement of the selection parameters adopted.

Table 1 Parameters adopted for the selection of suitable ground motions in Southern Italy

Return period	Magnitude radius	Distance radius (km)	Maximum scaling factor
98	0.50	50	2.0
224	0.50	50	2.5
475	0.50	50	3.0
975	0.75	75	3.5
2475	0.75	75	4.0
4995	1.00	100	4.5
9975	1.00	100	5.0

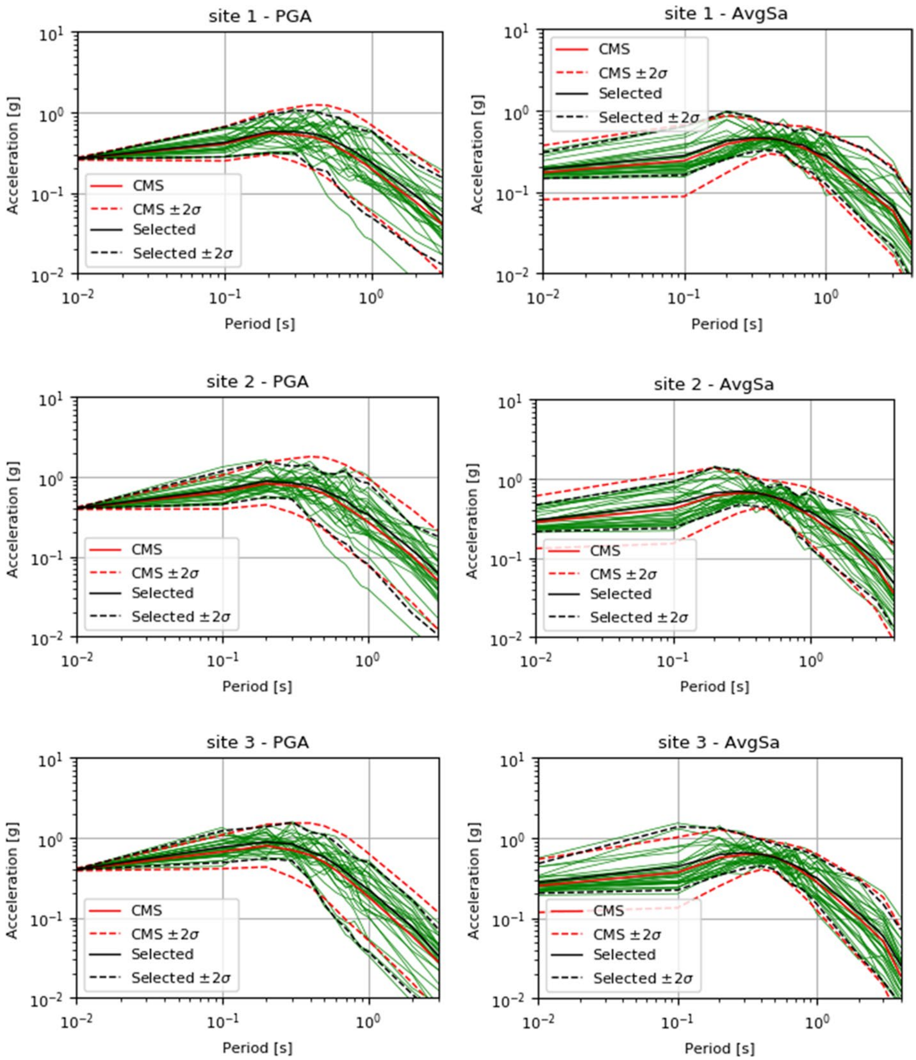

Fig. 4 Conditional spectrum record selection performed for the 475-year return period. The 30 green lines are the *RotD50* response spectra of selected ground motions, while the black lines represent their distribution. The red lines represent the target conditional spectrum. Solid lines: average spectrum, dashed lines: average spectrum values ± 2 standard deviations. (left columns) Selection conditioned at the *PGA* value; (right column) selection conditioned at the *AvgSa* value in the period range [0.20 s ÷ 1.0 s]. Each row refers to one of the six sites

A summary of the scaling factors (average, minimum, maximum) associated with all the selections is provided in Table 2 as a function of the return period and the IM.

The selected accelerograms were also used in Abarca et al. (2021) to evaluate the performance of the two different IMs from a structural perspective, showing the improved accuracy of *AvgSa* with respect to *PGA* when applied to the regional assessment of RC bridges, leading to less dispersion in the observed behaviour of the bridge inventory and a more refined overall performance considering the evaluated metrics.

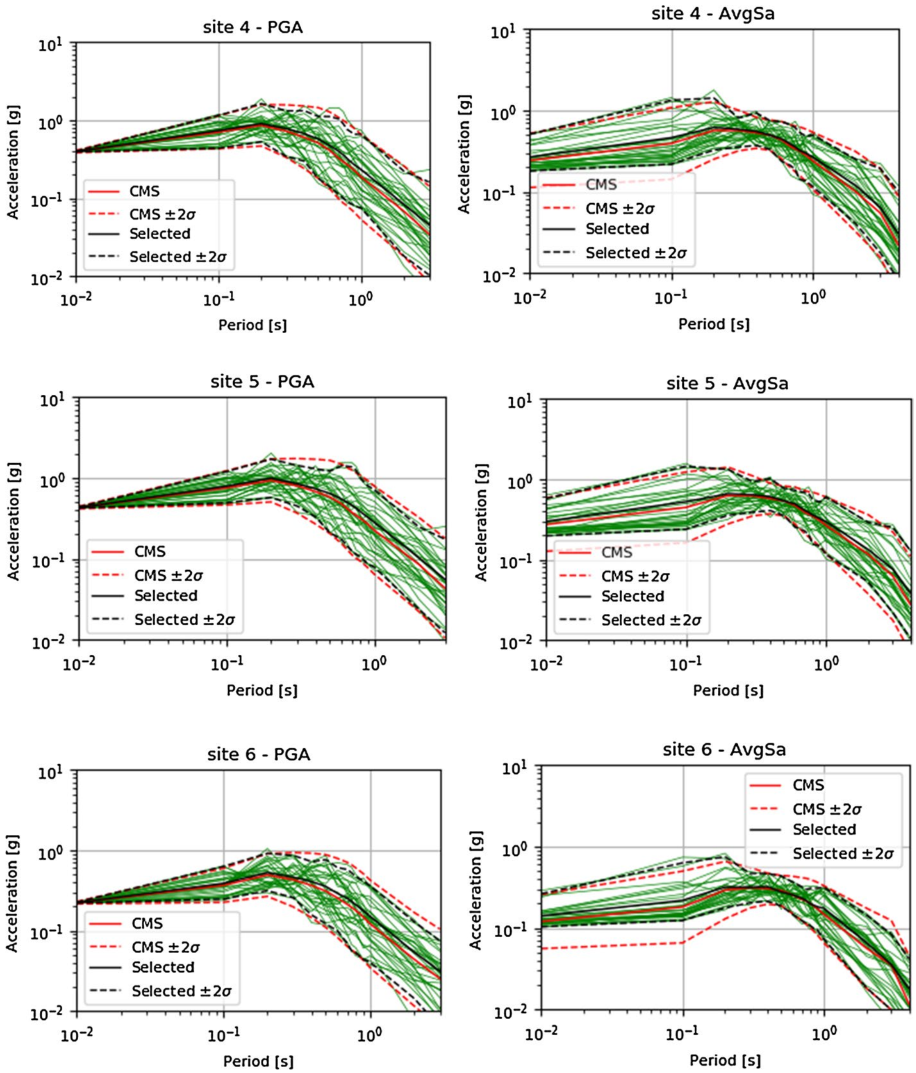

Fig. 4 (continued)

6 Conclusions and future developments

We presented haselREC, a useful open-source tool, capable of selecting and scaling recorded accelerograms to be used for dynamic analyses. Being open-source, interested readers are encouraged to use or modify the tool according to their needs. The code depends on the libraries of the open-source software OpenQuake and has been designed to directly interact with the outputs from a classical PSHA and disaggregation analysis performed in OpenQuake. Record selection is possible for both commonly-employed intensity measures (IMs) *PGA* and *Sa*(*T**), as well as for *AvgSa*, which was directly added to the OpenQuake functionalities, as it has been demonstrated to be a preferable IM for structures

Table 2 Scaling factors (SF) adopted for the INFRA-NAT Project

Return period (years)	*PGA*			*AvgSa*		
	Average SF	Minimum SF	Maximum SF	Average SF	Minimum SF	Maximum SF
98	1.20	0.51	2.00	1.22	0.51	1.98
224	1.37	0.41	2.50	1.44	0.47	2.48
475	1.68	0.36	2.99	1.65	0.37	2.93
975	1.89	0.29	3.47	2.16	0.32	3.50
2475	2.18	0.32	3.98	2.37	0.30	3.98
4995	2.51	0.33	4.49	2.90	0.39	4.49
9975	2.88	0.42	4.99	3.20	0.56	4.94

characterized by more than one single dominant period or for regional assessment of multiple structures (O'Reilly and Monteiro 2019; Abarca et al. 2021; O'Reilly et al. 2018; O'Reilly 2021b; Heresi and Miranda 2021b). For this purpose, we illustrated an example of record selection for the Italian territory, to demonstrate the feasibility of selecting ground motions according to two different IMs.

haselREC selects two-component ground motion recordings based on the Conditional Spectrum (CS) selection procedure by Baker and Lee (2018). Any model produced by OpenQuake can be used for the calculation of the CS. At the moment, parsers for the NGA-West2 and the ESM strong-motion databases are included in haselREC, but modules for additional databases can be easily integrated. haselREC has also the capability to handle several sites, return periods and IMs in a single run while preserving the format compatibility with OpenQuake. Missing input parameters for complex GMMs that are based on a finite earthquake source characterization, such as the NGA GMMs, are directly computed by the code using the relationships by Kaklamanos et al. (2011) to facilitate its use, especially by non-seismology expert users. After the selection of records, the tool can perform their scaling, also taking advantage of the automatic download of records from the ESM web service. Therefore, the tool can be easily included in automatic scripts for seismic hazard analysis and hazard-compatible selection and scaling of real ground motion records, thus minimizing the operations that a user has to perform manually, which are present in some other similar tools.

As a future development, we would like to include an exact calculation of the CS, considering multiple causal earthquakes and GMMs, which are usually included in a PSHA. Moreover, we plan to add a graphical user interface to make the code more user-friendly.

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Code availability haselREC is available on GitHub: https://github.com/elisa82/haselREC.

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