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Seismology and Earthquake Engineering
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DELIVERABLE

D28.2 Report on attenuation models at regional scale for real-time ground shaking prediction. Implementation at the prototype stage in a real-time, automatic software platform.

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Lead	T. Dahm, GFZ
Authors	A. Michelini, INGV
	N. Melis, NOA
	C. Cauzzi, ETHZ
	L. Faenza, INGV
	D. Bindi, GFZ
	S. Heimann, GFZ
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Summary

In the past decade, real-time seismology has moved from providing post-event information within minutes from earthquake occurrence, to issuing event information during or short time after the rupture. Task 28.2 concerns the availability and reliability of ground shaking predictions over a large range of spatial and temporal scales, close to the ruptured fault, in regional distances, and in near-real time or long time after the earthquake. The procedures developed and tested in this task have the potential to be implemented and standardized within a unified European ShakeMap system.

1 Introduction and Concept

This short chapter is intended to give an overview on the achievements, before we come to the specific deliverables

Activity 1 – Wave energy magnitude and attenuation:

The aim is to evaluate the possibilities to implement GMPE's based on the energy magnitude for shake map estimation. For this activity, in a joint effort, GFZ and University of Naples investigated whether the variability of ground motion residuals can be reduced when using different magnitude scales including energy-based magnitudes. Using earthquake data recorded in Central Italy since 2009, the frequency-dependent correlation between source parameter and inter-event residuals were studied, applying different GMPEs. In summary, five papers were published with direct association to SERA (**Bindi et al, 2018a, 2018b, 2019; Picozzi et al., 2018; Spallarosa et al., 2019**).

Activity 2 – Toolbox development for GM simulation using synthetic waveforms:

In this activity, we developed and tested a framework to estimate GM parameter from real-time synthetic seismogram simulations. The synthetic waveform GM parameter can fill gaps in conventional GMPE approaches for near source regions, where empirical databases are typically poor, or for considering first order effects of rupture directivity, source depth and variations in structural models. The challenge is to provide a flexible and fast simulation tool, easy to use, so that it can be implemented in existing shake map procedures in future. The GFZ group tested the feasibility of the approach for two recent, small magnitude in Germany (**Dahm et al., 2018**). The GM simulation approach was then integrated in a novel, python-based toolbox in seismology (**Heimann et al., 2017**) and combined with a systematic database structure of pre-calculated, synthetic Green functions (**Heimann et al., submitted**). The open source software development is usable by a well defined application programming interface (API) and fully documented.

Activity 3 – Testing and integrating real-time GMPE procedures:

Community developments for GM and shakemap simulations include databases and software packages as *USGS Shakemap*, *EMSC event alerts*, Rapid Raw Strong Motion (*RSSM) and Engineering strong motion (ESM) databases,* and existing regional and global GMPEs. In this activity WP28.2 implement, test, and standardize real-time selection frameworks within a European ShakeMap system that considers regional GMPEs. INGV, ETHZ and NOA joint efforts for this development. The prototype system set up by ETHZ, INGV and KNMI chiefly builds upon the modern strong-motion portals. **The prototype project is an opportunity** for international and inter institutional collaboration, a networking and research activity that, when mature, can **evolve as a consolidated European service.**

2 Work report

2.1 Regional and local scale attenuation models

The quality of European ShakeMap and ground motion (GM) services depends on the reliability of local and regional attenuation models. In regions with few or no strong earthquake occurrence, the local, empirical GM databases are often poor. Attenuation models from other regions often cannot be easily adapted. The task 28.2 has tested two lines of research to complement and improve attenuation models in future, (1) the consideration of different waveform attributes as the energy magnitude, and (2) the possibility to estimate ground motion parameter from synthetic waveforms for filling data gaps close to the earthquake sources.

2.1.1 Wave energy attenuation

(Dino Bindi)

Although modern Ground Motion Prediction Equations (GMPEs) can include several tens of coefficients **(Abrahamson et al., 2014)**, the source scaling is generally described by relative simple functional forms constructed over a single source parameters, i.e., the earthquake magnitude (**Douglas and Edwards, 2016**). Therefore, the median predictions rely on the assumption of source self-similarity (**Aki, 1967**) according to which the source spectra can be described, under some assumptions, by a single parameter. In the framework of Probabilistic Seismic Hazard Assessment, the moment magnitude M_w is used as the primary measure of the earthquake size and hence implemented in the GMPEs. Since M_w is based on an estimate of the seismic moment M_0, it provides fault-averaged, low-frequency information on source processes but relatively less information about the small-wavelength high-frequency rupture details. Since the median prediction from a GMPE based on M_w are controlled by the seismic moment, differences in the ground shaking at high frequencies generated by dynamic features (e.g., variability in the rupture velocity or in the stress drop) are absorbed by the inter-event component of the residual distribution (also called between-event residuals). On the other hand, different magnitude scales provide different information about the static and dynamic features of the earthquake rupture, and magnitudes other than M_w could better characterize the earthquake size in terms of high-frequency energy release. For example, both the local magnitude and the energy magnitude depend not only on the seismic moment but also on the stress drop and on the apparent rupture velocity (**Deichmann, 2018**) and therefore could be more suitable to describe the ground shaking and its variability at frequencies around the corner one. Using a data set of earthquakes recorded in Central Italy since 2009, we investigated the correlation between source parameters and the inter-event residuals associated to GMPEs implementing different magnitude scales (i.e., moment, local and energy magnitudes) **(Bindi et al., 2017; Picozzi et al., 2017; Bindi et al., 2018; Bindi et al., 2019)**.

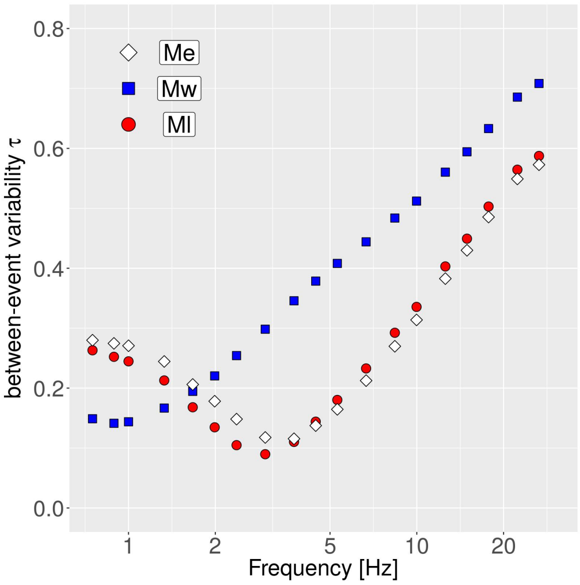

Figure 1. Standard deviation τ of the between-event residuals versus frequency for GMPEs calibrated in central Italy considering moment magnitude (blue), local magnitude (red) and energy magnitude (white) (**Bindi et al., 2019**).

Figure 1 shows the frequency dependence of the standard deviation τ of the between-event residuals evaluated for GMPEs calibrated in the Fourier domain. Since Me and Ml depend on both seismic moment and stress drop, the GMPEs calibrated for these magnitude scales show a lower between-event variability over the frequency range mostly spanned by the corner frequencies of the events (2-6 Hz, for the analysed data set), where the ground motion variability exhibits a strong correlation with the stress drop variability. At lower frequencies, the inter-event variability is mostly controlled by uncertainties in the seismic moment while, at higher frequencies, it is also correlated with high-frequency characteristics of the source spectra which are not captured by Mw and Ml.

The results about ground motion variability over a wide frequency range confirm the complementarity of the magnitude scales considered in the GMPE development (**Picozzi et al, 2019**). Since the shaking potential of an earthquake, and therefore its damage potential, can be quantified through intermediate and high frequency features like the peak ground velocity (PGV) and acceleration (PGA), a first-order rapid-assessment of the stress drop would improve the characterization of the ground shaking severity from an engineering seismology point of view. Therefore, we developed a procedure for the rapid assessment of the earthquake shaking potential by estimating the seismic moment and the radiated energy from proxies measured over the seismograms (**Picozzi et al., 2018**). Following similar approaches developed for Earthquake Early Warning (EEW) (e.g., see references in **Spallarossa et al., 2019**), we calibrated an attenuation model relating the seismic moment and the radiated energy to the peak ground displacement (PD) and the integral of the squared velocity (IV2) for the S-waves, respectively. Then, the empirical models are applied for the rapid assessment of M_0 and E_R and, in turn, of the apparent stress. The possibility of detecting transient phenomena by monitoring the temporal variability of the between events (**Bindi et al., 2018b**) or monitoring the apparent stress for specific fault systems (e.g., for the Irpinia fault system in Southern Italy) is under investigation.

2.1.2 Near source PGV attenuation from synthetic waveforms

(Sebastian Heimann, Torsten Dahm)

Green's functions (GFs) are used abundantly to represent force excitations of many different processes inside the Earth. A GF source representation is a mathematical concept to synthesise finite spatio-temporal sources. Simulating waveforms for different rupture scenarios with finite duration and finite extent involves the repeated numerical calculation of a large number of GFs for combinations of force excitations, especially if uncertainties of source parameters are bootstrapped. GF calculation is a computational costly effort. If it is done on-the-fly, it may strongly dominate the overall computational costs of effort even render real-time simulations impractical.

The structured storage of GFs in *GF databases* (*GF stores*) allows to query pre-calculated GFs for individual source-receiver configurations, rather than time-consuming re-calculation. The conceptional architecture of this approach is sketched in Figure 2. Often, *GF stores* are in-house developed database solutions, or other structured storage, that are linked to specific forward modelling and inversion codes. However, these rigid database schemes are restricted to the modelling method that has been used to create them, and they are often confined to specific applications.

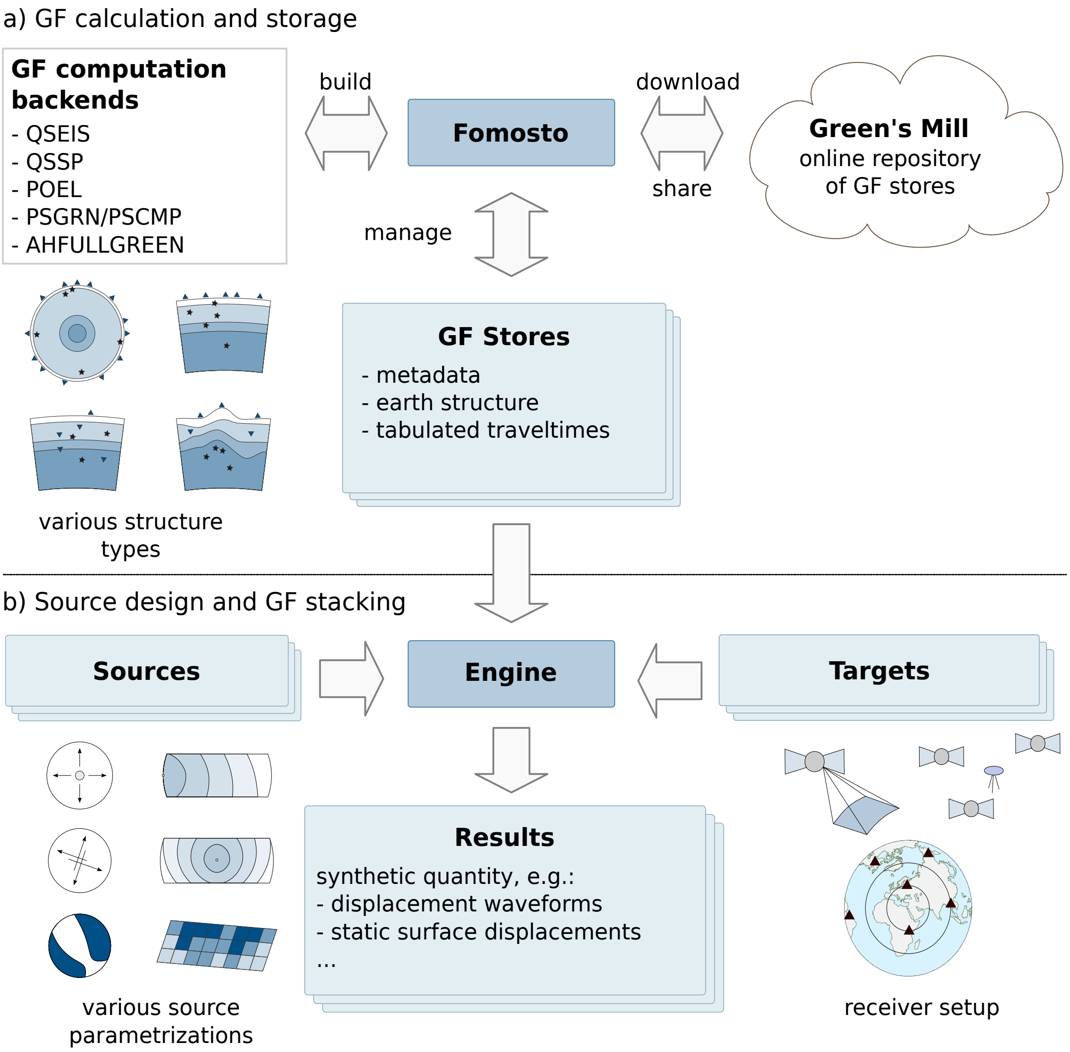

Figure 2. The architecture of the *Pyrocko-GF* and object oriented implementation. The *fomosto* program is a command-line interface (CLI) to create GFs using the backends, to inspect and manage *GF stores*. b) The *engine* is the central object that accesses the computed *GF stores* and calculates the synthetic waveforms based on the specified source (e.g. moment tensor, double-couple source or finite-

rectangular) and targets (e.g. virtual accelerometers, GNSS stations, or InSAR line-of-sight displacements) (**Heimann et al., submitted**).

We developed a Python-based framework and toolkit – *Pyrocko-GF* - that enables pre-calculation of synthetic GF stores, which are independent of their numerical calculation method and GF transfer function. The aim of this stand-alone open-source toolbox is to simplify the calculation and storage of GFs, suited for an easy integration into individual routines and methods for ground motion simulation. To achieve this, we made our framework independent of the GF type and the GF calculation method that synthesises the physical quantities. The architecture of the GF stores is flexible to allow the storage of extra attributes, e.g. travel timetables. We put special efforts to find a good balance between stability, numerical performance and user-friendly implementation. While being stand-alone, our framework is easily linked to other seismological Python toolboxes, e.g. *pyrocko* (**Heimann et al., 2017**) or *ObsPy* (Krischer et al., 2015). We also openly share various existing *GF stores* on https://greens-mill.pyrocko.org. The *Pyrocko-GF* toolkit comes with a well-documented application programming interface (API) for the Python programming language to efficiently facilitate forward modelling of earthquake rupture in near real-time, e.g. synthetic waveforms or static displacements for a wide range of source models.

Dahm et al. (2018) used the synthetic GF approach to validate peak velocity attenuation relations in central Germany, where damaging earthquakes did strike in historical times, but not during the instrumental period. Two similar GF stores were created to calculate peak ground velocity for two deep crustal earthquakes. One store contained GFs for a medium with a hard rock surface layer, while the other store had a soft sedimentary surface layer (*GF stores* provided at https://greens-mill.pyrocko.org). GFs are pre-calculated for distances between 0 and 300 km, for source depths ranging between 0 and 35 km, at intervals of 1 km with a sampling rate of 16 Hz. Peak ground velocities were extracted for 6 Hz low-pass filtered seismograms (PGV_{6Hz}). The PGV_{6Hz} attenuation reproduced well the observed averages and their variability for the two deep crustal earthquakes, while empirical attenuation relations derived for other regions over or under-predicted the observations.

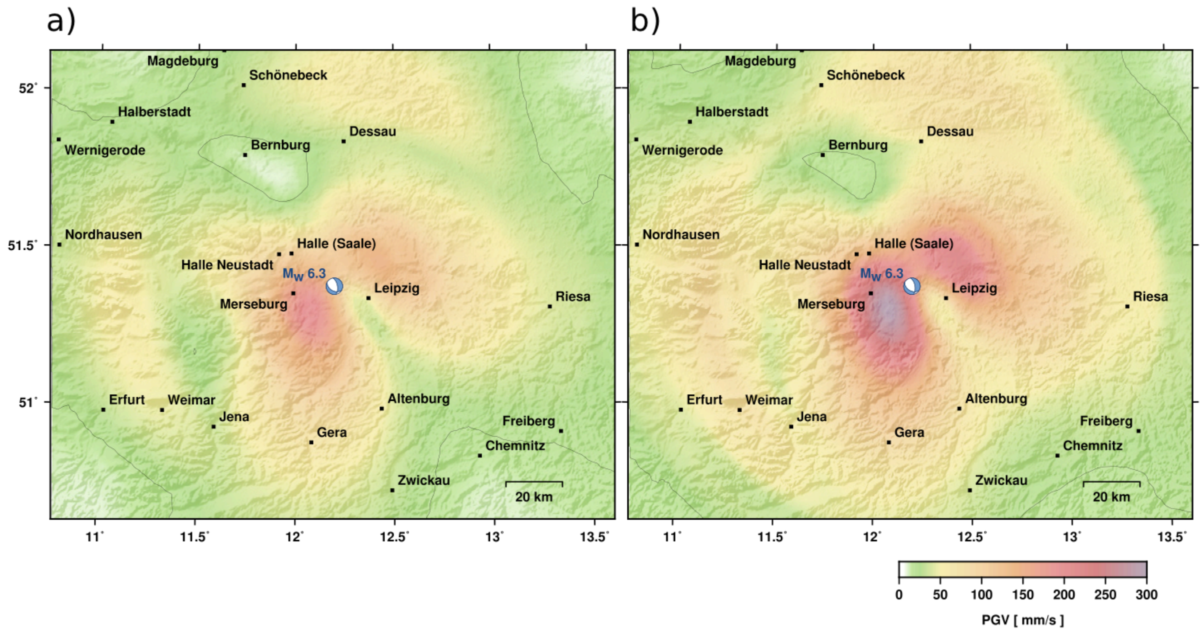

Figure 3. Shake map scenario of a M_W 6.3 characteristic lower crust earthquake in 25 km depth between Halle and Leipzig, Germany (**Heimann et al., submitted**). (a) Predicted PGV6Hz assuming hard rock upper layer model. (b) Predicted PGV6Hz assuming a 500 m thick soft layer beneath the surface with P and S wave velocities of 2.5 km/s and 1.2 km/s, respectively. The contour line shows the 20 mm/s threshold (see **Dahm et al., 2018**, for further explanation).

Fig. 3 shows, as an example, PGV_{6Hz} ground motion predictions for a magnitude M_W 6.3 earthquake scenario near the cities of Leipzig and Halle, Germany.

2.2 Integrating procedures in real-time frameworks

2.2.1 Prototype realtime European ShakeMap system

(Carlo Cauzzi, Alberto Michelini, L. Faenza)

During the last year, ETHZ, INGV and KNMI have tested the feasibility and realized a prototype implementation of a European ShakeMap system. The aforementioned Institutions are in charge of managing and maintaining the European peak- and strong-motion databases and related web services that constitute one of the key input to ShakeMap. ETHZ and INGV are among the few international active collaborators of the USGS ShakeMap development group. There seems to be increasing support in the European seismological and engineering Communities concerning the importance of establishing a European ShakeMap system that, in addition to situational awareness, could provide the ground-shaking input to rapid loss and impact assessment.

The prototype system set up by ETHZ, INGV and KNMI chiefly builds upon the modern strong-motion portals developed within the EC-funded project NERA, mainly based on the European Integrated Waveform Data Archive (EIDA; https://www.orfeus-eu.org/data/eida/), namely: (a) an automatic peak-motion database (RRSM; http://www.orfeus-eu.org/rrsm) that delivers earthquake and peak-motion information within minutes of any event with M >= 3.5 and; (b) a manually revised strong-motion (M >= 4.0) database tailored to engineering applications (ESM; http://www.orfeus-eu.org/esm). Within ongoing projects EPOS-IP (https://www.epos-ip.org) and SERA (http://www.sera-eu.org/en/home/), the content of the two databases has been made accessible via event, station, peak-motion and waveform web services, thus considerably improving users' access to strong-motion data and automation of downstream products, like ShakeMap. The prototype European ShakeMap system uses the USGS ShakeMap codes and input from the RRSM and ESM to deliver maps of expected and recorded ground shaking within minutes of any event with M >= 4.0 in the Euro-Mediterranean region (27° ≤ lat ≤ 81°, -32° ≤ lon ≤ 51°). The predicted maps are initially constrained by the earthquake locations and magnitudes provided by Euro-Mediterranean Seismological Centre (EMSC) together with the recordings of the RRSM and subsequently updated as soon as manually revised ESM ground-motion estimates are available. The system uses ground-motion prediction tools suitable for the European context and adopts the seismotectonic regionalisation of project SHARE (http://www.share-eu.org/) to identify subduction, volcanic, shallow active crustal and stable continental seismicity. Site amplification is modelled based on the best available proxies. The system uses the authoritative configuration for Switzerland and Italy and can easily include any other regional configuration as adopted by other European Institutions running USGS ShakeMap. The system, presently accessible at http://shakemap-eu.ethz.ch/, is based on ShakeMap v3.5 and will soon require a transition to ShakeMap v4.0, including new developments concerning map and web rendering. ShakeMapEU can: (i) provide a single source for ShakeMaps at the European scale that builds on EPOS-IP services and modern future-proof community software and tools; (ii) serve as a backup to local authoritative ShakeMap implementations and (iii) deliver ShakeMaps for regions where no local capability is yet available. ShakeMapEU can also act as a research platform for testing novel methodologies aimed at improving the temporal and spatial prediction and mapping of the experienced ground shaking. Further developments and consolidation of the prototype system should be preferably carried out within the framework of EPOS Seismology, based on close collaboration among ORFEUS, the EMSC, EFEHR, and the community of European ShakeMap operators and stakeholders, if the final goal is to establish a reliable and carefully curated European service.

Presently this prototype project is an opportunity for international and inter institutional collaboration, a networking and research activity that, when mature, can evolve as a consolidated European service.

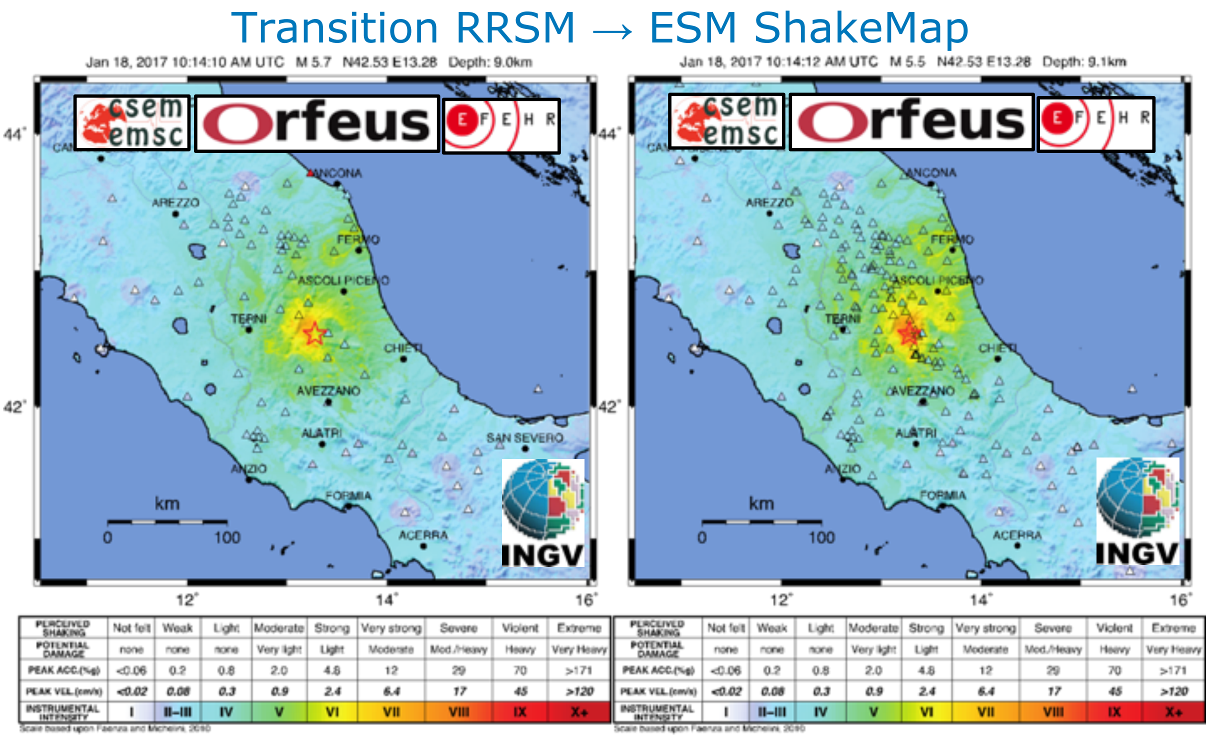

Figure 4. Transition from a quasi-real-time RRSM-based ShakeMap to an ESM-based one, including revised location, peak-motions and removal of outliers.

2.2.2 Pilot ShakeMap 4.0 API at NOA serving Earthquake Catalogue in Greece

(Nikolaos Melis and Ioannis Kalogeras)

During the last year at NOA, a pilot deployment of ShakeMap 4.0 alongside the existing 3.5 version was established. It was designed to serve as an interface to SeisComP3 already operating at NOA and to use all available data streamed in real time. It has to be noted that the updates through USGS were also followed from time to time in order to keep an up to date process in operation for the pilot review period. Additionally, as more stations and especially accelerometer data were made available in real time, they were also added. Currently a web API, based on Leaflet, has been formed and it is under continuous trial/review and update. The following figures 5 and 6 demonstrate comparisons between the two operating versions 3.5 and 4.0 for the latest 2019-03-30 magnitude 5.4 earthquake that took place in the western Gulf of Corinth. An example of the front face of the API with the catalogue view is shown in Figs. 7 and 8.

It must be noted that the API will serve NOA and the Greek coordinating ShakeMap production after the present trial phase and once all real time data will be made available. It will also serve as an interface to the past produced ShakeMaps by updating the whole database and making it open to the public. This will lead to the first established Greek National RRSM database.

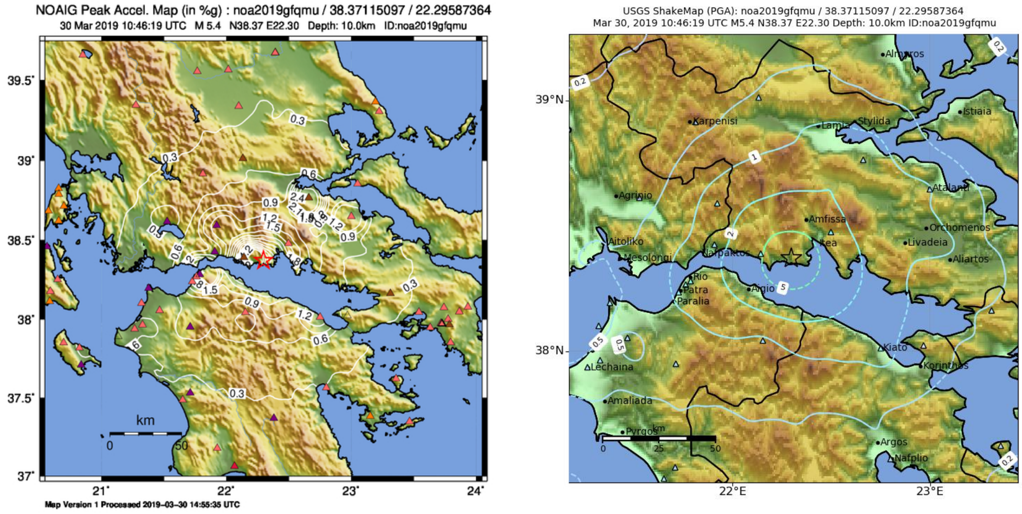

Figure 5. ShakeMap 3.5 (on the left) and 4.0 (on the right) version alongside, showing PGA distribution, as they were produced for the latest 2019-03-30 event with 5.4 magnitude in the Western Gulf of Corinth.

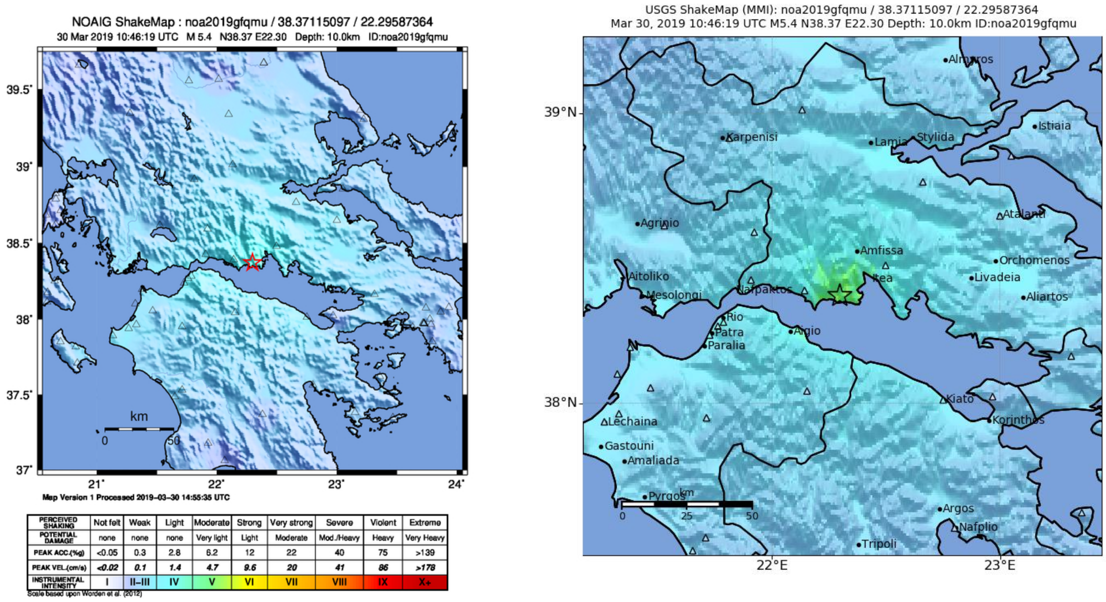

Figure 6. ShakeMap 3.5 (on the left) and 4.0 (on the right) version alongside, showing Intensity MMI distribution, as they were produced for the latest 2019-03-30 event with 5.4 magnitude in the Western Gulf of Corinth.

By Day		30
By Mag		3

#	Event	Lat [°]	Lon [°]	Magnitude	Depth	Date (Gmt)
1	noa2019gayen	36.858	27.592	3.060	10.000	2019-03-27T08:59:10
2	noa2019gcwf	37.509	29.532	3.485	10.000	2019-03-28T10:03:42
3	noa2019gdtmf	38.358	22.36	3.500	5.000	2019-03-29T10:00:40
4	noa2019gernd	37.656	20.704	3.116	10.000	2019-03-29T10:09:01
5	noa2019gfqmu	38.371	22.296	5.407	10.000	2019-03-30T10:46:19

Figure 7. Screen dump of the current NOA web API presenting the available earthquake catalogue through SeisComp3 for Greek seismicity.

	Instrumental Intensity	Acceleration	Velocity
JPEG	intensity.jpg	pga.jpg	pgv.jpg
Stations	stationlist.json		

#	Intensity	Station (Net.Sta.)	Lat [°]	Lon [°]	Elev [m]	Station Name	Epi. Dist. [km]	Max PGA [cm/s²]	Max PGV [cm/s²]
1	null	STC	40.6487	23.3049		STC			
2	1	AMGA	36.8316	25.8938		AMGA		0.0042	0.0042
3	2.2	LKD2	38.7889	20.6578		LKD2		0.0571	0.0571
4	2.6	ACRJ	37.9711	23.7273		ACRJ		0.1802	0.1802
5	1.7	MHLO	36.6898	24.4017		MHLO		0.0429	0.0429

Figure 8. Screen dump of the current NOA web API presenting the latest 2019-03-30 event with 5.4 magnitude in the Western Gulf of Corinth. The view shows MMI isolines. Top left selection Leaflet tool can be used to show any other result presented by the API. The table shows the auto processed resulted values, i.e. PGA, PGV as an example for trial.

2.2.3 Prototyping API and Green function database for near source ground motion parameter

(S. Heimann)

An example illustrating the use of the Pyrocko-GF API is given in the listing in Fig. 8.

```python
from pyrocko import gf, io

engine = gf.LocalEngine(store_superdirs=['.'])
store_id = 'global_2s'

# Define three seismogram targets representing East-North-Vertical(up) channels
targets = [
    gf.Target(
        quantity='displacement',
        lat=37.29, lon=-121.31,
        store_id=store_id,
        codes=('', 'STA', '', channel_code))
    for channel_code in 'ENZ']

# Initialise a Double-Couple dislocation source
source_dc = gf.DCSource(lat=52.41, lon=13.06, magnitude=7.3)

# Create synthetic seismograms
response = engine.process(source_dc, targets)
synthetic_traces = response.pyrocko_traces()

# Save seismograms to Mini-SEED files
io.save(synthetic_traces, 'output/%(station)s-%(channel)s.mseed')
```

Figure 8. Python script example for forward modelling a synthetic seismogram with the *Pyrocko-GF* framework. More examples are available on https://pyrocko.org/docs/current/library/examples/gf_forward.html (**Heimann et al., submitted**).

The object-oriented programming model provides *Source* objects defining the dislocation source(s), *Target* objects defining the modelling target (e.g. seismometer components or GNSS station), and the *Engine* object being responsible for forward modelling. The source properties may include the location, mechanism and origin time.

The *Source* object is responsible for the discretisation of point- and finite-extent sources into their moment tensor representations for weighting of the store's GF traces.

The *Target* object defines the parameters of the synthesised quantities such as location of receivers and the requested quantity type. Yet, seismic targets can provide derivatives of the synthetic displacements (i.e. velocity and acceleration).

The *Engine* connects the *Source* and *Target* objects to the *GF store*. Based on the configuration of the *Source* and *Target*, the *Engine* extracts the required GF traces from the store and realises the stacking of delayed and weighted traces and their subsequent convolution with the *Source*'s source time functions. Finally, the *Engine* returns the synthetics for the request defined by the *Target* and *Source* objects.

In order to use the API for the real-time simulation of ground motion parameter, the listing in Fig. 8 is supplemented to consider a variety of source mechanism and source depths within the given uncertainties of from fast location and rupture analysis. The stations are placed on a regular grid at the surface, or within the region of interest. Waveform attributes, e.g. peak ground velocities, are extracted from bandpass-filtered seismograms, and average PGV values are provided for plotting or other use. Additional to peak values, other waveform attributes as the duration of shaking, the wave energy and energy derived intensities, can be easily extracted.

3 Conclusions

The work and the deliverables of task 28.2 has been achieved as planned. The testing of attenuation models from earthquakes recorded in Central Italy confirmed the strong frequency dependence of ground motion residuals and variability, and the complementarity of the magnitude scales considered in the GMPE. As a first-order rapid-assessment of the stress drop can improve the characterization of the ground shaking severity, we developed a procedure for the rapid assessment of the shaking potential by estimating the seismic moment and the radiated energy from proxies measured over the seismograms. The attenuation model relating the seismic moment and the radiated energy to the peak ground displacement (PD) and the integral of the squared velocity (IV2) for the S-waves, respectively, were calibrated.

The development of numerical Green function databases was integrated into a python based simulation toolbox, in order to rapidly simulate ground motion parameter for different earthquake scenarios. The procedure has been tested and calibrated for small to moderate earthquakes in Germany in a pilot study. The open source software products have been provided and are documented, including simple examples included in an online documentation and a submitted paper.

The feasibility of a European ShakeMap system has been further tested and realized by prototype implementations at ETHZ, INGV and NOA. The ETHZ/INGV system (http://shakemap-eu.ethz.ch/) uses the authoritative configuration for Switzerland and Italy and can easily include any other regional configuration as adopted by other European Institutions running USGS ShakeMap. ShakeMapEU can: (i) provide a single source for ShakeMaps at the European scale that builds on EPOS-IP services and modern future-proof community software and tools; (ii) serve as a backup to local authoritative ShakeMap implementations and (iii) deliver ShakeMaps for regions where no local capability is yet available.

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