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D2.16 Final summary report addressing professional stakeholders

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Summary

The final summary report is addressed to professional stakeholders and presents the background, mission and main achievements of the SERA (Seismology and Earthquake Engineering Research Alliance for Europe) project. SERA's networking activities were shaped to pool know-how, data, and tools to facilitate exchange between professionals and researchers from different fields. For this purpose, SERA organized several workshops for teachers, engineers and the interested public. SERA offered access to the largest collection of high-class experimental facilities for earthquake engineering in Europe to talented researchers from both academia and industry. The research facilities comprise reaction walls, shaking tables, facilities for integrated studies on geotechnical site effects and engineering seismology as well as an infrastructure for array seismology. SERA facilitated access to data and products of seismology, engineering seismology and anthropogenic seismicity to help seismologists understand the nature of earthquakes. SERA contributed to answering the question of how earthquakes start and evolve with multi-disciplinary science and joint research activities targeted on pooling data and expertise. SERA also delivered hazard and risk related products, which were based on the integration of competences from different domains.

Acknowledgement

Acknowledgement

Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe

Final report

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Background

Europe has a long history of destructive earthquakes, and recently the impact of induced seismicity by underground technologies has gained importance. A better understanding of the relevant processes involved is indispensable for being able to best assess the seismic risk and for minimizing related damages and casualties. This is where the SERA project sets in.

Mission

The Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe (SERA) aims to reduce the risk posed by natural and anthropogenic earthquakes based on innovative research and development projects.

SERA integrates data, products, infrastructures and know-how in seismology and earthquake engineering. Specifically, SERA…

…collaborates with researchers involved in previous seismology and earthquake engineering projects like EPOS, NERA, SHARE, SERIES, NERIES, and SYNER-G;

…facilitates access to ten high-class experimental facilities such as shaking tables and reaction walls;

…offers access to data and products in seismology and anthropogenic seismicity in Europe;

…promotes multi-disciplinary science across the domains of seismology, anthropogenic seismicity, near-fault observatories, and deep underground laboratories to achieve an improved understanding of earthquake occurrence;

…facilitates collaboration and innovations in the fields of deep seismic sounding, experimental earthquake engineering, and site characterization. It does so by expanding the access to seismological observations and infrastructures as well as by strengthening exchange within the expert's community.

Outcome

The joint efforts within SERA led to several remarkable outcomes. In the following, the key achievements are highlighted:

- transnational access to ten high-class earthquake engineering and array seismology facilities;
- virtual access to the main seismology data and products in Europe;
- substantial advance in the integration of seismology and earthquake engineering;
- European seismic hazard model for inclusion in the European design code;
- European seismic risk model, including physical and socioeconomic factors;
- promotion of multi-disciplinary science;
- inputs for the design of future experiments in seismology and earthquake engineering;
- new methods for real-time assessment of construction shaking and damage;
- new test results in the area of structure resilience;
- further development of school-level educational seismology;
- integration of past infrastructure projects.

Networking activities

SERA's networking activities were shaped to pool know-how, data, and tools to facilitate exchange between professionals and researchers from different fields. For this purpose, SERA organised several workshops for teachers, engineers and the interested public.

13 with **>2 500** from **38**

workshops   participants   countries
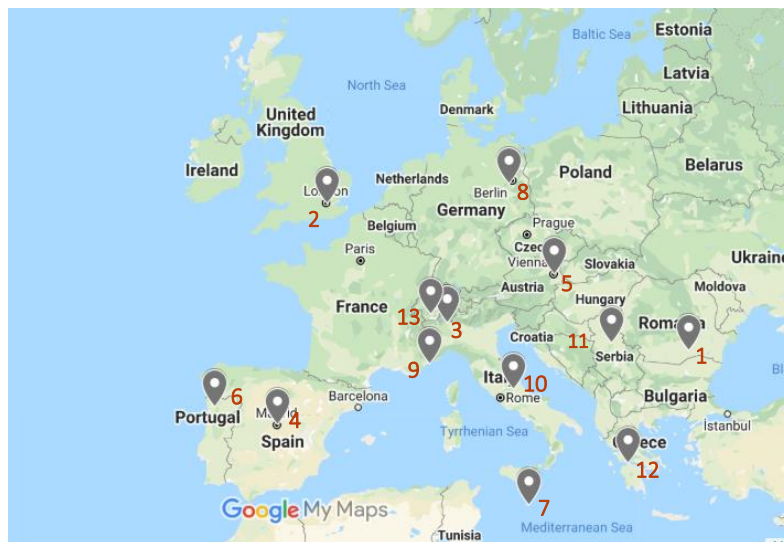
Location of workshops within SERA's networking activities

1. Romanian teachers' workshop in educational seismology, November 2017, Bucharest, Romania
2. Discussion workshop for educational and citizen seismology, February 2018, London, U.K.
3. Workshop on seismic hazard, March 2018, Ispra, Italy
4. EIDA – Iberian node workshop, March 2018, Madrid, Spain
5. Workshop on deep seismic sounding, April 2018, Vienna, Austria
6. Workshops for teachers in educational seismology, July 2018, Guimaraes, Portugal
7. European Seismological Commission General Assembly, September 2018, Valletta, Malta
8. Future design of seismic networks and instrumentation workshop, November 2018, Potsdam, Germany
9. Insight education meeting, January 2019, Nice, France
10. Strong motion site characterisation workshop, March 2019, L'Aquila, Italy
11. EIDA Balkans workshop, June 2019, Belgrade, Serbia
12. Seismology in education and society workshop, June 2019, Patras, Greece
13. ERA meeting and Mars@School workshop, February 2020, Sion, Switzerland

Networking seismo@school outreach programs

The networking activity aimed to widen the scope of past seismology@school initiatives to support newer educational programs in Romania, Portugal and Greece. This aim has been achieved by sharing experiences, resources and best practices, via workshops reaching more than 1 200 teachers and school-age students. The underpinning goals were to raise awareness of seismic hazard, risk and preparedness amongst local populations; to link schools with researchers and research data; and investigate the potential to use data acquired via citizen science in research and in near real-time operational reporting during earthquake crisis. It is perhaps very early to measure the direct impact of the workshops on local communities, but it is recognised that the effect of these events on ongoing networking activities has extended the reach and impact beyond SERA in numerous ways.

Examples of outreach programs:

- France: research data has been used in teaching by schools (the InSight Blind Test and MERMAID).
- Greece: 300 students in Patras engaged with citizen science via the LastQuake App and science fairs to promote earthquake resilience and awareness.
- Portugal: seismology at schools was widened via additional seismic sensors and sismologianaescola has developed experimental and digital resources for seismology earthquake preparedness and awareness.
- Romania: the National Institute for Earth Physics deployed a 'flipped classroom' approach to link research with schools and explain earthquake hazard to the public via a mobile exhibition (MOBEE).
- Switzerland: the Earthquake Education Centre (CPPS) was developed to raise awareness of seismic hazard, risk and preparedness; 4500 students and professionals visited the CPPS in the last three years.
- U.K.: the United Downs network of seismometers links nine schools with research and the geothermal industry.

Activity demonstrations and the MOBEE mobile exhibition panels during the 2017 teachers' workshop in Romania

Expanding access to the European seismic monitoring infrastructure

SERA fostered the collaboration between seismological observatories and the Observatories and Research Facilities for European Seismology (ORFEUS, www.orfeus-eu.org) in the Balkans and South-West Europe. The number of seismic stations providing data to the European seismological data infrastructure increased from about 7 000 to over 11 000 during SERA.

Access to seismological waveform data in the European Integrated Data Archive (EIDA) vastly improved during SERA through a) the implementation of standardised webservices across EIDA, b) the implementation of DOIs in metadata and c) the development and deployment of the Federator. The Federator provides a single, unified access point to waveform data from EIDA. EIDA fosters sustainable high quality of services by the establishment of a User Advisory Group, a ticketing system for reporting problems, and the implementation of a new authentication system for restricted data. Data quality is provided by the EIDA WFcatalog webservice, however new tools are being developed and tested.

Within SERA, a comprehensive overview of metadata for other geophysical data was made to prepare EIDA for other types of time series data (e.g. distributed acoustic sensing and near fault observatories). The EIDA StationBook (www.orfeus-eu.org/stationbook), providing interactive access to seismic station metadata, was completely redesigned and prepared for these other types of data.

Finally, SERA facilitated long-term sustainability of the EIDA infrastructure by the setup of a version-controlled documentation system, best practice guidelines for data acquisition and distribution, and technical support. Also, upcoming scientific questions and their impact on network design, data storage and services were evaluated to help preparing the European seismological infrastructure for these future challenges.

EIDA: 12 nodes, 4 EPOS compliant webservices	April 2017	April 2019	April 2020	SERA increase
Permanent networks	89	100	107	+ 18
Temporary networks	61	104	190	+ 129
Sensor networks	7 217	8 437	11 576	+ 4 359
- Seismometers	6 606	7 754	10 658	+ 4 052
- Accelerometers	1 243	1 269	1 626	+ 383
- Other (e.g. infrasound)	130	148	167	+ 37
- Multiple sensors	744	819	944	+ 200

European Integrated Data Archive (EIDA) in numbers (www.orfeus-eu.org/eida)

Networking deep seismic sounding data and products

SERA targeted to develop the networking and roadmap required to secure archiving European active seismology experiments and the required access service (discovery platform, data/metadata format and structure), covering, where possible, products ranging from raw data to interpreted structural models.

The Institute of Earth Sciences Jaume Almera (ICTJA-CSIC) has generated numerous data in the fields of geophysics, mineral geochemistry and volcanology, among others. The work within SERA provided a review of the most important seismic campaigns and a comprehensive dataset of geophysical data acquired in the Iberian Peninsula since the 1990's, both onshore and offshore. The Iberian Peninsula has attracted the attention of international researchers in the fields of geology and geophysics for decades due to the exceptional outcrops of the Alpine and Variscan mountain ranges, wide Cenozoic foreland basins, its offshore margins and its potential for

natural resources. The dataset was acquired at very different scales, from continental/crustal scale to local/exploration scale in different geographical and geological settings. The aim was to make old and recently acquired seismic data easily accessible and, therefore, set the basis for the future campaigns of seismic data acquisition in order to create a FAIR (Findable, Accessible, Interoperable and Reusable) dataset.

The dataset increased since the last two years following the national and international mandates of open access data. In addition, the statistics based on total visits and downloads since its beginning show an increased interest in the research carried out. According to these statistics, the dataset is being used more and more by users all around the world – mostly from USA and Canada, followed by European users and China being the third country in number of downloads.
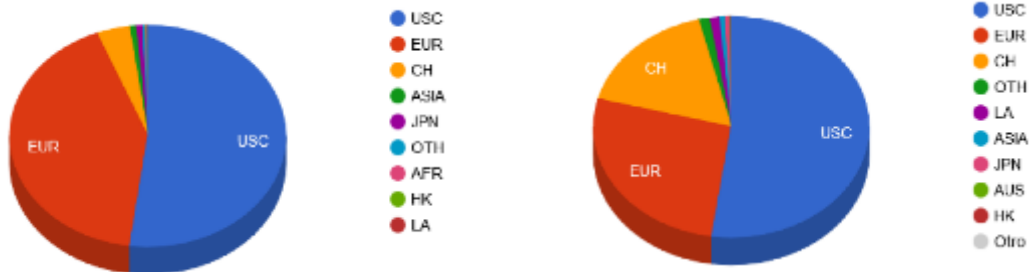
Total visits to the ICTJA-CSIS dataset per region, last access December 2019

Total downloads of data from the ICTJA-CSIS dataset per region, last access December 2019

USC: USA and Canada, EUR: Europe, CH: China, OTH: others or not defined, LA: Latin America, ASIA: Asia, JPN: Japan, South Korea and Taiwan, AUS: Australia and New Zealand, HK: Hong Kong, AFR: Africa.

Networking experimental seismic engineering databases

The SERIES (Seismic Engineering Research Infrastructures for European Synergies) project represents the most significant effort in Europe towards the interoperability of earthquake engineering experimental data. The work conducted in SERA fostered the networking of earthquake engineering experimental facilities in order to:

1. provide access to the databases of experimental testing results and analyses collected during the SERIES project,
2. build a common data archive and exchange tool,
3. expand the SERIES database with the most recent experimental data, incorporating also new data from SERA transnational access projects, and
4. design a new service provision for EPOS (European Plate Observation System).

A roadmap for the integration of data banks and access services from the earthquake engineering (SERIES) and seismology (EPOS) research infrastructures was proposed, namely with the integration of the SERIES databases in the existing EPOS service as a new Earthquake Engineering Thematic Core Service (TCS) and exploring possible interoperability with other TCSs (e.g. Seismology) and with international partners. This strategy is envisaged to be performed in three steps (short-, mid- and long-term).

Within the frame of SERA, the short-term goals have been fulfilled, i.e. it has been demonstrated that the SERIES metadata can be technically ingested into the EPOS test environment. The pre-operational access service is available for further validation and involvement of the user community and for further integration in EPOS.

Mid-term activities beyond SERA include a review if the newly developed services and products are fully compatible with the requirements of EPOS, at technical, legal, governance and financial levels.

Full integration of the earthquake engineering TCS in EPOS will be achieved in the long-term perspective by also providing access to research infrastructures, laboratories and data centres established outside Europe, thus improving the international dimension of EPOS. This new TCS will be a new important pillar of EPOS that will provide access to data, services and infrastructures that are important for other Thematic Core Services and the society at large.
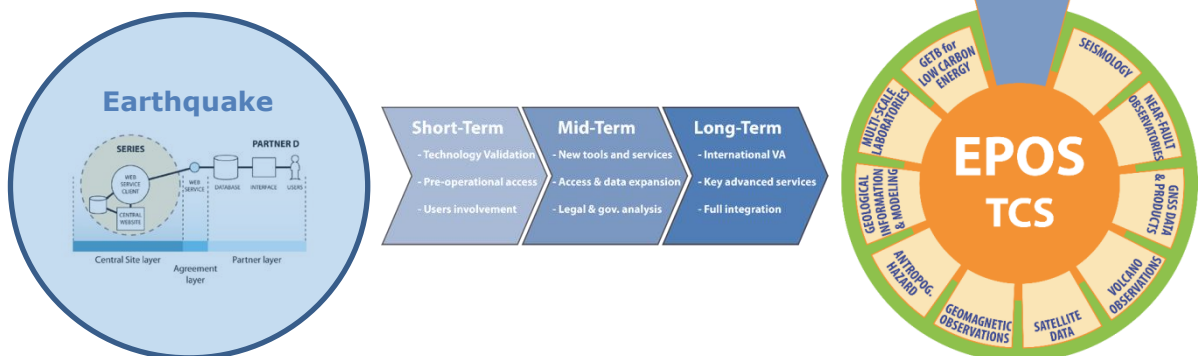
The strategy for integrating SERIES database in EPOS as a new Earthquake Engineering Thematic Core Service (TCS)

# Networking databases of site and station characterisation

This networking activity is leading to the definition of a European strategy and standards for site characterisation of seismic stations. Based on the results of an international online questionnaire, a list of indicators was defined as mandatory for a reliable site characterisation: fundamental resonance frequency, shear-wave velocity profile (V_s), time-averaged V_s over the first 30 m (V_{S30}), depth of seismological and engineering bedrocks, surface geology and Eurocode 8 soil class.

A summary report for each indicator is proposed, containing the most significant background information of data acquisition and processing details, and a quality metrics scheme. This requires the evaluation of both (i) reliability of the site characterisation indicators provided by different methods, and (ii) consistency among the indicators according to the current knowledge of the scientific community.

The applicability of broad site condition indicators or proxies, at a wide scale, was investigated to correlate them with measured local seismic amplification based on an extensive database comprising more than 1 000 instrumented sites in Switzerland and Japan. Furthermore, parameters derived from local geological models or databases generally show a stronger correlation with site amplification when compared to indicators from global models/databases.

The most relevant direct proxy to predict local amplification over a wide frequency range is the quarter-wavelength parameter. Predictions based on V_{S30} give satisfying results only in intermediate frequency bands (1.67 – 6.66 Hz) while all direct site condition indicators, except the quarter-wavelength parameters, perform well in low and intermediate frequency bands (≤6.66 Hz). For indirect proxies (topography, geology, etc.), the prediction performance at all frequency bands shows best results when using all information that is available. The study also clearly outlines the importance of common geological classification from maps with different origins and scales.
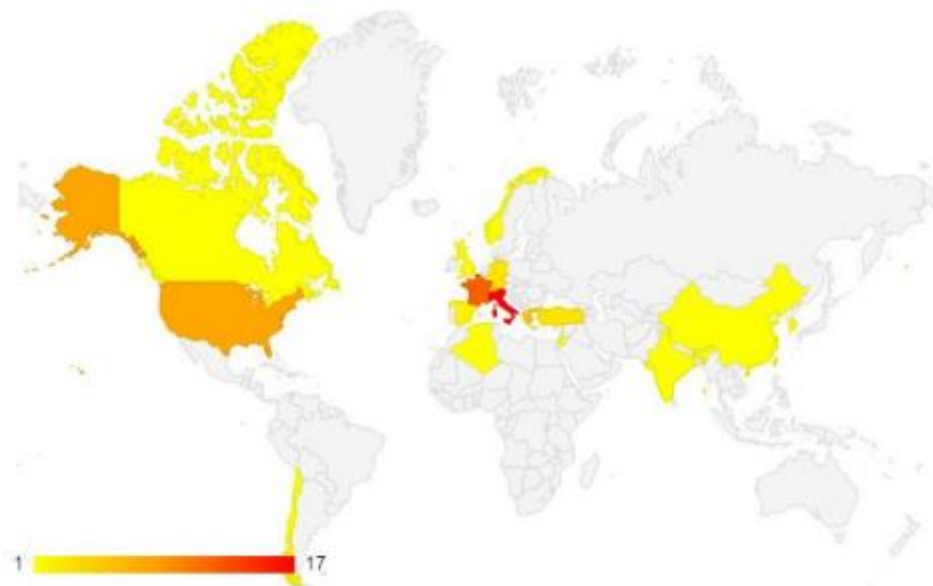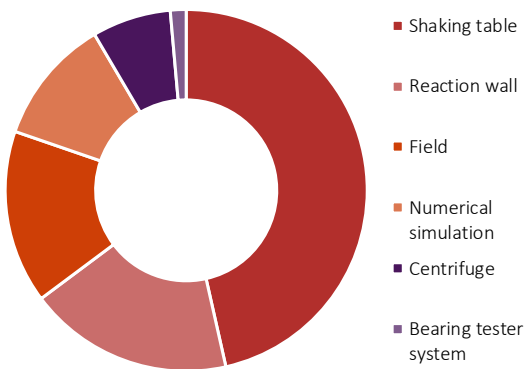

Countries contributing to the online questionnaire regarding the site characterisation in seismic site response sites: colours are proportional to the number of researchers; about 300 research groups contributed, 69 % from Europe and 31 % from other countries

Access to research infrastructures

SERA offered access to the largest collection of high-class experimental facilities for earthquake engineering in Europe to talented researchers from both academia and industry. The research facilities comprise reaction walls, shaking tables, facilities for integrated studies on geotechnical site effects and engineering seismology as well as an infrastructure for array seismology.
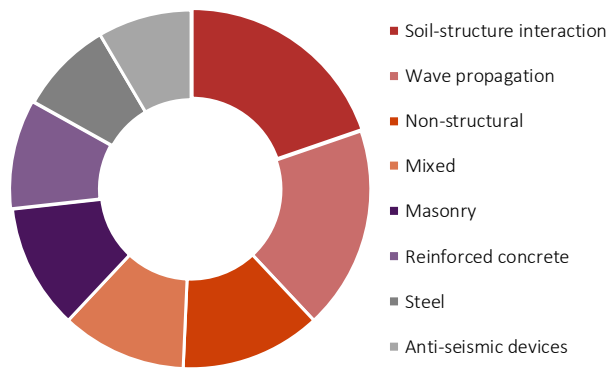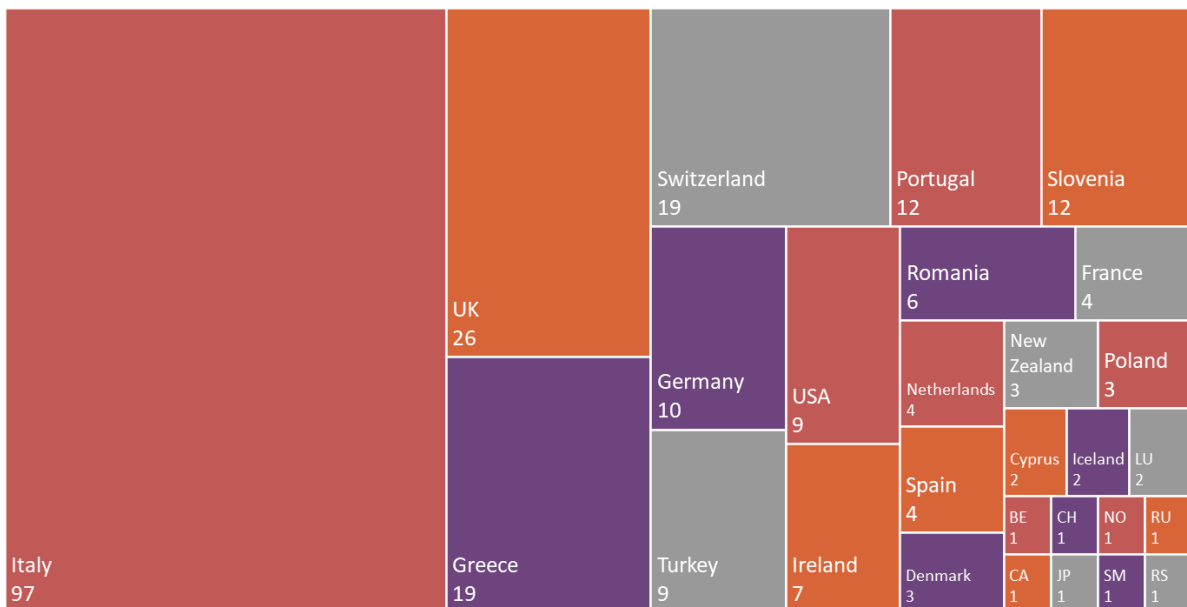
71
projects proposed

44
projects selected

261
users

- Shaking table
- Reaction wall
- Field
- Numerical simulation
- Centrifuge
- Bearing tester system

Testing techniques in proposed projects

- Soil-structure interaction
- Wave propagation
- Non-structural
- Mixed
- Masonry
- Reinforced concrete
- Steel
- Anti-seismic devices

Type of specimen in selected projects

Italy 97

UK 26

Greece 19

Switzerland 19

Germany 10

Turkey 9

USA 9

Ireland 7

Portugal 12

Slovenia 12

Romania 6

France 4

Netherlands 4

New Zealand 3

Poland 3

Spain 4

Denmark 3

Cyprus 2

Iceland 2

LU 2

BE 1

CH 1

NO 1

RU 1

CA 1

JP 1

SM 1

RS 1

Number of users by country

Reaction walls

ELSA, Joint Research Centre

The ELSA reaction wall consists of a reinforced concrete vertical wall, which is rigidly connected to a horizontal floor, allowing to test the impact of earthquakes and other hazards on the vulnerability of buildings.
More information: https://ec.europa.eu/jrc/en/research-facility/elsa

STRULAB, University of Patras

STRULAB is particularly suited to seismic testing of small to medium-sized structures. It has an 18 m x 16 m strong floor and two 5.5 m tall strong walls in an orthogonal configuration for biaxial testing. Its main equipment comprises eight actuators (capacities 360 kN-1 MN, strokes ±0.25-1.0 m) and nine pistons (300-1000 kN capacities).
More information: www.strulab.civil.upatras.gr

Shake tables

Shake lab bearing tester and shake table, EUCENTRE

EUCENTRE offers a bi-axial bearing bester system for testing full-scale bearing and isolation devices with five degrees of freedom and with high dynamic and forces capabilities: vertical forces up to 50 MN and horizontal forces up to 2 MN with horizontal displacements of ±480 mm. This experimental equipment is unique in Europe.
The shaking table simulates any real event that has been measured in order to test large-dimension prototypes. The structure of the table is a honeycomb-like steel network guaranteeing high stiffness and reduced mass, compatible with the forces developed during the structural tests. Six guides, supported with hydrostatic bearings, ensure minimum friction.
More information: www.eucentre.it/shakelab-laboratory

AZALEE, TAMARIS/CEA

The AZALEE shaking table, with 100 t allowable model mass, is one of the largest shaking tables in Europe. To date, tests with masses up to 92 t have been successfully performed. The shaking table is 6 m x 6 m and 6 Degrees-of-Freedom (DoF), and allows to test specimens under independent excitations of various types: sinusoidal, random, shock and time-history with 0 to 100 Hz frequency ranges.
More information: www-tamaris.cea.fr

3D shake table, LNEC
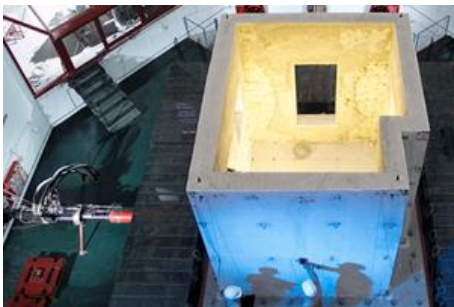
The LNEC-3D shake table is capable of testing large civil engineering structures subjected to seismic actions of different intensities up to imminent collapse condition of structures or substructures. The specimens can be in real or in reduced scale depending on the dimensions of the prototype.
More information:
www.lnec.pt/estruturas/en/core/earthquake-engineering-and-structural-dynamics-unit

EQUALS, University of Bristol

This shaking table comprises a 3 m x 3 m platform supported by eight hydraulic actuators. The table can carry up to 15 t and (depending on the loading) can reach acceleration levels up to 5 g with peak displacements of ±150 mm, making it ideal for testing specimens to destruction.
More information:
www.bristol.ac.uk/engineering/research/earthquakegeo

DYNLAB, IZIIS

DYNLAB offers a five-degrees-of-freedom MTS shaking table. It is presently one of the most advanced shaking tables since it is operated with a new state-of-the-art digital control system produced by MTS as the most renowned producer of these simulators.
More information: www.iziis.edu.mk

Centrifuge

Centrifuge, University of Cambridge

This 150 g-ton machine can carry payloads of up to 1 t. It is used to test soil-structure systems like buildings with pile foundations, retaining walls at the correct prototype stresses and strains. To model earthquake, loading specialist actuators are mounted on the centrifuge swings that deliver earthquake input motions to the model soil-structure systems.
More information: www-geo.eng.cam.ac.uk

Field testing

EUROSEISTEST & EUROPROTEAS, Aristotle University

EUROSEISTEST combined with the EUROPROTEAS and its data providing web portal is among the most powerful and advanced large-scale infrastructures in Europe and supporting advanced research in earthquake engineering, geotechnical earthquake engineering, soil dynamics and seismology worldwide.
More information: http://euroseisdb.civil.auth.gr

Array Seismology, NORSAR

The infrastructure at NORSAR consists primarily of a data centre and field installations on Norwegian territory and the European Arctic, comprising four different seismic arrays (with apertures ranging from 1 to 60 km equipped with 1C or 3C short-period or broadband sensors) and three single 3C broadband stations.
More information: www.norsar.no

Transnational access projects

Transnational access was provided to selected talented researchers for the design and the implementation of the testing campaign. The services given to the users ranged from the collaboration with national and international experts in the field, to technical assistance in the definition of the specimen, the testing setup and protocol and assistance for the proper instrumentation choice and positioning, data-processing, results interpretations and advanced numerical modelling.

The following transnational access projects were developed:

1. Multi-hazard performance assessment of structural and non-structural components subjected to seismic and fire following earthquake by means of geographically distributed testing
2. Slab structural response for seismic European design
3. Dynamic testing of variable friction seismic isolation devices and isolated systems
4. Seismic resilience of museum contents
5. Full-scale experimental validation of steel moment frame with EU qualified joints and energy-efficient claddings under near fault seismic scenarios
6. (Towards the) ultimate earthquake-proof building system: development and testing of integrated low-damage technologies for structural and non-structural elements
7. Seismic response of masonry cross vaults: shaking table tests and numerical validations
8. Seismic assessment of reinforced concrete frames with smooth bars : proposals for EC8-Part 3
9. Effect of axial restraint on the seismic behaviour of shear-dominated coupling beams
10. Seismic response of novel integral abutment-bridges
11. Statistical verification and validation of 3d seismic rocking motion models
12. Response of as-built and strengthened three-leaf masonry walls by dynamic tests
13. Influence of the floor-to-wall interaction on the seismic response of coupled wall systems
14. Seismic behaviour of anchored steel sheet-piling retaining walls: experimental investigation, theoretical interpretation and guidelines for design
15. Structure-tunnel interaction in liquefiable sand
16. On the broadband synthetic signals enhancement for 3D physic-based numerical analysis, the EUROSEISTEST case study
17. Blind beamforming in array processing
18. Seismic response of actual steel silos
19. Seismic testing of adjacent interacting masonry structures
20. Hybrid testing of an existing steel frame with infills under multiple earthquakes
21. Ductile steel fuses for the protection of critical non-structural components
22. Seismic behaviour of scaled models of groin vaults made by 3D printers
23. Investigation of seismic deformation demand, capacity and control in a novel self-centring steel braced frame
24. Seismic behaviour of rigid pile inclusions
25. Change of seismic motion due to pile-soil kinematic interaction
26. Dynamic soil structure interaction: 3D time-domain analysis of field model scale experiments
27. Seismic impedance for soil-structure interaction from on-site tests
28. Ambient and forced vibration techniques for improving design and performance assessment of structures with consideration of soil-structure interaction
29. Seismic site effects in sedimentary basins from 3D physics-based numerical modelling
30. Comparison of rocking on rigid and compliant base using the EUROPROTEAS real-scale facility
31. Seismic tremor detection in Greece using small aperture arrays

32. The velocity model up to 300 km deep using NORSAR array data (Baltic shield) based on p and s receiver functions
33. Joint processing of seismo-acoustic array data as tool to discriminate between man-made explosions and earthquakes
34. Seismic performance of multi-component systems in special risk industrial facilities
35. Shaking table testing for near fault effect evaluation
36. Soil-structures interaction effects for steel structures
37. Infills and masonry structures protected by deformable polyurethanes in seismic areas
38. Resonant metamaterial-based earthquake risk mitigation of large-scale structures and infrastructure systems: assessment of an innovative proof-of-concept via medium-size scale testing
39. Dynamic identification and monitoring of scoured bridges under earthquake hazard
40. Soil frame-interaction analysis through large-scale tests and advanced numerical finite element modelling
41. Earthquake spectral provisions and urban fragility evaluation
42. Beamforming of aftershock strong-motion time-histories recorded on the ICEARRAY for earthquake source studies
43. Investigation of (micro)seismicity of the Laptev Sea using a small-aperture array
44. Design, location and processing of a regional array in SW Portugal – Europe

See all projects at https://sera-ta.eucentre.it.

Access to data and products

To understand the nature of earthquakes, seismologists need data from historical earthquakes as well as from earthquakes caused by human activities, such as drilling or fracking. Collecting these data is resource intensive. SERA facilitates access to data and products of seismology, engineering seismology and anthropogenic seismicity.
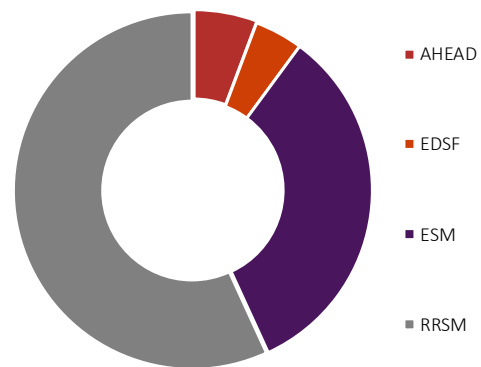
177 725
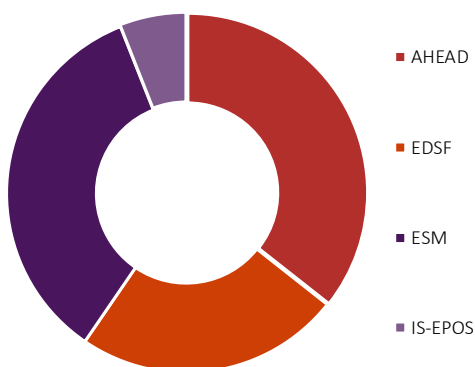### unique visitors
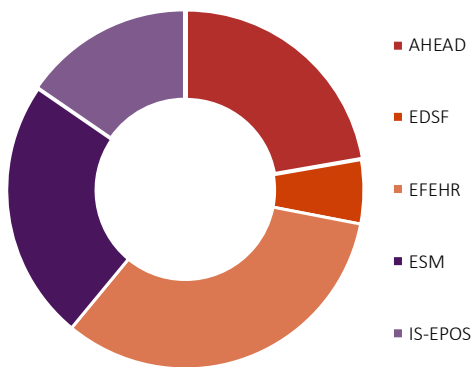
Unique visitors by service

- AHEAD
- EDSF
- EFEHR
- ESM
- IS-EPOS

> 10×10^6
requests for data

Requests for data by service

- AHEAD
- EDSF
- ESM
- RRSM

visitors from 155 countries

Countries of origin of visitors by service

- AHEAD
- EDSF
- ESM
- IS-EPOS

AHEAD: European archive of historical earthquake data portal

EDSF: European database of seismogenic faults

EFEHR: European facilities for earthquake hazard and risk

ESM: Engineering strong motion database

IS-EPOS: Platform for induced seismicity and anthropogenic hazard

RRSM: Rapid raw strong motion database

Access to seismological products and information

Within the SERA project, the European-Mediterranean Seismological Centre (EMSC) has developed and maintained a service that provides access to the eyewitness data collected in real time by EMSC.

EMSC gives access to all collected seismic and eyewitness data and takes care of traffic measurements of its services. The traffic monitoring shows the overall popularity of the EMSC among the general public and the seismological community. The desktop and mobile EMSC websites (www.emsc-csem.org and http://m.emsc-csem.org) are the traditional places to find real-time data and search for earthquakes information and more information about EMSC. Contrary to Twitter or the LastQuake mobile application, websites are often used by seismologists.

People who feel an earthquake and want to share their experience have the opportunity to evaluate the level of shaking via EMSC's services by selecting from a collection of thumbnail images (felt reports). This approach replaced the traditional online questionnaire of the LastQuake mobile application and the mobile website. These thumbnails are available to anyone who wants to integrate them in their collection system, offering the chance to homogenise data collection amongst institutes.

In addition to the felt intensity, each felt report has an individual geographical location. Felt reports are collected in real-time and associated to seismic events received by the EMSC. Moreover, felt reports are collected from all continents and, generally, almost 50 % of felt reports are collected only 10 minutes after the earthquake occurrence.

The popularity of felt report data is increasing and beginning to interest the scientific community. Several ongoing studies are trying to incorporate felt intensities in the construction of shakemaps and to constraint rupture models. This service is a valuable resource for such endeavours.
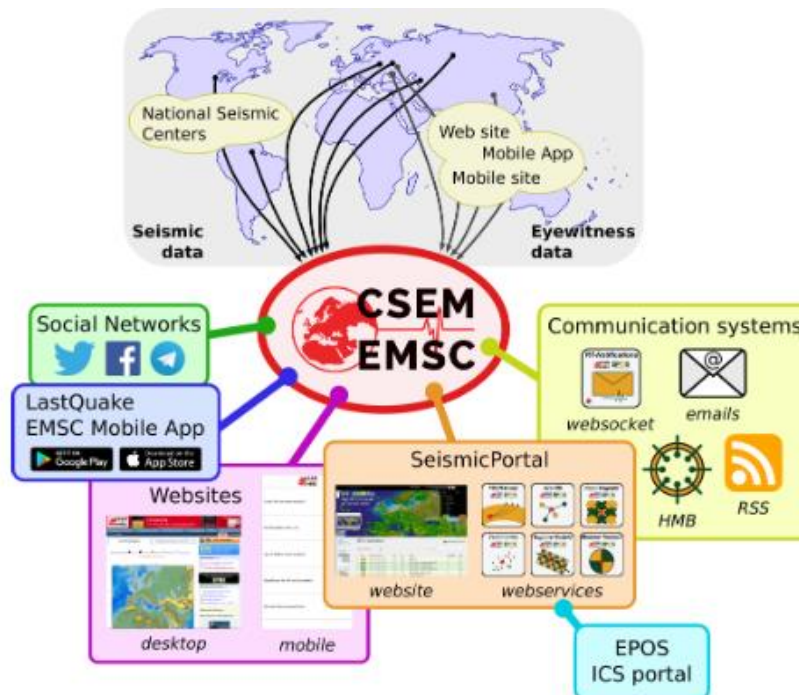
Overview of the main EMSC (European-Mediterranean Seismological Centre) services

www.emsc-csem.org | www.seismicportal.eu | www.resorce-portal.eu
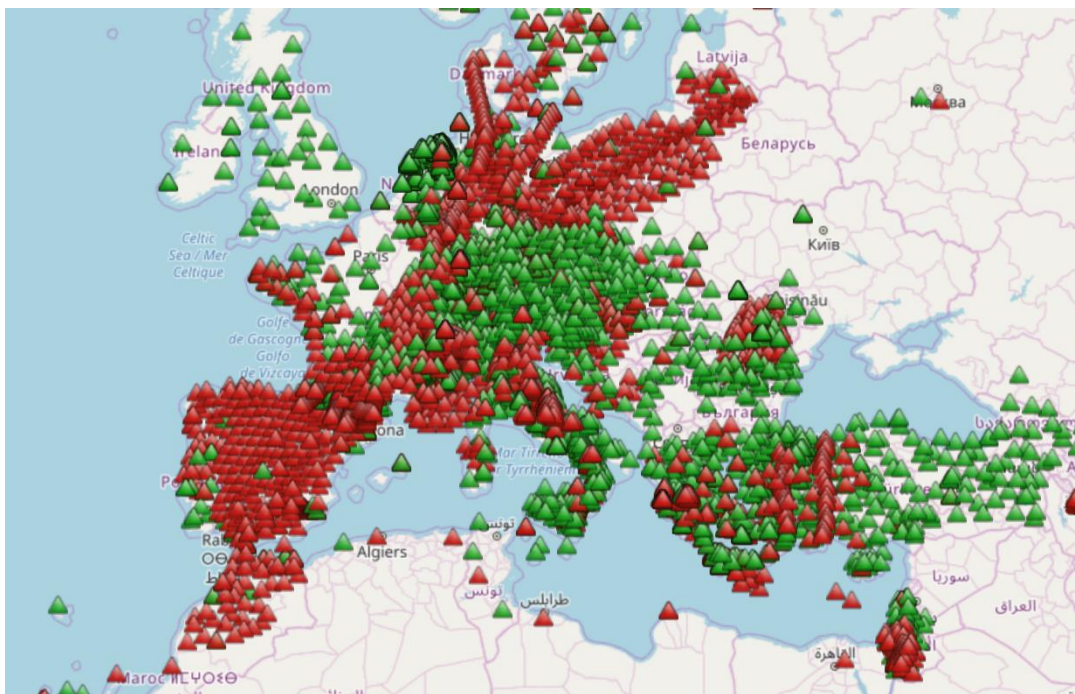
Access to seismic waveforms

The ORFEUS infrastructure (www.orfeus-eu.org) is one of the largest infrastructures in the world to provide seismological waveform data and derived products for the scientific research community. The infrastructure comprises European seismological networks, seismic monitoring observatories, waveform data archives and data services. A key component is the European Integrated waveform Data Archive (EIDA; www.orfeus-eu.org/eida) that federates 12 European data archives with 450 TB of data from nearly 300 seismic networks with a total of more than 11 000 seismic stations.

ORFEUS offers internationally standardised services to the solid Earth research communities to access raw waveform data, related metadata and data products. These services comprise: ORFEUS website, EIDA data access portal, EIDA webservices, RRSM (Rapid Raw Strong Motion) database (www.orfeus-eu.org/rrsm) and EIDA StationBook (www.orfeus-eu.org/stationbook).

SERA leveraged the amount of data available through EIDA significantly, fostered the standardisation of services and metadata to its current internationally accepted level and vastly progressed the evolution of ORFEUS services to be aligned and compatible with EPOS.

Moreover, interactive services like StationBook and RRSM have been re-designed with modern technologies to offer flexibility with respect to on-going, changing community requirements. Finally, the ORFEUS EIDA infrastructure started to deploy the EIDA Federator, a service to offer a one-stop-shop to access EIDA. Together with migration into cloud computing, these developments will provide a unique platform in seismology for fast and efficient accessing and processing of data over the Internet for the scientific earthquake engineering and risk research communities.

The ORFEUS / EIDA infrastructure provides access to raw seismological waveform data and related metadata from more than 11 000 sensors throughout Europe and beyond, obtained by permanent (green) and temporary (red) seismic networks

Access to data and services for engineering seismology

The access to data and services for engineering seismology includes the following databases: the engineering strong motion database (ESM), the European archive of historical earthquake data (AHEAD), and the European database of seismogenic faults (EDSF).

ESM is a centralised collector of strong motion data for earthquakes with M ≥ 4. It archives the waveforms recorded since 1969 by about 50 seismic networks and provides end-users with quality-checked and manually processed waveforms.

AHEAD is a distributed archive aiming at preserving, inventorying and providing, to investigators and other users, data on the earthquake history of Europe (in the period 1000-1899), including macroseismic data points or parametric catalogues.

EDSF collects and grants access to data on geometry and behaviour of seismogenic faults for earthquakes of M ≥ 5.5 in the Euro-Mediterranean region. It deals with 1 128 crustal faults and three subduction zones.

The three databases deal with intrinsically diverse data that can now be accessed through a single access point via web services. They have been and are currently used by the seismological and the engineering seismology communities in the analysis of seismic and tsunami hazards, in risk analyses, tsunami early warning systems, and various types of natural earthquake scenarios.
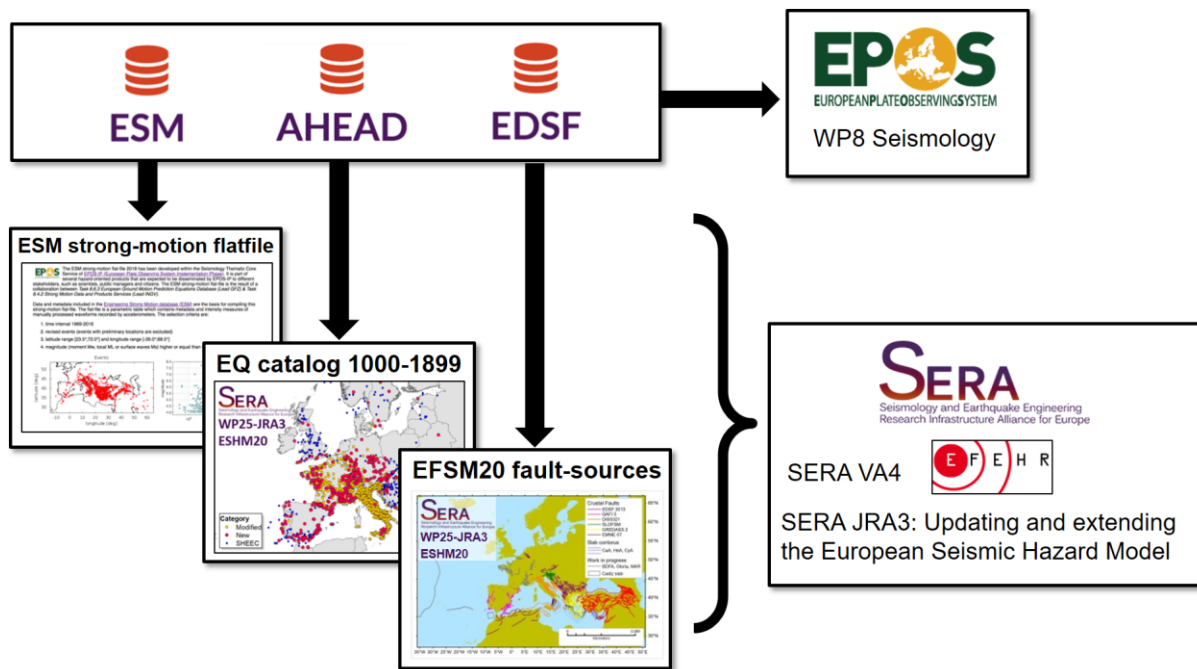
Access to data and services for engineering seismology within SERA activities includes the engineering strong motion database (ESM), the European archive of historical earthquake data (AHEAD) and the European database of seismogenic faults (EDSF)

http://sera-va3.rm.ingv.it | esm.mi.ingv.it | www.emidius.eu/AHEAD | www.seismofaults.eu

# Access to earthquake hazard and risk products

Within SERA, the European Facilities of Earthquake Hazard and Risk (EFEHR, www.efehr.org) has been developed and maintained. EFEHR provides interactive gateways to access and visualize seismic hazard and risk models across the Euro-Mediterranean region. The web-platform is the host of the 2013 European seismic hazard model, of the new coming 2020 European seismic hazard (also an outcome of SERA's research activities) and risk models (outcome of SERA research activities).

The web-traffic analytics of the EFEHR web-portal indicates worldwide visitors. A total number of 58 000 unique visitors with a monthly average of about 2 500 new users have been accessing and/or visualising the hazard data, models and products (hazard maps, curves and spectra). An average of 6 000 requests per month are observed for all the web-services. In terms of outcomes resulting from this access, there are about 650 citations

of the datasets, results, models provided by EFEHR web-portal since 2013.

The statistics of the web-traffic analytics, indicate that EFEHR web-platform is invaluable in better communicating seismic hazard to decision-makers and the general public. This is illustrated by the increase of new users when a new dataset is published. As an example, earthquake model for the Middle East was published in June 2018, and the increase on the new users was recorded in November due to the occurrence of significant earthquakes in Europe, i.e. the 5.4 M_w earthquake in France (November 11th) and the 6.4 M_w earthquake in Albania (November 24th).

To conclude, there is considerable interest in the information available on the website, and the EFEHR web-platform provides valuable resources to scientists, academia, engineers, insurance, commercial entities, decision makers and the general public.
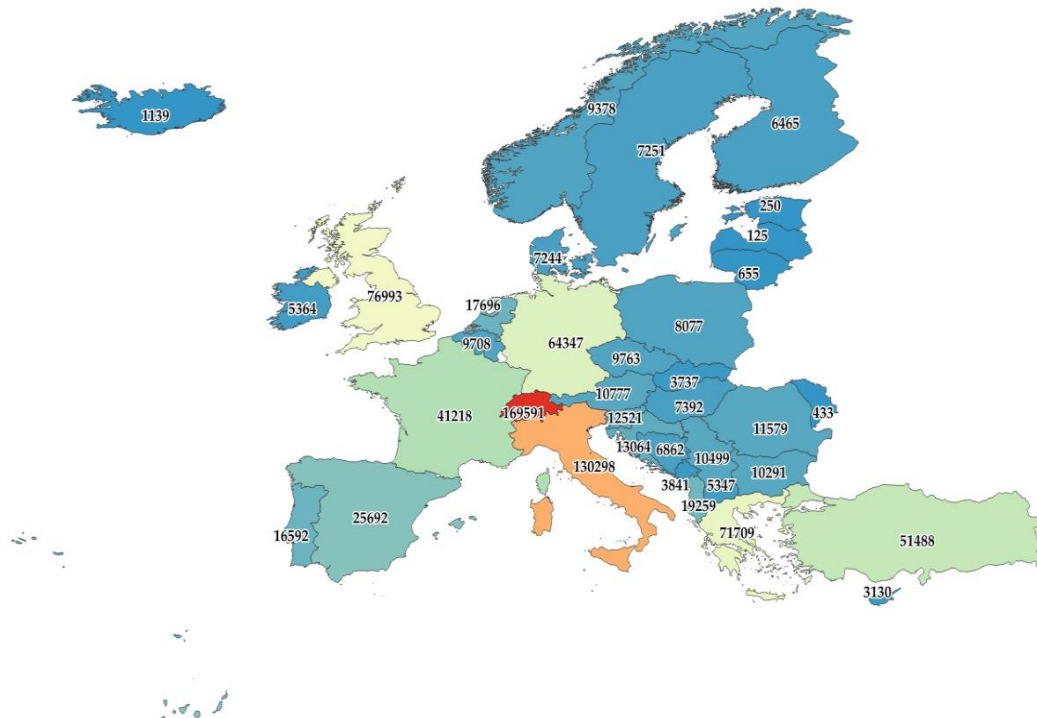
Spatial distribution of the user access of EFEHR web-portal per country in Europe between March 2019 and February 2020

Access to data and products of anthropogenic seismicity

In the frame of SERA, virtual access was provided to new data from all types of anthropogenic activities that induce seismicity from underground mining, geothermal energy production, oil and gas exploration and exploitation, water reservoir filling and many other sources.

These so-called episodes hold seismological data as well as provide crucial information about the reactive process itself, like data on mining front advances, water level changes or injection rates.

The central tool for hosting, managing, or analysing this kind of data is the IS-EPOS platform for induced seismicity and anthropogenic hazard (https://tcs.ah-epos.eu). The platform is permanently being developed, formerly under the IS-EPOS and EPOS-IP (EPOS implementation phase), now under the EPOS-PL (Polish national contribution towards EPOS infrastructure) projects.

The platform also offers tools with which the users can easily gain an overview of the wide range of datasets, and perform detailed analyses and visualisation of the selected episodes. Together, this linking of data with analysis tools is dedicated to scientists, engineers, public entities and to the interested public.

The frequency of use of some selected applications and the worldwide usage of the platform was recorded. The increasing number of users demonstrates the usefulness of the platform for the European as well as for a wider international researcher community.

Future developments will comprise enhancements of tools for collaboration among users. The major emphasis lies on fostering comparative studies between many cases worldwide, which will allow more reliable hazard estimates.

Worldwide use of the IS-EPOS platform

Research activities

How earthquakes start and evolve is one of the big unsolved problems in earth sciences. SERA contributes to answering this question with multi-disciplinary science and joint research activities targeted on pooling data and expertise. This approach shall lead to an improved understanding of why earthquakes occur. SERA also delivers hazard and risk-related products, which are based on the integration of competences from different domains.

Physics of the earthquake initiation

For progressing on the short-term prediction of earthquakes, in a probabilistic sense, work is necessary both on statistically significant sets of observations, and on the refinement of robust, physics-based models of earthquake initiation and triggering. Within SERA, work focused in: i) natural seismicity in the active faults systems of Italy, Greece, Chile, Turkey; ii) induced seismicity in an industrial context (geothermal area of Geysers, active mines in Sweden and Poland), and iii) deep underground laboratory experiments with water injection in Switzerland.

As a result of SERA's activities, several automated procedures were developed and are freely available on various platforms, like IS-EPOS (induced seismicity European plate observing system, https://tcs.ah-epos.eu) or Github, for better resolving and characterising in real-time the relevant parameters of the microseismicity, like location, magnitude, fault mechanism, size of rupture, and stresses. Such advances allow better detecting the start of mechanical instability, possibly leading to failure of major faults.

The space-time evolution and dynamics of the microseismicity, spanning months to decades, sometimes complemented by high-resolution measurement of strain, has revealed the importance of unstable, transient slow slip and water pressure migration in the fault zones. These sometimes coupled processes may force the initiation of large seismic ruptures and can contribute to identifying the location and size of threatening patches of the faults. They, thus, bring valuable information for short- and long-term seismic hazard, whether natural or induced, to be rapidly interpreted and communicated, when relevant to the local authorities or to the operating industry.
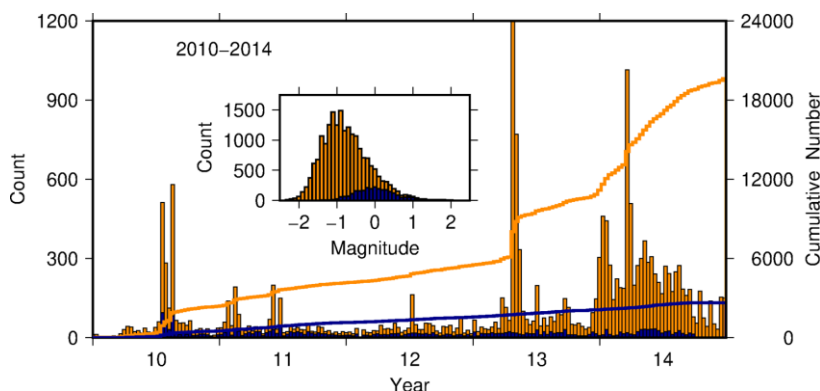

Cumulative seismicity in the Alto Tiberina Fault (Italy) for the original catalogue (blue) and for the catalogue enriched with the events extracted by the template matching method (orange)

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Characterising the activity rates of induced and natural earthquakes

Within SERA, the general problem of characterising the statistical properties of past earthquake occurrence to refine the capability of forecasting the future probability of occurrence was addressed. Owing to the increasing amount of high-quality data and the sophistication of recent hazard analysis, many of the assumptions and processing tools commonly used for statistical seismicity and hazard analysis are rapidly becoming obsolete. This research activity has refined the analysis tools and used them on applications and testbeds of natural and anthropogenic seismicity, to deliver a validated set of statistical tools for the analysis of earthquake occurrence at different spatial and temporal scales. The following results have been obtained at various scales (local, regional and European):

- New tools (e.g. PyMPA algorithm) have been developed and can be successfully used in identification of new events related to induced seismicity.
- Testing datasets (e.g. Grimsel) and test bench framework have been developed.
- Regional seismicity (e.g. Italy) analysis have shown that i) traditional declustering methods in probabilistic seismic hazard analysis may result in underestimation of seismic hazard and ii) short-term seismic clustering significantly impacts long-term seismic hazard.
- A new and harmonized M_L magnitude scale has been developed for applications where small-magnitude earthquakes rates need to be characterised and local-to-moment magnitude conversions are required.
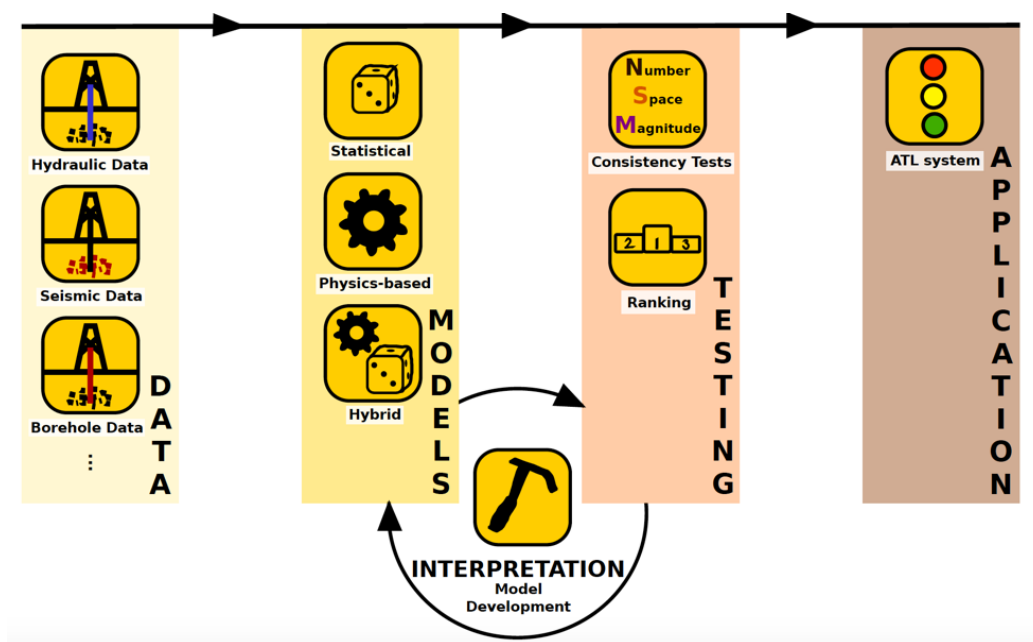
Test bench for induced seismicity evaluation

# Updating and extending the European seismic hazard model

Since the last European seismic hazard model was released in 2013, there have been several advances in the available data and in our understanding of ground motions caused by large earthquakes. Within SERA, the 2020 European seismic hazard model (ESHM20) was produced, providing an updated version of the earthquake hazard assessment of the Euro-Mediterranean region. The ESHM20 development phase involved several regional workshops where the national experts have been consulted, and their feedback was acknowledged and considered.

The newly-developed seismogenic source model encompasses fully harmonised as well as cross-border seismogenic sources and is following the recent national earthquake hazard models. The ground motion characteristic model is built upon the most complete ground shaking recordings in Europe. It aims at capturing the effects of source and attenuation path of the expected ground shaking at a site. The regional variability of ground shaking is assessed based on the most updated dataset of ground motion recordings across Europe. A novel statistical approach was developed to assess the regional ground motion characteristics, and the overall uncertainties are handled in a backbone logic tree. Finally, a complex input model, handling the intrinsic epistemic uncertainties of both seismogenic sources and ground shaking models, was used for assessing the earthquake ground shaking across the entire Euro-Mediterranean region.

A full set of hazard results such as hazard curves and maps as well as uniform hazard spectra is provided for the entire region covered by ESHM20. Two additional hazard maps describing the spatial distribution of the engineering spectral factors are also provided with a uniform probability of exceedance of 10 % in fifty years. These two factors will form the basis of the future update of Eurocode 8 (the European seismic design code).

All datasets, key components and results are open for access and re-use at the web-platform of European Facilities of Earthquake Hazard and Risk (www.efehr.org).
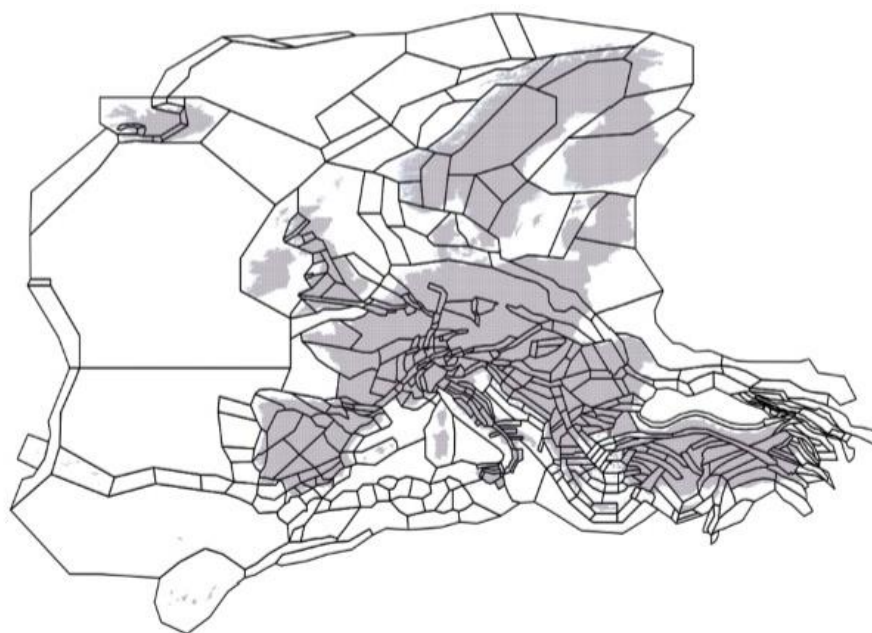
Updated area source model of Europe and Turkey comprising new seismogenic sources

Risk modelling framework for Europe

A European seismic risk model will be released in 2020 (ESRM20) as a direct output of SERA, building also upon the research efforts of many previous projects. The hazard component of this risk model is being developed within SERA, and this will be combined with European exposure and vulnerability models for the residential, commercial and industrial building stock that have also been developed.

The European exposure model (https://eu-risk.eucentre.it/exposure) describes the distribution of the count, replacement cost and occupants of buildings, classified according to their seismic performance, for 45 European countries. It is based on best available and publicly accessible datasets and studies, as well as the contribution of several local experts (https://eu-risk.eucentre.it/contributors). A significant contribution that distinguishes this exposure model from other similar efforts, is the data collected of the temporal and spatial

evolution of seismic design in Europe over the past 100 years.

Physical vulnerability models were developed by combining analytical fragility models with semi-empirical consequence models that relate the damage level with the probability of loss. For the engineered buildings in the exposure model, a simulated design is undertaken for the design codes and a range of lateral force coefficients, thus directly connecting the vulnerability model to the exposure model.

The main risk metrics that will be released include national and sub-national maps of average annual loss and probable maximum loss and national loss exceedance curves.

All of the models and datasets will be released with Creative Commons licenses through the https://gitlab.seismo.ethz.ch/efehr repository and maps of risk results will be made available at https://maps.eu-risk.eucentre.it.
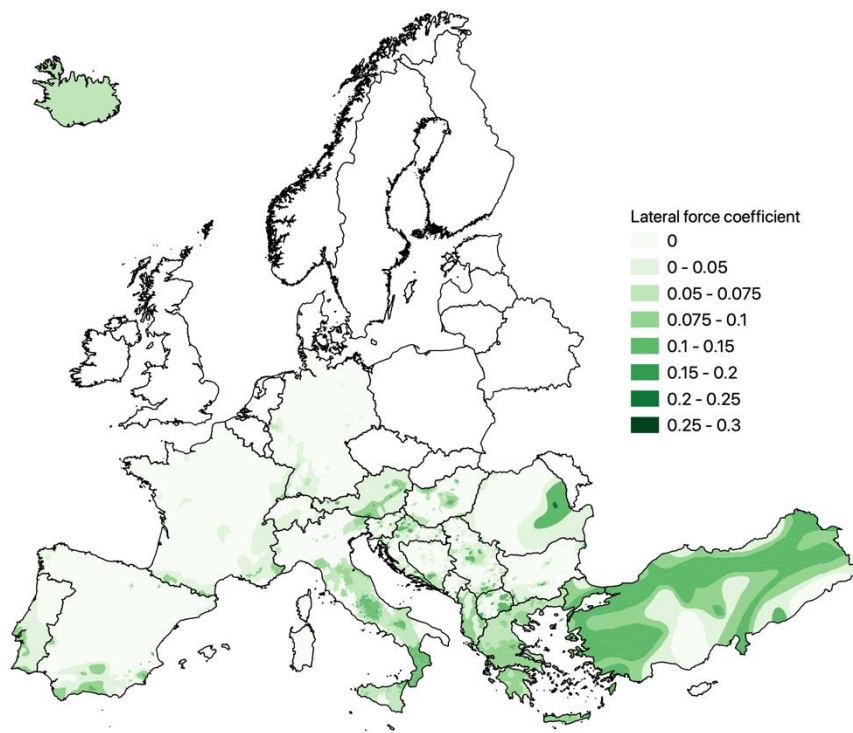
Spatial evolution of the design lateral force (as a fraction of the building weight), as specified in the first generation of seismic design codes in Europe

Innovative testing methodologies for component/system resilience

Inspired by recent findings in the field of metamaterials, finite lattice locally resonant metafoundations (RF) and resonant metabarriers (RM) represent an innovative solution for the seismic protection of whole industrial plants and their components.

RFs were conceived to be used as a foundation system endowed with the capability to effectively isolate a large component or structure from low-frequency seismic bulk P and S waves. Conversely, RMs were imagined to be placed within the ground around a component, a structure, or a cluster of structures. Furthermore, it is purposely designed to interact and reduce the incoming surface waves.

With regard to RFs, optimisation procedures were developed in the frequency domain to design resonators stiffness and damping ratio. Time-history analyses validated the efficacy of the proposed systems both for operating basis and safe shutdown earthquakes.

As regards RMs, the performance of a medium-scale metabarrier was tested. The barrier was designed according to the stratigraphy of the site, exploiting dispersion curves and time-history analysis developed within a FE framework. The experimental tests, designed according to such numerical indications, are expected to confirm a significant attenuation of the ground motion.
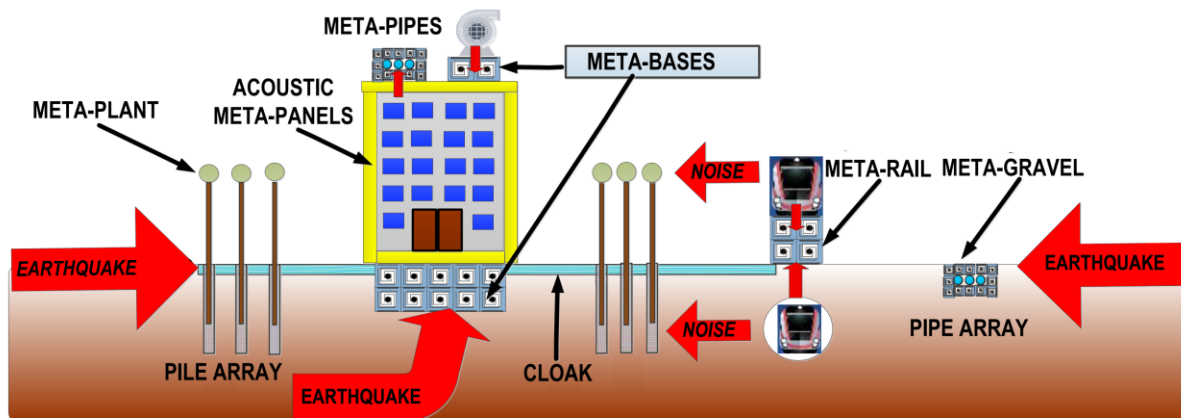
Schematic presentation of the metamaterial concept

Real-time earthquake shaking

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 shortly after the rupture. The final main outcome within SERA was the provision of rapid estimates of exposure and qualitative assessment of the impact of an earthquake and its strong ground shaking.

Procedures for rapid assessment have been developed using very diverse approaches. For example, the European Mediterranean Seismological Centre (EMSC) uses crowdsourced data to detect earthquake damage and perform a very fast estimate of the location and magnitude estimate of felt earthquakes. Also, the near real-time system for estimating the seismic damage in Romania and the ARISTOTLE project (All Risk Integrated System TOwards Trans-boundary hoListic Early-warning; http://pilot.aristotle.ingv.it/) provide a rapid calculation of exposure and a qualitative assessment of impact. The services developed within the framework of SERA to ease access to public databases will provide more complete descriptions of exposure and impact assessment.

INGV (National Institute of Geophysics and Volcanology, Italy) and SED (Swiss Seismological Service at ETH Zurich) have started the migration of their institutional ShakeMap systems to the new USGS version 4.0. this new version features an improved interpolation method and makes use of the ground motion models as implemented in OpenQuake. The transition of the European prototype system to v4.0 is planned along with further community-building activities.

Within SERA, an approach that combines crowdsourced earthquake detection with seismic data from the GEOFON global networks was followed to produce faster and reliable estimations of earthquake location. In the best cases, when the station coverage is adequate in the region, seismic locations can be obtained in less than one minute of the origin time. It is a cheap way to improve earthquake network time performance at little cost, for felt earthquakes where the public desire for information is high.
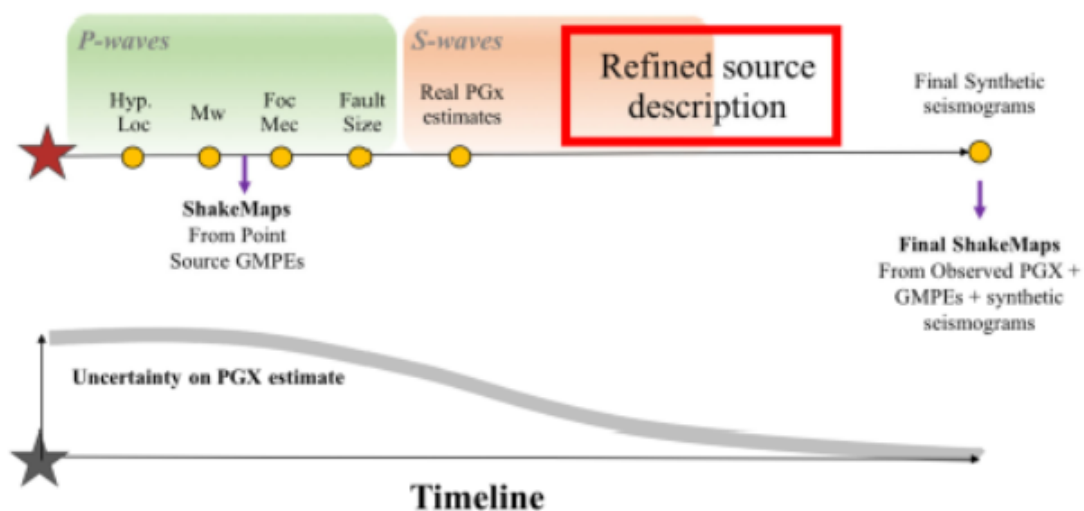
At the occurrence of an event, fast estimates of the hypocentre, magnitude and fault geometry are computed. The S-waves recording along with the previous estimates are then used to compute refined source models.

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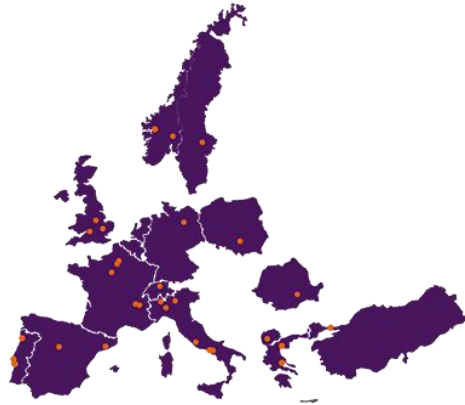
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