



## VIGIRISKS platform, a web-tool for single and multi-hazard risk assessment

Caterina Negulescu, Farid F Smaï, Robin Quique, Audrey Hohmann, Ulrich Clain, Agnès Tellez-Arenas, A. Quentin, Gilles Grandjean, Romain Guidez

### ► To cite this version:

Caterina Negulescu, Farid F Smaï, Robin Quique, Audrey Hohmann, Ulrich Clain, et al.. VIGIRISKS platform, a web-tool for single and multi-hazard risk assessment. Natural Hazards, 2022, 10.1007/s11069-022-05567-6 . hal-03782834

**HAL Id: hal-03782834**

**<https://brgm.hal.science/hal-03782834>**

Submitted on 21 Sep 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



# VIGIRISKS platform, a web-tool for single and multi-hazard risk assessment

C. Negulescu<sup>1</sup> · F. Smai<sup>1</sup> · R. Quique<sup>1</sup> · A. Hohmann<sup>1</sup> · U. Clain<sup>1</sup> · R. Guidez<sup>1</sup> · A. Tellez-Arenas<sup>1</sup> · A. Quentin<sup>1</sup> · G. Grandjean<sup>1</sup>

Received: 18 February 2022 / Accepted: 12 August 2022  
© The Author(s) 2022

## Abstract

Enabling storing, scenario design, documentation, access and execution of scientific computations for multirisks mapping is the aim of the VIGIRISKS web platform currently designed and developed by the BRGM (French Geological Survey). VIGIRISKS platform insures geohazards data management, reproducibility of risks calculations, allows information transparency and improving efficiency by easing collaborative work and sharing results and practices. The scientific scope is multirisk mapping, including cascading effects, in the domain of natural hazard (earthquake, landslide and submersion) from the phenomenon modelling to the impact evaluation on exposed elements such as buildings. VIGIRISKS web platform initially designed for BRGM experts aims to be in a long-term an open repository for national and international experts working on natural hazards management. Integration and deployment of new datasets and computational processes oriented towards risks mapping is as automatic as possible for the convenience of users.

**Keywords** VIGIRISKS · Platform · Cromwell · Web-tool · Scientific codes · Multi-hazard · Risk assessment

## 1 Introduction

Natural hazards threaten many parts of the world and cause many deaths and significant damage every year. Moreover, some natural hazard (landslides, flood, sea level rise, ...) should increase in the future due to climate change (e.g. Debortoli et al. 2017; Gallina et al. 2016; Philippenko et al. 2021). To cope with this situation and prevent natural hazard impacts, scientific community develop a large variety of hazard and risk mapping tool, either to assess current potential risks caused by a hazard or by a combination of hazards (Rossi et al. 2010; Thiebes 2013) or to predict those that will appear in the near future (Bernardie et al. 2021).

These tools are progressing with the evolution of software/hardware capabilities. From the 2000s onwards, stand-alone applications for modelling risks from different natural

---

✉ C. Negulescu  
c.negulescu@brgm.fr

<sup>1</sup> Department of Risks and Prevention, BRGM, Orléans, France

hazards and for various exposed elements, are being developed. Generally, these tools were first developed for seismic risk and later added risk analysis for other natural hazards such as tsunamis, landslides, floods, etc. Concerning first stand-alone applications for risk assessment, we can mention some of the software's best known and most used (e.g. HAZUS (FEMA 2004); RiskScape (King and Bell 2005; Schmidt et al. 2011); EQRM (Robinson et al. 2006); MAEviz-HAZTURK (Elnashai, et al. 2008); CAPRA—Central America Probabilistic Risk Analysis (Gill et al. 2009); SELENA-SEismic Loss EstimationN using a logic tree Approach (Molina et al. 2010); ELER—Earthquake Loss Estimation Routine (Hancilar et al. 2010); Armagedom (Sedan et al. 2013)). These tools perform either deterministic or probabilistic analysis and are based on the convolution between the hazard and the vulnerability of the exposed elements. The hazard is described either by PGA (peak ground acceleration) and spectral values of acceleration or by intensity value. The vulnerability is described by a taxonomy at which we attached either the parameter for the description of the capacity curve and of the fragility curve (most of software's) or a vulnerability index (e.g. Armagedom software). These tools have been developed by different teams around the world and have been applied, firstly, specifically in the respective territory (e.g. Capra mainly used in South America, HAZUS in the US, and RiskScape in New Zealand, Armagedom in France) before being extrapolated for use worldwide if the required input data are available. Most of these stand-alone tools have evolved, in general, into what we call now a “platform”, as they are meant to be deployed to a large community of users, to offer a wide variety of methodological approaches, with the ability to be used with a user-friendly front-end web application. For example, initial Capra multi-risk assessment tools become a platform (ecapra.org). SELENA open source tool (Molina et al. 2010) is currently in implementation in the platform developed in TURNKey project (<https://earthquake-turnkey.eu/>). The standalone Armagedom software (Sedan et al. 2013), which calculated EMS98 damage degrees of building affected by earthquake based on the methodology development on RISK-UE project (Mouroux and Le Brun 2006), is currently implemented in VIGIRISKS platform.

Moreover, in parallel the above-mentioned software which have adapted their IT infrastructure to become a platform, a new generation of platforms (e.g. Openquake, Rasor, risk. EFEHR) in field of natural's hazards was developed more recently and there are based on open-source codes and on WebGIS technologies. These new platforms are not necessary based on previous standalone tools, but, as the previous ones, on the most update research methodologies in the field of natural hazard engineering. Basically, we will consider here that a platform is a combination of computational scripts consisting of commands integrated with some visualization and documentation, and in our case, all of these functions being oriented towards multirisks mapping. Table 1 (Supplementary material) attempts to define some of the functions of these web-tools that might be interesting to know from the user's point of view, i.e. how they can be used, whether they provide known databases and/or case study datasets, whether we can import our own files into any study area to make calculations and whether we can download the results.

### Discussion related to the manner of using the web-tools (Column 2 – Table 1 in supplementary material)

- For the *manner of using the web-tools*, some of them can be download and used like any other desktop software (e.g. Capra, Prevention Web), other need registration for accessing to a Web portal (e.g. PREVIEW, INFORM RISK) and some others are compatible with Qgis/ARCGIS plugin (e.g. HAZUS-MH) or some of them allow several of

these uses together (e.g. Openquake, VIGIRISKS, Rasor, ...). The Column 2 in Table 1 in supplementary material tries to describe *the manner of use* of each tool/platform (e.g. software desktop and standalone application/plugin Qgis/Web portal). Beside of these use modes, the automatic mode for a rapid response can be considered independently or in relation with some other institutions and teams that can provide hazard ShakeMap. In relation with ShakeMap (USGS4.0), VIGIRISKS developed automatic damage calculation that are presented in SEISAid reports, for Mayotte Islands, and, for French-Spanish-Andorra borders, in the ongoing European project Pocrisc, (<https://pocrisc.eu>). Along the same lines, Silva and Horspool (2019) combined USGS shakemaps and the openquake-engine for damage and loss assessment. Considering this specific issue, the software and tools that treat about the Rapid earthquake response the authors suggest to the readers to look to the detailed paper of Guérin-Marthe et al. (2021).

#### Discussion related to hazards/phenomenon's treated (Column 5: Table 1 in supplementary material)

- **Considering the hazards treated**, some of them consider one hazard (e.g. for earthquake Openquake, risk.EFEHR, IRMA, for landslide and flood Aye et al. 2015 ...) and its associated risk but some others consider several hazards and associated risks and losses (e.g. PREVIEW, Capra, DRMKC/JRC, RiskScape, Hazus-MH, InaSAFE, ...). For the works that refer to the hazards only (do not perform risk assessment), among others tools, we can mention the Thinkhazard! Web-tool (<https://thinkhazard.org/en/>). ThinkHazard! (Fraser et al. 2016), developed at the GFDRR and World Bank initiative, provides a general view of the hazards, and highlights the likelihood of different natural hazards affecting project areas (very low, low, medium and high), provides guidance on how to reduce the impact of these hazards, and where to find more information. The hazard levels provided are based on published hazard data, provided by a range of private, academic and public organizations.

#### Discussion related to what the platform does (Column 6: Table 1 in supplementary material)

- From the user's perspective, it is important to mention ***what the platform does***. We have noted that the different tools perform several tasks and that each of them has its importance and usefulness in different risk management contexts. Although it is difficult to establish exact categories, knowing that all of them are interconnected, we can mention some of them that seem to us to be the most specific: displaying or visualizing, crossing maps, providing indicators in tabular form, presenting pre-calculated scenarios and direct calculation by the user. This last issue has a strong link with the possibility of upload and use of your own dataset and with the possibility to ***download your own results*** or to download the provided information (Column 3—Table 1 in supplementary material).

Considering earthquake risk platform that perform ***detailed calculation***, one of the most recent and used in the field of earthquake risk is OpenQuake Platform, Engine and Tools, which is a product developed at the initiative of Global Earthquake Model (GEM) Foundation (<https://www.globalquakemodel.org/>). GEM started in 2006 to develop open source tools and models for earthquake risk assessment. Openquake web-

based platform offers an interactive environment in which users can access, manipulate, share and add data, and explore models and tools for integrated assessment of earthquake risk. GEM data gives the possibility to make a platform for a specific region, as is the case for Seismic Risk in Mediterranean Countries (SEISMEC) platform. EUCENTRE and the Italian Civil Protection in collaboration with the countries of the Maghreb and the Middle East develop this. They use data from GEM and the US Geological Survey (USGS)-ShakeMap based on VS30 (S-wave velocity in the uppermost 30 m) values or on soil site classification. The interface is user-friendly, with the possibility to run scenarios of damage to a selection of past earthquakes by exploring a catalog of historical seismicity. EUCENTRE has also developed further platforms (e.g. IRMA, Borzi et al. 2018, 2021) for assessing seismic risk for some European-funded projects generally specific to a country, city or to the selected testbeds of the projects. At the end of December 2020, a new platform, risk.EFEHR (Crowley et al. 2021a; Crowley 2021) was released. risk.EFEHR is a web platform hosted at the EUCENTRE (Italy) that provides the risk services of the European Facilities for Earthquake Hazard and Risk (EFEHR), a consortium of organizations and community resources aimed at advancing earthquake hazard and risk assessment in the European-Mediterranean area.

The European Commission Disaster Risk Management Knowledge Centre (DRMKC) integrates existing scientific multi-disciplinary knowledge and co-develops innovative solutions for existing needs. Theirs Risk Data Hub (<https://drmkc.jrc.ec.europa.eu/risk-data-hub#/>) is a GIS web platform of European wide risk data and methodologies for Disaster Risk Assessment. A complete explanation of methodologies developed for Risk Data Hub and its software and data architecture is included in “Risk Data Hub “ JRC technical report (Antofie et al. 2018; JRC 2020; Marin-Ferrer et al. 2019). Another multi-risks platform is InaSAFE (Home · [inasafe/inasafe Wiki](https://inasafe.org/) · GitHub) that has been jointly developed by the Indonesian Government-BNPB, the Australian Government, the World Bank-GFDRR and independent contributors. An analysis from the point of view of using InaSAFE is the process whereby a hazard layer, an exposure layer and an optional aggregation layer are used to determine the potential impact of the hazard data on the exposure. The analysis results are grouped by region (as defined in the aggregation layer). It considers several hazards and the vulnerability is mainly related to the people and demographic description. RASOR platform (Rudari et al. 2015; Arrighi et al. 2018) developed during Rapid Analysis and Spatialization and Of Risk (RASOR) EU project performs multi-hazard risk analysis to support the full cycle of disaster management. RASOR adapts the 12 m resolution TanDEM-X Digital Elevation Model (DEM) to risk management applications, using it as a base layer to interrogate datasets and develop specific disaster scenarios. RASOR platform performs calculation and provide datasets for the case studies development in the project.

Among platforms based on *previously performed calculations*, we can cite the PREVIEW Global Risk Data Platform (Giuliani and Peduzzi 2011), which is a multiple agencies effort to share spatial data information on global risk from natural hazards. This is very useful for the users that want to visualize, download or extract data on past hazardous events, human & economical exposure and risk from natural hazards. It covers almost all natural hazards (e.g. tropical cyclones and related storm surges, drought, earthquakes, biomass fires, floods, landslides, tsunamis and volcanic eruptions). The main force is that the collection of data is made via a wide range of partners (see about for data sources on the website <https://preview.grid.unep.ch/>). This was developed as a support to the Global Assessment Report on Disaster Risk Reduction (GAR) and

replace the previous PREVIEW platform already available since 2000. The CEDIM Risk Explorer Germany (Müller et al. 2006; Köhler et al. 2006) is a web-based map viewer that interactively presents the results of the CEDIM Research Focus Risk Map Germany. In 2021, the platform moved and was integrated into the CEDIM/Risklayer Explorer (risklayer-explorer.com). The CEDIM software was developed by the Center for Disaster Management and Risk Reduction Technology in Potsdam, Germany, but it was used for damage and risk analysis on other earthquake prone areas of the world.

In the *fields of floods and landslides*, we can mention Aye et al. (2015) that develop a *prototype* web-GIS (Geographic Information System) decision support platform. This web application uses open-source geospatial software and technologies, particularly the Boundless (formerly OpenGeo) framework and its client side software development kit (SDK). The main purpose of this tool is to assist the experts and stakeholders in the decision-making process for evaluation and selection of different risk management strategies through an interactive participation approach, integrating web-GIS interface with decision support tool based on a compromise programming approach. For the *hydro-meteorological hazards* and associated risks in Europe, we can mentioned the CHANGES network (Changing Hydro-meteorological Risks—as Analysed by a New Generation of European Scientists) and platform (<http://www.changes-itn.eu/>) that aimed to develop an advanced understanding of how global changes (related to environmental and climate change as well as socio-economical change) that will affect the temporal and spatial patterns. For Natech (Natural Hazard Triggering Technological Disasters, Cruz et al. 2006), we can mention Rapid Natech Risk Analysis and Mapping System: RAPID-N (Girgin 2012) system that allows the rapid analysis of Natech risks at a specific industrial unit, at an industrial facility (multiple units), or at multiple facilities regionally in a scalable manner. It is unique in that it covers all functionalities required for Natech risk analysis including on-site natural-hazard severity assessment, estimation of the type and extent of damage at industrial units, development of accident scenarios, analysis of hazardous consequences, and visualization of the results in one tool. European Commission's Joint Research Centre (JRC) develops the Geospatial Risk and Resilience Assessment Platform (GRRASP, <https://ec.europa.eu/jrc/en/grrasp>), a web-oriented architecture bringing together geospatial technologies and computational tools for the analysis of critical infrastructures (CI). In addition, to classical risk-based approach, Resilience-Based Risk approach (Kammouh et al. 2018a; Marasco et al. 2022) are in development. For example, PEOPLES framework (Kammouh et al. 2018b) is a hierarchical framework developed at the Multidisciplinary Center of Earthquake Engineering Research (MCEER), in which objective is to identify the resilience capabilities of communities at different scales (spatial and temporal) and to anticipate potential responses of a community to future hazard events. The PEOPLES framework has also been implemented as an online tool (<http://www.resiltronics.org/PEOPLES/logic.php>). After providing all necessary data, the tool evaluates the analysed community's Loss of Resilience (LOR). The full description of the tool can be found in Kammouh et al. (2018b). Moreover, PEOPLES framework and resilience quantification methodologies are implemented in Prevent Web platform.

**Discussion related to database and datasets (Column 4: Table 1 in supplementary material)**

- Another important attribute of a platform is the possibility to *share database and datasets*. Significant efforts have been made in the last 25 years towards the development of regional, national, continental, or even global databases that can be used for risk models, such as the National Risk Assessment (NRA) for Italy (Dolce et al. 2019, 2020), the Global Earthquake Risk Model developed by the Global Earthquake Model (GEM) Foundation (Crowley et al. 2018; Silva et al. 2020) and, more recently, the European Seismic Risk Model ERSSRM20, which is an output of the European Horizon 2020 SERA project (Crowley et al. 2020b). Some of the platform provide database (e.g. risk.EFEHR, Openquake, PREVIEW, Hazus, Capra, ...), some others provide case studies datasets (VIGIRISKS, Rasor, ...) and are using many open data sources (usually the one provided by the other platforms) to compose its own datasets. risk.EFEHR, Openquake, Hazus are the most representative for the standardized database provided. Hazus provide building stock and vulnerability characterization for the US territory. As a product of GEM foundation, Openquake engine (Silva et al. 2014; Pagani et al. 2014) is in line with the GEM databases (<https://www.globalquakemodel.org/openquake?tab=oq-data-and-tools>). risk.EFEHR perpetuates and update the European Database acquired into the last 10 years of Europeans projects supported by FP5 to FP7 and Horizon 2020-supported program (RISK-UE, Mouroux and Le Brun 2006; LESS-LOSS, Calvi and Pinho 2004; SYNER-G, Pitilakis et al. 2014; NERA ([www.nera-eu.org](http://www.nera-eu.org)); SERA, <http://www.sera-eu.org/en/home/>) and works to develop a comprehensive framework for seismic risk modelling at the European scale. EU-RISK portal (<https://eu-risk.eucentre.it/exposure/>) provide the exposure database according to the GEM Building Taxonomy. Crowley (2021) presents the most up-to-date State-of-The-Practice for the European Exposure (Crowley et al. 2020a, 2021b) and Vulnerability Models that was considered for the development of the European Seismic Risk Model (ESRM20) by the European Facilities for Earthquake Hazard and Risk (EFEHR) Consortium. The European Building Vulnerability Data Repository is provided by Romão et al. (2020). Fayjaloun et al. (2021) present earthquakes damage calculation for Luchon area using 3 datasets with different resolution level: Europe resolution using the European soil map and the European database for the buildings (issued from SERA project), France national resolution using the National soil map and the national statistics database for the buildings (Tinard et al. 2020), at the municipal level and Luchon specific area resolution using the soil maps and building data issued at the district level (SISPyR and POCRISC projects). The VIGIRISKS platform includes a workflow for the extraction of the building census information from the national resolution database of France, adapted during the project Tinard et al. (2020) based on National statistics Institute information (INSEE).

Column 7 in Table 1 in supplementary material shortly resumes the *approaches used in the platforms*. Some are using statistical approaches based on inventories (e.g. RISK-UE; Thierry 2007), some other are using complexes description of the phenomenon (Vandromme et al. 2020), some are performing probabilistic Risk Analysis (e.g. SELENA, CAPRA, Prevention Web, ...) some others deterministic scenarios and some other both of them (e.g. Openquake). For more complete and details information about each platforms the main references are presented in Column 8 in Table 1 in supplementary material.

The main complexity for developing a multirisks assessment platform is that two communities that, generally, do not work together should consider the subject jointly (e.g. software developers and phenomenological researchers). Indeed, software developers are concerned by subjects that are quite obscure for the phenomenological



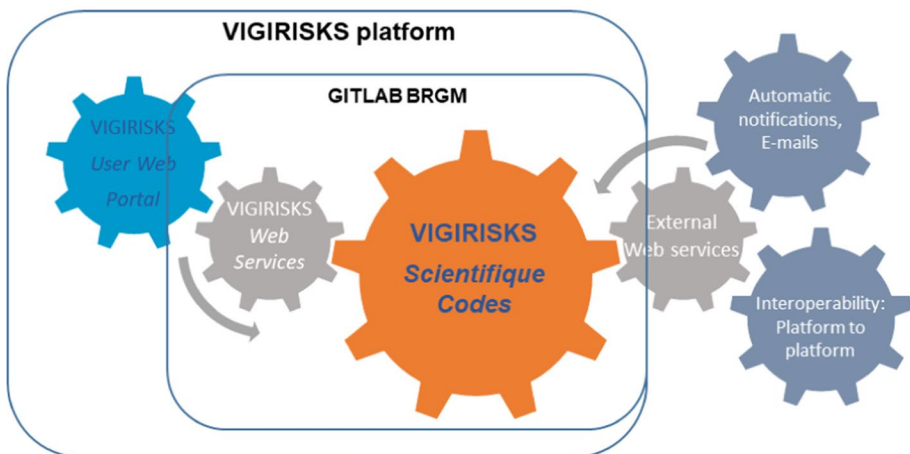
researchers, such as automated and reproducible builds, the need and process of thorough testing, or the importance a flexible design. On the other way, software developers need to have reliable methodologies and dense input databases that describe a physical phenomenon like earthquake, landslides and the exposed elements that can be affected.

In the following, we present the basis of the VIGIRISKS multirisks web platform (Tellez-Arenas et al. 2019; Negulescu et al. 2019). This web platform has the ambition to propose computations allowing multi-risks mapping in a realistic manner, e.g. including cascading effects, vulnerability assessment and damages evaluation. We particularly show the computing infrastructure, the different digital functionalities, the different ways to use the platform as digital lab to develop methodological risks assessment algorithms and the way to test, manage, and disseminate cases studies where the VIGIRISKS platform is used. Although we have tried to be as comprehensive as possible, given the rapid emergence of new technologies and platforms, the introduction to this article does not present an exhaustive view of web-based risk platforms and related risk datasets used in risk assessment. The main objective of our paper is to present the current advances of the VIGIRISKS platform in terms of web-based infrastructures and risk assessment capabilities for different natural hazards.

## 2 The VIGIRISKS platform

### 2.1 General considerations

VIGIRISKS is a web platform designed by the BRGM for developing, managing and disseminating multirisks mapping products for decision-making purposes. VIGIRISKS is composed by different components that communicate with each other in order to improve the relation between researcher develop code to user and the interoperability between other platforms. From a simplified point of view and with the concern of being straightforward, we can summarize these components as follows: VIGIRISKS *User Web Portal*, VIGIRISKS *Web Services* and VIGIRISKS *Scientific codes*,



**Fig. 1** Simplified representation of components that form the VIGIRISKS platform: VIGIRISKS *User Web Portal*, VIGIRISKS *Web Services* and VIGIRISKS *Scientific codes*



**Mes études** + Créer une étude

Affichage 1-12 de 33 études

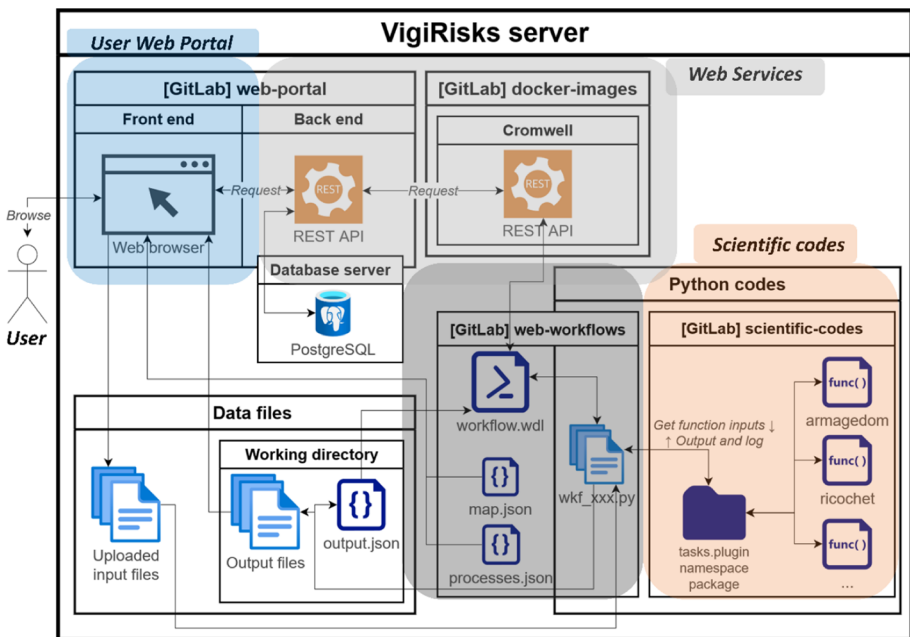
TITRE	CONTACT	EMPIRE	DERNIÈRE MODIFICATION
Viella landslide, Pyrenees, France	Severine Bernardie (BRGM)	France	04/02/2022
Troyes Métropole	Hélène Bessière (BRGM French Geological Survey)		15/10/2021

**Tous les workflows** + Créer un workflow

Affichage 1-12 de 16 workflows

TITRE	CONTACT	TYPE	DERNIÈRE MODIFICATION
Alice - ALICE (Assessment of Landslides Induced by Climatic Events)	Rosalie Vandromme (BRGM)	Mono-aléa	23/06/2022
Armagedom - Seismic Risk Assessment	Caterina Negulescu (BRGM)	Mono-aléa et risque	23/06/2022

**Fig. 2** VIGIRISKS platform: *User Web Portal*—general considerations (internationalization FR/EN ongoing)



**Fig. 3** VIGIRISKS IT architecture—software aspects that make the relation between *User Web Portal*, *Web Services* and *Scientific codes*

VIGIRISKS *Web Services* and VIGIRISKS *Scientific codes* (Fig. 1). Note that in this paper we use these three syntaxes in *Italic* and **Bold** in all the paper in order to indicate in a homogeneous way the three parts of VIGIRISKS. The development of the VIGIRISKS platform is based on GITLAB, which is a server that allows code to be versioned. *Brgm's Gitlab* store in different repositories the complete part of the last two components and some parts of the *User Web Portal*. Figure 3 presents a more detailed chart of the IT Architecture, which is detailed in Sect. 2.2. Conceptual framework of the platform.

The *User Web Portal* (Fig. 2) offers its users an interface in which several actions are possible depending on the role of the connected actor (admin, developer, expert). Its main functionality is the ability to run workflows. A menu lists the three main components of VIGIRISKS: *Studies* (“*Mes etudes*”), *Workflows* (“*Mes workflows*”) and *Data* (“*Mes données*”).

A user can create a “*Study*”, which will correspond to a repository grouping together data and workflows common to each other. The “*Data*” is nothing more than files that can be uploaded to then be used as “*Workflow*” inputs. For each workflow (Fig. 2), the list of entries to be used is displayed in the form of dialog boxes. Depending on the type of entry required, it becomes possible, for example, to enter text, specify a file from the uploaded data, or select a field from a drop-down list. Then, a button is used to launch the execution of the workflow during which the logs produced by the code are displayed in real time. If an error occurs, execution stops and alerts the user. Otherwise, when all the outputs have been calculated and produced, a list of output files are displayed with the possibility of downloading them. These different parts of VIGIRISKS platform are detailed in next two chapters Sects. 2.2 and 3.1.

## 2.2 Conceptual framework of the platform

The architecture includes a repository of available datasets, documents, links and reproducible versioned workflows in order to build an informational environment useful to risk engineer for elaborating the most reliable risks assessment solution. The executions and records of the results are described by metadata allowing discovery, evaluation and use. This is possible thanks to the use of “*Cromwell*”, which is a Workflow Management System geared towards scientific workflows most of all related to human genetics research (Tanjo et al. 2021). The use of “*Cromwell*” for VIGIRISKS platform is quite innovative comparing to existing natural risks platforms.

The heart of the architecture (Fig. 3) is the workflows description and execution mechanism, based on JSON and python descriptions defining acyclic graphs of processes, executed through interoperable web services. This is particularly important to test algorithmic solutions and disseminate them to the community. Figure 3 details from software point of view Fig. 1, hence we try to correspond the software components that make up the three parts of the VIGIRISKS platform mentioned in Fig. 1: VIGIRISKS *User Web Portal* in blue, VIGIRISKS *Web Services* in grey and VIGIRISKS *Scientific codes* in orange. All the words in “quotation marks” in this Chapter can be find in Fig. 3 that shows their importance and position in the software architecture.

It is important to note that the VIGIRISKS *Web Services* (Fig. 3 in grey), that makes the web integration, has two parts one lighter (scientific workflow engine “*Cromwell*”) and one darker (preparation form for web integration). The darker part named “web-workflows”, together with the “*wkf\_xxx.py*” file, makes the relation between *Scientific codes* and the other parts of the platform. This part is like a funnel (for execute the code the arrows pass

mandatory from it) in this software architecture which can have advantages and inconvenient. The advantage is the first benefit of the platform, and can be resumed as the fact that for adding a new functionality only this part, composed by four files, should be adapted. This is the main outcome of the platform that enable, with minimum modifications, the rapid transfer between the research development and the applications by the Users.

Three JSON files (“processes.json”, “map.json” and “inputs.json”) and a “workflow.wdl” (workflow description language) file presented in Fig. 3 compose specifically the part “web-workflows”, which is the “modifiable” part of the **Web Services**. The WDL (<https://openwdl.org/>) is a community-driven specification and is supported by several workflow engines, among “**Cromwell**” (<https://github.com/broadinstitute/cromwell>). The Workflows are executable as a whole or step-by-step, with detailed logs. The execution engine ensure security, robustness, flexibility and scalability. Used in a multi-users context, it requires asynchronous mechanisms and scheduling of computations. “**Cromwell**” (Fig. 3) allows the execution of workflows (files in WDL format) that describe several lines of commands that can be executed in parallel.

### 2.2.1 VIGIRISKS web services

The VIGIRISKS platform uses **Web services** which can be divided into two denomination: “Internal” **Web Services** which are used only for communication between **Scientific Codes** and the **User Web Portal** and “External” **Web Services** which could be used for communication with others platforms and codes. The use of “Internal” **Web Services** can be summarized in several steps that are illustrated in Fig. 4. Thanks to the metadata, the web portal finds the (1) gitlab url and (2) generates the web forms. Through the web form, the user configures (3) its inputs and parameters and then he request the web service. Following this request, (4) the Scientific Workflows Engine answers using the WDL file. The WDL contains the command lines and dockers and (5) executes the code. The directory of the web-workflow defines how it will be interpreted by the web application. The Workflow Directory content three JSON files and a WDL file:

- inputs.json: Defines the expected data and their default values
- maps.json: Defines the configuration and options of the maps associated with the workflow

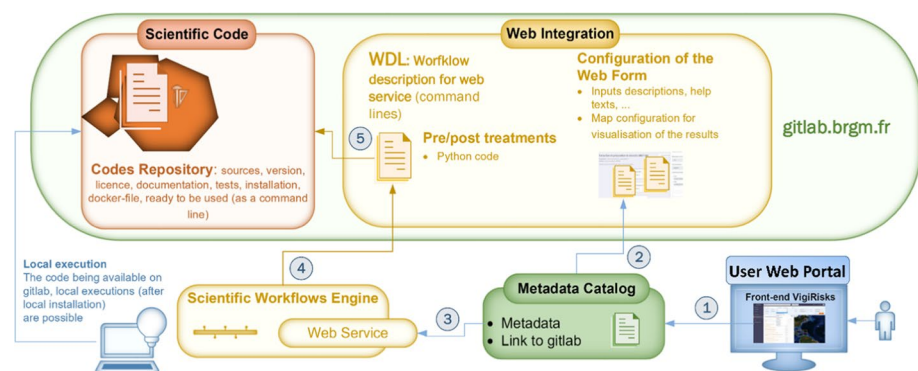


Fig. 4 User Web Portal and Web services

- `processes.json`: Defines the process boxes that appear in the web application and serve as data input to users for the workflow.
- `workflow.wdl`: Interface between user-entered data and *Scientific Code*.

### 2.2.2 VIGIRISKS user web portal

VIGIRISKS was designed with a “front-end” (*User Web Portal*) connected to a “back-end” Java-web server (Fig. 3). The “front-end”, named also the graphical user interface (GUI) is implemented as developed from the open source tool (JavaScript using Angular). The OpenLayers JavaScript library allows the display and manipulation of produced maps. The back-end server produces web services and uses a Postgres database for data management, scenarios translated into workflows, input parameters and simulation results (Fig. 3). To make this work, containers “docker-images” own the configuration files of the Docker image integrating “*Cromwell*” and others applications. Docker supports the development of VIGIRISKS platform. Docker is an open platform for developing and running applications that provides the ability to package and run an application in a loosely isolated environment called a container. VIGIRISKS platform uses several containers under Docker: (i) one to manage multiple environment (Development, Stage, Production environments) and (ii) others to manage applications (e.g. *Cromwell*: workflow management system (web app java) + VIGIRISKS python modules; backend: VIGIRISKS back-end web services (web app java); front-end: VIGIRISKS front end (angular application)). For resuming, the Execution Core relies on *Web services* which are a Java scientific workflow engine (“*Cromwell*”), the definition of workflows as text files (WDL) and the description of Parameters in JSON (including Docker, python, HPC and command line execution).

VIGIRISKS has three environments: (1) Development or local: for developing and testing codes on PC; (2) Stage: for staging these codes with tags version (rec-vigirisks.brgm-rec.fr) and (3) Production: dissemination of final codes (vigirisks.fr). The Development is where the unfinished code is updated between the co-workers, and committed on different branches live. The Stage environment is as similar to the Production environment as it can be. The production environment is where users access the final code after all of the updates and testing. It is possible for a particular execution of any workflow, to register inputs, parameters and resulting computed datasets, which become new records in the repository. Datasets and workflows will be shareable between groups of users or even publishable as web services when relevant.

In order to extend the usefulness of workflows, we can also “Tag” a code appertaining to the *Scientific Codes* entity of VIGIRISKS platform. This gives the ability to mark specific points in history as being important. The Tags can be compiled and released for a local execution on PC. This is an important issue, since during a natural crisis it is probable to not have available internet connection and hence enable to use the web services and the Portal.

## 3 Vigirisks platform for multi-risk assessment application

As mentioned previously, the scientific scope of VIGIRISKS platform is the hazard evaluation and risk assessment in the domain of natural hazard (e.g. seismic, landslide, submersion) from the phenomenon modelling to the impact evaluation on exposed elements such

as buildings and networks. It is intended to have a wide range of methods for calculating hazard and, susceptibility and relations between hazard and vulnerability, for calculating the risk. Workflow for data analysis, preparation and transformation are also in the scope of this platform in order to facilitate the work of scientists in manipulating their datasets.

In its first version, this VIGIRISKS platform was designed for the use of BRGM experts and is now in a long-term ambition an open repository of executable workflows for national and international experts in the domain of natural hazards. Currently several workflows are implemented for damage calculation for different combinations between several hazards and different levels of description of the exposed elements. Among these workflows, we can summarize some of them that are currently used, in France, more often by the BRGM hazard and risk experts:

- Landslide damage scenarios where the hazard is represented by the official risk prevention plans (PPR) and by superposing the hazard levels with the number of the exposed elements affected by it.
- Landslide damage scenarios where the hazard is represented by the settlements obtained using remote sensing technics and the vulnerability of the exposed elements is described by fragility curves.
- Deterministic seismic damage scenarios using real-time generated ShakeMap, and considering site effects
- Tsunami damage scenarios where the water height and water velocity describe the tsunami hazard and, yielding acceleration and ultimate acceleration describe the vulnerability.

The number of existing codes and workflows is not the most important think that is emphasis in the publication, but rather the flexibility and the maneuverability of introducing and implementing new scientific methods. This is the main outcome of the platform and the innovation part is the merge between the scientific, generally static platform and new information architecture that can manage dynamic use. This platform allows the use of scientifically validated methods but it also serve as an innovation tool allowing scientists to propose new methods of risk assessment and to proceed their validation more easily on several datasets covering different study areas. The transition between the scientific code that is developed by the researcher and the Web Portal that is employ by the users, stand in some, surely important but easy, json description files and hence, can be applied very quickly. Chapter 3.2. Applications presented briefly some projects in which VIGIRISKS platform was used.

### 3.1 Data description

The main idea of the VIGIRISKS platform is to put together the existing tools used for different hazard calculation and for risk assessment in BRGM (e.g. Armagedom, Sedan et al. 2013; Alice, Vandromme et al. 2020; SEISAid; Watersed, Landemaine 2016; Grangeon et al. 2021). Starting with this enouncement, VIGIRISKS use python library and, when necessary, develop specific tool (toolbox) in order to manage and treated different GIS formats that are generally used for spatial description of natural hazards. Consequently, the input files have different formats depending on the type of analysis and on the field to fill in order to have all the necessary entrances and parameters for applying the chosen risk assessment calculation. Moreover, the *User Web Portal* boxes related to each approach

```

1 {
2   "name": "coord_mult_field",
3   "description": "Description du champ",
4   "label": "Champ de type ensemble de coordonnées",
5   "type": "coord_mult",
6   "istline": true,
7   "values": [
8     {
9       "x": -2.3510742187500036,
10      "y": 44.0771484375
11    },
12    {
13      "x": 0.30761718749999645,
14      "y": 47.63671875
15    }
16  ],
17  "targetProj": "EPSG:4326",
18  "readOnly": false,
19  "hidden": false,
20  "required": true
21 }

```

Champ de type ensemble de coordonnées

X	-2,3510742187500036	Y	44,0771484375	×
X	0,30761718749999645	Y	47,63671875	×

+ Ajouter une coordonnée

Sélectionner sur la carte

**Fig. 5** Relation between the JSON configuration file stored on the gitlab and the corresponding boxes on the *User Web Portal*

are described by the user through the JSON configuration file, input.json (Fig. 5). We describe in the next Chapters some data needed for hazard, exposed elements and damage calculation.

### 3.1.1 Hazard data

After UNDRR (2022) terminology, the hazard is a “process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation”. There are several type of hazard with regards of his origin (e.g. natural, anthropogenic, socionatural). We are speaking here

Coordonnées de l'épicentre (long/lat)

X	767263.89	Y	1554363.17
---	-----------	---	------------

Sélectionner sur la carte

Profondeur Z (km) de l'épicentre

40

Magnitude

6.5

Résolution de la grille à exporter

50

Accélération minimale à prendre en compte

3

SRS de la shakemap à générer (entrer le code numérique EPSG)

SRS de la shakemap à générer (entrer le code numérique EPSG)

32620

Loi d'atténuation

Chiou\_2008

loi de conversion acceleration intensité

Atkinson\_Sonley\_2000

Choisir les effets de site

Sans effet

Avec effet

Sans effet

Annuler

Appliquer

Choisir une ShakeMap depuis une étude locale pour la zone effet de site

Choisissez une donnée existante ou créez-en une nouvelle en déposant un fichier qui sera ajouté à l'étude courante.

Donnée existante

Nouvelle donnée

ESlitho\_v2.tif

Choisir un coefficient d'amplification depuis une étude locale pour la zone effet de site

Choisissez une donnée existante ou créez-en une nouvelle en déposant un fichier qui sera ajouté à l'étude courante.

Donnée existante

Nouvelle donnée

100 Mo maximum

+ Choisir

Calcul de l'aléa sismique : carte accélération

Annuler

Appliquer

**Fig. 6** Windows to fill for calculation of earthquake hazard: (left) localization, depth, magnitude, grid resolution, geographic coordinate system, (central) choice of attenuation laws (GMPE) and acceleration-intensity conversion equations (G), choice of using or not site effects; (right) when considering site effects, two files should be provided, zonation and amplification factor

about natural hazard which are associated with natural phenomenon and more specifically to the geological or geophysical hazards originate from internal earth processes.

A given hazard may be characterized by different parameters: for example, an earthquake by its intensity, peak ground acceleration, spectral acceleration values, etc.; flooding by submerged depth, water velocity, landslides by a safety factor (SF), by a displacement, but also by depth and velocity for flow debris, etc. The issue is to identify the adapted parameters which allows estimating damage induced by a given hazard by means of a damage function. Figure 6 shows the windows related to the earthquake calculations and the information that have to be provided by the user: epicenter location, focal depth, magnitude, and attenuation laws depending on the fault mechanism. If the user has the site effects description, in order to be considered for the calculation of earthquake hazard, it should provide a grid map with the zonation of the site zones and a corresponding.xml file that describe the amplification coefficients for each zone in the grid file. The values that characterize the hazard are calculated for each cell of the grid map. The row and column of the cells are correlated with the geographical coordinate. The product of the calculation is stored in the Data file of the “Study”.

Figure 7 shows two other workflows, left one, related to tsunami hazard calculation and, right one, related to the pretreatments of files with the aims to apply one hazard workflow. In the left side of Fig. 7, we can see the necessary files for the calculation of moment flow, which is the intensity measure (IM) parameter for the damage calculation methods proposed by Hazus (FEMA, 2017). In this case, the input file are two-georeferenced raster that

### Configuration de l'aléa de vitesse et d'eau

Choisir un tiff depuis une étude ou importer un nouveau

1 Choisissez une donnée existante ou créez-en une nouvelle en déposant un fichier qui sera ajouté à l'étude courante.

Donnée existante    Nouvelle donnée

v\_max\_uv\_UTM20N\_2989.tif

Choisir un tiff depuis une étude ou importer un nouveau

1 Choisissez une donnée existante ou créez-en une nouvelle en déposant un fichier qui sera ajouté à l'étude courante.

Donnée existante    Nouvelle donnée

heau\_max\_UTM20N\_2989.tif

1 Texte à mettre à jour ici pour les aleas

Annuler    Appliquer

### Extraction depuis MNT

Résolution de la donnée source (RGE ALTI)

1 m

Format d'export

GeoTIFF

GeoTIFF

Arc/Info ASCII Grid (.asc)

Binary Grid (.grd)

6.7667171927006455    43.99232733939987

X max    Y max

6.786296104679339    44.00660441876237

Sélectionner sur la carte

Annuler    Appliquer

Fig. 7 Left—Tsunami inputs windows and right—extraction of a MNT zone



contain the water velocity and the water depth. In the right side of Fig. 7, we present one of the most used pretreatments workflow, which consists to extract for the area of study the Digital Elevation Model (DEM, MNT in French) with different resolution and projection.

### 3.1.2 Exposure data

Exposure defines here the buildings, infrastructure and population located in hazard-prone areas. For each of the exposed elements corresponding files that describe their vulnerability (i.e. the capacity to resist to a particular hazard) are needed for performing risk calculation.

Most of the existing exposure and vulnerability database can be used directly or with minimum format changes. For typology and vulnerability, input files can be described by Excel as.xls or.csv files or ASCII-table files. The name of the files for typology and vulnerability are modified from an approach to another in order to indicate the function and information that they have inside. Generally, for a damage calculation we need a file containing the number of buildings for each typology in a homogeneous census zone called “district”, a file containing the vulnerability index, a file containing the number of apartments, a file containing the number of persons by apartment and a file containing the casualties matrix (e.g. Coburn et al. 1992). For each method, the csv or ASCII template files, that are needed as an input file for the description of the exposed elements and its vulnerability, can be provided to the users. Figure 8 shows the windows for upload the description of the expose elements and the typical csv and ascii files that describe the number of buildings by typology and by homogeneous census bloc, and respectively the necessary information for estimate building vulnerability or capacity.

### 3.2 Applications

In this chapter, we present three applications (Seismic Risk, Tsunami Risk and Landslide Risk) in which we have calculated the risk using the intensity measures of the hazard maps,

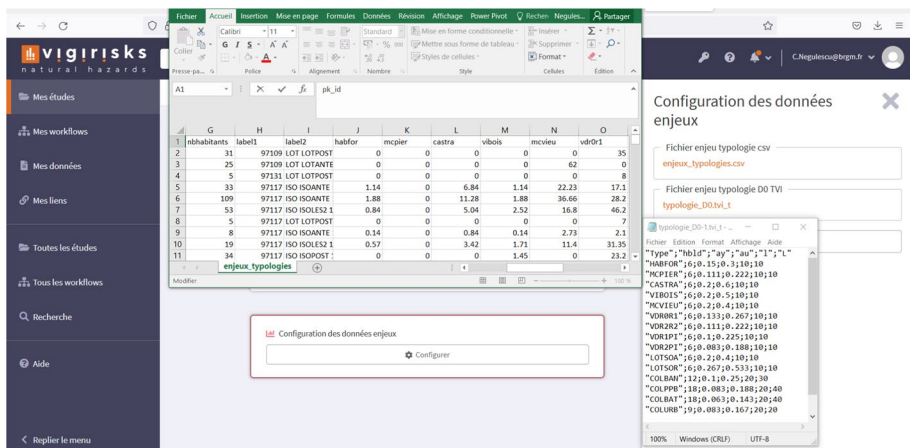
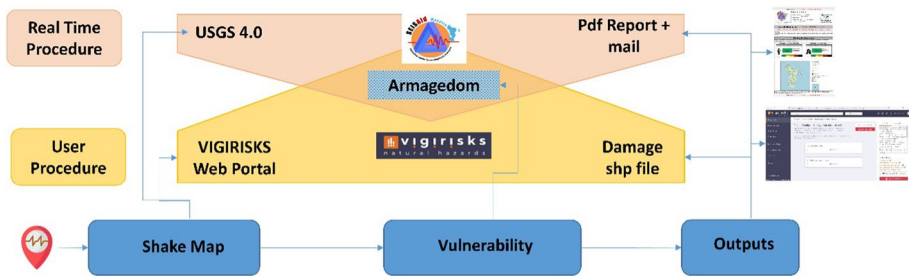


Fig. 8 Typical csv and ascii file for description expose elements



**Fig. 9** General procedure and workflow for the damage scenarios in Mayotte. Adapted from Taillefer et al. (2022)

the identification of the exposed elements and their vulnerability, and a suitable method of calculating the risk for the given phenomenon and from the corresponding input data.

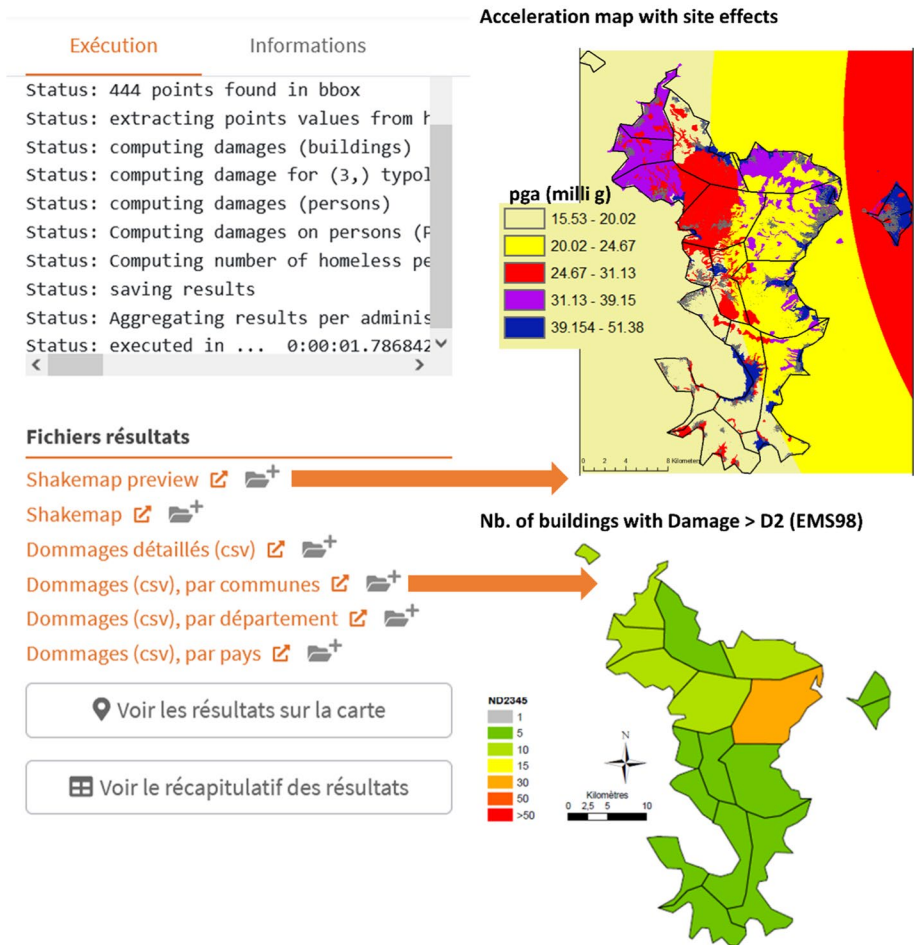
### 3.2.1 Seismic risk assessment

The VIGIRISKS platform was used by BRGM for building damage assessment after the Mayotte seismic crisis started in May 2018. Two different calculation modes are applied for Mayotte, one using User Web Portal and the second one using SEISAid Web Services. Figure 9 shows the two possible modes of damage assessment. For **Real Time Procedure**, initially, the SEISAid tool (Auclair et al. 2015) makes an estimate of the number of people exposed to each one of the intensity levels of the ground shaking as does the PAGER approach. This procedure does not take into account the vulnerability of buildings. To consider vulnerability information, we linked the shaking map outputs to the **Scientific Codes** of VIGIRISKS (e.g. the Armagedom code). Currently, **SEISAid** is an application that automatically retrieves earthquake shaking data from instruments (using SeisComP, Helmholtz-Centre Potsdam 2008), localize the earthquake, generate the ShakeMap using USGS 4.0 software, calculate the damages in the impacted area using Armagedom code, from the gitlab **Scientific Codes** from VIGIRISKS platform, post-processes the results and sends email notifications of potential damage to specified operators, via the SEISAid web services. This operation is automatic (i.e. there is no manipulation by an expert during this process). This is fully operational for Mayotte. It takes around 10 min between the earthquake detection and the e-mailing of the notification. So, thanks to **Web Services**, the **Scientific codes** hosted by the Gitlab of the VIGIRISKS platform can also be used independently from the **User Web Portal**.

In the same time, for **User Procedure**, a user using the **User Web Portal** can do the same earthquake risk calculation. This is a complementary manner for having the results that can be managed directly through the **Web Portal** and reproduced with the new or more detailed information about the event location and characteristics.

For the case study of Mayotte, Taillefer et al. (2022) detail the manner of acquisition of input data, both those related to seismological features (Fig. 6 left) and those related to the description of site effects and vulnerability of the exposed elements. For the description of site effects, ambient vibration measurements were carried out to identify the response of the soils. The windows necessary for entering all these information are presented in Fig. 6 central and right. Figure 10 presents the window of execution, the output files and the representation of results using a GIS Tool. Keeping the

## Simulation of May 15, 2018 Earthquake



**Fig. 10** Window of execution, the output files and the representation of results using a GIS Tool for Mayotte seismic risk scenario

characteristics of the May 15, 2018 earthquake of magnitude 5.8 and assigning site effects to EC8 classes (A, B, E) we obtain PGA values of the same range of value (observed 52.7 mg vs. calculated 51.38 mg) with those recorded (Fig. 10 top right).

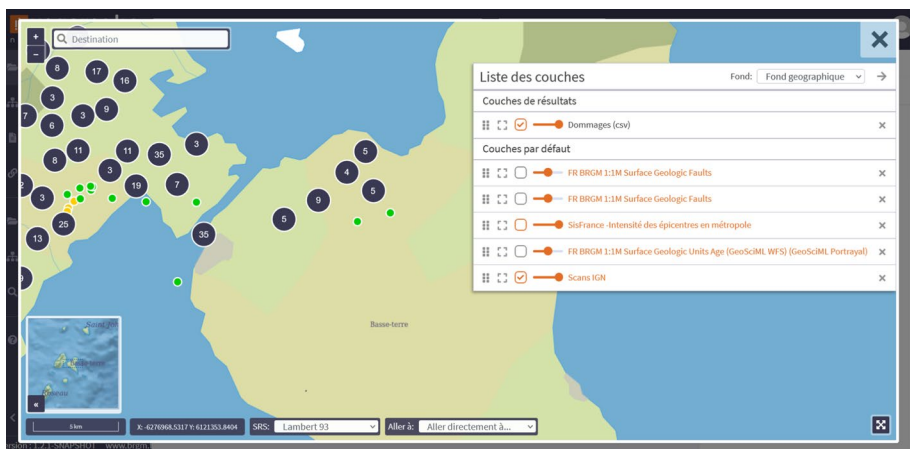
For the characterization of the exposed elements and their vulnerability, a field inventory was carried out (Taillefer et al. 2022) in order to validate the structural typologies which were established, in first approach, from the French National Statistic Data (INSEE). The spatial distribution of buildings according to their vulnerability level is packaged in two files as shown in Fig. 8. Damage assessment procedure follows the framework developed in RISK-UE (Lagomarsino et al. 2002; RISK-UE 2003; Mouroux and Le Brun 2006). This approach was applied on French overseas territories

and other countries (Douglas et al. 2015; Boutaraa et al. 2018; Monfort et al. 2019; Negulescu et al. 2020). This approach is relevant statistically and the results are rendered at the scale of the municipality and are expressed in five degrees of damage according to EMS-98 (Grünthal 1998). The data described by Taillefer et al. (2022) and the simulations of seismic risk calculations made using *Scientific Codes* are stored on the VIGIRISKS platform for future use. Figure 10 (down right) presents a representation of the number of building that reached or exceed the damage degree D2 (Moderate Damage).

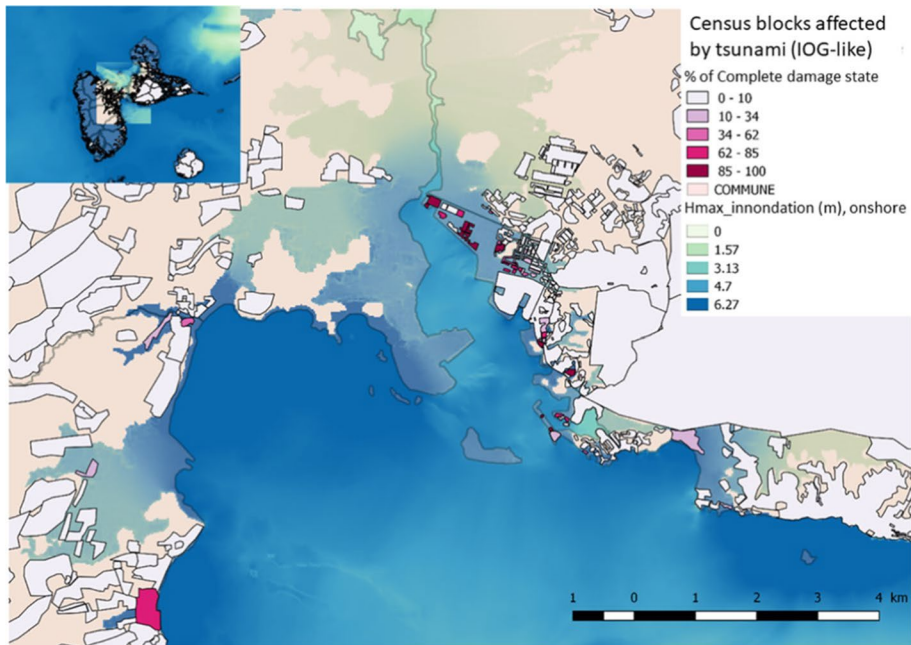
More recently, Fayjaloun et al. (2021) use VIGIRISKS platform and data coming from three different databases with different resolutions (European scale -SERA, National Scale and Regional Scale) for investigate the sensitivity of earthquake damage estimation to the input data (Soil Characterization Maps and Building Exposure) for a Case Study in the Luchon Valley.

### 3.2.2 Tsunami risk assessment

VIGIRISKS platform was used for the tsunami damage assessment for two large destructive thrust interplate earthquakes occurred in the area of French West Indies. The first one is the 11 January 1839, east of Martinique Island (referred as Interplate Offshore Martinique (IOM) scenario) and, the second one, is the 8 February 1843, east of Guadeloupe Island (referred as Interplate Offshore Guadeloupe (IOG) scenario) (e.g. Bernard and Lambert 1988; Feuillet et al. 2011). In this, study Negulescu et al. (2020) consider maximum moment flux as the tsunami intensity measure (IM) parameter. This was establish as HAZUS (2017) recommendations, that uses the median value of the maximum inundation height,  $H$ , (also called the water depth or flood depth, that is, the sea surface elevation minus the topography), and the median value of the maximum velocity of the water,  $v$ . The inundation height grids and flow velocities grids were calculated based on numerical simulations involving modelling the tsunami source, propagation and inundation. The tsunami hazard data includes inundation grids provided from an external numerical tsunami hazard model (Le Roy et al. 2017; Poisson et al. 2009). Two grid files were provided as



**Fig. 11** Visualization through the User Web portal of VIGIRISKS of the damage results for moment flux as intensity measure parameter for submersion



**Fig. 12** Guadeloupe tsunami, IOG-like event (inspired from 1843 earthquake), zoomed in on Pointe-à-Pitre Bay: percentage of complete damage state per census block. Aadapted from Negulescu et al. (2020)

shown in Fig. 7, left. The exposed elements were characterized by two files: a csv file that presents the number of buildings in each typology and in each homogeneous census bloc and an ASCII file that presents the yielding, ultimate acceleration and some other parameters for each typology. HAZUS methodology (published in November 2017—FEMA 2017) which is a Performance-Based Tsunami Engineering (PBTE) approach for tsunami damage assessments is implemented in VIGIRISKS workflow. We use the functions developed for tsunami “flow” hazard since the lateral forces due to tsunami flow are the primary cause of damage to the building structure, including building collapse. Hence, the damage on structures is due to the lateral forces caused by drag effects and debris carried along by the tsunami flow (Sect. 5.5 HAZUS Tsunami).

Figure 11 shows a first visualization of the results through *User Web Portal* and Fig. 12 presents the results for the VIGIRISKS that have been downloaded and re-arranged for a more detailed presentation by an external GIS software. The visualization of the results through *User Web Portal* represents a quick overview of the results (no dynamic thematic analysis are available for the Portal, the thematic analysis that colored the points is predefined). The small points (e.g. green, yellow in Fig. 11) are colored according to the percentage of the area’s building in the degree of complete damage: green (between 0 and 0.2), yellow (0.2–0.5), orange (0.5–0.8) and red (>0.8). Each colored point represents an area with a number of buildings (considered to have a “homogeneous” behaviour) inside. By clicking on the colored points, you can see the number of buildings in each damage level. The black bullets (Fig. 11) are used for dynamic visualization. As we cannot see all the points if we zoom out, in this case, the colored points are grouped into the black bullets (if in a black bullet it is written, for example 35, it means that this bullet has grouped 35 small colored points which each represent a “homogeneous” area).



### 3.2.3 Landslide-induced settlements risk assessment

Raucoules et al. 2018 use space-borne high-resolution L-band Synthetic Aperture Radar (SAR) images (ALOS-2/PALSAR2 data in SM1 mode) for mapping deformation of slow landslides. The methods combined are sub-pixel correlation offset tracking techniques and differential SAR interferometry. Hell-bourg and Grand Ilet landslides (our test cases) are located on La Réunion Island in the Indian Ocean with motions up to about 1 m/yr. They use this mapping deformation for assessing the damage that can arrive to the building affected by vertical motion in Hell-Bourg and Grand Îlet municipalities and the probability of damage has been identified. By superposing the vertical displacement rate map in m/yr and the map of the exposed elements, the building vulnerability was analysed at the scale of the single buildings or at the homogeneous census block. The procedure for the assessment of damage probability was performed using VIGIRISKS platform. It is articulated as follow: (1) evaluation of differential settlement as difference between the maximum and the minimum vertical displacement (inside the building footprint) and (2) estimation of the probability of damages on the basis of the fragility curves proposed by Negulescu and Foerster 2010 (that takes into account the differential settlement) at 1, 5, 10 years.

Figure 13 shows, through the *User Web Portal* of VIGIRISKS, the visualization of the damage results layers for homogeneous census bloc, and the default layers. As mentioned in the previous chapter, no dynamic thematic analysis is available for the portal and the thematic analysis that colors the areas in Fig. 13 is predefined (in this case, the areas are colored according to the percentage of buildings in the full degree of damage: green (between 0 and 0.2), yellow (0.2–0.5), orange (0.5–0.8) and red (>0.8)). This is a quick preview of the results, and for a better thematic analysis of the results, we recommend importing the results into a GIS software.



**Fig. 13** Visualization through the *User Web portal* of VIGIRISKS of the damage results for mapping deformation of slow landslides in La Reunion

## 4 Discussion

The designing of the workflows is created in order to approach custom and automatic workflows to reduce the gap between the scientific method and its real application on case studies, as well as between development environment and production environment. The main targets of the VIGIRISKS platform are: (1) to easily install and run code on it, (2) to easily develop the code, (3) to integrate legacy code with minor changes, (4) to reduce code duplication as possible, (5) to have execution isolation and (6) to easily execute a workflow or create a new one. All this targets are compatible with execution trace and the re-playable, but easy to change execution parameters. Some issues are still under testing in VIGIRISKS platform. One of them is related to the limit of uploading files for **User Web Portal**. Currently, the maximum file size that can be unloaded is of 100 Mb. This is satisfactory when working on a case study at the scale of a region or a country for some hazards but this becomes insufficient when need to treat a hazard at the scale of the continent or the world, as can be the case for hazard related to climate changes (e.g. sea water level rise, ...). Of course, this problem does not happen when using the others two used mode (local PC and Web Services). Until now, the computing time is relatively short (range of tens of seconds) for the current workflows. On other issue is related to the visualization module and maps delivery. This part was not emphasis until recently since the user has the possibility to upload his own results files and make graphical representation with existing GIS software (e.g. QGIS, ARCGIS). Nevertheless, the last year several technics and libraries for visualization were considered and this gives a good returns for the representation of the results in vector and json formats (e.g. Figs. 11, 13). Beside the layers of the calculated results, default layers can be adapted from a project to another. For example, the Sisfrance database ([www.sisfrance.net](http://www.sisfrance.net)) for seismic simulation is very useful since we can have an idea about the historical earthquake in the area of interest. Concerning raster/grid format visualization, this part is on testing and under development and will be soon available.

## 5 Conclusion

Risk assessment in the domain of natural hazard (e.g. seismic, landslide, submersion) from the phenomenon modelling to the impact evaluation on exposed elements such as buildings and networks is still an import challenge. We present here VIGIRISKS platform developed at BRGM. In the Introduction, we have a look to existent platforms. The platforms dealing with Natural hazards evaluate rapidly and, hence is quite complicate to have a complete and exhaustive look. We have tried here to give a general overview of the situation concerning the platform which deals with nature risk. Some of the platform provides the possibility to perform calculation with the user data, some other are doing only visualization of previous performed calculations, or are developed for visualization of previously performed calculation. VIGIRISKS platform intends to have a wide range of methods for calculating hazard and susceptibility and relations between risk and vulnerability for calculating damage. Workflow for data analysis, preparation and transformation are also in the scope of this platform in order to facilitate the work of scientists in manipulating their datasets. Connecting heterogeneous *Scientific Codes* and different formats input data sources is a specific issue treated by VIGIRISKS platform. While *Scientific Codes* are implemented in various technologies, data to process can be for instance georeferenced databases, grids and vectors data



provided in various file formats, web services, and internal or external data sources, already referenced in the repository or uploaded by a user. In order to enable such an integration, we defined normalized code entry points and data connectors. Finally, a **User Web Portal** offers access to all the functionalities, but main components are also usable through web services or even directly when relevant. The Execution core, based on open sources Java and Python software, is entirely accessible from web services referenced in a metadata catalogue and a version control system. A strong security mechanism allows to publish studies when they are validated, and to ease collaborative work in private groups. A BRGM Python library completes the architecture, by providing specific algorithms for the domain, including data connectors, scientific modification, and data pre- and post-treatments. Currently, the platform is in French, but the internationalization (FR/EN) is ongoing.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s11069-022-05567-6>.

**Acknowledgements** We thank Boulahya Faiza for the useful discussions on various software aspects of this study and Nicolas Taillefer and Stéphane Loigerot for answering our questions on several managerial aspects. The authors are also very grateful to some colleagues of the DRP division who have provided much needed knowledge and insight on their respective physical approaches; namely Dr. Pierre Gehl, Dr. Anne Lemoine, Dr. Daniel Raucoles, Benoit Aunay and Samuel Auclair. We thanks Goncalves Jean who joint the IT Teams during the preparation of this publication. Finally, we would like to thank Karim Ben Slimane and Arnaud Garnier for the support and precious discussions during the Steering Committee of BRGM VIGIRISKS project. This article was supported by an internal BRGM research program (VIGIRISKS/MULTIRISK2018-2022). The research Fayjaloun et al. 2021 and the corresponding VIGIRISKS database was funded by the European Union's Horizon 2020 research and innovation program, grant number 821046, project TURNkey. The calculation of earthquake damages for French-Spanish-Andorra border territory in relation with automatic ShakeMap (USGS4.0) was performed during the ongoing European project Pocrisc, (<https://pocrisc.eu>), led by Institut Cartogràfic i Geològic de Catalunya (ICGC). We thank the anonymous reviewers for their comments on an earlier version of this article.

**Author contributions** All authors contributed to the study conception and design. CN and AH performed material preparation and data collection. The first specification of the platform were done by AT-A, SF, AH, CN, AQ, RQ and GG. The IT technical aspects were performed by SF, RQ, UC and RG. The analysis was performed by CN and AH. The first draft of the manuscript was written by CN, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

**Funding** The authors have not disclosed any funding.

**Data availability** The VIGIRISKS platform is open access via free registration on the website <https://vigirisks.fr/>. Open data used in the work mentioned in this paper are available in the following portals: For Luchon: <https://vigirisks.fr/#/my-projects/20220114084029922j.vieille@brgm.fr>. For French West Indies: <https://vigirisks.fr/#/my-projects/20210326090027419C.Negulescu@brgm.fr>. For Mayotte: <https://vigirisks.fr/#/my-projects/20210609111916844C.Negulescu@brgm.fr>. For national statistics database for the buildings typologies (Tinard et al. 2020) adapted from INSEE: <https://vigirisks.fr/#/my-projects/20210326090027419C.Negulescu@brgm.fr/workflows/20200610072514701r.quique@brgm.fr>.

## Declarations

**Competing interests** The authors have no relevant financial or non-financial interests to disclose.

**Disclaimer for the shared data** These projects shared through the VIGIRISKS platform have been the subject of scientific publications. Although the platform and the data has been subjected to rigorous review, we reserve the right to update the software as necessary as a result of additional analysis and review. No warranty, express or implied, is made to the functionality of the platform and related materials, nor does the release of the software constitute such a warranty. Further, these datasets are distributed on the condition that we not shall be liable for any damages resulting from its authorized or unauthorized use. The projects should be cited using the corresponding reference which are given in this article.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## References

- Antofie T, Doherty B, Marin Ferrer M (2018) Mapping of risk web-platforms and risk data: collection of good practices, EUR 29086 EN. Publications Office of the European Union, Luxembourg. <https://doi.org/10.2760/93157> (ISBN 978-92-79-80171-6)
- Aye ZC, Jaboyedoff M, Derron M-H, Van Westen CJ (2015) Prototype of a web-based participative decision support platform in natural hazards and risk management. *ISPRS Int J Geo-Inf* 4:1201–1224. <https://doi.org/10.3390/ijgi4031201>
- Arrighi C, Rossi L, Trasforini E, Rudari R, Ferraris L, Brugioni M, Franceschini S, Castelli F (2018) Quantification of flood risk mitigation benefits: a building-scale damage assessment through the RASOR platform. *J Environ Manag* 207:92–104. <https://doi.org/10.1016/j.jenvman.2017.11.017> (ISSN 0301-4797)
- S Auclair, D Monfort, B Colas, T Langer, P Perrier (2015) Evaluation rapide des bilans matériels et humains : une aide essentielle à la gestion opérationnelle des crises sismiques. 9ème Colloque National AFPS 2015, Champs-sur-Marne, France. (hal-01243222)
- Bernard P, Lambert J (1988) Subduction and seismic hazard in the northern Lesser Antilles: revision of the historical seismicity. *Bull Seismol Soc Am* 78(6):1965–1983. <https://doi.org/10.1785/BSSAO780061965>
- Bernardie S, Vandromme R, Thierry Y, Houet T, Grémont M, Masson F, Grandjean G, Bouroulec I (2021) Modelling landslide hazards under global changes: the case of a Pyrenean valley. *Nat Hazards Earth Syst Sci* 21:147–169
- Borzi B, Faravelli M, Onida M et al (2018) Piattaforma IRMA (italian risk maps). In: 37esimo Convegno Nazionale GNGTS. Bologna, pp 102–106
- Borzi B, Onida M, Faravelli M et al (2021) IRMA platform for the calculation of damages and risks of Italian residential buildings. *Bull Earthq Eng* 19:3033–3055. <https://doi.org/10.1007/s10518-020-00924-x>
- Boutaraa Z et al (2018) Buildings vulnerability assessment and damage seismic scenarios at urban scale: application to Chlef City (Algeria). *KSCE J Civ Eng* 22(10):3948. <https://doi.org/10.1007/s12205-018-0961-2>
- Calvi GM, Pinho R (2004) LESSLOSS—a European integrated project on risk mitigation for earthquakes and landslides. IUSS Press, Pavia
- Coburn AW, Spence RJ, Pomonis A (1992) Factors determining human casualty levels in earthquakes: mortality prediction in building collapse. In: Proceedings of the tenth world conference on earthquake engineering, vol 10. Balkema, Rotterdam, pp 5989–5994
- Crowley H, Rodrigues D, Silva V, Despotaki V, Romao X, Castro JM, Akkar S, Hancilar U, Pitilakis KPD, Belvaux M et al (2018) Towards a uniform earth-quake risk model for Europe. In: Proceedings of the 16th European conference on earthquake engineering, Thessaloniki, Greece, 18–21 June 2018
- Crowley H, Despotaki V, Rodrigues D, Silva V, Toma-Danila D, Riga E, Karatzetou A, Fotopoulou S, Zugic Z, Sousa L, Ozcebe S, Gamba P (2020a) Exposure model for European seismic risk assessment. *Earthq Spect*. <https://doi.org/10.1177/8755293020919429>
- Crowley H, Dabbeek J, De Maio FV, Despotaki V, Rodrigues D, Faravelli M, Borzi B, Silva V, Martins L, Kalakonas P, Weatherill G, Riga E, Karatzetou A, Pitilakis K, Anastasiadis A, Pitilakis D, Fotopoulou S, Michelini A, Faenza L (2020b) D26.8 testing and verification of the European Seismic Risk Model (ESRM20), SERA Project Deliverable. [www.sera-eu.org](http://www.sera-eu.org)
- Crowley H (2021) European exposure and vulnerability models: state-of-the-practice, challenges and future directions. In: Advances in assessment and modeling of earthquake loss. Springer, Cham, pp 155–168

- Crowley H, Dabbeek J, Despotaki V, Rodrigues D, Martins L, Silva V, Romão X, Pereira N, Weatherill G, Danciu L (2021a) European seismic risk model (ESRM20). EFEHR technical report 002 V1.0.0, <https://doi.org/10.7414/EUC-EFEHR-TR002-ESRM20>
- Crowley H, Despotaki V, Rodrigues D, Silva V, Costa C, Toma-Danila D, Riga E, Karatzetzou A, Fotopoulou S, Sousa L, Ozcebe S, Gamba P, Dabbeek J, Romão X, Pereira N, Castro JM, Daniell J, Veliu E, Bilgin H, Adam C, Deyanova M, Ademović N, Atalic J, Bessason B, Shendova V, Tiganescu A, Zugic Z, Akkar S, Hancilar U (2021b). European exposure model data repository [data set]. Zenodo. <https://doi.org/10.5281/zenodo.4062044>
- Cruz AM, Steinberg LJ, Vetere-Arellano AL (2006) Emerging issues for Natech disaster risk management in Europe. *J Risk Res* 9(5):483–501. <https://doi.org/10.1080/13669870600717657>
- Danciu L, Wiemer S, Haslinger F, Giardini D (2018) European facilities for earthquake hazard and risk-EFEHR: status, activities and further updates of the 2020 European Seismic Hazard Model (ESHM20). In: EGU general assembly conference abstracts, p 18151
- Debortoli NS, Camarinha PIM, Marengo JA, Rodrigues RR (2017) An index of Brazil's vulnerability to expected increases in natural flash flooding and landslide disasters in the context of climate change. *Nat Hazards* 86(2):557–582
- Dolce M, Borzi B, Da Porto F et al (2019) Mappa di rischio per il territorio Italiano. In: Proceedings of the 18th Italian conference on earthquake engineering ANIDIS. Ascoli Piceno, Italy, pp SS02-21–SS02-34
- Dolce M, Prota A, Borzi B, Da Porto F, Lagomarsino S, Magenes G, Moroni C, Penna A, Polese M, Speranza E et al (2020) Seismic risk assessment of residential buildings in Italy. *Bull Earthq Eng* 19:1–34
- Douglas J, Climent DM, Negulescu C, Roullé A, Sedan O (2015) Limits on the potential accuracy of earthquake risk evaluations using the L'Aquila (Italy) earthquake as an example. *Ann Geophys* 58:1–17
- Elnashai A, Hampton S, Lee JS, McLaren T, Myers JD, Navarro C, Spencer B, Tolbert N (2008) Architectural overview of MAEviz—HAZTURK. *J Earthq Eng* 12(sup2):92–99. <https://doi.org/10.1080/13632460802013610>
- European Commission, Joint Research Centre, Luoni S, Antofie T, Eklund L, Marín Ferrer M (2020) Update of risk data hub software and data architecture: software solutions for disaster risk management. Publications Office <https://doi.org/10.2760/798003>
- Faravelli M, Polli D, Quaroni D, et al (2019) Italian platform for seismic risk and damage scenario evaluation. In: 7th international conference on computational methods in structural dynamics and earthquake engineering COMPDYN, Greece
- Fayjaloun R, Negulescu C, Roullé A, Auclair S, Gehl P, Faravelli M (2021) Sensitivity of earthquake damage estimation to the input data (soil characterization maps and building exposure): case study in the Luchon Valley, France. *Geosciences* 11(6):249
- FEMA (2004) HAZUS-MH technical manual. Federal Emergency Management Agency, Washington, DC
- FEMA (2017) Hazus Tsunami model technical guidance for Hazus version 4.0, contract no. HSFE60-17-P-0004
- FEMA (2018) Seismic performance assessment of buildings. Volume 1—methodology. FEMA P-58-1, 2nd edn. Federal Emergency Management Agency, Washington DC
- Feuillet N, Beauducel F, Tapponnier P (2011) Tectonic context of moderate to large historical earthquakes in the Lesser Antilles and mechanical coupling with volcanoes. *J Geophys Res* 116(B10). <https://doi.org/10.1029/2011JB008443>
- Fraser S, Simpson A, Núñez A, Vivien D, Simone B, Brenden J, Richard M, Nicolas T, Nicolas C, Olivier M, Audrey H et al (2016) ThinkHazard!—delivering natural hazard information for decision making. In: 3rd international conference on information and communication technologies for disaster management (ICT-DM), pp 1–6 <https://doi.org/10.1109/ICT-DM.2016.7857209>
- Gallina V, Silvia T, Andrea C, Anna S, Thomas G, Antonio M (2016) A review of multi-risk methodologies for natural hazards: consequences and challenges for a climate change impact assessment. *J Environ Manag* 168:123–132. <https://doi.org/10.1016/j.jenvman.2015.11.011> (ISSN 0301-4797)
- Gill S, Ghesquiere F, Anderson E, Holmes C (2009) The central American probabilistic risk assessment (CAPRA) a regional SDI for disaster risk reduction
- Girgin S (2012) RAPID-N, Rapid Natech Risk Assessment Tool, User Manual Version 1.0 Report EUR 25164 EN, JRC
- Giuliani G, Peduzzi P (2011) The PREVIEW Global Risk Data Platform: a geoportal to serve and share global data on risk to natural hazards. *Nat Hazards Earth Syst Sci* 11:53–66. <https://doi.org/10.5194/nhess-11-53-2011.2011>
- Grangeon T, Vandromme R, Cerdan O, De Girolamo AM, Lo PA (2021) Modelling forest fire and fire-break scenarios in a Mediterranean mountainous catchment: Impacts on sediment loads. *J Environ Manag* 289:112497. <https://doi.org/10.1016/j.jenvman.2021.112497>

- Grünthal G (1998) European macroseismic scale 1998. Council of Europe, Cahiers du Centre Européen de Géodynamique et de Sismologie
- Guérin-Marthe S, Gehl P, Negulescu C, Auclair S, Fayjaloun R (2021) Rapid earthquake response: the state-of-the art and recommendations with a focus on European systems. *Int J Disaster Risk Reduct* 52:101958. <https://doi.org/10.1016/j.ijdr.2020.101958> (ISSN 2212-4209)
- Hancilar U, Tuzun C, Yenidogan C, Erdik M (2010) ELER software: a new tool for urban earthquake loss assessment. *Nat Hazards Earth Syst Sci* 10:2677–2696. <https://doi.org/10.5194/nhess-10-2677-2010>
- Helmholtz-Centre Potsdam - GFZ German Research Centre for Geosciences and gempa GmbH (2008) The SeisComP seismological software package. GFZ Data Serv. <https://doi.org/10.5880/GFZ.2.4.2020.003>
- Kammouh O, Dervishaj G, Cimellaro GP (2018a) Resilience-Based Risk (RBR) Quantitative framework to assess resilience and risk at the country level. *ASCE ASME J Risk Uncertain Eng Syst Part A Civ Eng* 4(1):04017033
- Kammouh O, Marasco S, Noori AZ, Mahin GCS (2018b) PEOPLES: indicator-based tool to compute community resilience. In: Eleventh US national conference on earthquake engineering integrating science, engineering & policy, June 25–29
- King A, Bell R (2005). *Riskscape New Zealand—a multihazard loss modelling tool*
- Köhler P, Müller M, Sanders M, Wächter J (2006) Data management and GIS in the center for disaster management and risk reduction technology (CEDIM): from integrated spatial data to the mapping of risk. *Nat Hazards Earth Syst Sci*. <https://doi.org/10.5194/nhess-6-621-2006>
- Lagomarsino S, Giovinazzi S, Podestà S, Resemini S (2002) WP4—vulnerability assessment of current buildings: I level methodology for the vulnerability assessment of current buildings and guidelines for the implementation, RISK-UE project: an advanced approach to earthquake risk scenarios with applications to different European towns. Contract no. EVK4-CT-2000-00014
- Landemaine V (2016). Érosion des sols et transferts sédimentaires sur les bassins versants de l'Ouest du Bassin de Paris : analyse, quantification et modélisation à l'échelle pluriannuelle. Thèse de doctorat (in Fr). Université de Rouen-Normandie. HAL Id: tel-01937208
- Le Roy S, Lemoine A, Nachbaur A, Legendre Y, Lambert J, Terrier M (2017) Détermination de la submersion marine liée aux tsunamis en Martinique. Rapport BRGM/RP-66547-FR, 177 p., 105 ill., 7 Ann
- Marasco S, Kammouh O, Cimellaro GP (2022) Disaster resilience quantification of communities: a risk-based approach. *Int J Disaster Risk Reduct* 70:102778. <https://doi.org/10.1016/j.ijdr.2021.102778> (ISSN 2212-4209)
- Marin-Ferrer M, Vernaccini L, Poljansek K (2017) Index for risk management INFORM concept and methodology report—version 2017, EUR 28655 EN. <https://doi.org/10.2760/094023>
- Marin-Ferrer M, Antofie T-E, Eklund LG, Luoni S (2019) The Disaster Risk Management Knowledge Centre—Risk Data Hub: Vision Paper & Roadmap. NEW <https://drmke.jrc.ec.europa.eu/doc/18150>
- Molina S, Lang DH, Lindholm CD (2010) SELENA: an open-source tool for seismic risk and loss assessment using a logic tree computation procedure. *Comput Geosci* 36:257–269. <https://doi.org/10.1016/j.cageo.2009.07.006>
- Monfort D, Negulescu C, Belvaux M (2019) Remote sensing vs. field survey data in a post-earthquake context: potentialities and limits of damaged building assessment datasets. *Remote Sens Appl Soc Environ* 14:46–59. <https://doi.org/10.1016/j.rsase.2019.02.003> (ISSN 2352-9385)
- Mouroux P, Le Brun B (2006) Presentation of RISK-UE project. *Bull Earthq Eng* 4(4):323–339
- Müller M, Vorogushyn S, Maier P, Thieken AH, Petrow T, Kron A, Büchele B, Wächter J (2006) CEDIM risk explorer—a map server solution in the project “Risk Map Germany.” *Nat Hazards Earth Syst Sci* 6:711–720. <https://doi.org/10.5194/nhess-6-711-2006>
- Negulescu C, Foerster E (2010) Parametric studies and quantitative assessment of the vulnerability of a RC frame building exposed to differential settlements. *Nat Hazards Earth Syst Sci* 10:1781–1792. <https://doi.org/10.5194/nhess-10-1781-2010>
- Negulescu C, Hohmann A, Tellez-Arenas A, Smal F (2019) A web platform for storing, sharing and executing scientific workflows for Natural Risk Assessment: part 1—data, approaches and case studies. *Geophys Res Abst* 21:1–1
- Negulescu C, Benaïchouche A, Lemoine A et al (2020) Adjustability of exposed elements by updating their capacity for resistance after a damaging event: application to an earthquake–tsunami cascade scenario. *Nat Hazards* 104:753–793. <https://doi.org/10.1007/s11069-020-04189-0>
- Pagani M, Monelli D, Weatherill G, Danciu L, Crowley H, Silva V, Henshaw P, Butler L, Nastasi M, Panzeri L, Simionato M, Vigano D (2014) OpenQuake Engine: an open hazard (and risk) software for the global earthquake model. *Seism Res Lett* 85(3):692–702
- Philippenko X, Goeldner-Gianella L, Le Cozannet G, Grancher D, De la Torre Y (2021) Perceptions of climate change and adaptation: a subarctic archipelago perspective (Saint-Pierre-and-Miquelon, North America). *Ocean Coast Manag* 215:105924

- Pitilakis K, Franchin P, Khazai B, Wenzel H (eds) (2014) SYNER-G: systemic seismic vulnerability and risk assessment of complex urban, utility, lifeline systems and critical facilities: methodology and applications, vol 31. Springer
- Poisson B, Garcin M, Pedreros R (2009) The 2004 December 26 Indian Ocean tsunami impact on Sri Lanka: cascade modelling from ocean to city scales. *Geophys J Int* 177(3):1080–1090. <https://doi.org/10.1111/j.1365-246X.2009.04106.x>
- Raucoules D, Tomaro F, Fournel M, Negulescu C, de Michele M, Aunay B (2018) Landslide observation from ALOS-2/PALSAR-2 Data (Image Correlation Techniques and Sar Interferometry). Application to Salazie Circle Landslides (La Reunion Island), IGARSS 2018—2018 IEEE international geoscience and remote sensing symposium, 2018, pp 506–509. <https://doi.org/10.1109/IGARSS.2018.8517998>
- RISK-UE (2003) RISK-UE WP4 handbook. Vulnerability of current buildings—an advanced approach to earthquake risk scenarios with applications to different European towns. Zoran V. Milutinovic & Goran S. Trendafiloski, September, 2003
- Robinson D, Fulford G, Dhu T (2006) EQRM: geoscience Australia's earthquake risk model: technical manual version 3.0. Geoscience Australia
- Romão X, Pereira N, Castro JM, De Maio F, Crowley H, Silva V, Martins L (2020) European building vulnerability data repository (Version v1.1). Zenodo. <https://doi.org/10.5281/zenodo.4087810>
- Rossi M, Guzzetti F, Reichenbach P, Mondini AC, Peruccacci S (2010) Optimal landslide susceptibility zonation based on multiple forecasts. *Geomorphology* 114(3):129–142
- Rudari R (2015) Rasor project: rapid analysis and spatialization of risk, from hazard to risk, using eo data. *Geophys Res Abstr* 17:2538
- Schmidt J, Matcham I, Reese S et al (2011) Quantitative multi-risk analysis for natural hazards: a framework for multi-risk modelling. *Nat Hazards* 58:1169–1192. <https://doi.org/10.1007/s11069-011-9721-z>
- Sedan O, Caterina N, Monique T, Agathe R, Thierry W, Didier B (2013) Armageddon—a tool for seismic risk assessment illustrated with applications. *J Earthq Eng* 17(2):253–281. <https://doi.org/10.1080/13632469.2012.726604>
- Silva V, Horspool N (2019) Combining USGS XE “USGS” shakemaps and the openquake-engine for damage and loss assessment. *Earthq Eng Struct Dynam*. <https://doi.org/10.1002/eqe.3154>
- Silva V, Crowley H, Pagani M, Monelli D, Pinho R (2014) Development of the OpenQuake engine, the global earthquake model's open-source software for seismic risk assessment. *Nat Hazards*. <https://doi.org/10.1007/s11069-013-0618-x>
- Silva V, Amo-Oduro D, Calderon A, Costa C, Dabbeek J, Despotaki V, Martins L, Pagani M, Rao A, Simionato M, Viganò D, Yepes-Strada C, Acevedo A, Crowley H, Horspool N, Jaiswal K, Journeay M, Pittore M (2020) Development of a global seismic risk model. *Earthq Spect*. <https://doi.org/10.1177/8755293019899953>
- Taillefer N, Didier B, Caterina N, Agathe R, Christian I, Samuel A, Robin Q (2022) Seismic damage scenarios for Mayotte—a tool for disaster management. *C R Geosci* (**in proof**)
- Tanjo T, Kawai Y, Tokunaga K et al (2021) Practical guide for managing large-scale human genome data in research. *J Hum Genet* 66:39–52. <https://doi.org/10.1038/s10038-020-00862-1>
- Tellez-Arenas A, Hohmann A, Quentin A, Negulescu C, Smaï F (2019) A web platform for storing, sharing and executing scientific workflows for Natural Risk Assessment: part 2—description of an interoperable architecture based on open-source components. *Geophys Res Abstr* 21:1–1
- Tinard P, Rey J, Monfort-Climent D, Imtiaz A, Hoste-Colomer R, Negulescu C, Gehl P (2020) New insights into the evaluation of financial impact of earthquakes in France: benefits for compensation and prevention, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-5128. <https://doi.org/10.5194/egusphere-egu2020-5128>
- Thiebes B, Bell R, Glade T, Jäger S, Anderson M, Holcombe L (2013) A WebGIS decision-support system for slope stability based on limit-equilibrium modelling. *Eng Geol* 158:109–118
- Thiery Y, Malet J-P, Sterlacchini S, Puissant A, Maquaire O (2007) Landslide susceptibility assessment by bivariate methods at large scales: application to a complex mountainous environment. *Geomorphology* 92(1–2):38–59
- UNDRR (2022) <https://www.undrr.org/terminology/hazard>. Accessed 2022
- Vandromme R, Thiery Y, Bernardie S, Sedan O (2020) ALICE (Assessment of Landslides Induced by Climatic Events): a single tool to integrate shallow and deep landslides for susceptibility and hazard assessment. *Geomorphology* 367:107307. <https://doi.org/10.1007/s00421-008-0955-8> (ISSN 0169-555X)