An open source platform addressing structural stability risk assessment in historical centres

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Abstract:

The management of stability risk assessment in historical centres in a project that aims to design and develop an open platform where blocks of buildings and large structures may be represented in damage maps before the event occurs, addressing damage forecasts for seismic movements impacting on the structural stability of the CH. The structural stability is calculated using a Matlab code developed at the National Technical University of Athens, translated to an open source programming language (Python) using the software tool GeoPandas to enable operations that would normally require spatial database software (PostGIS). Furthermore, the use of open source technologies like QGIS desktop software will provide open and free access to view and contribute in the future.

Keywords: cultural heritage; open source; european project; risk assessment.

FOSS software used and licence: QGIS (*GNU General Public License*), PostGIS (*GNU General Public License (GPLv2 or later)*)

Introduction

STABLE (STructural stABiLity risk assEssment, 2018-2022, Horizon2020, MSCA - Marie Sklodowska Curie Actions - RISE - Research and Innovation Staff Exchange - grant agreement nº. 823966) has the goal of developing a digital platform to forecast earthquake damage to Historical City Centers in Europe combining different techniques and methodologies: structural stability models, earthquake simulation tools combined with geotechnical data, remote sensing and in situ monitoring technologies.

The STABLE team is composed of seven different partners from Italy (Sapienza University, Rome; University of Tuscia, Viterbo), Greece (National Technical University and Geosystem Hellas from Athens and FORTH from Rethymno) and Cyprus (Frederick University and System Space Solution Ltd), with specific expertise, coordinated together by ALMA Sistemi Srl (Italian SME), and with a plan of collaborations and staff exchanges in order to allow interdisciplinary research.

Some emblematic case studies of buildings from different countries were selected as test cases: a few blocks in the city centre of Rieti, Italy; city blocks in Nafplion and the Lavrion area, Greece; a few buildings in the central region of Strovolos, a district close to Nicosia, Cyprus; and, recently, some buildings in the historic centre of Rethymno in Crete, Greece.

The goal of the project is to define a risk modelling system through the integration of different data, from SAR satellite images to geological and geotechnical information, in order to create deformation soil maps. Additionally, we use free and open source solutions, as far as possible, to achieve all the above.

The risk map generation

The study aims to investigate the vulnerability of the architectonic heritage and to combine the results with hazard scenarios, as a first fundamental step in the seismic risk mitigation process. The two key elements of a vulnerability analysis are the capacity (strength and deformation) of a structure and the seismic demand. From these elements it is possible to predict expected vulnerability functions of possible damage to the structure as an effect of the seismic input. Corresponding fragility curves will be determined, expressing the probability of a structure, belonging to a certain class, reaching or exceeding a particular damage grade given a deterministic estimate of the spectral displacement caused by an expected hazard (e.g. Kappos et al. 2008).

The expected risk is determined according to the following expression:

Risk = *f* (Hazard, Vulnerability)

where:

Hazard: seismicity of the region and accepted probability of exceedance of the destructive action

Vulnerability: capacity of the structure as described below.

The *f* function is dependent on the various methods for the assessment of the structure's vulnerability and the hazard of the soil. The type of method chosen depends mainly on the objective of the assessment, but also on the availability of data and technology. In general, a vulnerability function is a relationship which defines the expected damage on a structure or a class of structures as a function of the ground motion (fig. 1). The two key elements of a vulnerability analysis are the capacity of the structure and the seismic demand. In order to estimate the damage (*D)*, the ability of the structure to resist constraints (capacity of the structure) must be compared with the constraints on the structure due to the earthquake ground motion (seismic demand).

To express the seismic demand, until very recently, the "intensity" was used nearly exclusively. This is a descriptive parameter of an earthquake based on observations of the effects of the earthquake on the environment. It has the advantage that historical data on earthquakes are available. However, information on the real ground movement is lost, and empirical relationships between intensity and peak ground acceleration vary a lot. Some methods use peak ground acceleration as the parameter defining the earthquake. Nevertheless, in that case, not only the information on the duration of the earthquake is lost, but also the information on the frequency content. Thus, a better parameter is the spectral acceleration (*Sa)* or the spectral displacement (*Sd).*

The estimation of damage probability will be performed by means of a simplified mechanical methodology (Lagomarsino and Giovinazzi 2006). This method provides results of satisfactory accuracy for relatively simple constructions, while the assessment of structural capacity for more complex constructions, such as monuments, requires more elaborated methodologies (Spyrakos et al. 2015). Initially, the required input parameters will be collected, including:

- *Structural data* (typology, construction period, use of the building, post-earthquake damage data, detection of different construction phases, etc.)
- *Geometrical data* (total height, number of storeys, perimeter, footprint area, average bearing wall thickness of masonry structures, plan view of at least the ground floor, etc.)
- *Satellite data* (coordinates of each building, number of building blocks, number of buildings in each building block)
- *Vulnerability data* (estimation of vulnerability by rapid assessment methods related to the evaluation of conservation of the structure and materials used)

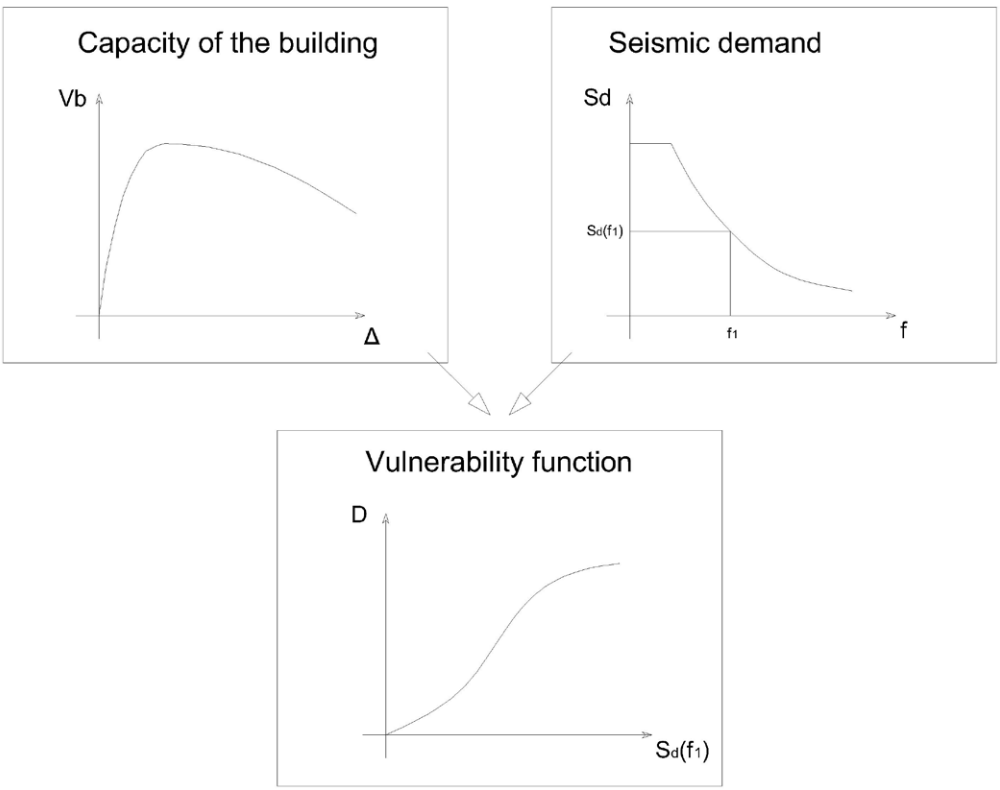

Figure 1. Principle of a Vulnerability function

The Structural Model Processor

This program calculates the risk map of the building stroke of an area for a given seismic hazard by applying a simplified mechanical method. The risk is defined as the probability of a certain level of damage being exceeded. Four levels of damage are examined, namely P1, P2, P3 and P4. The level of damage Pi increases with increasing i = 1 to 4. The probability takes values from zero (totally unlikely) to one (certainty).

All the calculation process has initially been done in MATLAB, a programming platform designed to allow expressions of computational mathematics, which for our experimental process means facilitating the use of mathematical complex functions. With this, it has been possible to analyse data, develop algorithms and create models and applications, with the final aim of defining the capacity curve and the exact displacements related to specific damage states, which may be derived through sophisticated analysis of a selective building case-study.

The code from MATLAB (wrote by C. Maniatakis) has been translated to an open source programming language (Python) using the software tool GeoPandas (translation by N. Schetakis). GeoPandas enables the user to easily do operations in Python that would normally require spatial database software. PostGIS is used for the webGIS representation of the final risk map. By translating the code to Python we further ensure the open source capability.

The code requires as inputs both Structural data and seismic spectral data.

The structural data

The structural data related to the building to be examined are included in a Geopackage file containing information on the geometry, average height (Z) and different typologies of the building, stored in the parameters Type 1, Type 2, Type 3, Type 4, Type 5, Type 6, Use, WT. GeoPackage is an open, standards-based, platform-independent, portable compact format for transferring geospatial information.

The following tables better explain the meaning of each parameter:

Typo 1 - general classification

Typologies	**Building types**	**Type 1**
Unreinforced Masonry	Rubble stone	1
	Adobe (earth bricks)	2
	Simple stone	**3**
	Massive stone	4
	U Masonry (old bricks)	5
	U Masonry – R.C. floors	6
Reinforced/confined masonry	Reinforced/confined masonry	7

Reinforced Concrete	Concrete Moment Frame	8
	Concrete Shear Walls	9
	Dual System	10

Typo 2 - type of horizontal structure (diaphragm/ slab/ vault)

Typologies		**Type 2**
Unreinforced and/or reinforced Masonry	wood slabs	1
	masonry vaults	2
	composite steel and masonry slabs	3
	reinforced concrete slabs	4

Typo 3 - presence or not of a soft first story in reinforced concrete structure.

Typologies		**Type 3**
Reinforced Concrete	soft first storey - pilotis	1
	regular along height	2

Typo 4 - presence or not of infill walls in reinforced concrete structure.

Typologies		**Type 4**
Reinforced Concrete	infill walls	1
	no infill walls	2

Typo 5 - ductility class.

Ductility class		**Type 5**
	without ductility class	1
	low ductility class	2
	medium ductility class	3
	high ductility class	4

Typo 6 - irregularity along height for every structure related to a reinforced concrete structure.

Typologies		Type 6
Reinforced Concrete	irregular	1
	regular	2

Use - main use of the structure.

Typologies		Use
Reinforced Concrete	residential	1
	public	2

WT - The average bearing wall thickness for masonry structures.

If the WT field is unavailable, a value of WT = 0.60 is assigned by the code, assuming an average thickness of 60 cm for bearing walls.

The Seismic hazard data

The seismic hazard data are included in a Geopackage file that includes different seismic acceleration spectra as a grid of points within the area of interest. The side of the grid is proposed to be 5.0 m x 5.0 m. Each point corresponds to an acceleration spectrum which resulted from a seismic hazard analysis, considering the seismic sources and the local soil effect (e.g. Tselentis et al. 2010). In case of active faults at a short distance from the buildings, a more detailed approach would include the examination of the particular phenomena that take place in the nearby field of active faults, the so-called near-fault area (Spyrakos et al. 2008; Maniatakis and Spyrakos 2012).

The Geopackage file includes information on the Geometry and the Spectrum type defined for each point and included in separate **"Spectrum" TXT** files, where the "name" is the corresponding value included in the relevant field of acceleration shapefile referred to geohazard. For example, if four areas with different seismic hazards are defined, the TXT files 1, 2, 3 and 4 should also be provided. The content of the TXT files is formatted into two columns, with the first including period values and the second spectral acceleration values in g units, without any text, as shown below:

0.01	0.3241
0.02	0.3243
...	
...	
4.0	0.0203

The acceleration values should be provided in the range of 0 ~ 4.0 seconds.

The final output

The code may be executed, provided that the above-mentioned input data are available in the same folder with the code and four figures in TIFF format; namely P1, P2, P3 and P4.

Every figure depicts with colours the value of probability Pi for the given seismic scenario. In figure 2, indicative results of the code are presented for probabilities P1 and P2. The results regard a seismic scenario that assumes peak ground acceleration equal to a_{gR}=0.30 g on rigid bedrock.

The GIS platform

All the data derived will be stored in the STABLE GIS platform. More specifically, and concerning the processing of the Structural Model processor outputs, automated workflows are used to convert the Georeferenced Fragility curves to actual classified Structural Vulnerability features in an open format.

The basic subject of analysis is a polygon feature covering each building of study. For the total sum of buildings, a classification process should be implemented in order to export the final

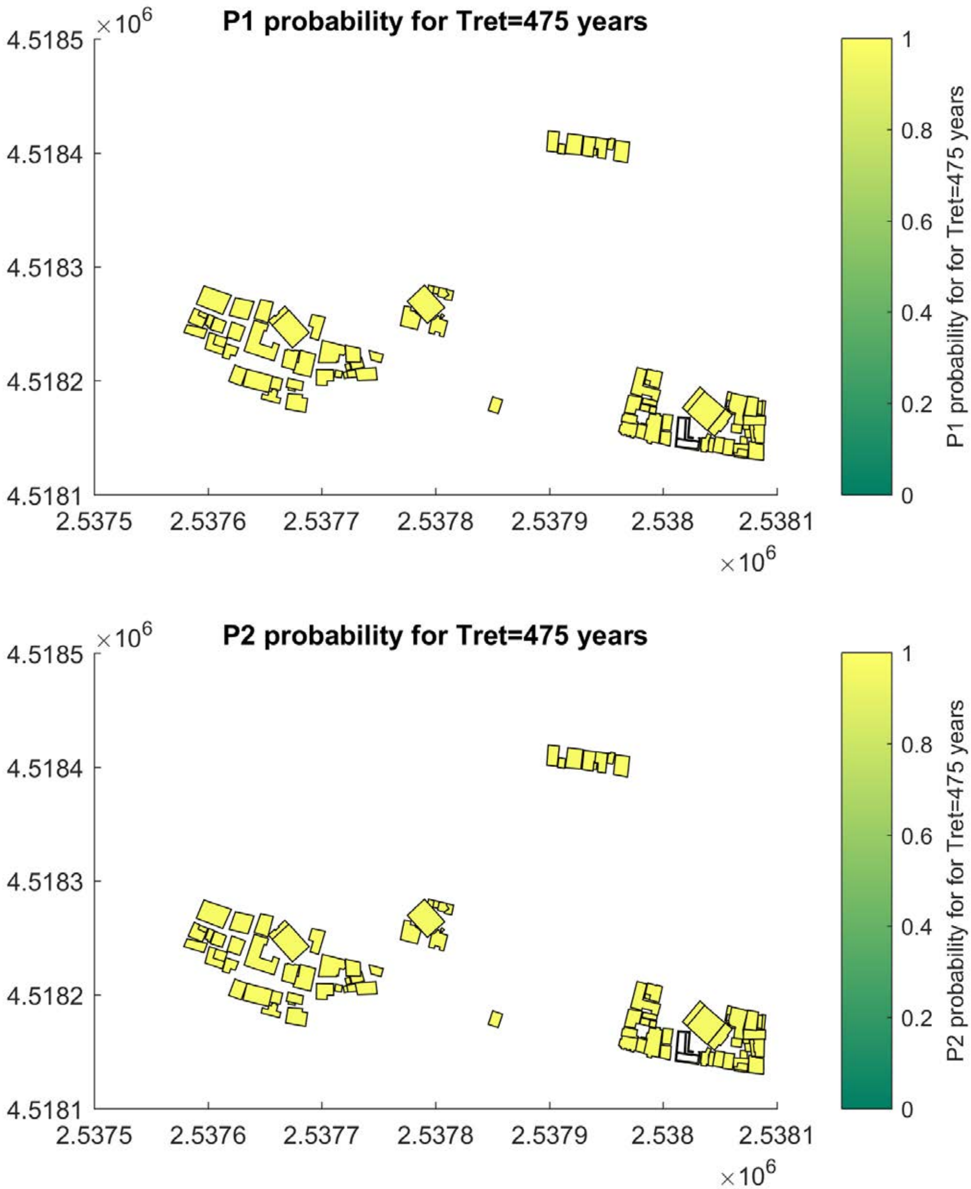

Figure 2. Indicative output of the code for the test case in Nafplion (Greece)

Structural Vulnerability map. Essentially, each building/feature is classified according to its assigned fragility value from the previous Structural Model processor step.

As illustrated in figure 3, the automated process through the SML operator takes as input building polygons, deriving from the Structural Model analysis, and extracts different classes of these buildings according to their vulnerability level.

The case studies

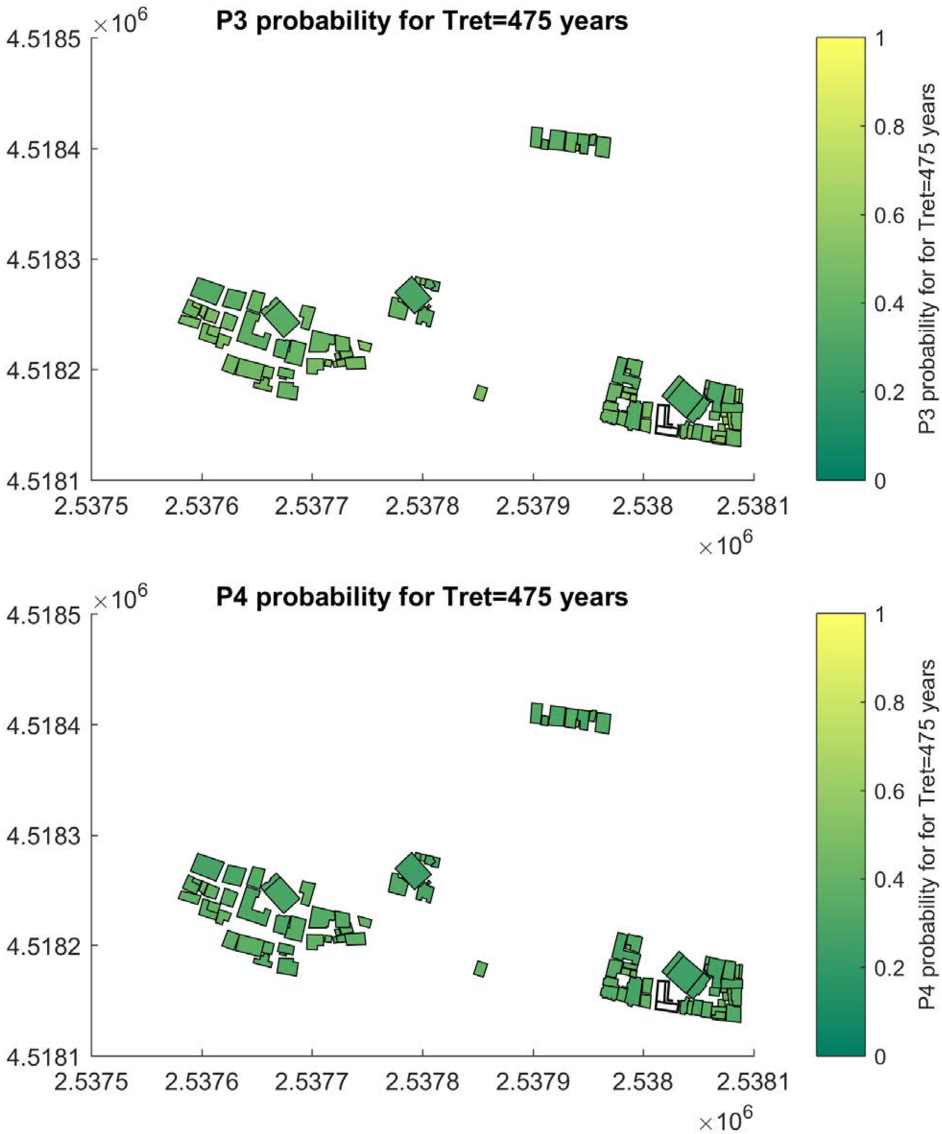

Figure 3. Result of the Spatial Model for building vulnerability classification

In the first phase of the project, the STABLE platform will contain within it selected sample cases. The cases are historical centres located in Cyprus, Greece and Italy.

Nafplio and the historic centre of Rethymno (case study recently included in the research) in Greece, Strovolos in Cyprus and Rieti in Italy (fig. 4). The aim is to start from individual buildings (monuments, historic buildings, etc.) and then hypothesise a future extension to the entire fabric that constitutes the historic centre.

To study how the structure of the building reacts in the presence of a seismic event of lesser or greater intensity, it is necessary to start from a careful study of mere basic maps, such as cadastral map, statistical data (age of the buildings, H maximum, number of floors), geological studies, aerial photos and historical maps. This will become part of a database of buildings that will allow you to select, investigate and observe all the information relating to the structure.

Details on the latest case study in Rethymno

The study area of the research is focused on the old town of Rethymno, on the island of Crete. The old town of Rethymno is one of the best-preserved towns of the Renaissance. Lying in the heart of modern Rethymno, it combines the oriental features of the Turkish period with Renaissance-style Venetian architecture. The plan of the old town of Rethymno has remained almost completely unchanged since the XVI century and it definitely needs a plan for the preservation of its architectural and historical evidence.

The main aim of our approach will be to assess the feasibility of Persistent Scattered Method (PSI) in estimating deformations and displacements in the broader area of the Old Town.

For this study, more than 100 S1B images were downloaded from the Copernicus Sentinel 1- Hub, concerning the monitoring period from January 2015 to June 2018. The Sentinel-1 mission comprises a constellation of two polar-orbiting satellites, operating day and night, and performing C-band synthetic aperture radar imaging, enabling them to acquire imagery regardless of the weather.

Afterwards, a combination of open source software such as the Sentinel Application Platform (SNAP), the Stanford Method for Persistent Scatterers (StaMPS), and the Statistical Cost Network Flow Algorithm for Phase Unwrapping (SNAPHU) package were installed in a Linux environment in order to carry out the PSI processing. The PSI requires at least 20 SAR images (Mora et al. 2013) to perform the analysis in C-band and measure surface deformation over a time period of months or years, removing atmospheric, topographical, and signal noise effects (fig. 5). In PSI, only the coherent pixels with stable phase or amplitude are used in the processing pipeline (Mancini et al. 2021). In this concept, the PSI exploits interferograms with a single master scene. In our case, 107 images in total were incorporated into the study (tab. 1):

Table 1. Analysed Tracks

Period (yyyy-mm-dd)	Master Science Acquisition date (yyyy-mm-dd)	Pass	Image Number

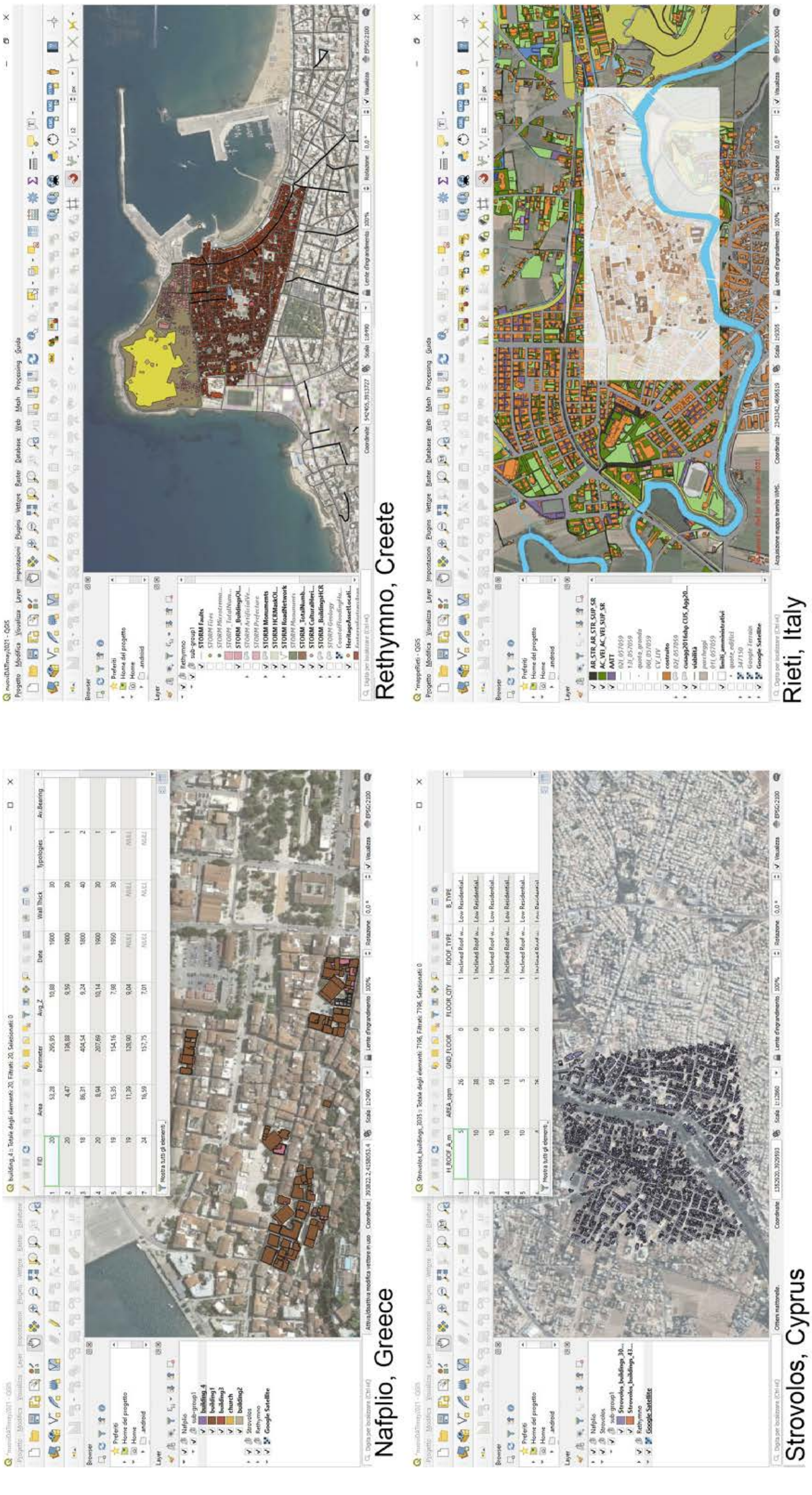

Figure 4. The test case location for STABLE project

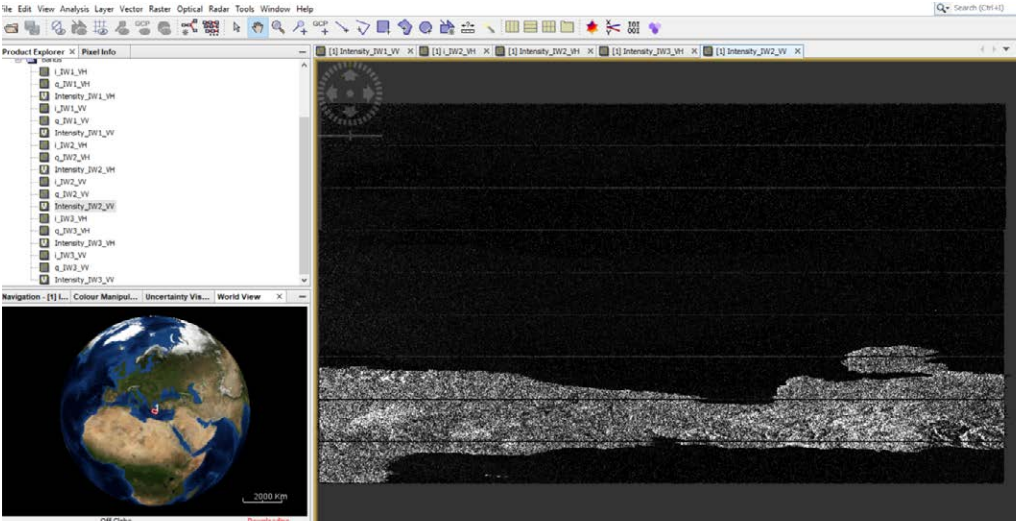

Figure 5. Processing of Sentinel-1 image in SNAP open source software environment

2015-01-05 / 2018-06-30	2017-23-02	Ascending	107

At the final step, the interferometric processing of S1 SLC images will generate a geolocated velocity map over the study area. This output will offer a ground deformation map which will provide us with useful knowledge about deformation phenomena occurring in the study area as a further contribution to geohazard analysis.

The methodology presented here will be applied also to the site of the Fortezza, a Venetian fort built in the XVI century on a rocky hill known as Paleochora. It is a site of particular interest since its walls (total length: 1.370 m) are well preserved, but at the same time, they are exposed to extreme climate events which endanger their integrity.

Actual achievements

The project is based on the application of the simplified structural stability model to the whole area of the city centre under analysis. The simulation of different earthquake scenarios, also considering the geological information available, and the response of the structures involved in the scenario will provide detailed damage maps of the area at building level, enabling preparedness for the seismic events. Public authorities, urban planners and cultural heritage responsible will have the capability to address preventive maintenance and consolidation of the structures that will be most damaged in future earthquakes.

This approach will have the twofold objective to drastically reduce the reconstruction and restoration costs as well as reduce the death toll associated with seismic activity.

The project has been running for almost one year and a half, mostly spent on the definition of the overall system, and will last until October 2023.

Acknowledgment

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