Wide area maps of building differential deformations

Michele Crosetto [1], Saeedeh Shahbazi [1], Anna Barra [1]

[1] Centre Tecnològic de Telecomunicacions de Catalunya – CERCA (CTTC-CERCA), Castelldefels, Barcelona, Spain
(mcrosetto, sshahbazi, abarra)@cttc.cat

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Abstract

The European Ground Motion Service (EGMS) uses Sentinel-1 data to monitor and measure land displacement across Europe, delivering information on ground motion phenomena. The EGMS service includes three types of products, enabling the analysis of annually updated ground motion data. The authors are working on a project aimed at computing the spatial gradient of land deformation and generating wide-area differential deformation maps. This type of maps can help identifying potentially vulnerable buildings and urban structures. The project involves developing a software pipeline to compute and convert original deformation data and creating a customized web viewer to display the results. Given the large volume of the processed datasets, with several millions of measurement points an accurate algorithm implementation is needed. The resulting information will aid in monitoring anthropogenic phenomena and their impact on building and infrastructures. This will be essential for urban management and risk mitigation planning.

1. Introduction

This paper focuses on the results of radar interferometry, specifically Advanced Differential Interferometric Synthetic Aperture Radar (A-DInSAR), a powerful remote sensing technique for monitoring ground motion (Crosetto et al., 2016). A-DInSAR has seen significant advancements in processing and data analysis, coupled with an increased SAR data acquisition capability from spaceborne sensors. A key advantage of A-DInSAR is its capability to cover extensive areas. Wide-area deformation monitoring has been successfully demonstrated at national and regional levels in Europe, with countries like Italy, Norway, and Germany implementing national Ground Motion Services. We here focus on the European Ground Motion Service (EGMS), part of the Copernicus Land Monitoring Service. The EGMS aims to provide consistent and standardized information on ground motion phenomena across European countries. It utilizes full-resolution Sentinel-1 SAR data, incorporating both ascending and descending passes.

The baseline EGMS processing covered the period 2015-2020. It involved approximately 750 Sentinel-1 SAR frames, with approximately 260 SAR scenes for each processed stack. The EGMS production is conducted by a consortium of four companies: e-GEOS, TRE-Altamira, NORCE, GAF. Each company operates its own processing chain. For more details see references such as Costantini et al. (2017), Crosetto et al. (2020), NGU (2022), Kalia et al. (2020), Larsen et al. (2020), and Crosetto and Solari (2023).

The EGMS offers three types of products, as it is illustrated in Figure 1.

- The first is the Basic Product, generated by independently processing each Sentinel-1 SAR frame. Each frame has its own reference for deformation measurements (we recall that such measurements have a relative nature) and includes deformation velocity and time series in the Line-Of-Sight (LOS) direction. This product, suitable for studying local deformation phenomena, is delivered at full resolution.

- The second product, the Calibrated Product, builds on the Basic Product by combining A-DInSAR results with data from a network of global navigation satellite system (GNSS) stations. The deformation measurements remain in the LOS direction, incorporating both A-DInSAR and GNSS data. This product considers the varying density of GNSS stations across Europe and uses a 50-km GNSS velocity model for calibration.

- The third product, the Ortho Product, refines the Calibrated Product by fusing the mono-dimensional LOS deformation data from both ascending and descending passes to derive 2D information, including the horizontal East-West and vertical Up-Down components. This fusion requires a lower spatial resolution, resulting in an Ortho Product generated on a coarse 100 by 100 m grid.

Quality control is a vital aspect of the EGMS, with various internal verification procedures, mostly automated, and an independent external team performing comprehensive validation of the service products. The EGMS products adhere to the Copernicus data policy and are freely and openly available. All the EGMS products can be accessed through a dedicated WebGIS (https://egms.land.copernicus.eu/), offering visualization tools for interactive data exploration and preliminary analysis. Users can download the products (including the Basic Product) in CSV format for local analysis, e.g. using GIS tools.

The EGMS offers a rich documentation. To encourage user adoption, guidelines are published, and workshops and training sessions are organized. For more information, visit the main page of the Service: https://land.copernicus.eu/pan-european/european-ground-motion-service. The EGMS is expected to attract a wide range of users, including research centres, universities, geological and geophysical surveys, civil protection authorities, public authorities, infrastructure administrations, water management authorities, cultural heritage institutions, the mining industry, the oil and gas industry, engineering companies, the insurance industry, and citizens.

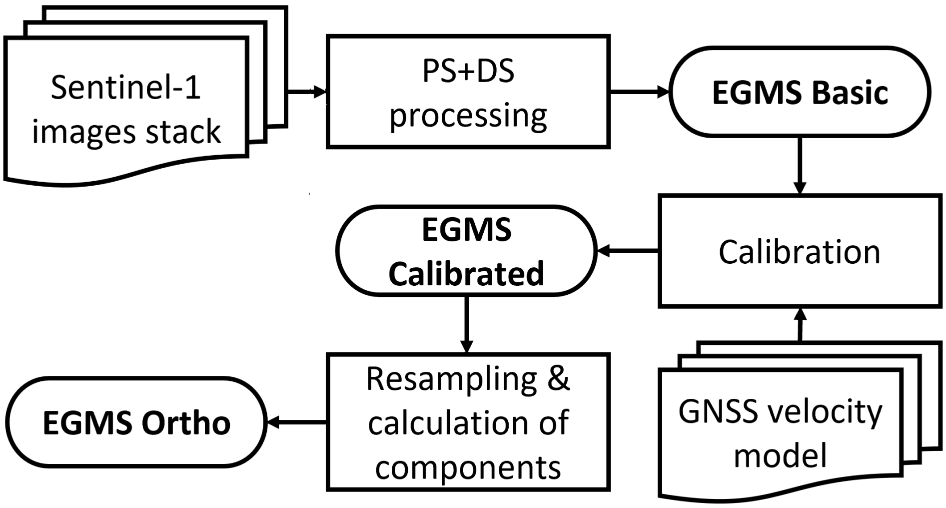

Figure 1. Flow chart of the EGMS.

The EGMS products contain deformation measurements. The goal of this work is to derive a new type of data starting from the EGMS products. In particular, we develop an automatic tool to derive spatial gradients of land deformation. Significant damage to man-made structures often occurs in areas with high deformation gradient values, making the monitoring of spatial and temporal variations in deformation gradients crucial for dynamic analysis, prompt intervention, and risk assessment in urban areas.

Our goal is to create wide-area differential deformation maps indicating the spatial gradient of land deformation across Europe. The final goal is to make this information publicly accessible via a web-based map. The primary objective of the project is to develop a methodology to efficiently utilize the displacement maps provided by the EGMS Basic product, to automatically identify buildings and urban structures potentially vulnerable to damage. To achieve this, a software tool was implemented to automatically obtain wide-area displacement data and compute the spatial gradient for buildings. The project handles vast amounts of data, involving several millions of measurement points and extended processing times, making automation crucial to its success.

In this paper we briefly describe our approach. We than illustrate some examples of differential deformation maps.

2. Methodology

The approach is designed to exploit wide-area displacement maps from EGMS, and it is aimed at identifying buildings and urban structures that may be vulnerable to damage. Local differences (spatial gradients) in such deformations can cause damage to the corresponding structures and infrastructure. By measuring these local variations, it becomes possible to assess the potential damage to specific buildings or structures affected by ground movements.

Given a generic building, our approach requires the availability of a sufficient set of Measurement Points (MP) over this building. If this is not the case, the analysis is not performed on the given building. The larger the set of MPs over a given building, the better.

The software tool, implemented in Python, requires input data from the EGMS Basic product, which contains MP coordinates, velocity, height, etc. In addition, it requires an ESRI shapefile containing building polygons. An example of such shapefile is available from the OpenStreetMap datasets. The methodology involves two key steps.

- The first step is selecting the MPs that pertain to a given building. A buffer around the building perimeters is used to take into account the uncertainty in the positioning of the A-DINSAR MPs. The MPs intersecting the building polygons and buffer are selected (shown in Fig. 1.b with a red boundary). The height of MPs is checked to ensure they belong to the given building, using a threshold: points above this threshold are considered to belong to the building. In order to compute the gradient, a minimum number of MPs is required (typically 5 is set as a minimum), with velocities exceeding ±3 mm/yr.

- The second step involves computing the spatial gradient of the displacements Firstly, the MPs are rasterized, as the gradient calculation is based on data in raster format. A grid with a specific pixel size is set up, followed by an interpolation. We use for this step the Inverse Distance Weighting (IDW) interpolation. Then the local gradient intensity is computed using the "slope" function. This is followed by the calculation of the "aspect" of the gradient, which is measured clockwise in degrees from 0 to 360, where 0 is north-facing, 90 is east-facing, 180 is south-facing, and 270 is west-facing.

The gradient intensity represents the severity of deformation gradients. Such intensity is usually classified into four categories: "Low", "Medium", "High", and "Very high". There is a fifth class which includes those cases where the gradient calculation is not reliable.

Figure 2 illustrates the main steps of the procedure: (i) the identification of the MPs that belong to a given building (using a buffer) and the velocity interpolation; (ii) the gradient intensity calculation in $mm*yr^{-1}*m^{-1}$; (iii) and the determination of the gradient intensity class.

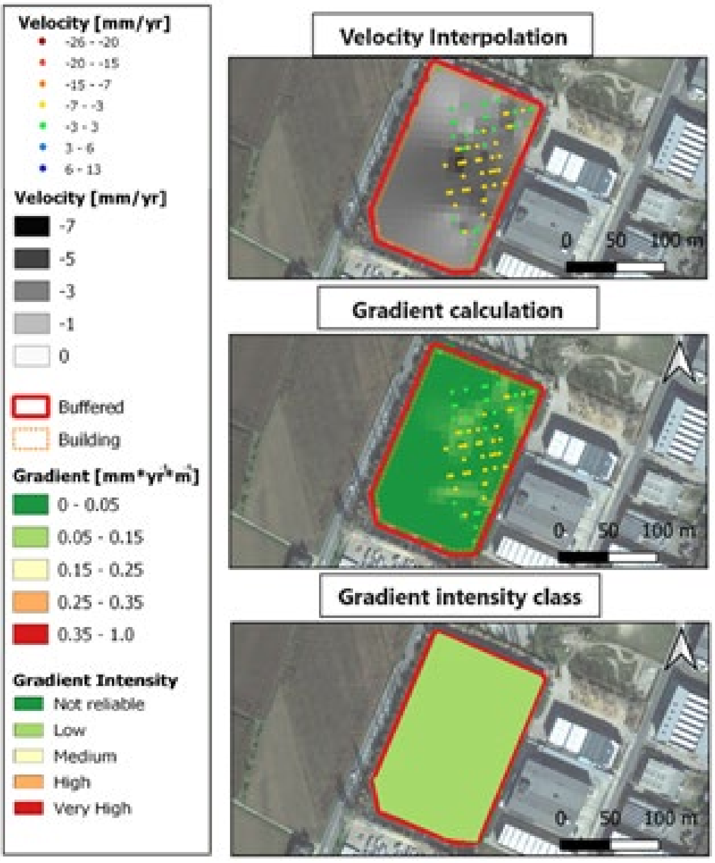

Figure 2. Illustration of the main steps of the procedure.

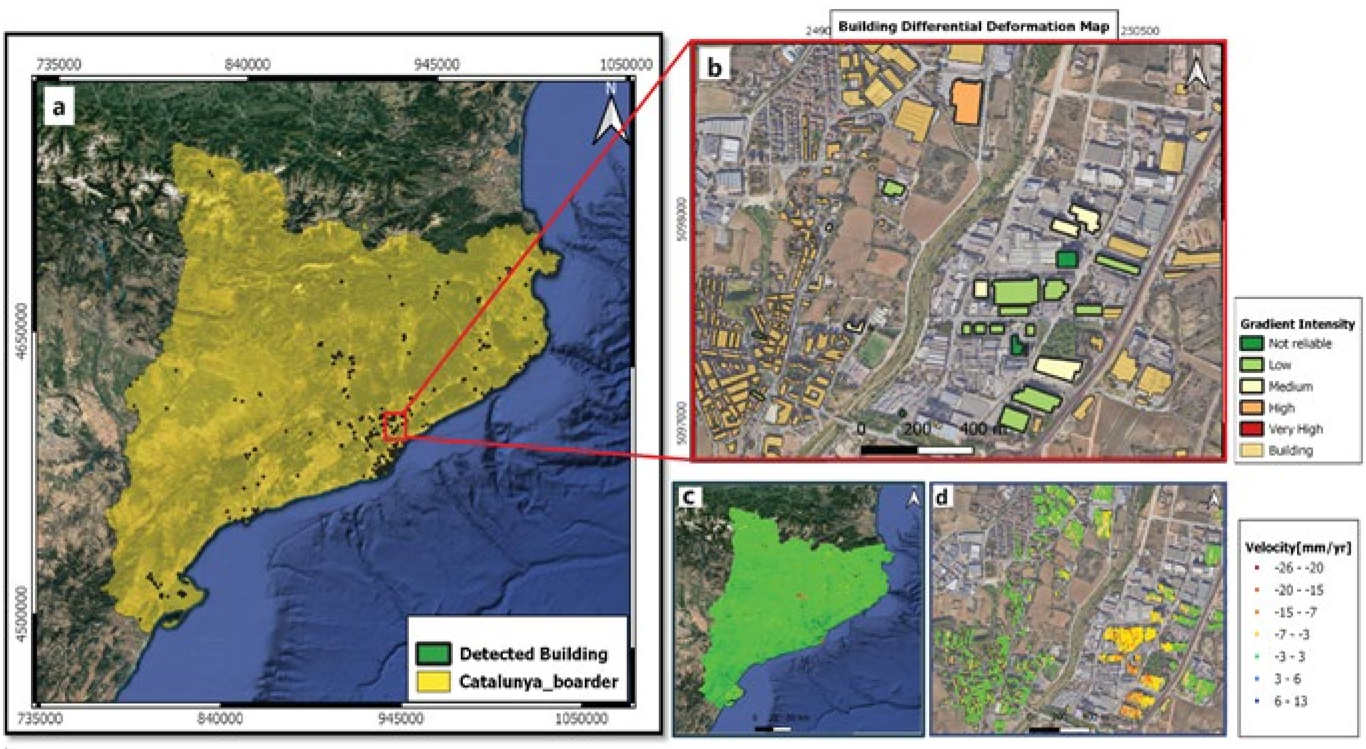

Figure 3. Building differential deformation map over Catalonia (Spain). Map of the detected buildings with significant gradient (a), gradient intensity map (b); deformation velocity map (c); and zoom of the deformation velocity map (d).

3. Examples of results

The proposed procedure is prepared to work with large datasets coming from the EGMS products. This means that it can be used to massively process interferometric data, covering potentially all Europe. We first describe the results obtained over the region of Catalonia (Spain).

The Figure 3 (left) shows the map of the detected buildings that have a significant spatial deformation gradient. Provided that a threshold of 5 MPs per building was set, most of the buildings are large industrial buildings. One of the figures on the right of Figure 3 (b) shows the deformation velocity map over Catalonia, which comes from the Basic product of EGMS. The contiguous figure (d) shows the zoom of the deformation velocity map over an industrial area located in the north of Barcelona. Finally, Figure 3 (b) shows the gradient intensity map obtained over the same area. In this case, the intensity ranges from low to medium and high.

The same processing has been performed over the entire territory of Spain (506,030 km^2). Figure 4 (upper left) shows the input building polygons coming from OpenStreetMap and the Inspire Spanish Cadastral dataset. Figure 4 (lower left) shows the deformation velocity map of Spain. Figure 4 (upper right) shows the location of the buildings that have non negligible deformation gradient (2958 building polygons were detected). We recall that building detection is based on two factors: the presence of deformation (velocity greater than ±3 mm/yr) and a sufficient number of MPs within a given building. The latter criterion leads to the exclusion of small-sized buildings. Finally, Figure 4 (lower right) shows the building differential deformation map of Spain.

The majority of detected buildings are concentrated in urban and industrial areas, where MPs are abundant, and buildings are sufficiently large to contain the minimum required number of MPs. In this case this number was set to 15. Figure 5 shows two examples of building differential deformation map over two areas: Lorca and Malaga. The Lorca area is affected by severe subsidence caused by underground water withdrawal. In this case one may notice the high density of buildings affected by differential deformations. The intensity ranges from low to very high (red buildings). Other examples are described in Shahbazi et al. (2024).

The results that concern Spain have been visualized using a WebGIS, see Figure 6. The web application has been developed in JavaScript and HTML. It can zoom, pan, and filter data using several criteria, such as the mean velocity of the polygons or its gradient intensity value. It is possible to use different background layers, such as OpenStreetMap, Google Satellite, or Google Terrain. To see the attributes of a given polygon, it is enough to click on it. The legend and filters are in the upper right part of the image; the attribute table for points and polygons is in the right bottom area. The WebGIS can be accessed at https://geokinesia.com/european-ada/.

4. Conclusions

In this work, we present a methodology for detecting and categorizing potential damage classes for buildings through the analysis of differential deformation. The proposed procedure can work with any type of A-DInSAR datasets. However, it has been particularly developed to work with the data coming from the EGMS products. With the proposed procedure we generate building differential deformation maps, facilitating the identification of buildings and urban structures at risk of damage due to differential movements. The procedure has been described in detail.

In this paper, some examples of building differential deformation maps have been described. The first results concern the Catalonia region, while the other ones come from the analysis of the entire Spanish territory. The differential deformation map can serve as an initial layer of information for a comprehensive analysis and risk assessment. Future research will involve, among others, the validation of the proposed procedure.

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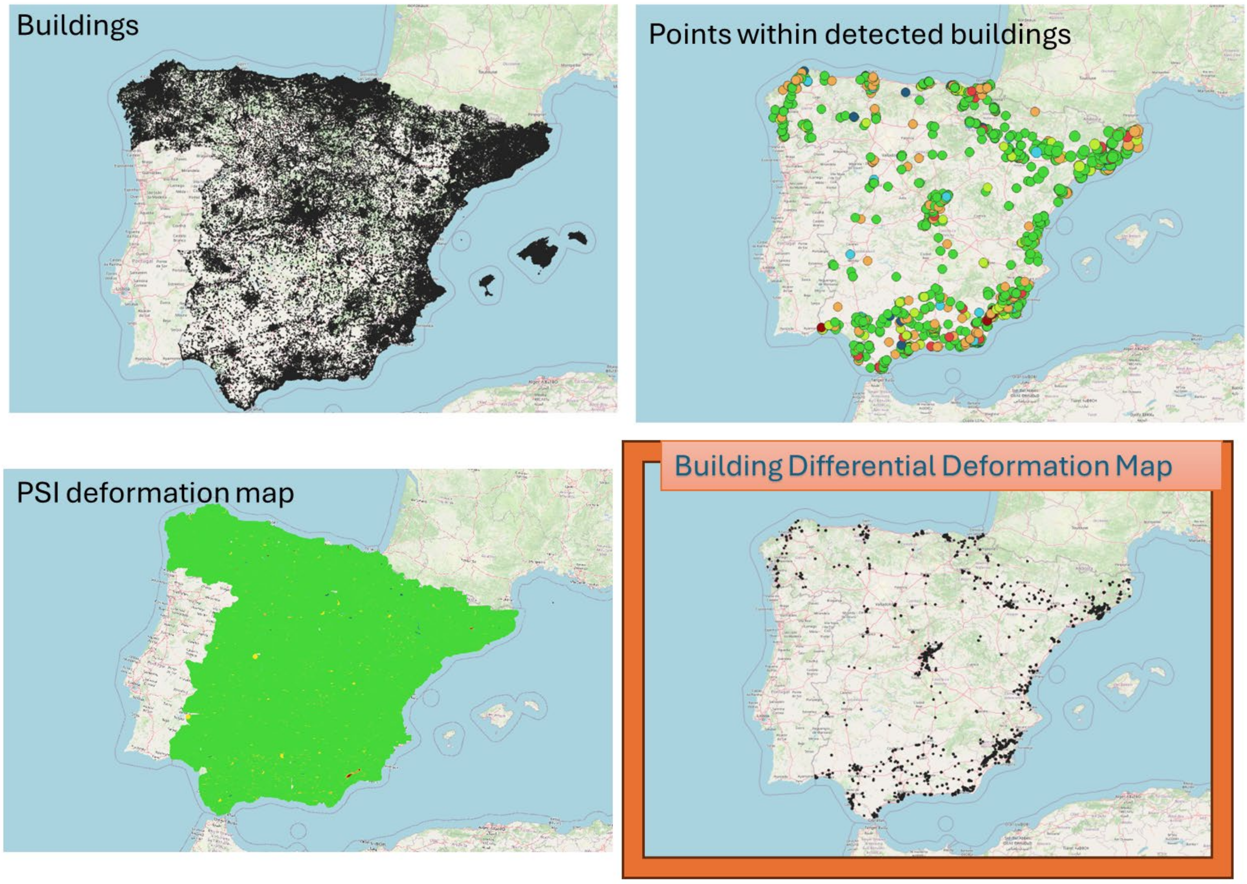

Figure 4. Building differential deformation map of Spain (lower right). Input building polygons (upper left). Buildings with non negligible deformation gradient (upper right). Deformation velocity map (lower left).

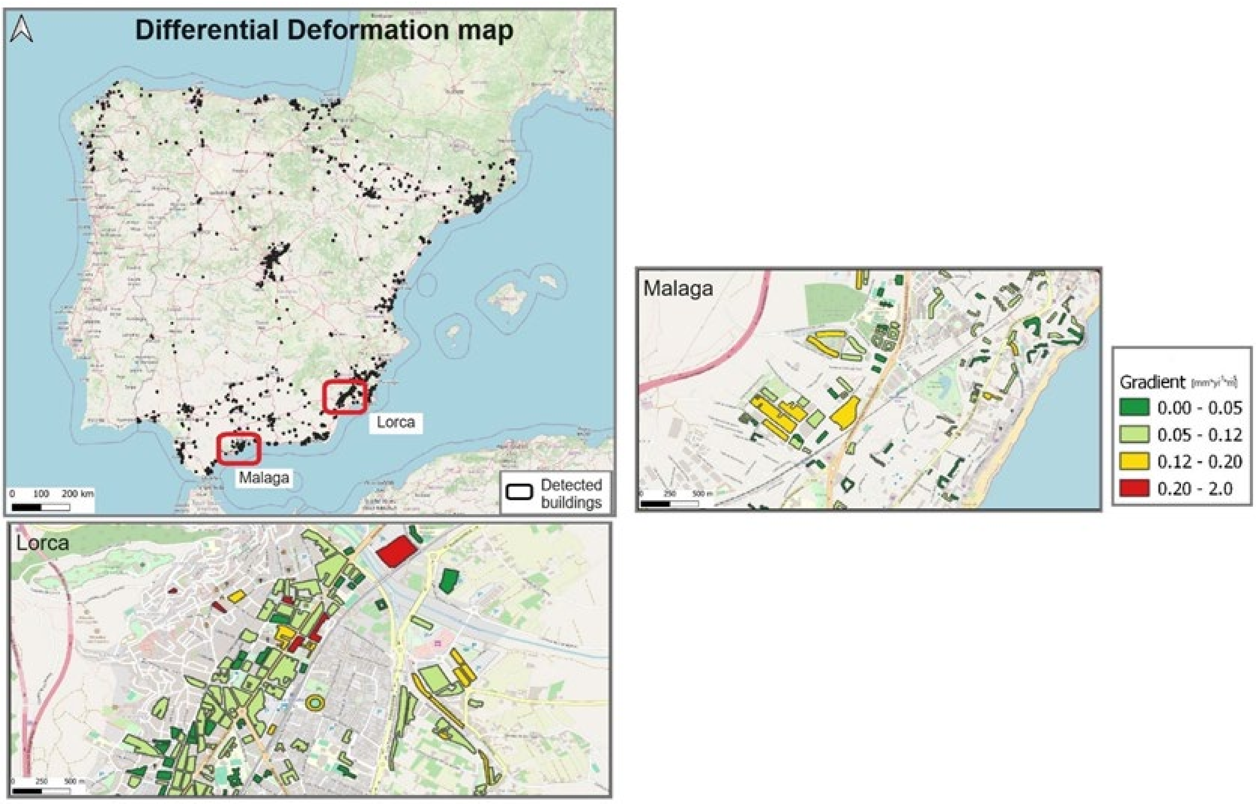

Figure 5. Examples of building differential deformation maps over Lorca and Malaga.

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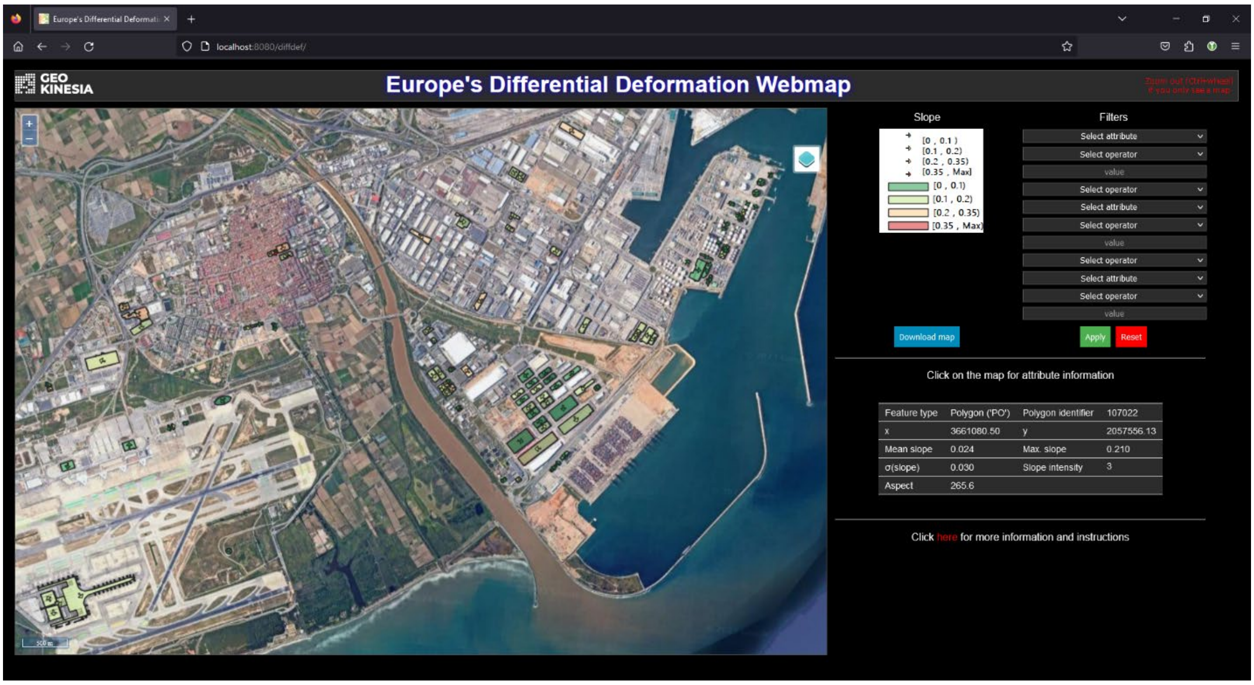

Figure 6. Differential Deformation Map shown through a WebGIS (https://geokinesia.com/european-ada/).