ADVANCED PROCESSING OF REMOTELY SENSED BIG DATA FOR CULTURAL HERITAGE CONSERVATION

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ABSTRACT

Damage assessment, protection and preservation of built patrimony are a priority at national and local levels due to their importance to many cultural and economic aspects. This paper presents a methodology to estimate the potential damage caused by ground settlement for cultural heritage buildings using remotely sensed big data. Specifically, it presents a framework to assess the potential damage caused by ground settlement for masonry, infilled and bare frames structures using Persistent Scatterer Interferometric (PSI) measurements. The proposed solution advances the state-of-the-art by integrating big Earth observation (EO), environmental, architectural and historical data, for estimating the settlement induced damage to hundreds thousands of buildings. The fully automatic scheme was created within cloud computing environment for accelerating data transfer, processing and modeling and for improving the visualization of image-derived products.

Index Terms— big data, settlement induced damage, PS-InSAR, cultural heritage, cloud computing

1. INTRODUCTION

Built heritage is of exceptional cultural and economic importance for a country and its protection is imperative. In Belgium, thousands of buildings categorized as cultural heritage and more than 300,000 as buildings for preservation. These buildings suffer from physical, mechanical, chemical, and biochemical types of pathologies due to settlement induced damage caused by heavy industrial and urban development [1]. The measurement of the progression and distribution of ground movement is necessary in order to create reliable forecasting models and to adopt an appropriate structural preservation [2]. However, traditionally it is measured using time consuming and costly in-situ terrestrial methods and by integrating large environmental, architectural and historical parameters.

In the last decade, PSI has been proven as a unique tool for low cost and precise ground surface deformation analysis method [3]. Lately, the spatial distribution of settlements [4] and the maximum settlement directions [5] derived by the radar measurements, compared to field evidences and showed high potential for monitoring and evaluating settlement induced damage to built heritage. The computation of PSI requires sets of dozens SAR images in order to accurately detect temporal ground deformations. In this context, ESA's Sentinel-1a/b mission provides an opportunity for short periodic monitoring with a revisit cover time which is either 12 or 6 days in the case of one or two operating satellites, respectively. However, the settlement rate and direction are only two from large set of parameters that are required for modeling the structural damage. Complex 2D or 3D damage models integrate large sets of building parameters including the geometry, material, loading, boundary conditions and tunneling induced strains [6]. The parameters are obtained from remotely sensed, historical, architectural and environmental data sources and their collection on continuous basis, for the entire national built heritage, is accumulated to big data that requires adequate storage, dedicated computational framework and adapted processing scheme.

The GEPATAR project (GEotechnical and Patrimonial Archives Toolbox for ARchitectural conservation in Belgium) aims creating an online interactive geoinformation tool that allows the user to view and to be informed about the Belgian heritage buildings at risk due to differential ground movements. The project developed a computing architecture in cloud environment that allows the integration and the storage of raw and processed big data, the processing of PSI and the modeling of settlement induced damage. The method advances other cloud based PS computing tools [7] and available settlement induced models by proposing a framework to integrate the PSI measurements with the analytical models for masonry proposed by [6]-[8] and an adaptation of the latter [8] for infilled and bare frames.

This paper presents the architectural computing framework selected for GEPATAR. It explains in details the proposed settlement induced model and demonstrates the results using test case of structural monuments in Belgium.

2. CLOUD PROCESSING ARCHITECTURE

The remotely sensed big data includes historical and recent SAR/SLC imaging collected since 1991 by the ERS-1/2, Envisat and Sentinel missions. The latter are directly obtained from the ESA hub or by opening a gateway to the Belgian Terrascope platform. It also includes very high resolution DEM and other geographical and geophysical data collected and mapped by the three regional administrations of Belgium. The federal and the regional cultural heritage data are migrated for ingestion and analysis. Other complementary data, as OSM layers and GoogleEarth are streamed from the web.

The architecture was created within the Amazon Web Service (AWS) and is conducted from five sections as presented in Figure 1. The platform consists of components that support both real-time and batch processing and is ingested using SQL for optimization and distribution.

2.1. Ingestion and data analysis

This computing section includes scripts for data analysis and data mining. The latter, searches within the sources key words and dates for assigning structural style (i.e. masonry, infilled or bare frame) to each polygon. The data analysis includes pre-processing workflow for multi-temporal SAR/SLC that were acquired over the same region and from the same look angle. The data set is integrated with the orbital information indicating the position of the satellite during the acquisition time, and a DEM of the investigated area for co-registration and geometrical correction. Images that are uploaded from the Belgian Terrascope site migrate with the other pre-processed images to the warehouse.

2.2. Warehouse

In the warehouse a Hadoop cluster is used to process and transform the large imaging set into structured data for further processing. It includes all the raster and the vector layers are required for further processing, modeling or visualization. The warehouse also includes SQL for space allocation, data mining and distribution paths.

2.3. PSI processing

The cloud provides massive and scalable computing infrastructure for handling the heavy processing tasks of PSI. The StaMPS (Stanford Method for Persistent Scatterers) / MTI (Multi-Temporal InSAR) V4.1b, which includes a processing scheme for Sentinel-1 data is integrated. The open-source package reads the unwrapped interferograms, references to the same coherent pixel, calculates the phase, inverts the network of the interferograms into time-series, calculates the “temporal coherence”, corrects stratified tropospheric delay and DEM error, removes phase ramps and estimates the velocity. The outputs migrate into the damage induced model for further processing and are classified for the creation of settlement risk map at a country scale (1:50,000). This risk map is used as an information layer in the interface.

2.4. Modeling

The results of the models described in Section 3 are threshold according to the ASCE7-16 design code [7] and classified for three damaged levels; negligible (1), moderate (2) and severe (3). For masonry, a mean of the three results is obtained before classification.

2.5. Interface

The interactive interface is designed within the cloud and is supported by image derived visualization tools as Jupiter, Tableu and D3.js. It integrates web map and GIS formats that allow to sort, visualize and query location in various information layers.

3. SETTLEMENT INDUCED DAMAGE MODELS

For the settlement induced damage models, three data sets migrate from the warehouse to the modelling section; the velocity ($vdos$) obtained using PSInSAR for a selected period (t), the polygons of cultural heritage buildings and a digital surface model (DSM) at very high spatial resolution ($\leq$ 0.5 m). The model creates a buffer of 10 meters around each polygon and identifies the persistence scatterer (PS) points are located within each buffer. The model requires minimum three PS points for each building to calculate the surface fit and to predict the settlement rate. Specifically, three settlement induced models are created for masonry structures following the methods are proposed by Boscardin and Cording [6], Giardina et al., [7] and Fischer [8]. Two other models for infilled and bare frames are adapted from the latter [8]. The models are calculated for 3D surface of each building by obtaining the surface slope and by fitting the vertical velocity and the position (x, y) of each PS point using the following multivariate linear regression:

$$z = X \cdot b \rightarrow z = \left[1\ PS_{1x}\ PS_{1y}\right] \cdot b \rightarrow \tag{1}$$

$$\begin{bmatrix} vdos_1 \\ vdos_2 \\ \vdots \\ vdos_n \end{bmatrix} = \begin{bmatrix} 1 & PS_{1x} & PS_{1y} \\ 1 & PS_{2x} & PS_{2y} \\ \vdots & \vdots & \vdots \\ 1 & PS_{nx} & PS_{ny} \end{bmatrix} \begin{bmatrix} a_f \\ b_f \\ c_f \end{bmatrix}$$

where PS_i $(i = 1, \ldots, n)$ and $b = (X'X)^{-1}X'z$.

The function in (2) fits the PS position to the image coordinates (x, y):

$$f_{fit}(x, y) = a_f + b_f x + c_f y \tag{2}$$

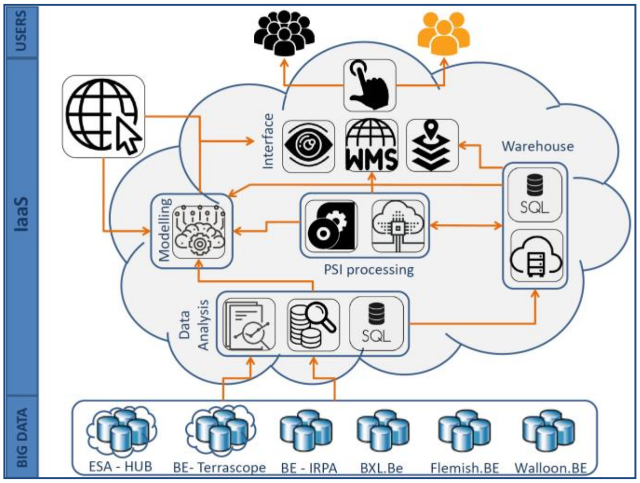

Figure 1: The cloud computing architecture created for GEPATAR

For obtaining the maximum surface slope (f_{max}) we sort the $vdos$ from the smallest to the highest values, where $vdos_{min} = PS_{1y}$ and $vdos_{max} = PS_{ny}$, and we resolve the following liner interpolation:

$$f_{max}(x, y) = a_g + b_g x + c_g y \tag{3}$$

where

$$a_g = -\frac{\left(PS_{1y}PS_{ny} - {PS_{1y}}^2 + PS_{1x}PS_{nx} - {PS_{1x}}^2\right)vdos_n}{\left(PS_{1y} - PS_{ny}\right)^2 + (PS_{1x} - PS_{nx})^2} + \frac{+\left(-{PS_{ny}}^2 + PS_{1y}PS_{ny} - {PS_{nx}}^2 + PS_{1x}PS_{nx}\right)vdos_1}{\left(PS_{1y} - PS_{ny}\right)^2 + (PS_{1x} - PS_{nx})^2}$$

$$b_g = \frac{(PS_{1x} - PS_{nx})(vdos_1 - vdos_n)}{\left(PS_{1y} - PS_{ny}\right)^2 + (PS_{1x} - PS_{nx})^2}$$

$$c_g = \frac{\left(PS_{1y} - PS_{ny}\right)(vdos_1 - vdos_n)}{\left(PS_{1y} - PS_{ny}\right)^2 + (PS_{1x} - PS_{nx})^2}$$

and (x, y) are the coordinates. After the 3D surface model is obtained, the differential settlement S_j is calculated for each external wall (j) and (m) number of walls using the absolute differences between the vertical velocities (z_j), where $S_j = abs[z_2 - z_1], \dots, S_m = abs[z_1 - z_m]$ and $z_j = f_{max}(x_1, y_1), \dots, f_{max}(x_m, y_m)$. After the 3D surface is obtained for each polygon, the damage models are estimated according to the structural typology.

The Boscarding and the Cording damage model for masonry ($MAS1_{DAM}$) [6] requires the calculation of the angular distortion rate (β_r) for period (t):

$$\beta_j = \beta_{r,j} t \tag{4}$$

$$\beta_{r,j} = 3\Delta_{r,j} \frac{1 + 4R\frac{H_j^2}{L_j^2}}{1 + 6R\frac{H_j^2}{L_j^2}} \tag{5}$$

where H_j ($H_j = H_1, \dots, H_m$) and L_j ($L_j = L_1, \dots, L_m$) are the height and the length of the walls j, respectively, R is the elasticity ratio and is calculated with a constant Poisson's ratio (ν_b=0.3) as following:

$$R = 2(1 + \nu_b) \tag{6}$$

The damage ratio Δ_r presents the difference between the settlement in normal S_{norm} and tilted S_{tilt} distribution curves and it depends on the angular (i_x) and the horizontal (d) extension strains:

$$\Delta_{r,j} = \left(\frac{S_{norm,j} - S_{tilt,j}}{L_j}\right)/1000 \tag{7}$$

$$S_{norm,j} = S_j \cdot exp\left(-d_j^2/\left(2i_{x,j}^2\right)\right) \tag{8}$$

$$S_{tilt,j} = S_j\left(1 - d_j/L_j\right) \tag{9}$$

where $d_j = 0.6L_j$ and $i_{x,j} = \frac{L_j}{\pi}$. The damage to the building is estimated for five angular distortion rates as following:

$$MAS1_{DAM} = \begin{cases} 0.75\left(0 + \frac{\beta_j - 0.0000}{0.0011 - 0.0000}\right) & for \quad 0.0000 \le \beta_j \le 0.0011 \\ 0.75\left(1 + \frac{\beta_j - 0.0011}{0.0016 - 0.0011}\right) & for \quad 0.0011 \le \beta_j \le 0.0016 \\ 0.75\left(2 + \frac{\beta_j - 0.0016}{0.0033 - 0.0016}\right) & for \quad 0.0016 \le \beta_j \le 0.0033 \\ 0.75\left(3 + \frac{\beta_j - 0.0033}{0.0067 - 0.0033}\right) & for \quad 0.0033 \le \beta_j \le 0.0067 \\ 3 & for \quad 0.0067 \le \beta_j \end{cases} \tag{10}$$

According to the tilt limits model proposed by Fischer [8] for masonry, the damage to the building $MAS2_{DAM}$ is estimated for five structural tilts (ω):

$$MAS2_{DAM} = \begin{cases} 0.75\left(0 + \frac{\omega_j - 0.000}{0.001 - 0.000}\right) & for \quad 0.000 \le \omega_j \le 0.001 \\ 0.75\left(1 + \frac{\omega_j - 0.001}{0.002 - 0.001}\right) & for \quad 0.001 \le \omega_j \le 0.002 \\ 0.75\left(2 + \frac{\omega_j - 0.002}{0.003 - 0.002}\right) & for \quad 0.002 \le \omega_j \le 0.003 \\ 0.75\left(3 + \frac{\omega_j - 0.005}{0.003 - 0.005}\right) & for \quad 0.003 \le \omega_j \le 0.005 \\ 3 & for \quad 0.005 \le \omega_j \end{cases} \tag{11}$$

where $\omega_j = \omega_{r,j} t$ and the tilt rate ω_r is calculated according to the differential settlements along the external walls:

$$\omega_{r,j} = \left(\frac{S_j}{L_j}\right)/1000 \tag{12}$$

Giradina et al., model [7] estimates the maximum damage for building due to ground settlements as a function of sets of geometrical, material properties and boundary conditions parameters. These include the percentage of facade openings (a_1), fracture energy (a_2), Young's modulus (a_3), tensile strength (a_4), normal stiffness (a_5) and the shear behavior (a_6) of the base interface, as well as the orientation (b_1), grouping (b_2), position (b_3) and alignment (b_4), as following:

$$MAS3_{DAM} = \max\left(\min\left(\frac{1, b_1 + b_2\Delta_j + b_3{\Delta_j}^2 + b_4\Delta_j^3 + a_1 dn_1}{2} + \frac{a_2 dn_2 + a_3 dn_3 + a_4 dn_4 + a_5 dn_5 + a_6 dn_6}{2}\right)\right) \tag{13}$$

These parameters as well as the normalized damage function parameters ($dn_{1...6}$) were defined and provided in [7].

The tilt limits model proposed by Fischer [8] for infilled (IF_{DAM}) and bare (BF_{DAM}) frames are estimated according to (14) and (15), respectively:

$$IF_{DAM} = \begin{cases} \left(0 + \frac{\omega_j - 0.000}{0.002 - 0.000}\right) & for \quad 0.000 \le \omega_j \le 0.002 \\ \left(1 + \frac{\omega_j - 0.002}{0.003 - 0.002}\right) & for \quad 0.002 \le \omega_j \le 0.003 \\ \left(2 + \frac{\omega_j - 0.003}{0.005 - 0.003}\right) & for \quad 0.003 \le \omega_j \le 0.005 \\ 3 & for \quad 0.005 \le \omega_j \end{cases} \tag{14}$$

$$BF_{DAM} = \begin{cases} \left(0 + \frac{\omega_j - 0.000}{0.002 - 0.000}\right) & for \quad 0.000 \le \omega_j \le 0.002 \\ \left(1 + \frac{\omega_j - 0.002}{0.006 - 0.002}\right) & for \quad 0.002 \le \omega_j \le 0.006 \\ \left(2 + \frac{\omega_j - 0.006}{0.010 - 0.006}\right) & for \quad 0.006 \le \omega_j \le 0.010 \\ 3 & for \quad 0.010 \le \omega_j \end{cases} \tag{15}$$

4. TEST CASE

The St. Paul's Church or Sint-Pauluskerk (in Dutch) is a Roman Catholic Church located near the Scheldt river at the Veemarkt in Antwerp (Figure 3). Its exterior is mainly Gothic with a Baroque tower while the interior is characterized by rich Baroque decoration. This small church was built by the Dominican Order in 1276 using masonry technique. Figure 2 presents the polygon of the church and its buffer superimposed on the cadastral map of the area. The Figure also presents the PSI points are located within this area for various periods (t).

The results of the three models estimate severe damage to the structure due to ground settlement. The church is located in soft sediment that is compressed and subsided due to heavy industrial and urban development around the port of Antwerp. For the period of 1992-2018, the average annual displacement measured using PSI is about -5 mm/year. Maximum yearly subsidence of 24.9 mm/year was recorded by PSI analysis for the period 1992-2001. In Figure 3 we present the interface page for the church. The page shows 3D image of the building and provides general information about its location, typology and estimated damage.

11. REFERENCES

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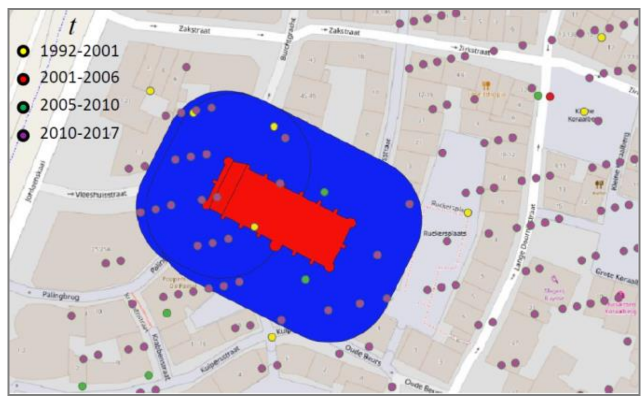

Figure 2: St-Paul polygon (red), it buffer (blue) and the measured PSI for different *t*, superimposed on cadastral map

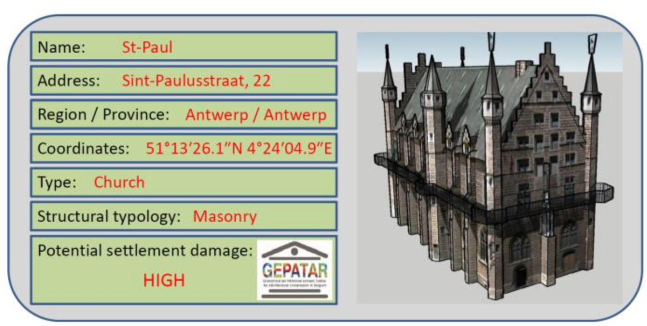

Figure 3: GEPATAR interface page for St-Paul