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SOIL SETTLEMENT AND UPLIFT DAMAGE TO ARCHITECTURAL HERITAGE STRUCTURES IN BELGIUM: COUNTRY-SCALE RESULTS FROM AN INSAR-BASED ANALYSIS

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Abstract. *Soil movement may be induced by a wide variety of natural and anthropogenic causes, which are detectable in the local scale, but may influence the movement of the soil over vast geographical expanses. Space borne interferometric synthetic aperture radar (InSAR) measurements of ground movement provide a method for the remote sensing of soil settlement and uplift over wide geographic areas. Based on this settlement and uplift evaluation, the assessment of the potential damage to architectural heritage structures is possible. In this paper an interdisciplinary monitoring and analysis method is presented that processes satellite, cadastral, patrimonial and building geometry data, used for the calculation of settlement and uplift damage to architectural heritage structures in Belgium. It uses processed InSAR data for the determination of the soil movement profile around each case study, of which the typology is determined from patrimonial information databases and the geometry is calculated from digital elevation models. The impact on the historic structures is calculated from the determined soil movement profile based on various soil-structure interaction models for buildings. The* *resulting damage is presented in terms of a numerical index illustrating its severity according to different criteria. In this way the potential soil movement damage is quantified in a large number of buildings in an easily interpretable and user-friendly fashion. The processing of InSAR data collected over the previous 3 decades allows the determination of the progress of settlement- and uplift-induced damage in this time period. With the integration of newly acquired and more accurate data, the methodology will continue to produce results in the coming years, both for the evaluation of soil settlement and uplift in Belgium as for introducing related damage risk data for existing architectural heritage buildings. Results of the analysis chain are presented in terms of potential current damage for selected areas and buildings.*

1 INTRODUCTION

The investigation of the response of building structures to soil subsidence and uplift is of great importance [1]. Historic buildings, which are often inherently lacking in ductility and left without effective maintenance, are especially vulnerable to damage induced by soil movement. It is therefore critical to develop analysis techniques specifically for existing and historic structures.

In the study of individual structures, it is possible to adopt finite element modelling for the analysis of the structure, since computational cost is not a critical issue [2]. Analysis of larger numbers of buildings over a wider area require the adoption of different strategies for the determination of the loading and the analysis of the buildings [3]. When dealing with country-scale assessment, a level which can affect decision-making and strategy at higher administrative echelons, a different approach needs to be adopted for analysis and result presentation. Space-borne Synthetic Aperture Interferometry (InSAR) methods are a powerful tool for the determination of soil subsidence and uplift profiles [4]. Such methods can be used for the analysis of anything from a single building or small clusters of buildings to entire cities. Application in soil-structure interaction thus far has been mostly limited to the analysis over relatively limited geographic areas [5].

Major difficulties arise in attempting to determine soil movement profiles for individual buildings using InSAR over wide geographic areas. Data point density may be too low for the accurate determination of the soil movement in the area of a particular building. Therefore, the calculation of soil movement intensity parameters commonly used in analytical models [6] may be problematic.

This paper presents a method for the country-scale analysis of buildings subjected to soil subsidence- and uplift-induced damage over an extended time-period. The method consists in country-scale processing of InSAR data, the processing of patrimonial and cadastral data, the calculation of soil movement intensity parameters from limited data and the calculation of damage potentially induced over the investigated period. The method is applied in the entirety of Belgium, involving thousands of architectural heritage buildings.

2 SATELLITE DATA ACQUISITION

2.1 Data Acquisition

Ground displacement, such as subsidence, uplift and horizontal movement can be calculated using InSAR. These methods rely on the measurement of distance change between emission

antennas and points on the ground between successive satellite passages. This distance is calculated through the phase difference of the signal emitted by the antenna, reflected on the point on the ground and finally received by the antenna.
The reflection points on the ground are called Persistent Scatterers (PS) and are characterized by high amplitude of reflection and good temporal [7] and spatial [8] correlation. These points are often located on buildings or other human-made constructions (e.g. at the roofs of buildings) and provide info on the vertical velocity at which a point is subsiding or uplifting.

2.2 Data Processing

PS data is processed using the StaMPS processing chain [9]. PS data collected over 26 years is used in this study, covering the period 1992-2018. This data was collected by three satellites covering the entirety of Belgium at different time periods: ERS 1/2, EnviSAT and Sentinel 1. The number of PS identified for each time period varies, but an average of 800 PS/Km^2 was attained in urban areas where the largest number of potential reflectors is located. For the construction of ground movement velocity fields over the area of Belgium, the PS velocity data is interpolated through inverse distance weighing with a grid spacing of 10 m.

3 BUILDING DATA

3.1 Identification of Analysis Cases

The buildings to be analysed are identified through data mined from the patrimonial databases of the three federal regions of Belgium: Brussels, Flanders and Wallonia. These databases contain basic information on the age, typology and function of every registered object. Several database entries refer to objects which cannot be considered buildings or that are not affected by soil movement. These entries include natural objects, parks and sculptures or public art. Through analysis of this data it is possible to isolate entries which should be considered for analysis.
Different typologies feature different capacity for deformation under induced ground movement. Bare frames are more ductile than infilled frames, which are in turn more ductile than masonry buildings. Data extracted from the databases allows the allocation of each building to one of these three types.
Overall, 269194 analysis cases were identified for Belgium, corresponding to roughly 70% of all patrimonial database entries.

3.2 Building Polygons

Through cross-processing of the patrimonial and cadastral databases of Belgium, the plan of each building was determined, represented by a polygon on the surface of the ground. The height of every building was calculated from subtraction of the digital terrain model from the digital surface model of the country.
In the study of soil-structure interaction, the movement of soil within a certain distance of a building can induce deformation on the superstructure. In order to consider this effect, an area of influence for each polygon was calculated, consisting in an outward offset of 10 m. The PS and interpolated grid values which fall within the area of interest are considered for the calculation of potential damage in each analysis case. Due to the grid spacing of 10 m, every

analysis case is guaranteed to include several grid velocity data points. This is critical for damage calculation due to soil subsidence and uplift, which is a function of the ground deformation gradient in an area rather than simply its magnitude.

4 SOIL DEFORMATION PROFILE

4.1 Calculation of Soil Deformation Surface

Country-scale processing of InSAR data results in a low density of PS due to processing power limitations. Therefore, it is not generally possible to extract detailed soil deformation profiles from the InSAR data available. In order to overcome this problem, an approach capable of calculating a simplified soil deformation profile from limited data is presented here.

A minimum of three data points in R^3 space is required for the calculation of a three-dimensional linear surface f. By assuming that the dip direction of the surface coincides with the direction of the vector connecting two points, then only these two points are required for the calculation of the surface. In the present context, each point is defined by two geographic coordinates and a value of vertical displacement. These points are provided by the PS or interpolated grid data. Based on these parameters, a surface of the type:

$$f(x, y) = a + bx + cy \tag{1}$$

where (x, y) are geographical coordinates and f is the vertical displacement, can be calculated from two points. This simple surface allows the calculation of the vertical displacement at every coordinate pair. When more than two data points are available, the surface f is calculated from the pair of points that yields the maximum tilt ω. Tilt is defined as the ratio of relative vertical distance s to horizontal distance d:

$$\omega = \frac{s}{d} \tag{2}$$

This calculation is executed for each of the building polygons of the analysis cases. The combination of the 10 m interpolation grid with the assumption of the dip direction of f ensures that f can be calculated for every analysis case regardless of PS density in the area of the polygon.

Considering the maximum tilt for the analysis is a conservative assumption. However, this assumption is supported by two facts: a) the number of PS per building polygon is low, even in urban areas where there is an abundance of reflectors, b) the maximum tilt approach can assist in highlighting local effects near the individual buildings which might otherwise be smeared out in a country-scale evaluation of InSAR data.

4.2 Calculation of Building Polygon Loading

By substituting the coordinates of the vertices of each building polygon to function f it is possible to determine the vertical movement each vertex. Since PS data provides info on the vertical velocity, the vertical displacement is calculated by multiplication of the velocity with

the length of time of the investigated period.
By substituting the relative vertical displacement values s for the vertices of each polygon edge to eq. (2) and dividing by the length d of the edge, the tilt ω for every edge is calculated. It is thus possible to calculate the damage at different parts of the structure according to the direction of tilting in the area near each building.

5 DAMAGE MODELLING

Each structure considered for analysis was placed in one of three categories depending on structural typology: a) masonry, b) infilled frame and c) bare frame structures. These typologies generally present very different sensitivity to soil movement, with masonry being the most sensitive and bare frames being the least sensitive to subsidence and uplift.
For the calculation of potential damage of the buildings, an approach of limits on the tilt is adopted. In this approach, the tilt of all the edges in every polygon is calculated according to eq. (2). The maximum tilt among the edges of the polygon is translated to a damage index I in the range of $[0,3]$. Based on this damage index, four damage levels are considered: a) null to negligible for $I \in [0,1)$, b) slight to light for $I \in [1,2)$, c) moderate to severe for $I \in [2,3)$ and d) very severe for $I = 3$. These damage levels correspond to indicative crack widths [10] as presented in Table 1.

Table 1: Correspondance between damage index, damage level and crack width in masonry strutures.

Damage index	Damage class	Crack width (mm)
0.5	Negligible	0.0 – 0.1
1.0	Slight	0.1 – 1.0
1.5	Light	1.0 – 5.0
2.0	Moderate	5.0 – 15.0
2.5	Severe	15.0 – 25.0
3.0	Very severe	>25.0

Based on the tilt limits proposed by Fischer [11], the damage index I in masonry or infilled frames as a function of the tilt ω is:

$$I(\omega) = \begin{cases} 0.75\left(0 + \frac{\omega - 0.000}{0.001 - 0.000}\right) & if \quad 0.000 \leq \omega \leq 0.001 \\ 0.75\left(1 + \frac{\omega - 0.001}{0.002 - 0.001}\right) & if \quad 0.001 \leq \omega \leq 0.002 \\ 0.75\left(2 + \frac{\omega - 0.002}{0.003 - 0.002}\right) & if \quad 0.002 \leq \omega \leq 0.003 \\ 0.75\left(3 + \frac{\omega - 0.003}{0.005 - 0.003}\right) & if \quad 0.003 \leq \omega \leq 0.005 \\ 3 & if \quad 0.005 \leq \omega \end{cases} \tag{3}$$

Considering the relatively higher ductility of bare frames compared to masonry or infilled frames [12], the damage index I for bare frames reads:

$$I(\omega)=\begin{cases}0.75\left(0+\dfrac{\omega-0.000}{0.002-0.000}\right) & if \quad 0.000\leq\omega\leq 0.002\\ 0.75\left(1+\dfrac{\omega-0.002}{0.004-0.002}\right) & if \quad 0.002\leq\omega\leq 0.004\\ 0.75\left(2+\dfrac{\omega-0.004}{0.006-0.004}\right) & if \quad 0.004\leq\omega\leq 0.006\\ 0.75\left(3+\dfrac{\omega-0.006}{0.010-0.006}\right) & if \quad 0.006\leq\omega\leq 0.010\\ 3 & if \quad 0.010\leq\omega\end{cases} \tag{4}$$

It is assumed, as shown in eq. (3), that infilled frames present the same sensitivity to subsidence and uplift as masonry structures. This assumption is supported by the fact that masonry infills are the most sensitive part of infilled frames and the location where the majority of damage in infilled frame buildings subjected to soil-movement develops. The curves of eq. (3) and (4) are plotted in **Figure 1**.

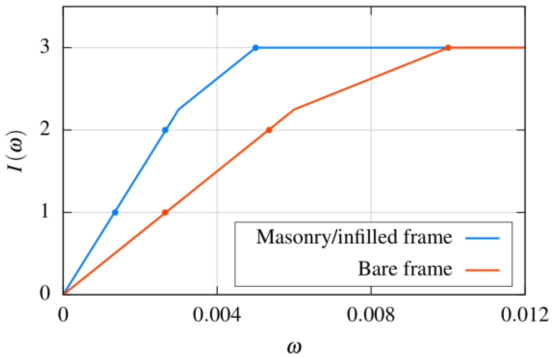

Figure 1: Damage models for tilt ω vs. damage index I.

The damage calculation is performed by accumulating the tilt that occurs during the different measurement periods. The model cannot consider damage that occurred before the beginning of the measurement in 1992. However, when manually working on individual cases, an initial damage index can be introduced, the calculation further increasing the damage index from accumulated tilt due to soil subsidence and uplift.

For the validation of the damage model, the building cases summarized by Namazi and Mohamad are used [13]. The building typology has been reported, along with a qualitative description of the damage reported. Only the cases where the tilt was directly reported were considered in this validation, amounting to 10 cases. The considered cases and the analysis results are presented in Table 2. The comparison of the reported with the predicted damage reveals that the employed damage model results in a generally accurate qualitative prediction of the damage. A small underestimation of the predicted damage is obtained in 2 cases with reported severe damage and a small overestimation is obtained in one case with moderate reported damage.

Table 2: Validation of damage model based on case studies from literature: comparison of reported with predicted damage levels. Accurate damage prediction highlighted in green, overestimation in blue and underestimation in red.

No.	Ref.	Building type	Reported damage	ω	$I(\omega)$	Predicted damage
1	[15]	RC	Severe	1/361	2.078	Moderate
2	[16]	RC	Negligible	1/900	0.833	Slight
3	[16]	Masonry	Very severe	1/240	2.688	Severe
4	[17]	Masonry	Very slight	1/520	1.442	Slight
5	[17]	Masonry	Slight	1/3330	0.225	Negligible
6	[18]	RC	Negligible	1/8333	0.090	Negligible
7	[19]	Masonry	Slight	1/388	1.933	Light
8	[22]	Masonry	Moderate	1/225	2.792	Severe
9	[23]	Masonry	Very severe	1/278	2.474	Moderate
10	[24]	RC	Slight	1/435	1.724	Light

6 ANALYSIS RESULTS

6.1 Potential Damage Calculation

The results of the analysis for the entirety of Belgium are plotted in **Figure 2**. The figure shows the number of buildings for each damage level at the end of the measurement period. The results are presented separately for each federal region and in the totals for the country.

Overall, thousands of buildings are identified as reaching or exceeding a damage index I of 0.5, which corresponds to negligible damage. While not detrimental to the structural safety of structures, distributed cracking of this type can affect durability. The number of buildings with a damage index I of 1.0, indicating slight damage, is in the several hundreds.

There is a foreseen drop in the number of buildings with potential light and moderate damage compared to the buildings with slight or negligible damage. However, there is a noticeable increase in the number of buildings with severe to very severe damage in all regions except Flanders, compared to the number of lightly to moderately damaged buildings. This is a possible effect of the conservative adoption of the maximum tilt curve f. This effect is more pronounced in Brussels, which is characterised by high-density InSAR data.

The majority of buildings with potential damage are located in Flanders, which also features the most populated patrimonial database. The number of potentially damaged buildings in Wallonia is low, yet in percentage compared to the total number of listed buildings, results are comparable among the three regions.

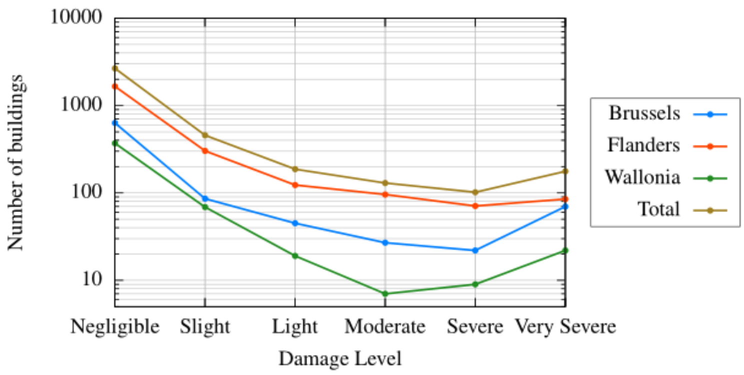

Figure 2: Potential damage analysis results for Belgium.

6.2 Verification and Evaluation of Analysis Results

The verification of the analysis results is accomplished through a sample inspection of selected buildings. Sixteen buildings were identified in the region of Limburg (Flanders) for inspection. The results of the analysis are summarised in Table 3.

Table 3: Potential damage prediction results for selected case studies.

No.	Case type	City	Building type	$I(\omega)$	Inspection
1	residential building block	Hasselt	Masonry	0.19	Negligible
2	large school building	Hasselt	Masonry	0.12	Negligible
3	public building (court house)	Hasselt	Masonry	0.32	Slight
4	public building (government)	Hasselt	Masonry	0.08	Slight
5	town house	Hasselt	Masonry	0.07	Slight
6	church and monastery	Hasselt	Masonry	0.38	Slight
7	hospital and monastery	Hasselt	Masonry	0.24	Negligible
8	industrial heritage (mining concession)	Genk	Masonry + RC	0.15	Moderate
9	public building (swimming pool)	Genk	RC	0.08	Negligible
10	church	Meeuwen	Masonry	0.21	Light
11	industrial heritage (mining concession)	Koersel	RC	0.17	Negligible
12	industrial heritage (mining concession)	Koersel	RC	0.17	Negligible
13	church with cemetery	Donk	Masonry	0.05	Negligible
14	town house	Leuven	Masonry	3.00	Severe*
15	workers' housing	Leuven	Masonry	3.00	Severe
16	coupled town houses	Leuven	Masonry	2.48	Moderate*

* Undergone structural renovation during measurement period

Despite having higher registered tilt values than other buildings in the immediate vicinity, the calculated potential damage was mostly negligible. Site inspection revealed no apparent damage for half of these structures. The other half presented slight to moderate damage, which, according to the inspection, was sustained and repaired before the measurement period. Therefore, the analysis results are considered to be in agreement with or more conservative than the site findings. Further, three buildings were singled-out for inspection in the city of Leuven. According to the analysis results, the potential damage in one of the buildings is moderate, while in the remaining two the potential damage is severe. One of the structures with predicted severe damage presented substantial ground movement-induced damage. The other building with predicted severe damage and the building with predicted moderate damage have undergone extensive structural renovation during the measurement period. Whether the interventions were due to ground movement damage, or whether the interventions themselves are responsible for the acquired measurements, is unclear. Regardless, the acquired data was able to reflect the movement on the building.

Due to the wide scope of the analysis, the total number of buildings affected by soil movement, namely buildings with any level of potential damage, is very high. It is noted, however, that some of these damages may have already been detected and repaired in the past. Nevertheless, potential damage that has arisen in more recent periods, as well as registered high intensity soil deformation, can assist in directing and focusing site inspection and structural movement monitoring efforts.

7 CONCLUSIONS

This paper presents a method for the acquisition and processing of InSAR and patrimonial data for their use in the calculation of potential damage on existing buildings due to soil subsidence and uplift. The method is designed to be usable in cases of sparsity of InSAR data, to be practical for country-scale assessment involving thousands of analysis cases and to be applicable in cases of arbitrary soil movement profiles.

A large number of potentially damaged buildings are detected. Site inspections are in general agreement with the analysis results.

Due to its flexibility, the proposed method is in principle equally applicable to smaller-scale assessment as it is at the country-scale. It is also suitable for manual calculations in individual buildings, where pre-existing damage can be included in the analysis.

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