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On safe ground? Analysis of European urban geohazards using satellite radar interferometry

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ABSTRACT

Urban geological hazards involving ground instability can be costly, dangerous, and affect many people, yet there is little information about the extent or distribution of geohazards within Europe's urban areas. A reason for this is the impracticality of measuring ground instability associated with the many geohazard processes that are often hidden beneath buildings and are imperceptible to conventional geological survey detection techniques. Satellite radar interferometry, or InSAR, offers a remote sensing technique to map mm-scale ground deformation over wide areas given an archive of suitable multi-temporal data. The EC FP7 Space project named *PanGeo* (2011–2014), used InSAR to map areas of unstable ground in 52 of Europe's cities, representing ∼15% of the EU population. In partnership with Europe's national geological surveys, the *PanGeo* project developed a standardised geohazard-mapping methodology and recorded 1286 instances of 19 types of geohazard covering 18,000 km^2. Presented here is an analysis of the results of the *PanGeo*-project output data, which provides insights into the distribution of European urban geohazards, their frequency and probability of occurrence. Merging *PanGeo* data with Eurostat's GeoStat data provides a systematic estimate of population exposures. Satellite radar interferometry is shown to be as a valuable tool for the systematic detection and mapping of urban geohazard phenomena.

1. Introduction

This article presents an analysis of results from the EC FP7 Space project named *PanGeo* (www.pangeoproject.eu) that ran from 2011 to 2014. Based upon the satellite remote sensing technique of radar interferometry, the project mapped 19 types of geological hazard within 52 European cities. Geological hazards, or 'geohazards', are conditions relating to geology that have the potential to cause harm or damage (UNISDR, 2016), often involving some form of ground motion or instability. Geohazards can be costly, dangerous, and affect many people. This is especially true in urban environments which greatly increase the impacts of geohazards and amplify their effects (Howard, 1999). Geohazards include fast-moving events, such as landslides, earthquakes or collapses associated with mining that often result in metre-scale ground movements occurring over a few minutes. Geohazards also include slower-moving (mm/year to cm/year) phenomena, that often remain hidden and undetected beneath the built environment, but that still present significant costs to society, e.g. the €11 bn of losses in the UK between 1971 and 2009 for damage caused by shrink-swell clays (MunichRe, 2016). Ground instability may lead to financial loss with regard to ownership or management of property, impacting on householders, businesses developers or local government (Booth et al., 2010). With 70% of the global population likely to live in urban areas by 2045 (Ministry of Defence, 2014), the vulnerability of society to urban geohazards is set to grow with increasing population density and collocation of high-value assets (European Environment Agency, 2010).

Although urban geohazards pose a significant threat to the European economy, information is scarce regarding the extent and distribution of geohazards within European urban areas. The ability to measure vulnerability and exposure, as a part of disaster risk reduction activities, was a priority in the Hyogo Framework for Action (2007), yet still no universal measurement methodology exists and there are few relevant quantitative data sets (Kaluarachchi et al., 2014). Even for landslides, ubiquitous and deadly in parts of Europe, there is no European overview or policy, there are discrepancies in databases, and information is not generally available (EEA: European Environment Agency, 2010). Indeed, that EEA reference only cites 77 landslides in Europe (although

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not specifying any size threshold), whereas the research presented here has recorded 292 landslides within just the 52 cities examined. National geological surveys maintain geospatial databases of geohazards, but these vary considerably in terms of convention, coverage and quality from one survey to another and cannot represent a systematic or accessible European geohazard inventory.

A reason for the lack of knowledge relating to the distribution of urban geohazards has been the impracticality of mapping the evidence for ground instability, or ground motions, over wide areas at an effective scale. This means that most inventories are ones of geohazard 'susceptibility' deduced from interpretations of geological maps which may vary considerably in scale, for instance, from 1:10,000 to 1:200,000. Inventories may also include data gathered in the field, but such observations are of necessity smaller-scale. Europe's cities have been built over centuries, layer on layer, and in many cases the underlying surficial geology has been obliterated or is unknown. An indicator of some urban ground instabilities would be insurance claims history, but on a European scale such data are incomplete, disaggregated, often non-standardised and/or subject to commercial confidentiality.

1.1. Satellite radar interferometry (InSAR)

The application of InSAR for detecting and measuring Earth-surface motions has revolutionised the capability to map geohazards (Gabriel et al., 1989; Massonnet et al., 1993). InSAR compares the phase of the radar echo on a pixel-by-pixel basis throughout a multi-temporal synthetic aperture radar (SAR) dataset to calculate changes in the line-of-sight distance between the satellite and the Earth's surface. In other words InSAR is able to map terrain motion. The simplest form of InSAR (commonly known as 'conventional') uses three SAR scenes of the same area separated in time to build two digital elevation models (DEM) that are differenced to reveal topographic change that might have occurred between the imaging dates (Gabriel et al., 1989). Two SAR scenes and a conventionally-derived DEM can also be used. The key limitation of conventional InSAR is atmospheric refraction influencing signal path length, in effect reducing displacement resolution to around a cm – too coarse to measure many slower-moving ground instabilities (although often suitable for measuring the larger, nearly-instantaneous, displacements relating to co-seismic events). The *PanGeo* project employed the more advanced and sensitive technique known as 'Persistent Scatterer' InSAR (PSI) that uses many tens of multi-temporal SAR datasets to facilitate a more accurate modelling of the atmospheric contribution, thereby increasing displacement resolution to sub-millimetre precision. PSI processing outputs a time-series for each radar-scatterer that is usually converted into a 2D map of average annual velocities covering the epoch represented by the dataset (Ferretti et al., 2001; Crosetto et al., 2016; Capes and Marsh, 2009)

The objective of *PanGeo* was to productise PSI within a geohazard information system aimed at the non-specialist, particularly local authorities who currently have little, if any, information on geohazards in their areas of responsibility. The project incorporated the InSAR technique into the mapping of unstable ground in 52 European cities, representing ~15% of the total EU population and nearly a third (29%) of the EU27 built environment (European Commission, 2016a). In partnership with all 27 of Europe's national geological surveys the project developed a standardised geohazard-mapping methodology (Table 1), and went on to record 1286 instances of 19 types of geohazard covering 18,000 km^2.

Presented here is an analysis of the results of further processing of the *PanGeo*-project output data to provide a first understanding of the distribution of geohazards across these 52 European urban areas, along with their frequency and probability of occurrence. Cross-referencing the *PanGeo* results with Eurostat's GeoStat data has produced the first systematic estimates of population exposures to urban geohazards across Europe.

Table 1
Geohazard Groups and Types as agreed between 27 national geological surveys for the PanGeo project. All involve ground movements.

1: Deep Seated Motions
1.1: Earthquake (seismic hazard); 1.2: Tectonic movement; 1.3: Salt tectonics; 1.4: Volcanic inflation/deflation
2: Natural Ground Instability
2.1: Landslide; 2.2: Soil creep; 2.3: Ground dissolution; 2.4: Collapsible ground.
3: Natural Ground Movement
3.1: Compressible ground; 3.2: Shrink-swell clays.
4: Man-Made Ground Instability
4.1: Shallow compaction; 4.2: Peat oxidation; 4.3: Groundwater abstraction; 4.4: Mining; 4.5: Underground Construction; 4.6: Made ground; 4.7: Oil & gas production.
5: Other 6: Unknown

Table 2
The 52 European cities for which geohazards were mapped.

Austria	Salzburg	Vienna
Belgium	Brussels	Liege
Cyprus	Lefkosia	
Czech Republic	Prague	Ostrava
Denmark	Copenhagen	Aalborg
Estonia	Tallinn	Tartu
Finland	Helsinki	Turku
France	Lyon	Toulouse
Germany	Berlin	Hannover
Greece	Athens	Larissa
Hungary	Budapest	Miskolc
Ireland	Cork	Dublin
Italy	Palermo	Rome
Latvia	Riga	Liepaj
Lithuania	Kaunas	Vilnius
Luxembourg	Luxembourg	
Malta	Gozo	Valetta
Netherlands	Amsterdam	Rotterdam
Poland	Nowy Sacz	Warsaw
Portugal	Faro	Lisbon
Romania	Bucarest	Cluj-Napoca
Slovakia	Kosice	Presov
Slovenia	Ljubljana	Maribor
Spain	Murcia	Zaragoza
Sweden	Goteborg	Stockholm
UK	London	Stoke on Trent

2. Method

The *PanGeo* project utilised InSAR as the basis for the development of a standardised geospatial inventory of urban geohazards. The inventory covered 52 of Europe's largest cities, all with populations >100,000 (Table 2 and Fig. 1). Each country has two cities included, except Cyprus and Luxembourg, as these countries have only one city each with a population exceeding 100,000.

Besides requiring a population of >100,000, the cities were selected in two ways: 27/52 were pre-selected on the basis of having already been PSI processed in the ESA project *Terrafirma* (www.terrafirma.eu.com): the use of *Terrafirma* output, plus the saving of the corresponding PSI processing costs was expedient to winning the EC *PanGeo* contract. 19 *Terrafirma* cities used in *PanGeo* were chosen to maximise population exposure, e.g. first or second largest cities, while 8 were chosen because of known or suspected ground instabilities, e.g. Palermo and Toulouse. The remaining 25/52 cities were nominated by each country's geological survey as part of the *PanGeo* project, 22 on the basis of population, and 3 due to geohazard drivers (Aalborg, Nowy Sacz and Faro). In summary, 11 (21%) of the 52 cities included in *PanGeo* were chosen due to known