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An innovative procedure for monitoring the change in soil seismic response by InSAR data: application to the Mexico City subsidence

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ABSTRACT

We developed an empirical procedure to evaluate the effect of the ground subsidence on the spatial and temporal seismic response of soils. The proposed method exploits the capabilities of the spaceborne SAR Interferometry technique to detect and map the ground subsidence with unprecedented spatial and temporal coverage. The information provided by satellites is combined with a-priori geological/geotechnical information to assess the soil compaction and the shortening of the soil vibration periods. The procedure was applied to estimate the shortening of the soil resonant period of Mexico City between 2005 and 2013. The results show that in approximately nine years the ground surface has subsided by approximately 0.5–3.5 m and the soil resonant period has decreased by approximately 0.1–0.4 s. The obtained results, validated with field measurements, highlight the effectiveness of the proposed procedure for the continuous monitoring of the soil resonant periods. The estimated change in resonant period on Mexico City has a great impact on the response spectra used for design, it is then necessary to update the map of the soil resonant period in order to account for the change of dynamic properties of soils caused by subsidence.

1. Introduction

During interseismic period, several instabilities may affect the soil and sometimes the overlying structures. In particular, the ground subsidence, either induced by natural or anthropogenic factors, often strikes large part of the territory and in particular urban areas, where subsidence causes differential settlements on buildings (Stramondo et al., 2008), ground cracks (Brunori et al., 2015; Cigna et al., 2012), damages to pipelines and modification of the drainage paths (Abidin et al., 2015). Among anthropogenic factors causing subsidence, the most relevant is groundwater withdrawal because it is able to produce significant subsidence rates, as observed in densely populated areas where the exposure to risk is particularly high (Holzer and Galloway, 2005; Hu et al., 2004).

Another important aspect, generally poorly investigated, concerns the potential effect of subsidence to modify the dynamic response of soils and the ground shaking in case of earthquakes.

The ground shaking depends on many factors such as the earthquake source mechanism, the propagation of the stress waves through the Earth to the top of bedrock beneath a particular site, and the characteristics of soils lying above the bedrock (Kramer, 1996).

Generally, the ground motion characteristics (i.e., the amplitude and frequency content) are estimated through predictive relationships (Douglas, 2001) that require some parameters such as the source-to-site distance, the earthquake magnitude, the focal mechanism and the soil type. In this perspective, it is very important to investigate the dynamic behaviour of soils and the modification of the seismic motion at the ground level respect to the bedrock motion immediately beneath. In fact, the seismic motion is modified when it travels through quaternary sedimentary basins and this modification depends on the seismic wave properties at the bedrock, the soil thickness, the stiffness and the damping properties (Kramer, 1996). Generally, the seismic motion is amplified in presence of soft soils with large thickness and low stiffness.

The soil seismic amplification is larger in correspondence of the natural oscillation frequencies of the soil and to each of these frequencies corresponds a different modal deformation of the soil stratum. Greatest amplification occurs at the lowest natural frequency of the soil, known as the fundamental frequency. The

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inverse of the fundamental frequency is the fundamental period or first resonant period. This quantity can be expressed according to Eq. (1) that is applicable in case of one-dimensional propagation of the seismic waves (Kramer, 1996):

$$T_s = \frac{4 \cdot H_s}{V_s} \quad (1)$$

where H_s and V_s are the soil thickness and shear wave velocity and T_s is the first resonant period. This relation provides very useful indications concerning the vibration periods at which corresponds the most significant soil amplification.

The long lasting presence of the ground subsidence modifies the soil response to seismic excitation. In fact, during the consolidation process, the soil reduces its thickness (H_s in Eq. (1)) and contemporarily increases its stiffness (V_s in Eq. (1)); thus, according to Eq. (1), the resonant period gradually decreases. The modification of the dynamic properties of soils modifies also the characteristics of the seismic waves at ground level, consequently buildings and infrastructures will be subjected to different seismic forces respect to those used for design.

Subsidence phenomena have been widely observed through remote sensing SAR Interferometry (InSAR) data. The large area coverage and the satellite viewing geometry make the InSAR a reliable tool in constraining the surface displacements induced by natural or anthropic subsidence. The InSAR technique is particularly suitable in detecting ground movements in urban environments because these areas are generally less affected by temporal decorrelation problems and provide dense and coherent scatterers for estimating the ongoing deformation (Brunori et al., 2015; Cabral-Cano et al., 2008; Chaussard et al., 2014; Polcari et al., 2014; Stramondo et al., 2007).

The ground subsidence rate provided by satellite measurements has been successfully integrated with geological/geotechnical information to generate subsidence hazard zoning maps (Pacheco-Martínez et al., 2015) and for ground rupture evaluation (Siles et al., 2015). The information content provided by the well-known Persistent Scatterers Interferometry (PSI) technique has been exploited to assess the health of engineering structures at urban and local scale (Pratesi et al., 2015). Moreover, the InSAR interseismic velocities have been correlated with the thickness and the resonant period of quaternary soft lithologies (Cornou et al., 2011), thus allowing to estimate the change of the soil resonant period through a systematic analysis of InSAR time series.

This correlation could allow to monitor the long-term subsidence and the consequent change in soil dynamic properties for wide areas and with relatively low costs, however, the InSAR-derived ground subsidence has never been used as a tool for seismic hazard assessment.

In this paper, we describe a procedure to monitor the change of dynamic properties of soils, in particular the resonant period. The empirical method proposed by Avilés and Pérez-Rocha (2010) is modified in order to estimate the change of the soil resonant period by exploiting InSAR-derived ground displacements. The procedure is applied to evaluate the modification of soil resonant periods in Mexico City. We selected this case study because the city is sinking from long time and the change of the soil resonant periods caused by subsidence has been proved by field measurements (Arroyo et al., 2013; Avilés and Pérez-Rocha, 2010).

We used C-band Envisat and Radarsat-2 data to highlight the fast subsidence that affects the urban environment. Furthermore, we exploited the processing capabilities of the on-line Geohazards Exploitation Platform (GEP) service provided by the European Space Agency (ESA) (European Space Agency, 2016) in order to obtain a reliable estimation of the ground displacements in time.

The paper is organized as follows. We first describe the procedure to derive the changes of the soil resonant period from the InSAR displacements, then we apply such procedure to Mexico City. The obtained results are compared with independent measurements for validation. Afterwards, we discuss about the significance of the results, their effect on the urban environment, the possible improvements and the applicability of the procedure in other similar scenarios.

2. Method

The study of seismic motion characteristics at local scale requires the identification of the dynamic properties of the sediments overlying the bedrock, i.e. the soil thickness, stiffness and damping properties. These data are retrieved with in-situ and laboratory investigations that require a considerable waste of time and money. If the ground is affected by a very fast subsidence caused by groundwater withdrawal, the monitoring of subsidence and the consequent changes of soil dynamic properties requires systematic and expensive surveys.

The role of groundwater extraction in increasing the overburden effective stresses and reducing the void spaces in fine-grained compressible soils is well known (Terzaghi, 1943). Despite that, the study of the consolidation problem presents many uncertainties because of the remarkable range and depth of the subsiding deposits, the incompleteness of the available information on the hydraulic and geotechnical properties of the subsoil, and the lack of information about the amount of the extracted water.

In the proposed procedure, the necessity to perform continuous surveys to monitor the change in soil's dynamic properties and the uncertainties related to the estimation of the spatial and temporal evolution of ground subsidence are overcome by exploiting SAR data together with a-priori geological/geotechnical information. In particular, the estimated surface movements for a series of coherent points located in the study area (i.e., the Persistent Scatterers (PS)) are related to the resonant period with an empirical relation. The main advantage of using remote sensing data consists in the large areal coverage offered by SAR images with a relatively low cost but the availability, density and the total number of the PSs depend on the characteristics of the study area (i.e., urban, rural, or vegetated area) and the adopted processing parameters.

The procedure is summarized in the flowchart of Fig. 1. The dataset consists of SAR images and some a-priori geological/geotechnical information. In particular, a map of the soil thickness and the first resonant period are needed to apply the procedure. These maps must be temporally coeval (or at least included) to the SAR dataset in order to correctly apply the procedure.

The processing of SAR images provides the Line-of- Sight (LOS) displacement ($w^i{}_{LOS}$) for each temporal observation (t^i) and for each PS but the procedure requires to estimate the vertical displacement component of the deformation field. Therefore, if SAR data are available on both ascending and descending orbits, we calculate the vertical component of the deformation by combining the two orbits, while if SAR data are available from one orbit, we neglect the horizontal component by assuming that the measured LOS displacement is due to vertical deformations. This assumption is reasonable in case the observed displacement field is caused by ground subsidence (Chaussard et al., 2014).

In the first step, we calculate the increment of soil compaction $\Delta H_s{}^i$ at each time interval t^i by subtracting the vertical displacement at the prior time (w^{i-1}) from the vertical displacement at the time t^i (w^i) (Eq. (2)).

$$\Delta H_s^i = (w^i - w^{i-1}) \quad (2)$$

In the second step, we calculate the reduction of the soil thickness ($H_s{}^i$) for each t^i by adding each $\Delta H_s{}^i$ to the soil thickness at the prior time ($H_S{}^{i-1}$) (Eq. (3)). The process starts from the initial