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Authors
Milillo, Pietro
Porcu, Maria Cristina
Lundgren, Paul
et al.

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The ongoing destabilization of the mosul dam as observed by synthetic aperture radar interferometry

Pietro Milillo[1], Maria Cristina Porcu[2], Paul Lundgren[1], Fabio Soccodato[3], Jacqueline Salzer[4], Eric Fielding[1], Roland Bürgmann[5], Giovanni Milillo[6], Daniele Perissin[7] and Filippo Biondi[8]

[1] NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, 91109 Pasadena (CA), USA. [2] Dept. of Mechanical, Chemical and Materials Engineering University of Cagliari, 09123 Cagliari , Italy [3] Dept. of Civil and Environmental Engineering and Architecture University of Cagliari, 09123 Cagliari , Italy [4] GFZ German Research Centre for Geosciences, Physics of Earthquakes and Volcanoes, Telegrafenberg, 14473 Potsdam, Germany. [5] Dept. of Earth and Planetary Science, University of California, Berkeley, 389 McCone Hall, 94720, Berkeley (CA), USA [6] Italian Space Agency, Contrada Terlecchia, 75100 Matera (MT), Italy [7] Lyles School of Civil Engineering, Purdue University, 550 Stadium Mall Drive, 47907 West Lafayette (IN), USA [8] University of L'Aquila

Abstract:

We present a detailed survey on the ongoing destabilization process of the Mosul dam. The dam is located on the Tigris river and is the biggest hydraulic structure in Iraq. From a geological point of view the dam foundation is unstable due to the underlying geology that is formed by alternate and variable strata of highly soluble materials such as gypsum, anhydrite, marl and limestone. Here we present the first comprehensive multi-sensor cumulative deformation map for the dam generated from space-based synthetic aperture radar (SAR) measurements from the Italian constellation COSMO-SkyMed and the European Sentinel-1a satellite. We compared 2014-2016 data to an historic dataset spanning 2004-2010 acquired with the Envisat ASAR sensor. We found that deformation was rapid during 2004-2010, slowed down in 2012-2014, and restarted in August 2014 when grouting operations stopped due to the temporary capture of the dam by the self proclaimed Islamic State in Iraq and Syria (ISIS). We took advantage of the availability of data from multiple SAR satellites to infer the deformation at the dam in great spatial and temporal detail and shed new light on the processes of the ongoing destabilization. This study highlights how new constellations of SAR sensors together with the availability of historical datasets are leading to important advances in deformation monitoring of small scale geologic and manmade features.

SECTION 1.

Introduction

The advent of constellations of synthetic aperture radar (SAR) satellites with short repeat time acquisitions allows us to shed new light on the behavior of earth processes and anthropogenic phenomena with an unprecedented spatial and temporal resolution [1]–[2][3]. Such improvement, highlights the dynamics of ongoing processes deforming the Earth's surface [4]–[5][6][7][8], allowing a better characterization of both seasonal and secular deformation trends. In this paper we take advantage of the availability of data from multiple SAR satellite constellations [2] to infer surface deformation at the Mosul dam, Iraq, in great spatial and temporal detail to highlight the dynamics of the ongoing destabilization [9]–[10]. the Mosul dam is at risk of failure and consequent catastrophic flooding affecting about 1.5 million people living near the Tigris river. Maintenance grouting, to close pathways opened by water infiltrating soluble evaporite deposits, has been performed since the construction of the structure [11]. A US$27 million reconstruction project was attempted by the US Army Corps of engineers in 2007 with modest success in shoring up the dam [11]. Here we present the first comprehensive multisensor cumulative deformation map for the dam generated from space-based synthetic-aperture radar measurements (Figure 1), which reveals that parts of the dam body are undergoing rapid subsidence. Deformation was rapid during 2004–2010, slowed down in 2012–2014 and restarted in August 2014 when the grouting operation stopped due to the temporary capture of the site by the self-proclaimed Islamic State. Precautions have been taken to limit the dam's water level at 319 m above sea level and limit the hydrostatic pressure on the dam foundation [11]. However, the spillways are blocked and no cement grouting has been performed since the dam was retaken in late august 2014.

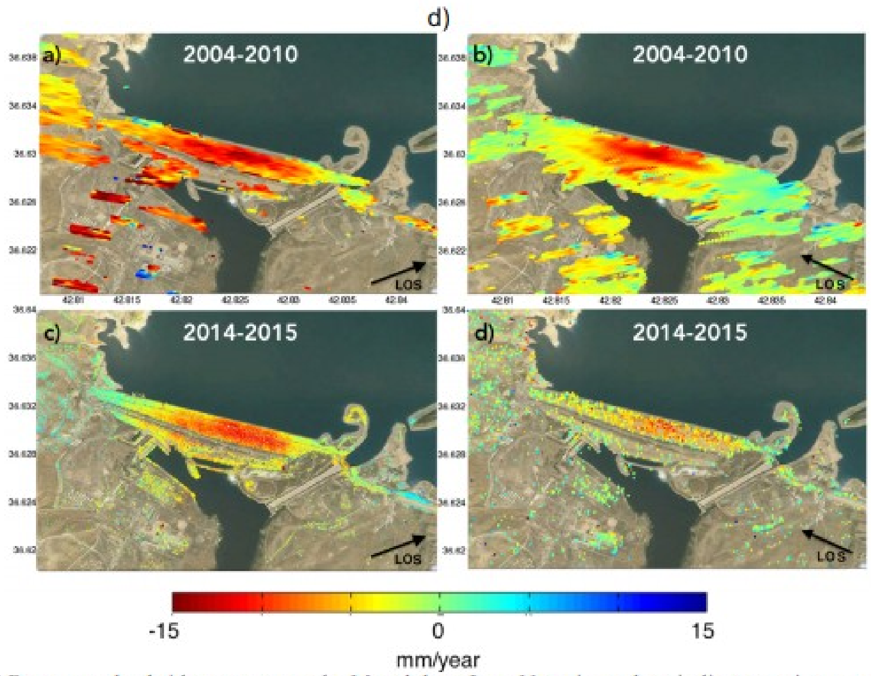

Figure 1 InSAR measured subsidence rates on the Mosul dam, Iraq. Negative values indicate motion away from the satellite, consistent with subsidence. (a) Envisat ascending covering May 2004 – August 2010. Horizontal/Vertical Profile O-O' is shown in Figure 2 (b) Envisat descending spanning May 2004 – August 2010 (c) CSK ascending covering Dec 2012- July 2015 (d) Sentinel descending covering October 2014 – March 2016. Figure adapted from [9]

SECTION 2.

Dataset and Methods

We processed 62 images from the Italian COSMO-SkyMed (CSK) constellation of four satellites acquired on ascending tracks to image ground deformation during 2012–2015. Six Interferograms from the European Space Agency's Envisat satellite from both ascending and descending geometries have been calculated for monitoring the destabilization process during the period 2004–2010 and 32 images acquired in descending geometry by the European Sentinel1/A sensor starting October 2014 and spanning 18 months have been used to shed new light on the ongoing deformation of the dam. A multi-temporal interferometric processing technique combines the phase measurement of the CSK and Sentinel-1A into two separate time-series of deformation exploiting both point-like and distributed scatterers (3,4).

SECTION 4.

Results and Modeling

Figures 1a and 1b show the displacement rate along the LOS direction of the radar over 10 months (October 2014- July 2015). The Envisat historic dataset gives a good constraint on the first-order deformation pattern (Figure 1c, 1d, Figure 2b), showing subsidence with only small horizontal motions. Envisat measurements from 2004 to 2010 indicate −10mm/year±6 mm/year LOS rates (−10.8 mm/year vertical, negative rates indicate LOS increase or subsidence). The fine spatial resolution (3 m) and dense temporal sampling of the CSK constellation allow us to better constrain the transient deformation during 2012–2015. A regression analysis suggests that the dam is deforming at a maximum rate of −7.8±1.8 mm/year LOS (−9.6 mm/year vertical; Figure 2a). Subsidence rates from December 2012 to December 2013 did not exceed 2.3±1.8 mm/yr [9].

Remote sensing measurements can be used to calibrate numerical models simulating the dam-soil interactions characterized by underlying soluble rock layers' progressive degradation (mainly gypsum). We implemented a 2D model of the most significant sections of the dam (Fig 2) using the finite element method FLAC software [12]. Specific material parameters are based on already published data for the Mosul dam site [13]–[14][15]. A view of the model showing geometrical data and the geological layers considered in the analysis is provided in Figure 2a. The numerical simulation aims at reproducing the subsidence observed by the interferometric SAR (InSAR) time-series analysis presented in [9]. It is important to highlight that this is a preliminary model and a complete 3D view of the initial stress state of the dam-soil system and the following stages will be given in future dedicated papers.

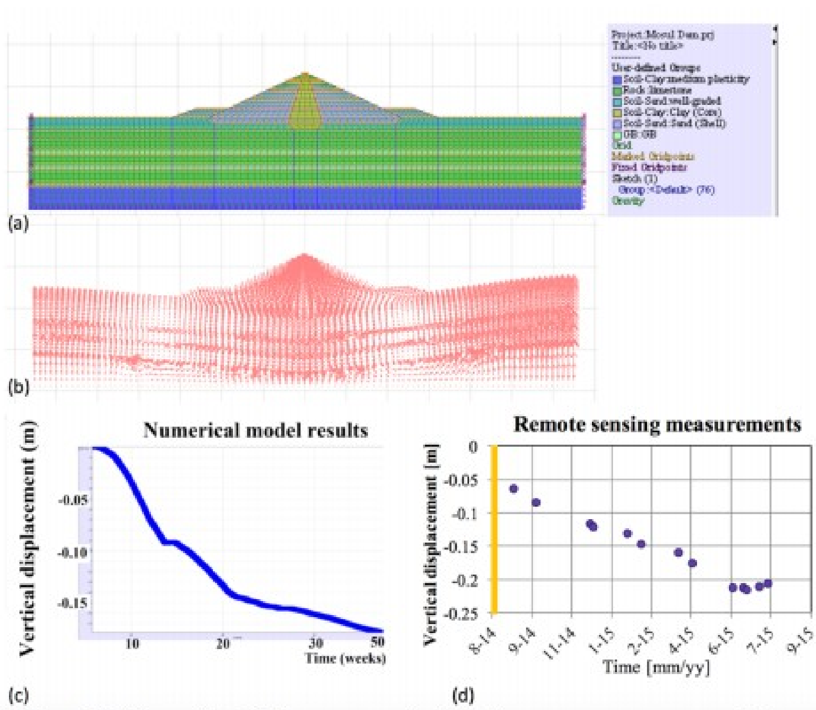

Figure 2 (a) Soil-dam FLAC model; (b) long-termvertical displacements vector map; (c) numerical vertical displacement time-history of a target point; (d) remote-sensing data of the same target point.

However, the crucial aspect of the numerical simulation resides in describing the complex chemical and physical phenomena which are involved in the long-term gypsum dissolution process. Although different approaches (and different levels of complexities) can be adopted for this purpose [16], the easiest way to proceed is to assume a generalized decay of the material mechanical properties. Based on the experimental tests carried out on gypsum specimens retrieved from the Mosul dam area [17], a time-dependent reduction of the gypsum elastic moduli was introduced in the FLAC dam-soil model (Fig. 1a). In this case, foundation soils were modelled with a simple elasto-plastic model. Some preliminary results were thus obtained showing the predicted vertical displacements map at long-time (50 weeks) (Fig. 1b). A comparison between the numerical and the InSAR cumulative displacement time-series of a target point (placed at the top of the dam) is provided in in Figs 1c and 1d, respectively. The data refer to the period following the interruption of the cement grouting campaign. Although preliminary, the results in Figs 1b-c show that by assuming a simple degradation of the elastic properties of the soil we are able to simulate the subsidence characterizing the Mosul dam. More sophisticated constitutive soil models able to better represent chemo-mechanical degradation and creep of gypsum are currently under study to improve our numerical simulation.

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