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MULTI-TEMPORAL INSAR MONITORING OF THE ASWAN HIGH DAM (EGYPT)

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ABSTRACT

The Aswan High Dam, Egypt, was built in the 1960s and is one of the biggest dams in the world. It stopped the seasonal flood of Nile river allowing the urban expansion of cities/villages and the full year cultivation, producing $10x10^9$ kWh of power annually. The dam is located in an area where several earthquakes (M_L<6) occurred from 1981 to 2007. In this paper, we want to identify any potential damage that could be caused to the dam, and assess its overall structural stability using Multi-Temporal InSAR (MT-InSAR). To reach this goal, we process Envisat data from descending orbits acquired between 2003 and 2010. Our initial estimates show relatively small rates (maximum around -3 mm/yr in the satellite Line-Of-Sight) of subsidence, whose implications must be further investigated. In addition, we perform a preliminary stress-strain analysis of the dam using FEL and FEM methods to assess if the detected movements correspond to the expected vertical behavior for such mega-structure.

Index Terms— Aswan High Dam, InSAR, monitoring, FEL, FEM.

1. INTRODUCTION

The Aswan High Dam, the target of this study, is one of the major artificial structures built up to the present. This dam, inaugurated in 1970, is 111 m height, although the maximum height of the reservoir is 92.8 m with a safety guard of 5.8 m. It has 3830 m in coronation length with a coronation width of 40 m. The width at the base is 980 m and the upstream and downstream slopes are 19º and 23º respectively. It is a rock-fill dam that forms an artificial lake (Lake Nasser) covering at maximum capacity an area of 5250 km^2 storing a water volume of 135 km^3. The dam is located in the Nile basin, in the town that gives it its name, and regulates the floodwaters of the river. The dam is found on fundamentally Quaternary materials, fluvial and alluvial terraces, as well as gray-blue marls. Like most of the sedimentary soils, it corresponds to the alluvial type, formed in general by boulders, sands, silts and clays, with medium to low permeability. The dam produces a hydroelectric output of 2.1 GW and has 12 generators of 175 MW each. The power supply began in 1967, when the dam reached its zenith of production, generating approximately half of the electricity needed for consumption throughout Egypt. In addition, about 95% of the population of Egypt lives within 16 kilometers of river zone. The dam is located at the geographical coordinates 23°58′11.57″N, 32°52′41.46″E. The location is depicted in Fig. 1.

Our project main idea focuses on the evaluation of vulnerability of structures affected by terrain movements. Generally, structure movements can be observed using satellite-based SAR interferometry (InSAR) techniques [1]. Within currently available data, it is theoretically possible to determine terrain deformations of any selected site worldwide. However, in practice, InSAR accuracy is limited by factors such as vegetation cover, data availability, structure orientation, or the direction of the displacements of interest (i.e. not in the direction of the satellite LOS). InSAR is less sensitive to horizontal movements, but can detect vertical changes in the order of millimetric accuracy. Though deformations in urban areas are well monitored and assessed already, InSAR should yield an additional value to optimize estimated subsidence/deformation models and potentially discover unknown dynamics thanks to its high revisit rate and unique opportunity of precise spatial information.

In this paper, we investigate the use of MT-InSAR techniques to detect and assess deformations at fault systems in Aswan area. Several active faults systems are present around the Aswan High Dam, which can pose a significant risk to this structure with huge implications of safety of the most of Egyptian population.

Figure 1. Location of the Aswan High dam in Egypt, the descending orbit and the line-of-sight direction.

2. DATA AND METHOD

In this work, we processed 31 Envisat ASAR C-band images acquired on descending orbits (track 350, frame 53) from 19/12/2003 to 03/09/2010 with an incidence angle of 23º at the central middle swath IS2, and a 5×25 m nominal pixel dimension. The direction of the satellite track and the LOS direction seeing from the top view are shown in Fig. 1.

InSAR exploits radar phase information of compatible SAR images acquired over the same region at different times (repeat-pass SAR interferometry). Two such images are used to form an interferometric pair (the interferogram). Satellite DInSAR was first described using Seasat data [2]. For a general review of SAR interferometry, the reader is referred to [3] or [4] among others.

InSAR is commonly affected by a series of limitations that should be considered including temporal and/or geometrical decorrelation [5], difficulties in unwrapping of ambiguous interferometric phase using a single interferogram [6], and errors induced by atmospheric artefacts. MT-InSAR techniques include solutions to some of the DInSAR limitations.

Existing MT-InSAR approaches exploit multiple SAR images acquired over the same area and lead to separation of phase displacement contribution from other phase components (topography, atmosphere etc.). MT-InSAR techniques focus in the identification of pixels in SAR images characterized by small phase noise which are typically related to two types of reflectors: those where the response to the radar is dominated by a strong reflecting object and remains constant over time (Persistent Scatterer, PS) and those where the response is constant over time, but is due to different small scattering objects (Slowly Decorrelating Filtered Phase pixels, SDFP, as they are known in the software used in this work, StaMPS-MTI (Stanford Method for PS) [7], [8]).

Originally named as StaMPS, one of its main characteristics lies in the fact that PS selection uses the phase spatial correlation characteristics, which is suitable to find low-amplitude natural targets with phase stability that cannot be identified by pure amplitude-based algorithms as in [9], [10], [11] and [12]. An important advantage is that StaMPS does not require a prior deformation model for phase unwrapping. This algorithm evolved into a hybrid method (StaMPS-MTI) combining both PS and SDFP points producing their deformation time series, the deformation velocity estimation, and the residual topographic error (w.r.t. height data from DEM).

In StaMPS-MTI, the algorithms for PS and SDFP pixels selection are basically the same. However, different interferograms are used. Single master interferograms are used for PS pixel selection, while multiple master interferograms with small baselines (SB) are used in the case of SDFP pixels. In this work, we performed both PS and SB processing as well as the combination of them. Fig. 2 shows the baselines (temporal vs. perpendicular) distribution of the used dataset. We removed the phase topographic contribution by means of the SRTM DEM. The inner workings of this software package are described in more detail in [7], [8], [13], [14], [15], [16] and [17].

3. RESULTS AND DISCUSSION

The ground motion estimated with MT-InSAR reveals a subsidence in the Aswan High Dam from 2003 to 2010. Results show a subsiding zone in the central part of the dam with a mean LOS velocity around -3 mm/yr at the coronation area (Fig. 3). In addition, it has also been detected a slope which could be potentially subsiding in the east bank 1 km north of the dam (Fig. 4).

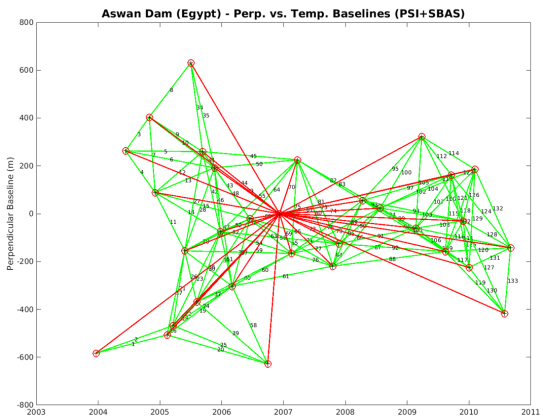

Figure 2. Perpendicular vs. temporal baselines distribution. Red and green connections correspond to PS and SB networks respectively.

To investigate the expected theoretical subsiding behavior due to the material consolidation through time, a preliminary calculation of stress-strain modeling of the dam has been performed using Limit Equilibrium Method (LEM) and Finite Element Method (FEM). It has been done along the wider section on the river axis since it is the most unfavorable due to the hydraulic load (blue arrow in Fig. 3). This gravity hearth dam is heterogeneous with an impermeable core and a waterproofing curtain for the foundation area. To carry out the study with LEM and FEM, and given the topography of the area only affected by the river channel, it has been discretized to a depth of the maximum height of the studied section and considered a transversal width equal to the maximum of the foundation of the dam, considering the geotechnical parameters of the materials that compose the foundation, the body of the dam, and the grout curtain [18]. For the calculation of the slip circle and probable slip mass, the methods of slices have been used within LEM. The FEM has been used to compute the possible deformation and vertical displacements.

Figs. 5 and 6 show the results of this analysis. The first indicates the most likely sliding circle and the second, the deformed mesh. For the studied section and at the maximum height of the reservoir, we got a safety factor SRF of 1.58, a weight of the possible sliding mass (according to loosely sliding circle) of 17.945 t, the critical safety factor SSR of 1.30, and the possible vertical deformation of 22.8 cm. This estimated settlement is caused by the secondary consolidation or fluency from 1970 to present without considering the settlement during the construction of the dam or other external influences from other sources such as the power plant attached to the plant.

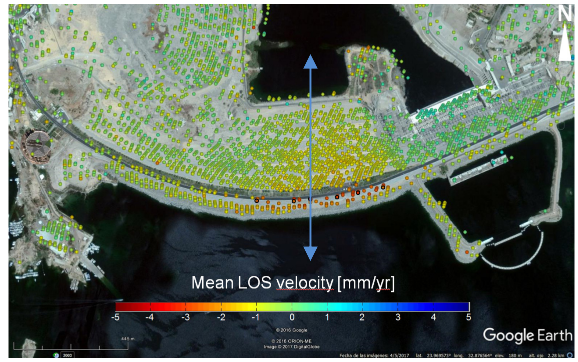

Figure 3. Mean LOS velocity derived from Envisat ASAR data.

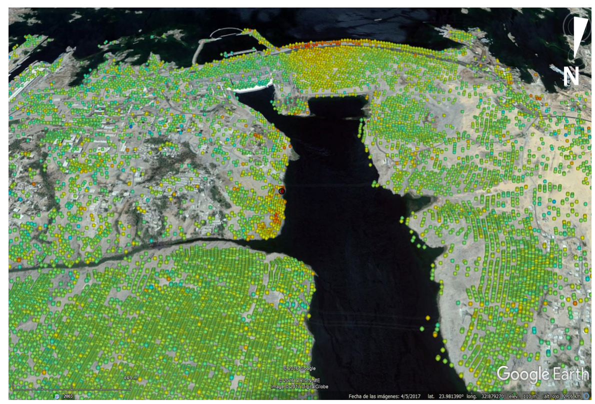

Figure 4. Location of a possible landslide 1 km north of the dam (red pixels in the center of the picture).

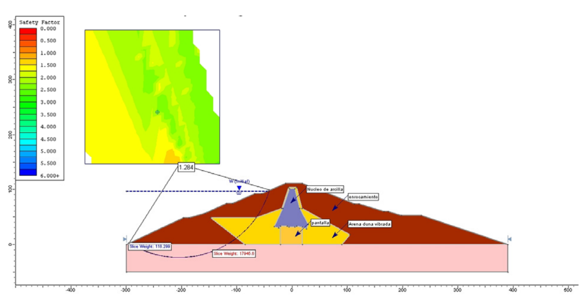

Figure 5. The most likely sliding circle.

4. CONCLUSIONS

For our best knowledge, this study and the previous one [1] represent the first attempt to monitor the Aswan High Dam using time-series of satellite radar interferometry of Envisat ASAR observations, in the period 2003-2010. The combined processing of (PS+SB) MT-InSAR methods shows some slight subsidence in the central part of the dam being higher at the coronation with mean LOS velocities in the order of -3 mm/yr. In order to validate this result, a preliminary stress-strain analysis of the dam has been performed using LEM and FEM. As the estimated critical safety factor (1.30) is greater than 1.2, the overall stability of the dam is fulfilled. And because of this, the settling probability of the dam coronation by the subsidence due to fluctuations in the level of the reservoir is moderate to high. Therefore, the deformation measured with InSAR in the period 2003-2010 agrees with the expected subsidence predicted from the stress-strain analysis.

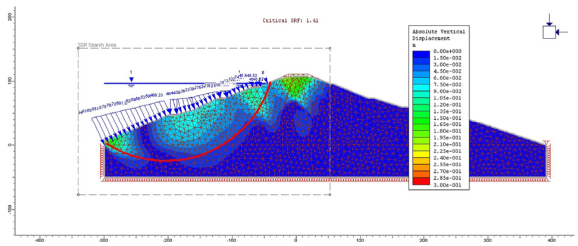

Figure 6. The deformed mesh from the FEM analysis.

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