Merging GBSAR and topographic surveys to measure pier deformations

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Abstract

In this work we describe a methodology for the non-destructive measurement of absolute displacements of a pier during a bollard pull trial by Ground-Based Synthetic Aperture Radar (GBSAR) interferometry, with a sub millimeter precision in any weather conditions. An experiment is carried out to measure pier's displacements at twelve co-located Corner Reflectors (CRs) and Surveying Prisms (SPs), by SAR interferometry (InSAR) and topographic techniques during a bollard pull trial. The GBSAR results have been validated at the CR locations using the displacement measurements provided by topographic survey. The pulling force applied to the bollard is measured by a load cell specifically customised to precisely meaure the pulling force during the trial.

Key words: Synthetic Aperture Radar (SAR), Ground-based SAR (GBSAR), SAR interferometry (InSAR), pier, harbour

1 INTRODUCTION

The bollard pull trial is a test carried out on a tug to measure the pulling force. The bollard pull is the static force exerted by a ship on a fixed towline at zero speed. Trawl pull is a force exerted by a ship on a towline at speed. The aim of bollard pull test is to measure displacement of the bollard and the pier around it, during the pulling action of the trawl tugs and it is of great importance when assessing the new mooring infrastructures and to perform back-analysis studies. (El Zaalik, M.A.A. et al. 2015). Usually, strain gauges are used to measure the concrete deformation on the pier and the strains in the bollard and anchor bolts. The displacement of the pier is measured with respect to a point away from the bollard and the edge of the pier to avoid to be directly affected by the effects of the pulling force. In some cases also a camera can be used to observe the condition of the concrete and to watch for cracking. However, the installation of such devices require a direct interaction with the bollard and pier concrete structure and the measurements provide displacements only in a few points where they are installed. The aim on this paper is to describe a new methodology, based on the use of Ground-Based Synthetic Aperture Radar (GBSAR), to measure 2D displacement patters of the whole pier structure during the bollard pull test. The technique of GBSAR interferometry has been applied to measure displacements induced by landslides and in natural-disaster affected areas (Leva, D. et al. 2003)., bridges (Dei, D. et al. 2009), dams (Mascolo, L. et al. 2014) with a sub-millimetre precision. The principle of radar interferometry relies on the acquisition of coherent SAR images with a time interval of few minutes. The GBSAR system can be installed at a distance ranging from less than one hundred meter up to four kilometers

(Caduff, R. et al. 2005) (Crosetto, M. et al. 2014). Besides the high precision of displacement measurements performed remote and non-destructive configurations, the GBSAR technique has the advantages of working in any weather and sun illumination conditions and to provide 2D maps of displacement pattern which are useful to get hints on the finite element modelling of pier mechanical behaviour. In this work GBSAR displacement maps are compared with measurements obtained by means of a topographic technique. The GBSAR system and two robotic total station have been installed at a distance of about one fifty meters from the pulled bollard in order to be in a place not affected by the pier deformation during the pulling trial. A few Corner Reflectors (CRs) and surveing prisms (SPs) have been deployed in the monitored area covering the area around the bollard, from the pier edge up to the most internal part closer to the installation sites of GBSAR and total station. Each CR has been co-located to a SP in order to compare the GBSAR and topographic measurements. It is worth noting that the GBSAR interferometry can only measure the line-of-sight (LOS) displacement of a target. Hence, the selection of the installation site of the GBSAR system with respect to the pier edge and the pulling force direction is important to correctly estimate the expected horizontal displacements of the pier. Another important point of this experiment is to verify the time needed by the GBSAR system to %measure the pier displacements during the bollard pull trial. This is a key point since the %tug cannot easily provide a almost constant pulling force for a long period, beside the issues of cost effectiveness and safety of the trial operations. Two robotic total stations have been used to measure the displacements of SPs in a reduced time of a few minutes. Since the aim of this paper is to demonstrate that GBSAR technology could be a useful technique to measure the pier displacement patterns during a bollard pull trial, a key point is to verify that the whole acquisition time of displacement measurements is compatible with pull trial operations. Measurements are provided for the whole pier portion illuminated by the radar and not in correspondence of CR that in this experience are used only to facilitate the comparison with topographic measurements.

2 GBSAR INTERFEROMETRY

A GB-SAR consists in a stepped frequency continuous wave (SF-CW) radar moved along a rail of finite length, that changes its position of a constant step, while a burst of pulses characterized by different progressive frequencies are transmitted and the correspondent backscattering echoes received. The raw data structure consists of a matrix with the number of columns given by the acquisition positions along the rail and the number of rows given by the transmitted frequencies. The Frequency-Domain BackPropagation (FDBA) is used to perform a coherent sum of the different frequency contributions for each radar position, corrected for the phase delay (Fortuny-Guasch, J., 2003). The most important application of GBSAR interferometry consists in the measurement of displacements patterns. The Line-of-Sight (LOS) displacement D of a target P in the scene has a linear function of the interferometric phase $\Delta\varphi$ with the constant factor given by the radar wavelength over 4π. The precision of displacement measurements can be a fraction of millimeter, if a high coherent target is observed. This technique has been mainly used for the monitoring of landslides (see (Antonello, G., et al. 2004) and (Nico, G. et al., 2015) and references therein), bridges .(Pieraccini, M. et al, 2006), dams (Mascolo, L., et al. 2014) and terrain mapping at a local scale (Nico, G. et al. 2004), (Nico, G. et al. 2005).

3 EXPERIMENTAL RESULTS

The aim of the experiment has been to demonstrate a procedure for the accurate measurement of the pulling force and the corresponding pier displacement pattern during a bollard pull trial. A set of of twelve Corner Reflectors (CRs) has been deployed over the portion of the pier monitored during the bollard pull trial. Furthermore, a set of fourteen surveing prisms (SPs) has been also deployed in the scene. Twelve of them have been co-located with the CRs to have points on the pier with both GBSAR and topopographic measurements.The GBSAR system and the two robotic total stations have been installed at a distance of about 50 m from the pier edge where the pulling force is applied. The acquisition geometry with the location of both GBSAR and the two robotic total stations, as the well as the location of CRs and SPs, is shown in Fig. 1. During the pull trial, the bollard has been pulled by two tugs. The bollard has been pulled with a force increasing up to 1000 kN with increasing steps of 200 kN and then decreasing in two steps of 400 and 600 kN, respectively. A key point of the experiment has been the accurate measurement of the pulling force by means of a customized load cell. In the following we summarize the results which have been obtained in the experiment. The resolution cell of SAR images around each CR and co-located SP is about 0.75 m in range and 0.45 m in azimuth. This allows to both compare the GBSAR and topographic measurements and have displacement measurements over the whole pier useful for the back-analysis. Fig. 2 shows an example of radar amplitude and coherence images obtained by GBSAR data.. Besides the twelve CRs, a few further targets, as the concrete basis of a light pole on the right-hand side of the scene, the bollard itself and the quay edge close to the sea side. The pier area close to the GBSAR installation site is also characterized by a high interferometric coherence. The maps of maximum displacements obtained by GBSAR and topography techniques are shown in Fig. 3. Useful information about displacements can be retrieved not only at the CR locations but also in a significant portion of the pier surface illuminated by the GBSAR. The differences between GBSAR and total station measurement have a median m = -0.05 mm and an interquartile distance d= 0.18 mm. The outcome of this experiment shows that GBSAR can provide accurate estimates of displacements even in case of sub-millimeter displacements and almost grazing angles. The main advantage of GBSAR with respect to the total station is its capability to provide accurate measurements in any weather condition and also without the need to deploy any CR. Furthermore, the GBSAR has the capability to measure displacements with the same precision up to a distance of about 4 km. This is the main advantage with respect to topographic techniques where the precision depends on the distance between the target scene and the total station.

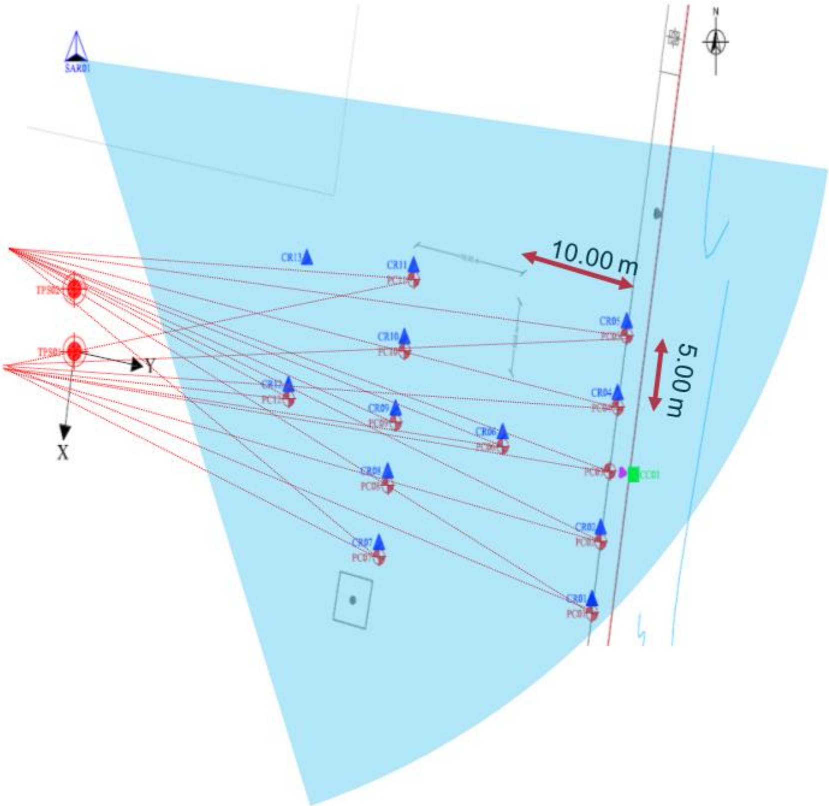
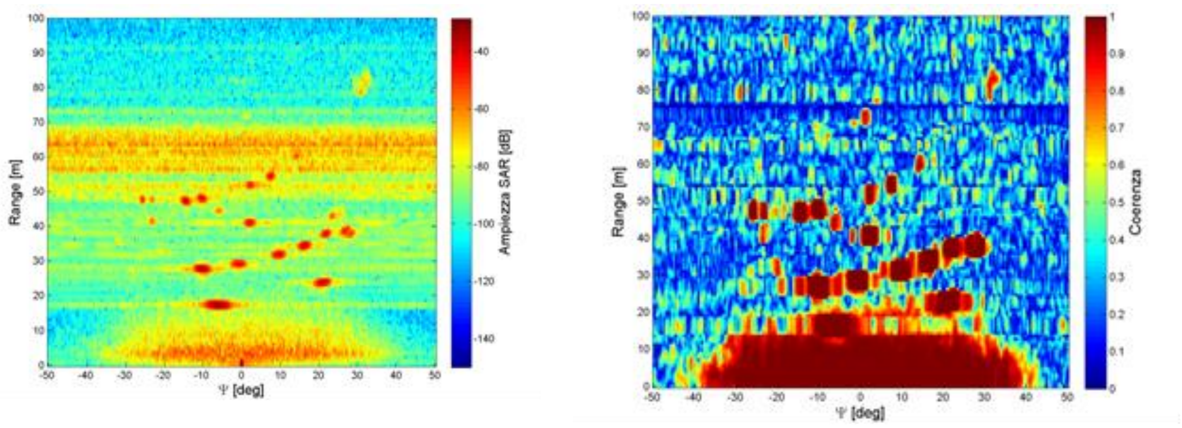
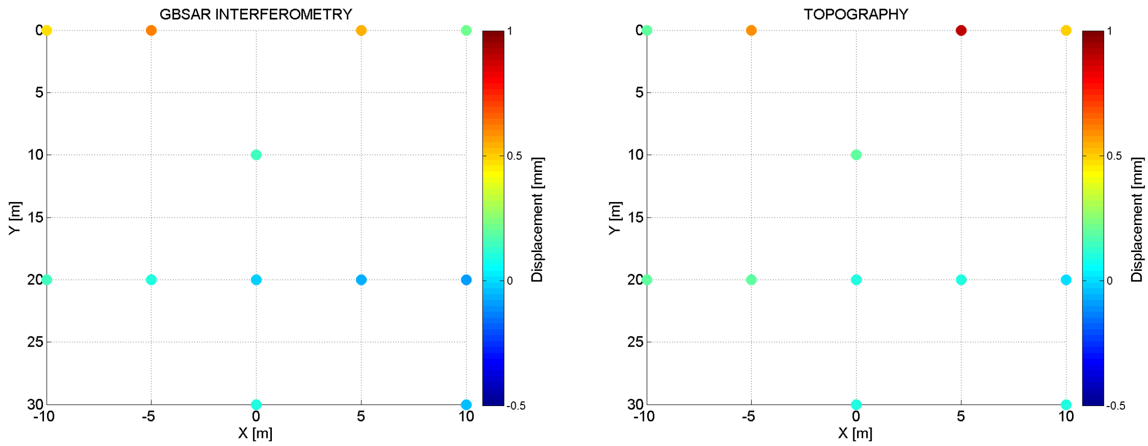


Fig. 1 Sketch of the study area with the location of Corner Reflectors (CRs).}



(a) *(b)*

Fig. 2 (a) Radar amplitude and (b) coherence images.



(a) *(b)*

Fig. 3 Displacments measured at CRs location by GBSAR (a) and topography (b).

4 CONCLUSIONS

In this work we presented the results of an experiment for the measurement of pier deformation pattern during a bollard pull trial. This kind of trials are usually carried out when building new harbour infrastructures and are of key importance in the back-analysis studies of those infrastructures. The motivation of this experiment has been to study the capabilities of GBSAR interferometry to measure absolute displacement patterns of a pier during a bollard pull trial, with a sub-millimeter precision and observing the target scene at a distance up to 4 km. This is a great advantage with respect to traditional techniques, such extensometers providing relative displacements in a few point of the pier. The GBSAR interferometry shows also a few advantages with total stations and topographic methdologies which in this work have been used for validation purposes. In fact, even if total stations can also provide measurement of absolute displacements in a few point, the precision of such measurements decreases with the distance from the target scene so limiting the maximum distance where to install the total stations in order to avoid to directly affected by the deformations induced by the tugs during the bollard pull trial. Furthermore, the topographic measurements are affected by weather conditions and this is of importance for this kind of applications which are performed close to oceans. The experiment has shown the good agreement between the displacements measured by GBSAR interferometry and topography techniques at twelve co-located CRs and SPs deployed on the pier. It has been found that the difference between the two sets of measurements has a median value smaller than 0.1 mm with a dispersion estimated by interquartile distance smaller than 0.2 mm.. Besides this, a correlation coefficient larger than 0.6 has been found for temporal profiles of measurements at locations characterized by significant displacements, above the precision limits of the two techniques. The results presented in this work show that the GBSAR interferometry could be a useful technique for the measurement of pier displacements, during a bollard pull trial. Besides using only the GBSAR interferometry to measure the pier displacements, also the possibility of merging both GBSAR interferometry of topography techniques is an interesting option during trial operations since the the two techniques could provide a useful tool for the precise measurement of aereal displacements of piers during bollard pull trials, with near-real time and any-weather capabilities.

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