

REMOTE MONITORING OF NATURAL SLOPES: INSIGHTS FROM THE FIRST TERRESTRIAL INSAR CAMPAIGN IN VIETNAM

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EXTENDED ABSTRACT

Il presente lavoro, realizzato nell'ambito di un progetto di ricerca finanziato dal *Vietnamese Space Science & Technology Program*, mostra i primi risultati di una campagna di monitoraggio da remoto della frana di Nam Dan (Vietnam settentrionale) dove, per la prima volta nel Paese, è stata utilizzata la tecnica dell'Interferometria SAR Terrestre (TInSAR). Tale tecnica si basa sull'utilizzo di un sensore radar installato su una piattaforma terrestre che trasmette il segnale nel campo delle microonde (banda Ku) e ne riceve gli echi di ritorno dai target riflettenti. Il sensore utilizzato è costituito da due antenne (una trasmittente e una ricevente) e si muove seguendo una traiettoria lineare lungo un binario. Grazie a questa tecnica è possibile effettuare da remoto il monitoraggio delle deformazioni del terreno, raggiungendo una precisione sub-millimetrica in condizioni ideali (ad es. breve distanza, alta riflettività, etc.).

Le attività di monitoraggio sono state condotte nel villaggio di Nam Dan, dove una frana attiva con diverse evidenze geomorfologiche quali scarpate, crepe, contropendenze con ristagni d'acqua, abitazioni e beni pubblici gravemente danneggiati, costituisce una seria minaccia per la popolazione locale. L'area di Nam Dan (22°36'N; 104°29'E) si trova nella parte meridionale del distretto di Xin Man, in prossimità del confine tra Vietnam e Cina. Tale distretto, caratterizzato da un clima monsonico umido subtropicale, si estende su un'area di circa 582 km² ed è caratterizzato da una topografia complessa con catene montuose, pendii terrazzati e valli molto profonde con processi erosivi avanzati. Gli archivi locali riportano che in tale area, dal 2012 al 2016, si sono verificate 967 frane, principalmente durante l'estate in corrispondenza delle piogge monsoniche del sud-ovest. Secondo recenti indagini e osservazioni sul campo, la frana oggetto di studio, verificatasi nel luglio del 2012 in seguito a forti precipitazioni, può classificarsi come uno scivolamento traslativo di detrito e si estende su un'area di circa 12.000 m² con una profondità media di circa 22,5 metri. Nell'agosto del 2013 la frana ha causato nuovi gravi danni a 5 abitazioni, al mercato comunale e alla strada provinciale n. 178 e rappresenta tutt'oggi un grave pericolo per la popolazione residente.

Le attività di monitoraggio sono state effettuate tra agosto e dicembre 2019 attraverso un nuovo interferometro radar denominato Phoenix, che è stato utilizzato in una delle sue prime applicazioni sul campo. Il monitoraggio tramite Interferometria SAR Terrestre ha avuto l'obiettivo di controllare l'evoluzione del versante instabile ed ha portato alla realizzazione di mappe di spostamento e delle relative serie temporali, fornendo informazioni dettagliate sulla localizzazione e sui tassi di deformazione dei processi gravitativi di versante presenti.

Sebbene nel periodo monitorato non siano state registrate deformazioni significative, l'utilizzo di questa tecnica di telerilevamento, insieme alla strumentazione a contatto precedentemente installata (inclinometri, piezometri, pluviometri) ed alle indagini sul campo, hanno contribuito a migliorare la conoscenza della frana di Nam Dan e la comprensione del suo cinematisimo, con particolare riguardo all'evoluzione temporale delle deformazioni superficiali, anche tenendo conto delle condizioni meteorologiche locali. I risultati ottenuti durante la campagna di monitoraggio, in combinazione con i dati precedentemente acquisiti ed elaborati, confermano che il versante oggetto di studio è caratterizzato da fenomeni di instabilità gravitativa, che possono essere innescati da precipitazioni intense che solitamente avvengono nell'area durante la stagione estiva.

In considerazione dei contesti ambientali dell'area, quali le severe condizioni climatiche e le aree impervie da percorrere in assenza di infrastrutture viarie adeguate, è stato posto l'accento sulle attività operative sul campo e sull'individuazione di soluzioni tecnologiche appropriate, che hanno rappresentato aspetti particolarmente sfidanti per il monitoraggio di fenomeni franosi tramite tecniche di telerilevamento.

ABSTRACT

The present work, realized in the framework of a research project funded by the Vietnamese Space Science & Technology Program, shows the first insights of remote monitoring at the Nam Dan landslide (Northern Vietnam). The Terrestrial SAR Interferometry (TInSAR) technique was used for the first time in the Country.

The activities were performed in Nam Dan village, where an active landslide with several geomorphological evidences as open cracks and scarps, severely damaged dwellings and public assets, constituting a serious hazard to the local inhabitants. The monitoring activities were carried out between August and December 2019 through a new TInSAR device called Phoenix which it was used for one of its first on-field applications. The Terrestrial SAR was aimed at creating displacement maps and related time series, providing detailed information on the location and deformation rate of the processes under investigation. The use of such a remote sensing technique, coupled with contact instrumentation (inclinometers, piezometers, rain gauge) and field surveys have contributed to improving the knowledge about the Nam Dan landslide and the understanding of its behaviour, with particular regard to the time evolution of deformations.

KEYWORDS: landslide, monitoring, Terrestrial SAR Interferometry, Nam Dan landslide

INTRODUCTION

Landslides represent a critical problem in many mountainous regions where slopes are often destabilized by both severe weather conditions and man-made factors. This problem is of particular concern in Northern Vietnam, where landslides occur in almost all mountainous areas due to the tropical rainstorms during the Southwest monsoon season (AHLHEIM *et alii*, 2008). In such contexts, as a result of landslide processes, roads are blocked for several days, agricultural fields are devastated, buildings and public structure register extensive damage. In these upland regions, populated by poor rural communities relying on agriculture for their livelihood, often on steep slope, natural hazard-induced disasters exacerbate their livelihood vulnerability reducing households' capacity to face risks (PHAM *et alii*, 2020). Therefore, studies focused on landslide processes for the definition of effective measures of landslide risk prevention and management are highly necessary for this area.

Among various methods for the landslide risk prevention, monitoring is considered one of the most effective ways and plenty of literature is available for successful applications of different monitoring systems, from regional to site-specific

scale, from short-term to long-term periods, from contact to non-contact instrumentations. In this context, remote sensing techniques represent one of the main innovations of the latest years in the field of landslide monitoring and assessment (MAZZANTI *et alii*, 2015). Terrestrial SAR Interferometry (TInSAR) is a fully remote monitoring technique allowing to identify possible unstable sectors of a slope thanks to a widespread view and to cross-validate the displacement time series by the huge number of monitoring points (BOZZANO *et alii*, 2010; LUZI, 2010; MAZZANTI *et alii*, 2015). It is important to highlight that the use of Terrestrial SAR technique is able to measure with high accuracy surface deformations, thus it is particularly suitable for shallow slope movements (ROMEO *et alii*, 2014). However, a multi-instrumental approach is essential to investigate both surface and in-depth movements, and the use of different monitoring techniques allows performing a cross analysis of the data and to minimize errors, to check the data quality and to improve the monitoring system (DI MATTEO *et alii*, 2016). In the present work, the integration of both remote sensing and contact measurements, supported by field observations, have led to the improvement of the landslide process understanding and to the quantification of deformations, which affected structures and buildings.

This work aims to present recent insight from the remote monitoring of a natural slope performed through Terrestrial SAR Interferometry technique (TInSAR) adding to the literature a challenging case study in the remote mountainous regions of northern Vietnam. This work demonstrates the versatility of such ground-based monitoring technique, which can be used in a variety of contexts including the most environmentally demanding.

STUDY AREA

General framework

The Nam Dan Municipality (22°36'N; 104°29'E) is located in the Southern part of Xin Man district, the western part of Ha Giang province, in the vicinity of the Vietnam-China border (Fig. 1a). The Xin Man district, that covers an area of about 582 km², is characterized by a complex topography consisting of high mountains, terraced slopes and very deep valleys with advanced erosive processes. The drainage system of the region is developed with the Nam Dan River and many its tributaries: Che La, Nam Tra, Nam Chien streams. Such a district, where the elevation ranges from 140 to 2,400 m a.s.l. (average elevation over 1,000 m a.s.l.), is a subtropical humid monsoon climate zone characterized by heavy rainfalls during the summer season (about 1,700 mm/year, QUOC ANH *et alii*, 2017) make it one of the most landslide-prone areas of the whole Vietnam. Local disaster archives report that in such area 967 landslides occurred

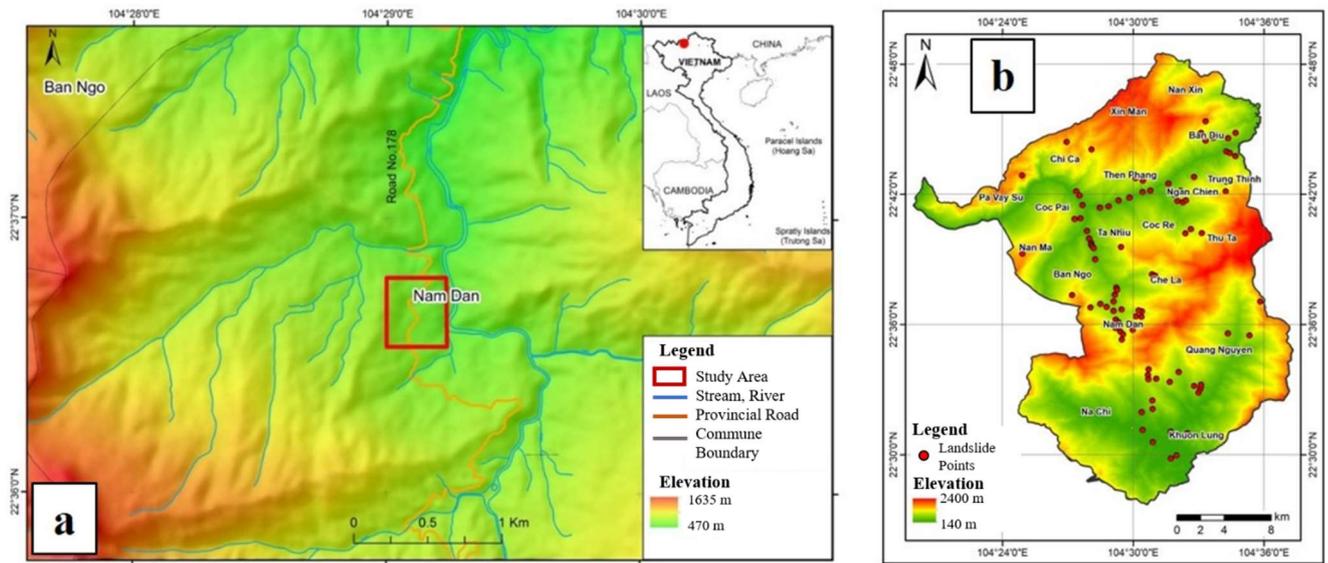


Fig. 1 - a) Location map of the study area; b) Landslides inventory map in the surrounding areas of Nam Dan village (data from program code SRV-10/0026 and project VT-UD.05/18-20)

from 2012 to 2016 (NGOC *et alii*, 2016), mainly during summer. Thanks to a recent field survey (DAO MINH *et alii*, 2018), more than 70 landslides have been detected in the surrounding areas of Nam Dan village, the most of which are located along the provincial road n. 178 (Fig. 1b).

Due to the favourable conditions, in terms of fertile soils and water supply, local people usually settle along the slopes where

they build terraced fields for rice and crop cultivation. Such farming method requires a large amount of water, which is stored directly on the terraced fields, affecting the slope stability conditions (Fig. 2).

Therefore, most landslide events occurring in this area directly affect the human's lives causing considerable damages both in terms of human and economic losses.



Fig. 2 - Typical rice terraces filled with water within the study area (pictures taken by authors in August 2019)

One of the most extensive and active landslides in the area affects a densely populated sector of the village of Nam Dan and it is located in the vicinity of the public market, along the provincial road n. 178, which represents a key location for the local community. Due to the recent reactivations of the landslide

(from 2014) some dwellings have been severely damaged, and the market has been closed (Fig. 3).

Several evidences (e.g. recent damages on structures, open cracks, scarps, etc.) prove that the process is still active constituting a serious hazard to the village. Besides this, local

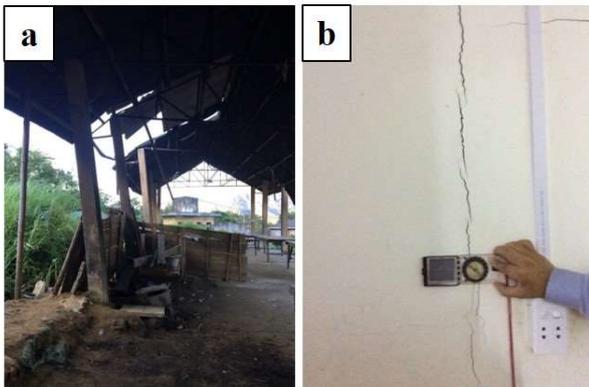


Fig. 3 - a) Damaged structure in Nam Dan market; b) cracking wall in a private house nearby the Nam Dan market (pictures taken by authors on 17th October 2019)

people are living on the body and foot of the landslide increasing the exposure of people and assets. In detail, farmers have transformed ground into terraced fields for rice and corn crops.

The Nam Dan landslide

According to recent field surveys and observations, the landslide covers an area of about 12,000 m² with an average deep of about 22.5 meters based on drilling data (total volume of about 270,000 m³). The surface of rupture is represented by the weathered soil and bed rock interface (Fig. 4).

The slope, the angle of which varies from 26° to 45° degrees, developed on anigneous bedrock belonging to Chay River complex, the largest igneous rock formation in Vietnam. The Chay River is divided into two main phases: the phase 1 consists mainly of porphyroid granite, medium to big- grained two-mica

granite with gneissose texture; phase 2 is represented by medium grained two-mica granite, biotitegranite. Moreover, the upper part of the bedrock has been strongly weathered, whereas, at the bottom, the bedrock acts as an aquiclude (QUOC ANH *et alii*, 2017). The thickness of the weathering layer is approximately from 1-3 m to 10-20 m including four levels: i) Fine sand layer with highly organic soils, ii) Clayey sand, iii) Poorly graded gravel with boulders, iv) Granitoid – gneiss rock with many cracks (Fig. 4a). Due to this weathering layer, shallow landslides often occur along the grooves that dissected these slopes. In addition, the diffused man-made rice terraces, saturated by water, drastically reduce the stability conditions (DAO MINH *et alii*, 2018).

The landslide occurred in July 2012 after one-week heavy rain. In August 2013, the landslide was still active, causing serious damages to 5 houses, Tan Son market and provincial road n. 178. In the middle of the landslide body is the central market where local residents concentrated with high density every weekend.

This indicates a high level of risk as the landslide may lead to huge damage of both people and properties. The Nam Dan landslide is an old translational debris slide (VARNES, 1978) and some evidence of reaction are clearly visible. On the landslide body, there are some gully erosion creating holes with 1.5 - 2 m depth, 6 m diameter on average. Those can be considered as ponds pounding over flow water, leading to internal erosion of materials on the landslide body.

It is also important to point out that, in the surrounding of the study area, old deep-seated landslides have been detected in Ban Diu, Nam Dan, Che La, Quang Nguyen and Trung Chinh areas (DAO MINH *et alii*, 2018, HUE *et alii*, 2015).

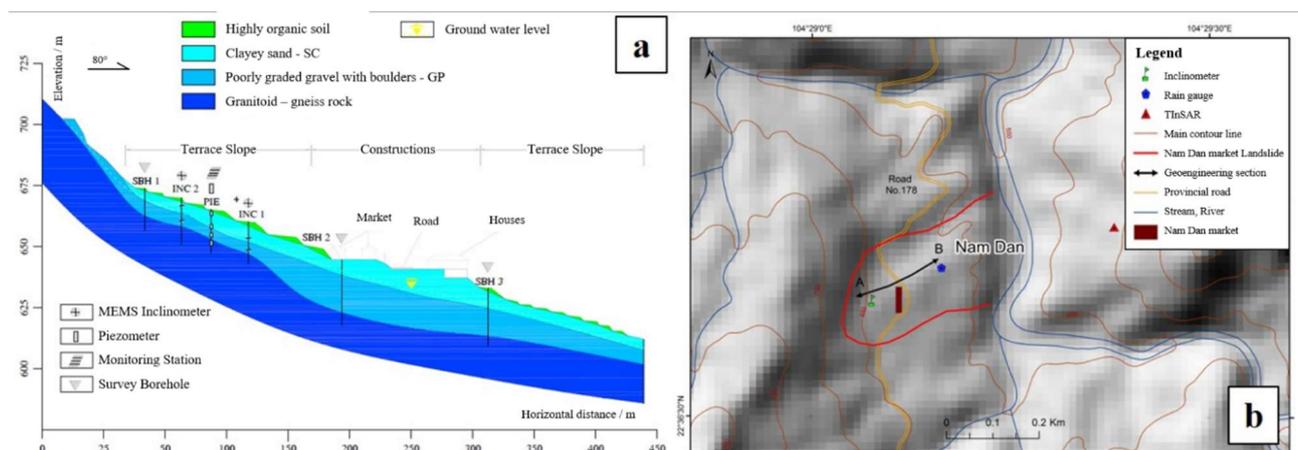


Fig. 4 - a) Engineering geological cross section of Nam Dan landslide with monitoring instruments installed; b) Location map of Nam Dan landslide with monitoring instruments installed

METHODS

In the framework of a research project coordinated by the Institute of Geological Sciences (IGS – VAST), an intensive monitoring campaign through a remote sensing technique for the monitoring of displacements was carried out, thanks to the collaboration of local authorities, between August and December 2019. A Terrestrial SAR Interferometer (TInSAR) was installed in the Municipality of Nam Dan, allowing to supply a deformation map of the natural slope, with related displacement time series for each pixel, without the necessity of positioning targets on the ground (BOZZANO *et alii* 2010; MAZZANTI 2015). This project represents the first monitoring campaign in the Country by using the “non-contact” TInSAR technique for landslide monitoring and assessment.

The Terrestrial SAR Interferometry (TInSAR) is a ground-based radar technique that allows to remotely perform real-time monitoring of ground deformations, reaching sub-millimeter accuracy under ideal conditions (e.g. short distance, high wave reflection, etc.). This technique is based on an active radar sensor, traversing a linear rail, that emits and receives electromagnetic waves in the Ku band (12–18 GHz) measuring the reflected signal (ANTONELLO *et alii*, 2004; Luzi *et alii*, 2010). By comparing the phase difference of two or more SAR images, collected at different times, the displacement along the instrument Line of Sight (LoS) can be estimated. Compared to Satellite InSAR, which is capable of monitoring large areas characterized by slow movements, Terrestrial InSAR is more suitable for the detailed and continuous monitoring of small areas (e.g. natural slopes, rock wall, structures, bridges). The latter is also useful to monitor area characterized by both slow and rapid movements. In order to perform TInSAR monitoring, the equipment should be installed in a stable location with a panoramic view of the area to be investigated. Due to the high data sampling rate and the 24/7 operability, under any weather and lighting conditions, this technique is particularly suitable for continuous monitoring of natural hazards.

The present study was performed by using a new TInSAR equipment called Phoenix, developed by the company Echoes Technologies S.r.l. (<https://www.echoes-tech.it/>). Phoenix is an active terrestrial Synthetic Aperture Radar (SAR) that synthesizes its antenna by moving along a suitable rail (Tab. 1). Transmitted microwaves have a central frequency of 13.7 GHz (Ku-band). Thanks to its continuous SAR acquisition mode, Phoenix can collect a single radar image in less than ten seconds, allowing an extremely short time interval between two consecutive acquisitions. However, it has been decided to set up a measurement time interval equal to 5 minutes, making data transfer sustainable due to the long-term monitoring period.

Four-months monitoring of the Nam Dan village was carried out from the opposite side of the valley (about 500 m away in Line of Sight), where an ad-doc shelter for the protection of TInSAR system was realized (Fig. 5).

Scan Length [m]	1.32	
Spatial Resolution	Range [cm]	50
	Cross Range [deg.]	0.48
Operating Range [m]	2 - 1200	
Central Frequency [GHz]	13.7	
Bandwidth [MHz]	300	
Scan Time [s]	10	
Polarization	Horizontal	
Acquisition mode	Continuous SAR	

Tab. 1 - Technical specifications of TInSAR equipment (Phoenix by Echoes Technologies S.r.l.)

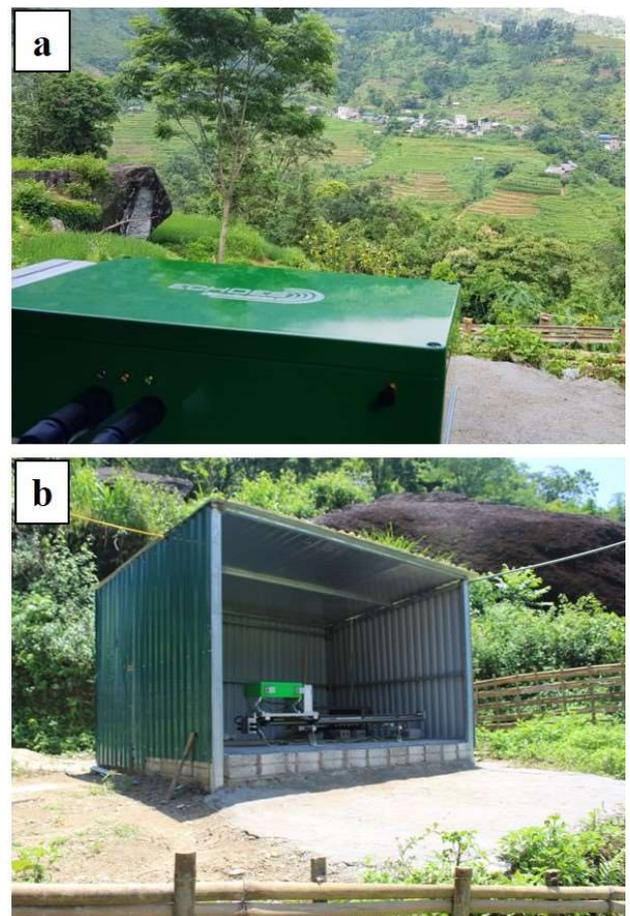


Fig. 5 - a) in the foreground, TInSAR Phoenix device, in the background the village of Nam Dan (about 500 m in line of sight); b) Shelter realized ad-hoc for the protection of TInSAR system (pictures taken by authors on August 2019)

The Nam Dan village and its surrounding are located in a remote area with few roads and urban settlements. In this context, installing the equipment and ensuring its full functionality was a challenging aspect that committed a multi-disciplinary team from Italy and Vietnam. The radar equipment was installed in a monitoring platform, with power supply, realized ad-hoc for the protection of TInSAR system and fenced to avoid animal disturbance. An IP camera was also installed for the continuous control of the TInSAR status. A high-speed mobile internet modem was provided for the remote control of the system and data transfer to the Data Processing Center. Also, NAS (Network Attached Storage) for the increasing of the local data storage capacity was deployed. Due to the frequent blackouts in the area, the monitoring platform was also equipped with a cabinet containing the electrical panel for the system power supply, backup batteries and the laptop for the system control.

Data acquired were processed by using a specific software (TRIVIA - Terrestrial Radar Interferometry Visualization and Analysis) developed by the company NHAZCA S.r.l., in order to perform advanced analyses of Terrestrial SAR images providing useful information to support the monitoring project. In detail, by comparing the phase difference of each pixel of consecutive SAR images collected at different times, the displacement along the instrument Line of Sight (LoS) was derived.

A processing algorithm, based on Ground Control Points (GCPs) identified by an expert user, was applied for the atmospheric model determination. Also, for the atmosphere correction an interpolation method based on GCPs values along range was used.

In addition to the recent surface monitoring of displacement through TInSAR technique, in the latest years fixed-in-place inclinometer probes and pore water pressure sensors were installed in the Nam Dan landslide allowing to investigate in depth the evolution of the process (DAO MINH *et alii*, 2018). In detail, four inclinometers (Geokon MEMS Model 6155) were installed in two different boreholes: 6.8 m and 12 m depth in borehole n. IPI1; 2.8 m and 8 m depth in borehole n. IPI2.

Also, four piezometers (Geokon Model 4500S) were installed in a single borehole (BH1) at various depths: 1.5 m, 6 m, 10.5 m and 13 m (Fig. 4). Results from this surveys and monitoring activities in depth allowed comparing recent data in surface acquired by TInSAR technique, also taking into account local meteorological conditions, monitored by a rain gauge deployed in Nam Dan area (22°36,823' N, 104°29,105' E).

RESULTS

In the present case study, the integration of both remote sensing and contact measurements have led to the quantification

of the structures and buildings displacements (TInSAR) as well as the rice terraces (TInSAR) and weathered layer (Inclinometer).

In order to obtain these results, as part of Terrestrial SAR monitoring, 15 points of interest (monitoring points), which basically correspond to the main buildings (Fig. 6), were chosen from the whole radar map selecting only the most reliable pixels showing high Signal to Noise Ratio (SNR) paired with high level of reflectivity.

On August 10th, the TInSAR unit was set to continuously collect data (24/7) at an appropriate sampling rate (i.e. about 5 minutes) and to start the calibration phase aiming at optimizing the acquisition and the processing parameters, also considering the extreme atmospheric conditions due to the Southwest monsoon season. After four months of monitoring campaign, tens of thousands SAR images were acquired.

During the entire SAR monitoring campaign, there were not detected significant movements both on the structures of the public market and on the buildings in the village of Nam Dan. This was also confirmed by contact instruments installed on the landslide. The displacement measured by the inclinometers and the excess pore pressure recorded by piezometers did not register any anomaly.

Displacement time series of the monitoring points show stable behaviour with deformations close to the instrumental accuracy. Some time series related to interest points in correspondence with metal structures/roofs, have shown daily cyclical movements due to thermal expansion of materials.

Fig. 7 shows, as an example, the displacement time series of P14 (red lines), which corresponds to the head of the borehole (IPI1) where the inclinometer was placed at 6.8 m depth. In this sector of the vegetated slope, high-quality radar parameters due to high-reflective target (i.e. solar panel) allowed to set a reliable monitoring point. The time series related to the inclinometer is reported in green while cumulative precipitation is shown in blue. Thanks to this spatial matching it was possible to compare the behaviour of surface organic soil with the underlying clayed sands. The TInSAR related time series shows a fairly stable behaviour during the four months of monitoring except for the end of September 2019, when in few days a displacement of -6 mm towards the radar sensor was recorded. Concerning to the inclinometer time series, it was characterized by a very slow and continuous displacement, which lead to a cumulative displacement of 2 mm in four months.

FINAL REMARKS

The main details and results deriving from the first monitoring campaign through Terrestrial SAR Interferometry

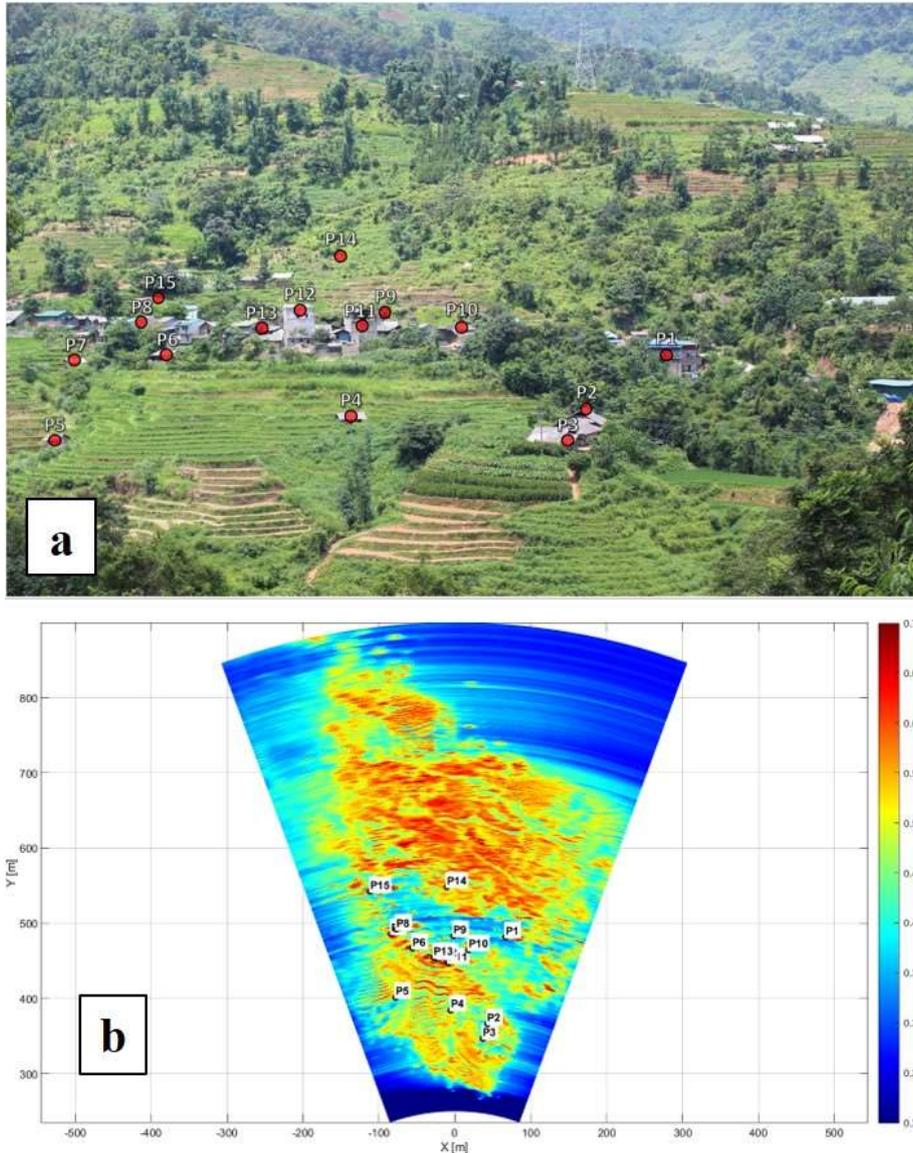


Fig. 6 - a) Image of the investigated scenario with monitoring points in evidence; b) map of thermal SNR (Signal to Noise Ratio) with monitoring points. In the lower part of the SNR map (300-500 m in range) the rice terraces reported in Fig. 2 and Fig. 6a are clearly identifiable

(TInSAR) in Vietnam have been presented. On-field operational activities and the identification of technological solutions represented particularly challenging aspects for the landslide monitoring using remote sensing techniques. These aspects are particularly important considering the environmental conditions of the area, such as the remoteness and the severe climatic conditions. The present study was carried out by using Phoenix, a new Terrestrial SAR device developed by the Italian company Echoes Technologies S.r.l. This monitoring campaign has represented one of the first applications on-field for such an instrument.

Although no significant evidence of movement was recorded in the monitored period, the use of such innovative technology (TInSAR) coupled with contact monitoring instruments (inclinometers, piezometers, rain gauge) and field surveys have contributed to improving the knowledge about the Nam Dan landslide and the understanding of its behaviour, with particular regard to the time evolution of displacements. As already shown, during the period of observation, in addition to daily cyclic movements due to thermal expansion of specific materials, only limited deformations were registered close to the instrumental accuracy.

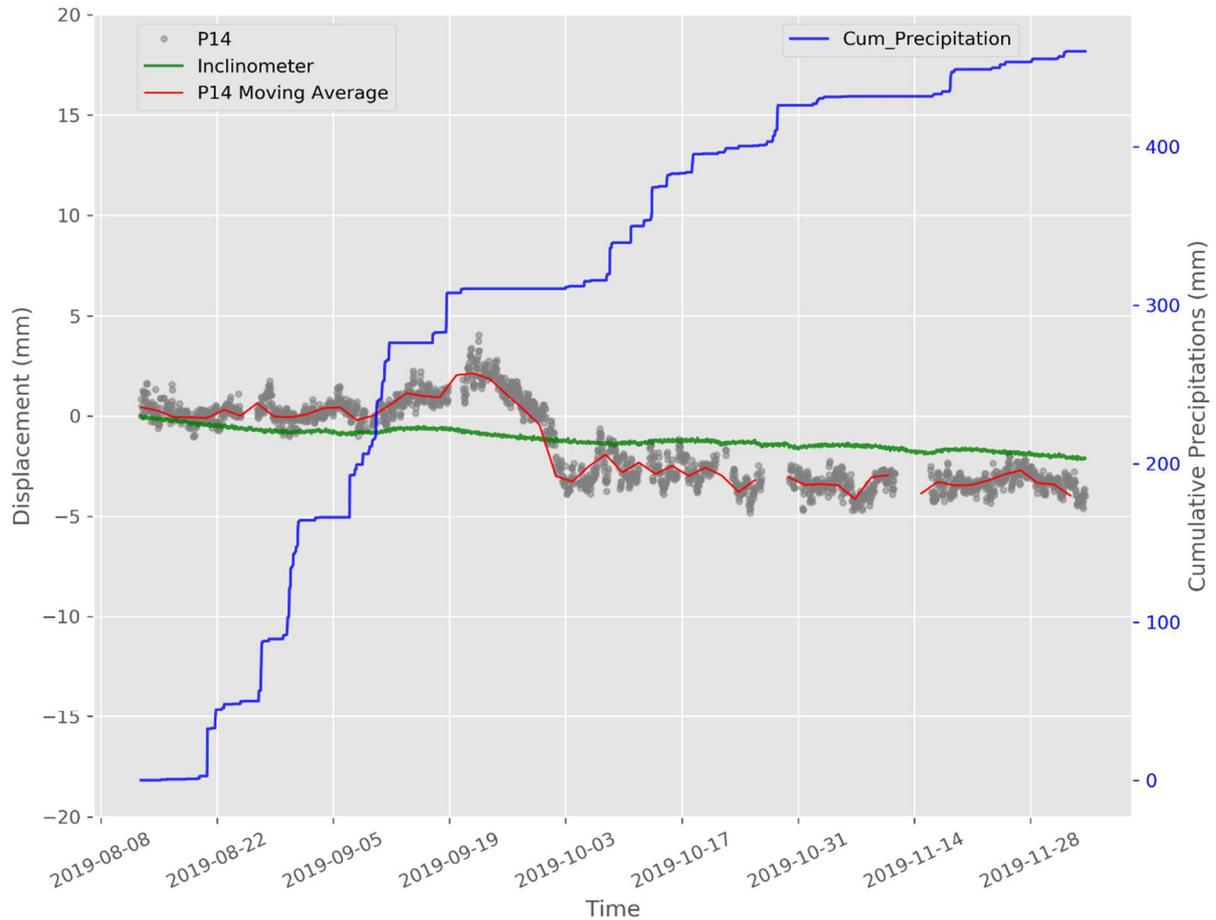


Fig. 7 - Displacement time series of monitoring point n. 14 recorded by TInSAR (in grey) with moving average (in red), displacement time series recorded by inclinometer placed on the landslide (in green), cumulative precipitation (in blue) for the whole monitoring period (from 10th August to 4th December 2019)

With regard to the use of different monitoring instruments, some considerations can be made:

- compared to other monitoring tools, the use of TInSAR technique (scan interval of 5 min) allowed the acquisition of a considerable number of data, useful to properly investigate the behaviour of the landslide;
- the integration of TInSAR and inclinometer displacements data have allowed monitoring both the surface and in-depth displacements;
- comparing data derived from the Terrestrial SAR with the inclinometers data, it seems that at the end of September the surface organic soil at the highest part of the slope (around P14) could be subjected to a sudden increase in the deformation rate, which in this case it was not related to rainfall occurrence.

However, this increment in deformation rate does not occur in the underlying clayed sand, suggesting a localized deformation process which involves only the upper part of the organic soil.

In conclusion, results achieved in the present monitoring campaign, in combination with the previously acquired data, also from field surveys, suggest that the current slope is predisposed to instability, which can be triggered by the first severe rainfall during the early summer season.

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