Brief communication: Landslide activity on the Argentinian Santa Cruz river mega dam works confirmed by PSI DInSAR

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Abstract. Safety and environmental aspects are crucial beyond production goals in the hydropower industry. By monitoring landslides associated with the construction of a hydro-power dam in the Santa Cruz River in the Argentine Patagonia, this paper contributes to the assessment of the project structural integrity of the construction and safety risks. Ground deformation is monitored using SAR satellite data and the Persistent Scatterer Interferometry technique, and contrasted with optical imagery, geological and technical reports and fieldwork. The results include maps of accumulated deformation and deformation time series for the locations of the anchorages of the dam, providing a new and independent dataset to assess the integrity of the construction.

1 Introduction

Infrastructure and natural hazard monitoring is nowadays a common application of remote sensing. Large civil works and landslides are among some of the most studied elements (Shugar et al., 2021; Moya et al., 2021) and, among the many possible techniques, Synthetic Aperture Radar (SAR) techniques and, in particular, differential satellite interferometry SAR (DInSAR) play a key role. The significant increase of data availability and the recent improvements on data processing and analysis enable measuring terrain deformations with unprecedent precision, reliability and chronological persistence. That is, it is therefore possible to assess terrain deformation of millimetric magnitudes for periods of several years and with observations every few days through satellite monitoring (Crosetto et al., 2016; Devanthéry et al., 2018).

Regarding the remote monitoring of civil constructions, dams and their possible structural failure are of particular interest. Despite being considered safe infrastructures, unfortunately and due to various causes, there are many examples of catastrophic failures throughout the planet (Shugar et al., 2021; Lumbroso et al., 2020), many of them listed on the specialized website: https://damfailures.org [accessed: August 2022]. Because of the fatal consequences that these failures may have, it is of utmost importance to closely monitor their structural safety.

In this research work, Sentinel-1 satellite data and Persistent Scatterer Interferometry (PSI) (Crosetto et al., 2016) are used to map ground displacements associated with the construction of a mega dam in Argentine Patagonia which suffered from serious structural problems during the still on-going construction phase (IEASA, 2020). The work carried out in this study has enabled to independently monitor such problems, and thus, to assess possible safety risks.

2 Dam project location

At latitude 50º South in the Argentine Austral Patagonia (Fig. 1 central planisphere), a large part of the thaw waters of the great Southern Patagonian Ice Field in the Andes and the great Patagonian lakes drain into the Atlantic through the Santa Cruz River. This river forms the backbone of a purely glacial allochthonous basin with global scale dimensions (Masiokas et al., 2019). It spreads across 30,000 km^2 and is in a vey good of environmental conservation. The river, located in the geological province of the Austral Basin, flows for 380 km from west to east, forming meanders with a large radius of curvature, and is dominated by an arid landscape of plateau and slightly undulating tertiary sedimentary strata. In the river valley, there are also some occasional ceilings of igneous deposits or Quaternary glaciolacustrine sediments (Astini et al., 2015).

3 Hydroelectric Developments of the Santa Cruz River Project

The Hydroelectric Developments of the Santa Cruz River (AHRSC in Spanish) consist of a hydroelectric project for the simultaneous construction of two mega hydroelectric dams on that river. Once completed, its reservoirs will flood 50% of the course of the river. This is the largest infrastructure project in Argentina in recent decades, the largest dam project under construction by Chinese companies outside China, and the southernmost mega dam on the planet, with a minimum cost of 4.5 billion dollars (Tamburini-Beliveau and Folguera, 2022).

Once built, the dams will have a joint installed capacity of 1,310 MW with an average annual plant generation of approximately 5,000 GW/h. This will contribute to 2.5% -5% of the maximum peak of national electricity consumption (EBISA, 2017).

Both dams are concrete face rockfill dam (CFRD) type. The Cóndor Cliff - Néstor Kirchner dam (CC-NK), the larger of the two dams and the one studied in this work (Fig. 1) is 68 m high from its crest to the bottom of the channel, and will store 5.3 km^3 of water. The second dam, La Barrancosa - Jorge Cepernic, which is downstream from CC-NK, is 41 m high and will generate a 3.5 km^3 reservoir (EBISA, 2017).

4 Geological framework and problems of the Cóndor Cliff - Néstor Kirchner (CC-NK) mega dam

According to official documentation (IEASA, 2020), at the end of 2018 and beginning of 2019, during the foundation excavations of the main wall of the CC-NK dam, several landslides appeared in the areas of the abutments on both banks of the river, endangering the construction and, therefore, leading to the interruption of the works and the complete redesign of the dam. The new design keeps its productive characteristics, but with a completely different morphology (Fig. 1 A and B). Because of this

situation, project deadlines and costs have substantially been affected, threatening its financial viability. Large sectors of the work already done until 2019 had to be removed to readapt the project from 2020 onwards. The structure has been substantially modified: without moving the central sector of the dam axis, its anchors have been diverted a few hundred meters upstream, also readapting the location of other key dam elements (deviation channel, machines hall, etc.) resulting in a roughly U-shaped dam very different from the original.

The geological characteristics of the CC-NK dam site hinder its construction. It is located in a canyon valley covered by loose Quaternary glaciofluvial sediments varying in thickness from 5 m to over 60 m, and accumulations of material from multiple mass-wasting events and paleo-slides from the same period (see geomorphological map in Fig. 1). Pliocene basaltic lava flows are also present in some elevated sectors, ie., the tops of the plateaus on the cliffs on the margins of the river canyon. (Astini et al., 2015; EBISA, 2017; IEASA, 2020, 2021).

All these materials are found over the Tertiary Santa Cruz formation, which consists of a lower Miocene homocline inclined a few degrees to the SE. It is formed by fluvio-lacustrine sedimentary strata that are very heterogeneous in the vertical direction (constant and transitional alternation of sandy and pelites packages), which are weak and poorly compacted due to their low diagenesis (Astini et al., 2015; Giambastiani and Filloy, 2018; Celli and Falcioni, 2022). From the Cenozoic to the last Pleistocene glacial period, this formation has been eroded and fractured by the action of large glaciers, generating glaciotectonic faults and diaclases of various magnitudes (Strelin and C., 1996).

Additionally, the ceiling of rigid, dense and compact basaltic lava flows, which are present mainly on the northern flank of the river, favors the occurrence of mass-waste processes due to the strong vertical contrasts between the physical characteristics of the multiple rock strata (Turazzini, 2002; Astini et al., 2015; EBISA, 2017).

Lastly, in the southern sector of the construction site, the rock (Santa Cruz formation) is too far from the surface, covered by glaciofluvial deposits, and consequently, the structure of the dam has serious difficulties for securing the foundations on (the weak) rock. On the north flank, a fault with NW direction at an elevation of 170-180 m is described, extending a few meters in the upper sector of the location of the axis and foundation of the dam (Capdevila et al., 2007). This fault is not represented on the project official geomorphological maps and it is consequently also absent in the figures of this text.

From the elements presented above, it can be deduced that a difficult and complex geotechnical scenario affects the CC-NK dam and its foundations on both flanks of the wall (Beigt et al., 2016; Pánek et al., 2018).

5   Methods and data

The anchorage area of the abutments of the CC-NK dam, where the slopes instabilities appeared, have been analyzed with PSI during the period ranging from November 2018 to April 2021. The particular PSI processing chain and algorithm used in this work is the PSIG approach (Devanthéry et al., 2018), developed by the Geomatics Division of the Centre Tecnològic de Telecomunicacions de Catalunya, and the input source data have been acquired by the Sentinel-1 SAR satellite constellation (see Tab. 1-A and Appendix A).
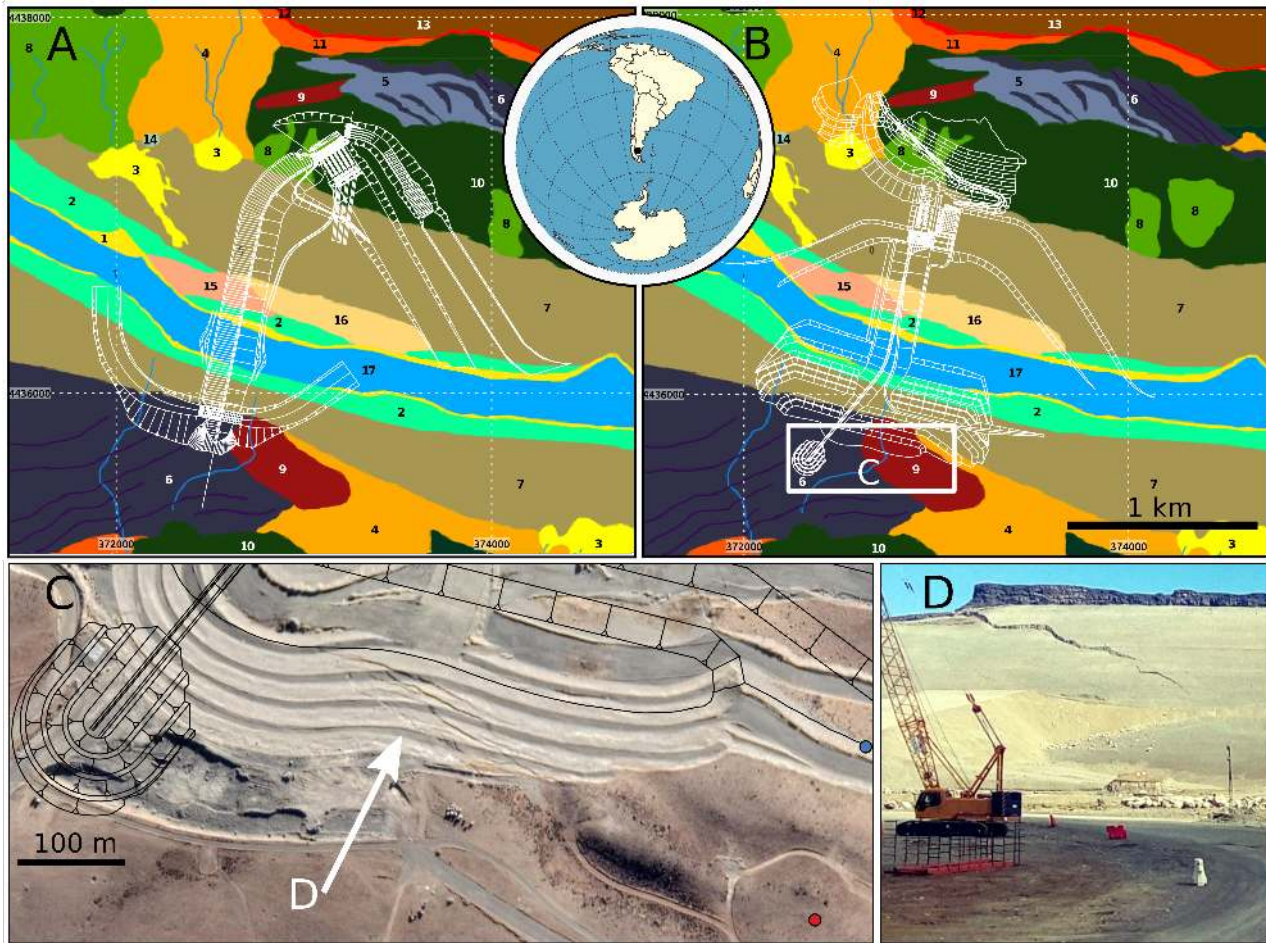
Figure 1. A dot in the very center of the planisphere (between A and B) shows the project location (50.21º South, 70.78º West), coordinates in planar system are UTM zone 19S. A: First design of the CC-NK dam (2015). B: Second design of the CC-NK dam after experiencing structural issues (2020). At the background, the geomorphological map with the following categories may be observed: 1, Alluvial plain. 2, Fluvial terraces. 3, Active alluvial fan. 4, Flank pediment. 5, Basal moraine. 6, Marginal moraine. 7, Glaciofluvial terrace covered by catastrophic flow deposits. 8, Rock avalanche deposits. 9, lateral spread and rotational landslides. 10, Rotational landslides. 11, Scree slope. 12, Rock fall. 13, Lava flow. 14, Seasonal lagoon. 15, Wind blowout. 16, Parabolic dune. 17, Santa Cruz river channel. Box C shows the optical satellite image where the cracks of the south bank can be seen. In D, a view from the ground of the crack on the south margin may be observed. Source: Our own elaboration based on (EBISA, 2017; IEASA, 2020), © Google Maps, www.worldmapgenerator.com [accessed August 2022] and on fieldwork.

The satellite DInSAR method exploits the phase differences measured in the radar signal between two satellite SAR images of the same area acquired at different times and from slightly different positions. The measured interferometric phase represents differences along the satellite-target travel of the radar signal. After the necessary corrections and parameterizations, the movement of the ground target between both acquisitions may be estimated.

The PSI method is an advanced DInSAR technique that exploits stacks of images acquired at different times of the same area to provide high precision ground (or ground fixed infrastructures) displacement measurements. This technique allows robust measurements along time providing displacement time series and velocity estimations for the location of each one of the measured points. Crosetto et al. (2016) provides a comprehensive review of PSI techniques. More in particular, the main steps of the here used PSI approach (PSIG), consist on the selection of points with high temporal coherence (above 0.7), obtain the unwrapped phases of these points, atmospheric filtering and time series estimation. The way how these steps have been carried out in this work are described in Krishnakumar et al. (2021). It is worth underlining that by "points" we refer to pixels of a satellite raster image representing a small portion of the surface of the Earth. The final PSI time series contains the accumulated magnitude of the deformation in correspondence with the time-ordered SAR images starting from a reference image.

Optical images have been used to monitor the evolution of the works and double check what was revealed by the PSI results (see Tab. 1-B). Other digital vector mapping data (geological and geomorphological maps, contour lines and plans of the dams) have been obtained from the dam's environmental impact assessment report (EBISA, 2017), other official technical documents (IEASA, 2020, 2021; Astini et al., 2015) and an online cartography server: https://observatorio.ieasa.com.ar/geovisor.php [Accessed: August 2022]. The information has been collected and analyzed with the QGIS software.

6   Results

The main result of this work consists of a map of accumulated ground displacement of the CC-NK dam and its surroundings (Fig. 2 and Appendix B1 and B2) and the displacement time series from November 2018 to April 2021. All the presented measurements are in the Line of Sight (LOS).

A total of 68,477 Persistent Scatterers (PSs) were obtained in a region of 37.1 km^2. This corresponds to a density of 1,897 PSs/km^2, approximately one point every 527m^2 (see Figs. 2-X and B2). Out of these, 1,018 PSs (0,7%) show a displacement above 3σ (σ=2.69), i.e. an accumulated deformation over 8.07 mm along the monitored period, which corresponds to a velocity displacement of 3.23 mm/yr. The value of 3σ was taken to clearly discriminate those points with random scattered values around 0 from those showing clear deformation trends (see Fig. B1-E). Consequently, to better focus the analysis, the first group of PSs displaying deformation $<3\sigma$ was discarded. Thus, only the reflectors with steep deformation trends have been analysed (Fig. 2-X).

From this initial dataset, the sub region that includes the work of the CC-NK dam was analysed in detail (Fig. 2-Y; small polygon on Fig. 2-X). This corresponds approximately to 9.6 km^2. There, 15,678 PSs were obtained, that is 1,742 PSs/km^2, approximately one point every 574 m^2, out of which 857 (5.5%) have magnitudes of $>3\sigma$ of the original dataset.

Remote sensors sources	
A) Characteristics of the SAR images used in the PSI process	
Platform	Sentinel-1B
Band	C
Acquisition mode	Interferometric Wide (IW) Swath
Temporal span	29 October 2018 - 28 April 2021 (2.4 years)
Number of images	77
Wavelength	0.055 m
Product type	Single Looked Complex (SLC)
Orbit	Descending
Incidence angle	32°
Track or relative orbit number	path 39 orbit 25,790
Minimum revisit period	12 days
Polarization	VV
Full resolution (azimuth/range)	5 m x 20 m
Number of processed swaths	1 (Swath 02)
Number of processed bursts	1 (Burst 08)
B) Basic characteristics of the optical sensors true color band combination	
92 Planet images	3 m resolution
3 Sentinel images	10.5 m resolution
2 Google Image	0.5 m / 0.3 m

Table 1. Main characteristics of the input satellite data for the research (Our own elaboration).

115   The 5.5% of PSs displaying deformation >3σ PSs of the detailed area of interest versus the 0.7% of the whole region reveals the evident concentration of ground displacement phenomena in the area where the dam is being built.

The results allow us to identify five area typologies showing distinct deformation behaviour:

1. Areas displaying negligible displacements (<3σ already mentioned).

2. Landslides on slopes, the focus of this study (see Fig. 2).

120   3. Foreseeable deformation trends associated with the contruction works. For example, terrain uplift caused by the progressive construction of a retaining slope, or subsidence due to the extraction of aggregates.

4. Systematic or random errors. Mainly phase jumps or atmospheric errors, respectively.

5. Absence of measurements, i.e. PSs, due to modification of the terrain due to the construction works. In the face of substantial changes in the surface, the possibility of attaining PSs is lost.
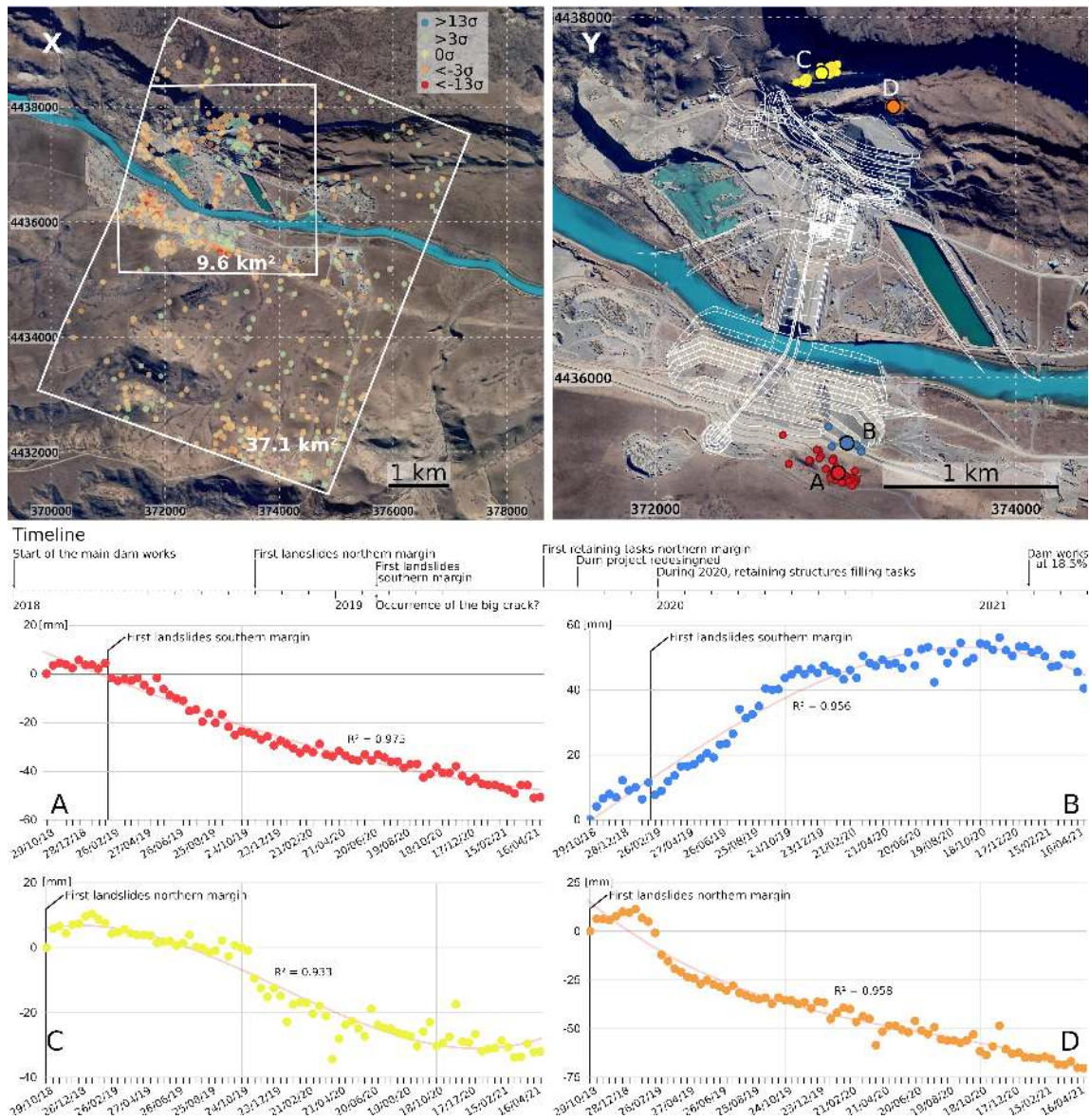
Figure 2. Top left (X). Area covered by the PSI processing. White polygons circumscribes the general (big polygon) and the detailed (small polygon) areas under study. The optical background image is from Google from July 2022 (© Google Maps). Coordinates are UTM zone 19S. Only reflectors showing deformation >3σ are represented, magenta negative and cyan positive deviation, scale ranges until 13σ. Top right (Y): construction site. The PSs of each landslide subgroup are represented on the southern (A, B) and northern (C, D) margins. Charts A to D correspond with the deformation time series of the calculated average for each one of the landslide (A to D). The plan of the second dam design has been superimposed. A timeline showing the phases in the dam construction is found at the figure center. The period not covered by the PSI analysis is shown as a dashed line over the timeline axis.

125   This paper focuses on item 2 of this list, i.e., landslides on slopes. More details on the characteristics of the other items may be found in Appendix B.

7   Discussion

The official reports (IEASA, 2020, 2021) indicate that the two areas of the dam abutments, on both the north and south banks of the river, are affected by landslides. More precisely, PSI measurements enabled the identification of two subareas with their
130 own deformation dynamics on each riverbank. All the PSs within each subarea were averaged, obtaining a single PSI value per subarea. The analysis of the optical images confirmed that these areas were not affected by significant changes in the ground surface during the monitored period. The largest of these areas approximately occupies an area of 2 ha., and the smallest, of 0.2 ha.

    The results are presented in Fig. 2. On the south bank, two deformation phenomena are identified, sector A with 51 (red)
135 PSs and sector B with 18 (blue). On the north bank the identified deformation phenomena are: sector C with 33 PSs (yellow) and D with 15 (orange).

    Maximum accumulated displacements between extreme values range from 40 to 80 mm. This represents 16 mm/yr for area C, and 32 mm/yr in sector D. A polynomial fit line with a determination coefficient R^2 (Mirmazloumi et al., 2022) has been superimposed in the chart to show the absence of noise in the measurements. It is worth underlining that the magnitudes
140 measured do not accurately reflect the real magnitude of the movements since:

1. PSI provides measurements along the LOS component, which only reflects part (a projection) of the real displacement vector,

2. PSI is opportunistic, that is, it only provides measurements on those points that provide permanent response to the satellite,

145   3. The period analysed does not cover the entire displacement period.

    Sector A is located in a flat area, so it could be said that most of the movement is vertical, which, according to the orbit direction of the satellite, is in agreement with the negative values of the LOS measurement showing subsidence.

    Sector B is located on the slope, so horizontal and vertical displacements are measured. The general orientation of this area is not the optimal to be observed with the descending satellite trajectory, but the considerable magnitude of the deformation
150 facilitated obtaining to obtain results. Presumably, deformation to the west and east of the A-B locations became invisible to the radar either by the large magnitude of the ground displacements (at west, in the crack, where data decorrelation is present, see Fig. B1-I in Appendix B) or due to the deficient orientation of the slope and the smaller magnitude of the displacements (to the east).

    Observing the situation on sectors A and B (with inverse trend sign), it is possible to suggest that a rotational mass wasting is
155 taking place, which agrees with the bibliography (Astini et al., 2015), but additional information is required to provide a more definitive conclusion.

Since sector C is mainly flat, it is possible to infer a relevant vertical component of the displacement. However, the PSI information is not enough to determine the exact direction of the deformation vector. In the chart (Fig. 2-C), a step in the trend is visible in October 2019, which coincides with the start of containment works in the area as revealed by the optical sources.

Finally, as sector D is found in a steep slope, both vertical and horizontal displacements are relevant, but further measurements are required to fully understand the situation. The strong slope of the curve around February 2019 (Fig. 2-D) confirms the ground instability trends described in the company reports (IEASA, 2020).

The time series of the four sectors shown in Fig. 2 show no signs of stabilization, so it is possible to affirm that the sliding processes were still active in April 2021 (date of the last observation). The construction works in general, and the deformation phenomena in particular, are clearly located in areas of Quaternary sedimentation and materials resulting from paleo mass wasting processes that had already been described as potentially conflictive in the preliminary project reports (see Fig. 1 A and B), such as:

- on the north bank: basal moraine (8), lateral expansion and rotational slide (18), rotational slide (20);

- and on the south bank: marginal moraine (9) and lateral expansion and rotational slide (18).

The ground dynamics described in this piece of research coincide with what may be consulted in the reports from the company contracting this study (IEASA, 2020), in which the landslides are associated with the reactivation of a paleo-slide in the southern sector, and to the presence of a subhorizontal stratum whose material presented very low resistance and high plasticity in the northern sector.

8 Conclusions

The PSI technique has allowed to confirm that, as indicated by civil organizations, the media and, finally, the official reports, slope instability processes have been activated or reactivated by the construction works, risking the integrity of the dam wall anchorages. This finding has been corroborated with optical satellite imagery and field work. According to official information, the period studied should cover the beginning and the end of the slides. However, the time series of the sectors affected do not confirm the stabilization of the movements.

We have presented relevant unpublished information regarding the integrity and safety of a large-scale civil infrastructure of international importance, since the Chinese and the Argentine governments and a world-class hydrographic basin are involved. Moreover, it is relevant to note that the ongoing construction work of a dam has been monitored and tracked, while finished and operative civil infrastructures are the most common cases found in the literature.

With this work, we have demonstrated that it is possible to effectively and rapidly contribute to the identification of structural problems that might increase economic costs and raise safety issues of ongoing construction works by applying remote sensing techniques.

A broad, exhaustive and systematic spatiotemporal monitoring of the terrain can be attained with DInSAR techniques from the beginning of any construction work in order to identify geological risks that might pose a safety risk. It is possible to cover

In this particular case, and with a minimum investment cost, we have been able to independently and remotely monitor a serious eventuality with potential dramatic consequences on a mega dam project located in a remote region. The weaknesses in the anchorages on both sides of a dam wall of an hydropower facility system with a capacity for 8.8 km^3 of water could be catastrophic if not detected in time.

Finally, and attending the magnitude of the experienced geotechnical problems, we hope we have made a valuable contribution to the adequate and safe evolution of the AHRSC project, which is located in a very challenging terrain.

Appendix A: Methods

We implemented the advanced differential interferometry SAR algorithm named Persistent Scatterer Interferometry (PSI) which is particularly suitable for monitoring outcrops, urban areas and man-made infrastructures (Devanthéry et al., 2018). The processing steps include: 1) Data download and extraction. 2) DEM Preparation. 3) Processing chain configuration. 4) Estimation of velocity of deformation (processing). 5) Phase unwrapping and time series estimation. 6) Geocoding.

A temporal baseline limit of 100 days has been applied to the interferometric pairs. Due to the small orbital tunnel configuration of the Sentinel-1 mission (i. e. short spatial baseline), the most important decorrelation factor comes from the surface changes along time. No perpendicular baseline limit has been applied.

77 high-resolution SAR scenes covering the period from 29 October 2018 to 28 April 2021 (2.4 years), with a 12-day revisit time. Single Look Complex (SLC) product and Interferometric Wide (IW) acquisition mode were selected and downloaded from the on-line ESA Copernicus Open Access Hub. The precise orbit files were downloaded from the Copernicus Sentinels POD Data Hub.

For each SAR image, the co-polar vertical-vertical (VV) channel was extracted from the original data in double polarization (VV+VH) and the corresponding swath of the area of interest (IW2). The 30 meters spatial resolution digital elevation model of Shuttle Radar Topography Mission (SRTM) was used to calculate the topographic component that was later extracted. The DEM tiles were downloaded from the United States Geological Survey (USGS) EarthExplorer catalog.

A transformation of the DEM to the SAR geometry of the super-master image was carried out. Interferometric pairs and corregistration were created between them. Interferometric phase quality indicators were created, such as the amplitude and the average dispersion. We generated 580 high-resolution differential interferograms. The deformation velocity and the residual topographic error were estimated. Then, the selection of the suitable points where the final solution would be obtained was

carried out. Other parameters defined for the PSs inclusion for the final results dataset were: 1) a maximum threshold of the average dispersion of the amplitude of 0.50 and, 2) a temporal coherence maximum value of 0.65.

Finally, the interferometric phase unwrapping was performed, obtaining the absolute deformation values for each PSs. The final coordinates of the PSs are offered in a global geographic coordinate system, based on a reference ellipsoid. Thereby, a georeferenced point cloud was obtained with information on the absolute displacements for each acquisition date and the deformation velocity, which allowed us to display, compare and analyze the deformation time series in a geographic information system (GIS).

Appendix B: Supplemental Figures

Figures B1 and B2 show examples of PSs with high σ values that have not been included in this work and correspond to items mentioned in page 6 and following briefly described. The letter notation is the same for both figures:

- E. Frequency distribution graph of the accumulated displacement of the PSs reflectors in the study area and the 3σ threshold.

- F. Time series of a stable PS with dispersed measurements due to random errors. Elevated σ between 2 and 3, R^2=0.082.

- G. Phase unwrapping error (PUE). 40 reflectors average. Red dots in the chart in Fig. B1 represent the series after applying a manual PUE correction jump of 28 mm (Mirmazloumi et al., 2022).

- H. Deformation trend (Fig. B1-H1) caused by construction works (B1-H2). 72 reflectors average.

- I. 11 phase unwrapping errors for a single reflector located in the root of the big crack in the southern margin (west of studied sectors A and B). This is an exceptional and isolated sample which preserved the coherence along the time series despite the high deformation rate. Chart in Fig. B1-I2 indicates the deformation trend without PUE correction. I3 corresponds to the same chart after applying a manual PUE correction. A visual detail of the crack is shown in Fig. B1-I.3 and the location of that reflector in Fig. B2 as a grey diamond. Official documentation describes the occurrence of the landslide on 14th February 2019. This is clearly visible in the charts (first vertical dashed red line). At the same time, it is clear that the trend was present before (at lower rates) and after this date. Dashed red vertical lines indicate the enforcement of a PUE correction, eleven times in this case. Official reports (IEASA, 2021) describe ground displacements up to 15 mm/day (5.5 m/yr) in the main sector of this big crack, where we could not obtain PSI. Observing this chart, we cannot confirm the end of the deformation trend in April 2021.

Fig. B3 presents three stages of the project evolution through optical sensors where main project changes can be seen.
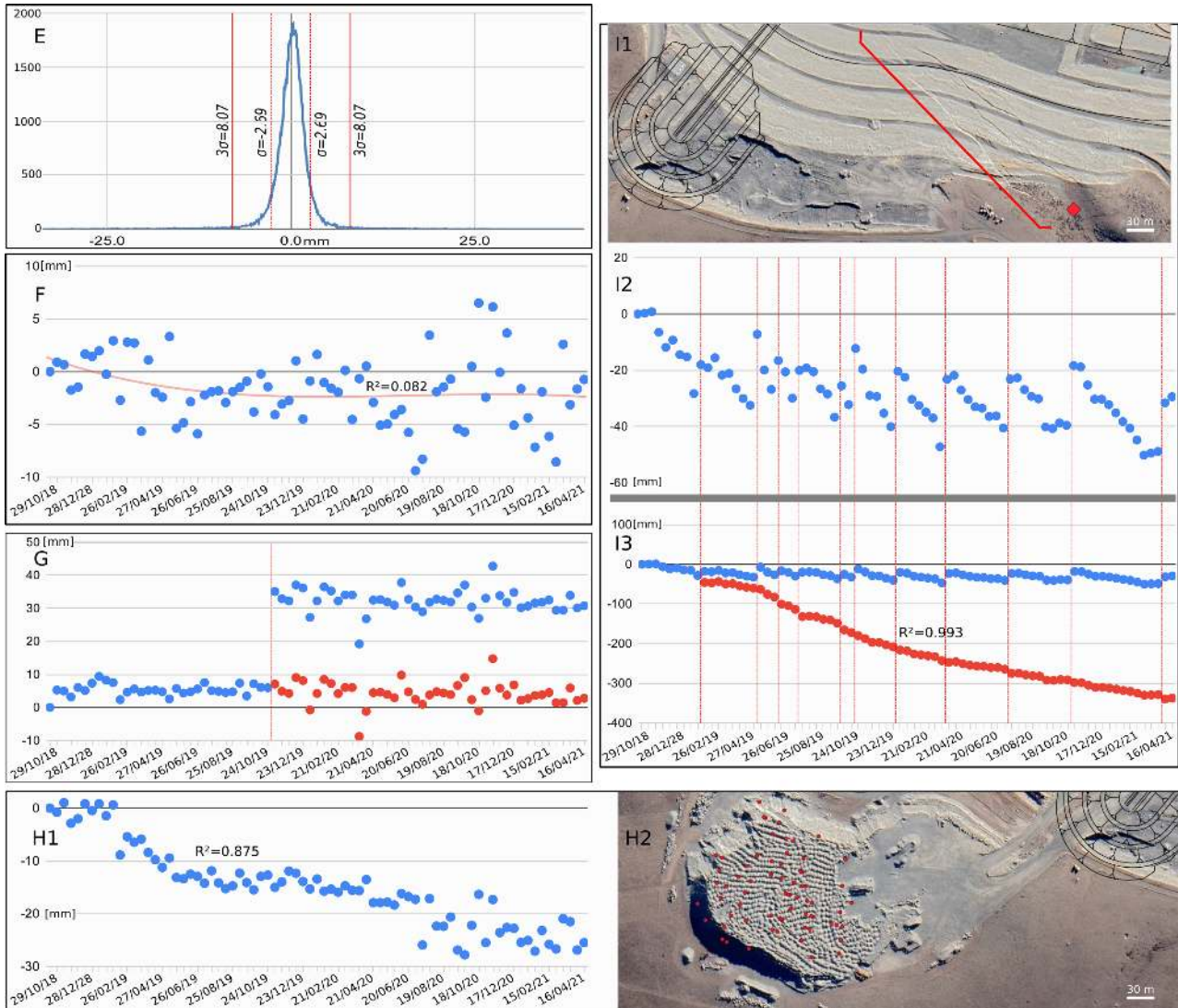
Figure B1. Examples of PSs with high σ values which, as presented in page 6 and following the same number notation, have not been studied in this work. Optical satellite images from © Google Maps
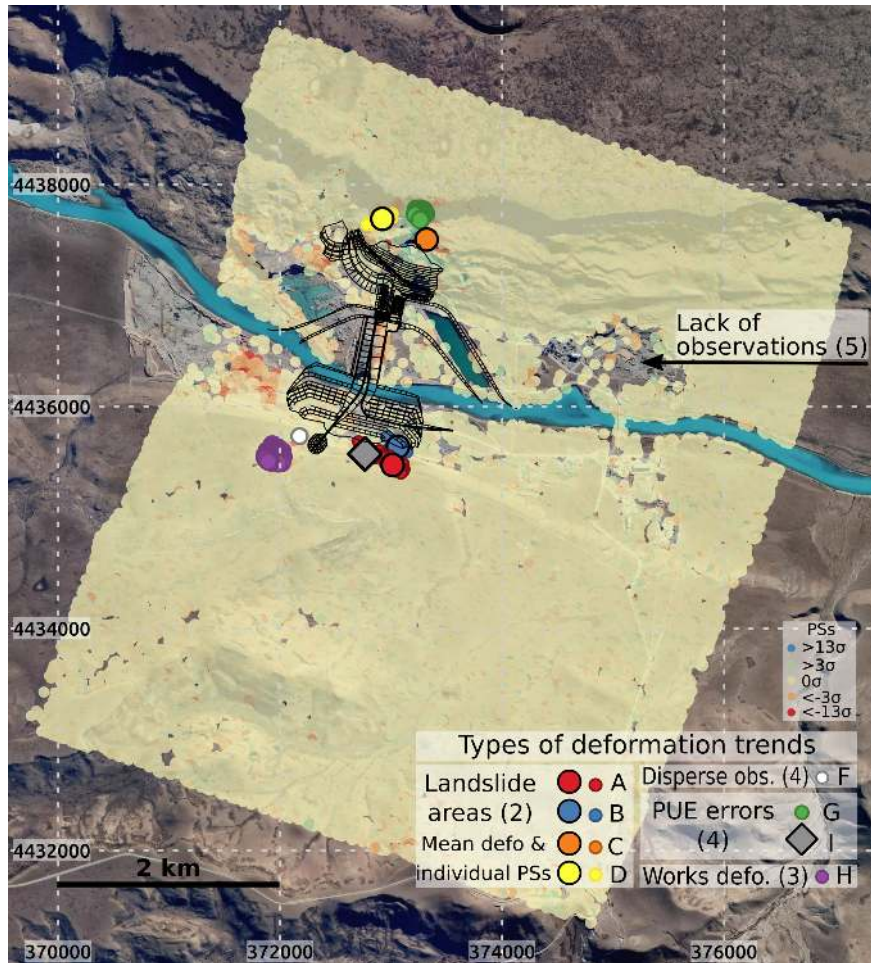
Figure B2. Map of the full PSI results and examples of the identified deformation trends, 1 to 5, as described on the items on page 6 or presented in previous B1. A to D are landslides studied in this work. F to I are the other time series trends briefly described in this Appendix. Arrow (number 5 as in page 6) is an example of the absence of observations due to the surface changes produced by the construction work. Our own elaboration. Background satellite image © Google Maps
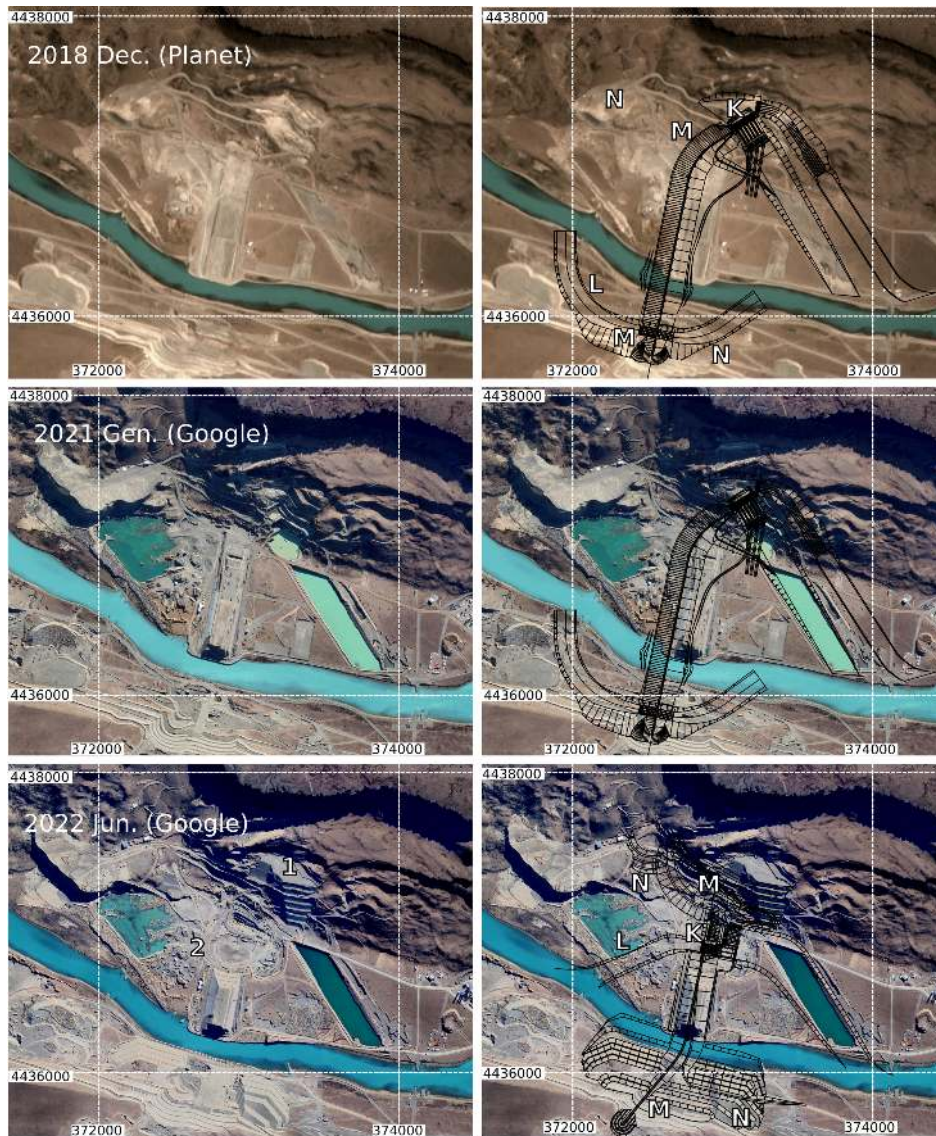
Figure B3. Three moments of the dam construction. In the left column, optical image, in the right, the dam plans have been superimposed (the third row corresponds to the new project). Letters identify main structural changes: K) machines hall, L) deviation channel, M) change of the dam wall direction, N) structural retaining walls. Numbers identify main correction works to the original project (modification of structures already built): 1) the space prepared to the main hall have been filled in again (over 1 million m^3), 2) an important part of the dam wall (which was originally planned to have 12.1 millions m^3) has been retired, and a big 10 m wide and 36 m deep exploratory well is built there to study the rock substratum. To dig the well, a volume of around 70,000 m^3 had to be previously removed at the ground level in the area which had already been filled with basement materials of the dam wall. Our own elaboration. Background images from Planet^{TM} and © Google Maps.

Author contributions. G. T. B. coordinated the team, wrote the text, designed the figures and performed the general research over the study
case: geological setting, engineering and environmental impact assessment, technical reports analysis, available data, etc. S. B. processed the
PSI data and developed the methods section. O. M. carried out a general supervision of the research work.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. Thanks to LaIC (Laboratorio de Inglés Científico - UNPA) and María Cuevas-González for their linguistic support and
corrections of this manuscript.

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