PERFORMANCE EVALUATION OF TEMPORAL MODEL AND SPATIAL CORRELATION METHODS FOR PERSISTENT SCATTERER DETERMINATION IN LANDSLIDE PRONE AREAS

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Abstract:
The Philippines is no stranger to natural hazards. Aside from flooding, landslides emerge as a primary contributor to damage dealt by natural hazards. Traditional methods for landslide monitoring require on-site field measurements, which makes them resource-intensive and time-consuming. Moreover, the frequency of updating of existing landslide hazard maps is limited by resources and manpower. This research introduces the application of remote sensing technology, specifically Persistent Scatter Interferometry (PSI), as a complementary tool for updating hazard maps. PSI enables the identification of stable ground points, eliminating the need for labor-intensive fieldwork and facilitating assessments of potential slope instability. Two distinct PSI processing methods are evaluated in the study; the Temporal Model approach and the Spatial Correlation model approach. Findings reveal that the Temporal Model approach successfully detected 11,647 Persistent Scatterers (PS) points, while the Spatial Correlation approach identified 272,614 PS points. Furthermore, the Spatial Correlation approach demonstrated its capability to detect PS points within high landslide susceptibility areas. Consequently, the results highlight the suitability of the Spatial Correlation approach for detecting PS points, particularly in landslide-prone regions, offering support to local landslide hazard monitoring systems. This research supports the initiative to a more efficient and cost-effective approach to maintaining up-to-date landslide susceptibility maps in the Philippines in enhancing disaster preparedness and mitigation efforts.

1. BACKGROUND AND SIGNIFICANCE

1.1. Landslides and the Philippines

The Philippines is one of the most exposed countries to natural hazards as it lies within the center of the Pacific Ring of Fire. Aside from frequent flooding, the country also experiences massive landslides that disturb the environment, economy, and livelihood of local communities. Even worse, these disasters end up causing massive casualties in the affected areas.

Landslides are defined as the movement of a mass of rock, debris, or earth down a slope under the influence of gravity. These occur when the resisting forces of gravity and the shear stress in the slope overcome one another. In a study by Durham University, the Philippines ranks 3rd in terms of landslide deaths and an estimated value of 5.1 Billion USD are lost in damages due to landslides events worldwide (CRED, 2018). For the past 20 years, the Philippines has recorded at least ten (10) major landslide disasters taking more than 3,000 lives and listing around 2,000 missing persons. Some of the most notable landslides that have devasted the Philippines are (1) The 1999 Cherry Hills Landslide which was induced by the Typhoon Olga. This landslide event ravaged the Cherry Hills Subdivision in Antipolo City taking at least 60 lives; another is (2) the 2003 Southern Leyte Debris Flow which destroyed houses at Barangays Pinut-an and Polacion killing at least 154 people in its wake. One more recent landslide event is the 2018 Itogon, Benguet Landslides caused by Typhoon Ompong – the strongest typhoon so far in 2018. At least 58 casualties were reported in the mining town of Itogon (Bueza, 2018).

Landslide hazard events are triggered by natural phenomena including earthquakes, rapid and intense or prolonged rainfall, or they are induced by human activities such as deforestation or road construction, or a combination of both (Alleoti, 1999). These natural hazards not only affect the environment but also cause ripple effects to the economy and the lives of people exposed to these events. Schuster (2001) enumerates some of the common environmental impacts of landslides; it changes the topography and morphology of the subaerial and submarine surface of the earth, it changes the morphology of rivers, streams, forests and grasslands. And it greatly affects the habitats of the natural fauna.

Traditionally, there are only 2 ways of classifying slope stability in terms of landslide hazard monitoring. Either the slope is stable and unstable (Crozier and Glade, 2005). However, this twofold classification of slope stability means little when looked at the context of landslide hazard monitoring. A better classification was proposed was Crozier to further understand the behaviour of slope stability.

Three new slope states were introduced. Stable, Marginally stable and actively unstable (Crozier, 1989). The evolution of these states is triggered by different factors until stability is achieved in the slope once again. The most significant cycle in the evolution of the slope states in terms of landslide hazard is the change from marginally stable to actively unstable which signifies the start of slope failure (Hungr et.al., 2014).

Failure is defined as the single most significant movement in the anticipated history of a landslide. Movements that occur in between the marginally stable to actively unstable are called the pre-failure movements. These movements are described in the context of slope stability wherein detected movements are considered significant manifestations of possible slope failure. Pre-failure movements are precedent movements that leads to slope failure (Hoser, 2018). However, to detect pre-failure movements, it is critical to identify points on the ground where the actual movements will be measured. In this study, the technology of remote sensing, particularly Synthetic Aperture RADAR will be explored to determine which among the two (2) most common methods of detecting stable points on the ground is more effective in a landslide prone area.

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1.2. Landslide Monitoring using Remote Sensing

Landslide hazard assessment are traditionally done using in-situ measurements and historical data in determining the condition, material type and environment of the hazard area. It is practically impossible to cover to perform these measurements to cover a large enough area due to the logistic and manpower demand. Remote sensing provides an important answer to this problem. Remote sensing combined with spatial analysis provides wide scale information with minimal to no field contact at all (Nikolakopolous et. al., 2015). This eliminates the enormous logistic and manpower requirement as well as the danger of physically testing in the landslide hazard areas.

Optical and microwave sensors have been utilized in landslide hazard assessment (Nikolakopolous et. al., 2005). Optical sensors allow for the detection of changes in land cover. This is specially pronounced in areas where landslides have occurred where materials are transported to another. However, this method allows for the detection of landslide areas and not the detection of the changes in the ground behaviour which may lead to slope failure.

Another remote sensing method that gives an insight on the ground movement is the use of Synthetic Aperture RADAR. This sensor operates in the microwave region of the Electromagnetic Spectrum. SAR, particularly, Interferometric SAR, utilizes a pair of RADAR images to determine the movements that have occurred in between acquisition period (Casagli et. al., 2016). This method allows the detection of minute movements up to mm level which may translate to the pre-failure movements that needs to be monitored as they are directly related to slop failure. Figure 1 shows the general setup of InSAR measurements. The antenna measures the distance and compares the same distance measurement in another acquisition period. Change in the distance is interpreted as movement that occurred in the measured point.

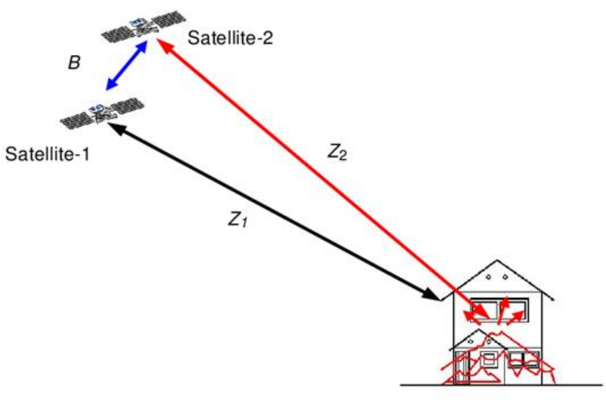

Figure 1. InSAR Repeat Pass Interferometry Setup (Matsuoka and Yamazaki, 2000)

The limitation of using only a pair of SAR images is the presence of decorrelation. This occurs when the point measurement between the acquisition dates are not consistent. Points within vegetated areas are expected to decorrelate due to the frequency of changes in the area. When this occurs, distance measurement in the points cannot be reliably retrieved. To overcome this limitation, another method of InSAR is utilized.

In this study, an extension of the InSAR technique is explored. Persistent Scatterer Interferometry (PSI) is a technique that stacks together multiple RADAR images to look for Persistent Scattering (PS) points that exhibit stable behaviour and acts are ground points where measurements are taken at each image acquisition to form a time series analysis (Crosetto et. al., 2015). This will show how ground points move in every image acquisition and is basis for pre-failure movement determination and landslide hazard assessment. Figure 2 shows a sample result of PSI analysis. The presence of PS points is crucial in detecting ground movements as these serve as the ground control points where the actual measurements are made.

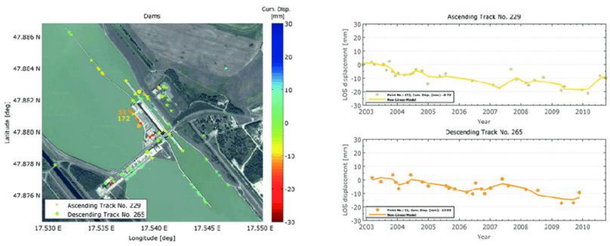

Figure 2. Sample PSI result and corresponding deformation model (Bakon, et. al. 2014)

Two (2) different methods of PSI is explored and analysed in this study with regards to the capability of detecting PS points which acts as ground points where direct measurements are made. These are (1) Temporal and (2) Spatial Correlation Models. These two methods are widely used models in performing PSI analysis. This study aims to show which among the two methods perform better in detecting PS points in landslide prone areas.

The study aims to supplement disaster risk and reductions initiatives by introducing remote sensing methods that will aid in landslide mitigation measures at the local level. The study uses free and open source data which can be accessed by the public. The study will help the local government in monitoring landslide prone areas without having the need to visit the actual site and eliminate further risk and logistical arrangements. Through the study, the local disaster monitoring office will be guided by satellite-based data and methods in their mission towards a safe and sustainable management.

2. MATERIALS AND METHODS

2.1. Study Area

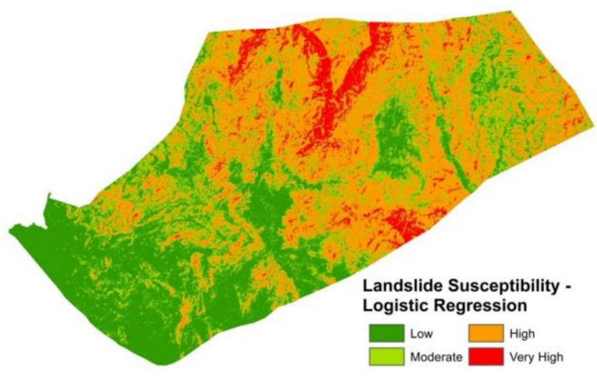

Figure 3. Landslide Susceptibility Map of Antipolo City (Victor and Zarco, 2018)

The chosen study area is within the province of Rizal, covering major portions of Antipolo, San Mateo, and Tanay due to the presence of highly elevated topography within the vicinity of the chosen area. Majority of the cities are within areas of steep slopes which makes them prone to landslides (Morales, 2001).

A study by Victor and Zarco (2018) found that the city of Antipolo contains a majority of high variability of topography and these areas are highly susceptible to landslides. The resulting susceptibility map was derived using geotechnical and spatial factors through logistic regression. See figure 3.

Presence of existing landslide hazard maps for the area is also considered for further analysis in the topic. The Philippines Nationwide Operational Assessment of Hazard of Project NOAH has classified majority of the city to be highly susceptible to landslide. This justifies the need for a continuous updating of the landslide hazard to determine potential failure movements that can result in a disaster. Along with this, the methodology used in this study aims to be adopted in the local planning context.

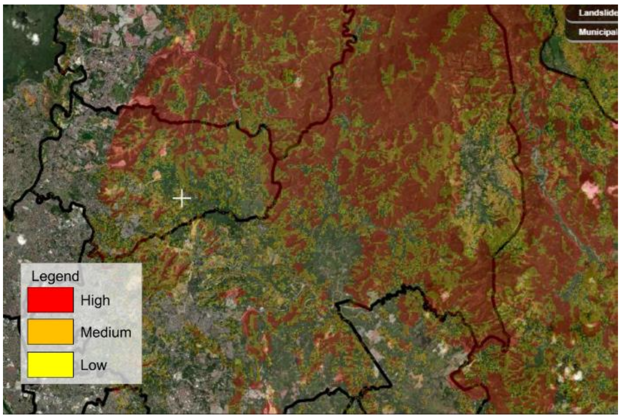

Figure 4. Landslide Susceptibility of the study area (Project NOAH)

2.2. Data Pre-Processing

Image Dates		
09 Jan. 2020	01 Jun. 2020	29 Sep. 2020
21 Jan. 2020	13 Jun. 2020	11 Oct. 2020
26 Feb. 2020	25 Jun. 2020	23 Oct. 2020
09 Mar. 2020	07 Jul. 2020	04 Nov. 2020
21 Mar. 2020	19 Jul. 2020	16 Nov. 2020
02 Apr. 2020	31 Jul. 2020	28 Nov. 2020
14 Apr. 2020	12 Aug. 2020	10 Dec. 2020
26 Apr. 2020	24 Aug. 2020	22 Dec. 2020
08 May 2020	05 Sep. 2020	03 Jan. 2021
20 May 2020	17 Sept. 2020	27 Jan. 2021

Table 1. SAR Acquisition Dates

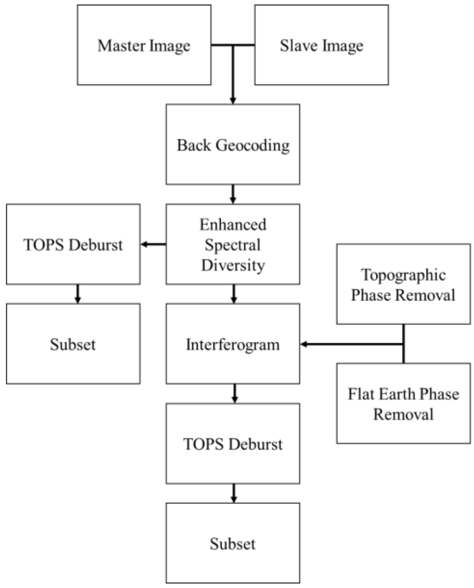

Figure 5. Data Pre-processing workflow

A total of 30 SAR images are used in the study spanning a total of 1-year period from January 2020 to January 2021. See table 1 for the full list of images used for the study. The master image is determined by computing the perpendicular baselines of each image relative to one another. The master image will be paired to each image. This ensures that the stacking of images will have minimal errors due to look geometry. For the stack of SAR images, the chosen master image is dated August 12. This SAR image contained the least amount of perpendicular baseline relative to all other images.

After pre-processing, the initial filtering of potential PS point candidates is done separately using the temporal and spatial correlation model approaches.

Prior to image stacking, each image is pre-processed. Orbit correction and TOPS splitting were applied to all images. Afterwards, the all slave images were paired to the master image through back-geocoding with Enhanced Spectral Diversity since the target area is within more than one burst. Interferograms are generated for all master – slave image pair with the correction to topography and flat earth applied. The resulting image is debursted to remove the burst lines. Figure 5 shows the general workflow of the data pre-processing

2.3. Temporal Model Approach

The original Persistent Scatterer approach is based on the the study by Ferretti (2001) that utilizes the Temporal Model approach. This method is implemented using SARPROZ developed by Perrisin (2011). SARPROZ is a commercial software built using MATLAB. All pre-processing and processing chain are done within the program.

$$ASI = 1 - \frac{\sigma_a}{a} \quad (1)$$

Candidate PS points are selected by computing the Amplitude Stability Index (ASI). See equation above Where σ_a is the standard deviation of the amplitude in the entire time series and a is the mean of the amplitude. For the index, the lower the value, the more points are selected as candidate PS points. The lower the value, the more relax the criterion gets thus the initial screening is more lenient. The suggested value of the ASI is 0.90 for highly urbanized up to 0.75 for vegetated areas (Qin, 2018). In the study, three (3) values of ASI are used; 0.85, 0.80, 0.75.

This value approximates the noise error using the amplitude measurement. After filtering the candidate points, the remaining potential PS points are connected through a network. The contribution due to the environment between nearby points are assumed to be the same or vary little over time. The phase differences between points are obtained to model the phase contribution of the DEM and deformation with the use of a steady-state model. Estimation of the deformation and DEM phase contributions are done simultaneously. After the phase contributions are obtained, the parameters are obtained at each individual potential PS points and integrated together using least squares. Atmospheric delays are estimated and subtracted from all potential points and the process is iterated to determine the final set of PS points. It is important to note that the steady-state model used is assumed to be linear. This implies that movement that are not linear may not be fully described by this method. These processes are done within 4 general workflows within the program (1) data preparation, (2) preliminary PS selection and analysis, (3) Atmospheric Phase Screen, and (4) Multi-Image Sparse Point Processing.

2.4. Spatial Correlation Model Approach

Another PSI method was developed by Hooper (2004). This is implemented through the Stanford Method for Persistent Scatterers (StaMPS) program. StaMPS is an open-source software developed through MATLAB. Pre-processing is done through SNAP and is ingested through the SNAP2StaMPS extension.

$$ADI = \frac{\sigma_A}{a} \quad (2)$$

In this method, candidate PS points are selected using the Amplitude Dispersion Index (ADI). See equation above. Amplitude is used in the initial estimation of the PS points since it is related to the amount of phase noise in the pixel. Note that this relationship only holds true as an approximate for small ADI values. The typical range for this index for PSI processing in StaMPS is between 0.40 to 0.42 (Serco Italia SPA, 2020) up to 0.45 for largely vegetated areas (Minh, 2020). For this study, the Amplitude Dispersion Index chosen was 0.45.

Unlike the temporal model, the spatial correlation model does not require an assumption on the deformation behaviour of PS points. This method is intended to work for areas experiences irregular deformation. The phase contributions of spatially correlated variables are estimated using an iterative spatial bandpass filtering. The contributions include the deformation, atmospheric, orbit, and spatially correlated topographic error. The spatially uncorrelated topographic error is estimated by inversion by relating it to the perpendicular baseline. Iteration is done to re-estimate the phase contributions to identify the final set of PS points. These are divided into seven (7) general steps in StaMPS.

ASI and ADI are related to one another in that ADI is the reciprocal of ASI. These values approximate the phase noise error using the amplitude values. However, this only reliably works for small values. In the case of temporal approach, ASI values of 0.7 – 0.9 for SARPROZ is recommended while ADI values for StaMPS is at a maximum of 0.45 for PSI analysis to be reliable. This selection is the initial filtering in determining potential PS points in the image stack. For the study, ASI values of 0.75, 0.80, and 0.85 are used in SARPROZ and 0.45 ADI value was used for StaMPS.

3. RESULTS AND DISCUSSION

3.1. Temporal Model Approach

The temporal model approach in PSI was originally designed to work in areas with stable structures such as built-up areas. This is due to the presence of stable scatterers in urban areas. There is little chance for pixels in highly urbanized areas to experience any sudden change in geometry within the span of the next acquisition period. With this, the approach will also work in areas with a dominant scatterer present outside urban areas such as large boulders. This study aims to see which among the two methods would yield more PS points in the study area which will be basis for landslide prone area monitoring.

Figures 7, 8, and 9 show the resulting PS points detection using the temporal approach (SARPROZ). The maps show how changing the ASI value will affect the number of detected PS points. This is due to the initial filtering done using the ASI values. In the case of SARPROZ, the higher the ASI value, the lower the detected PS points are as the initial filtering stage is already stringent enough. For an ASI value of 0.85, a total of 2,769 PS points was detected. For an ASI value of 0.80, a total of 6,302 PS points was detected and for an ASI value of 0.75, a total of 11,647 PS points was detected.

It is important to be careful in trying to lower the ASI value further to relax the filtering stage. The filtering stage sets the initial phase noise value by correlating it to the amplitude of the pixel. If the ASI value were to get lower, though the filtering will be more lenient, it will introduce more error. When this happens, the distance and temporal measurement of the PS points will not be reliable as they are plagued with noise. Although there is an increasing number of PS points as the ASI values get lower, it is equally important to note where the points are located. Majority of the detected PS points lie within the urbanized portion of the study area. In the context of the study, this does not contribute much in terms of landslide prone area monitoring since majority of the detected PS points do not lie within the area considered as moderate to high landslide susceptibility.

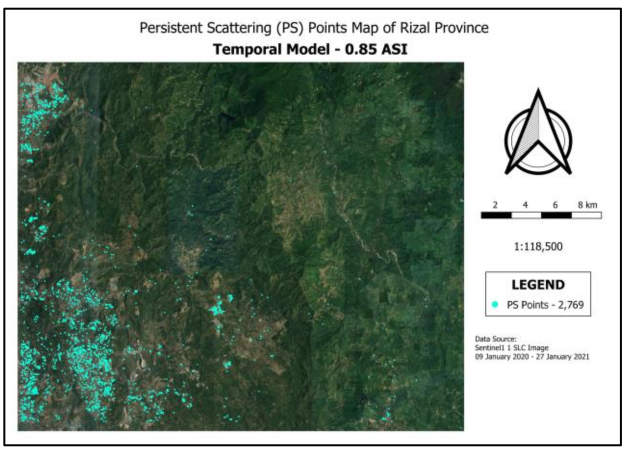

Figure 7. PS Points Map (0.85 ASI)

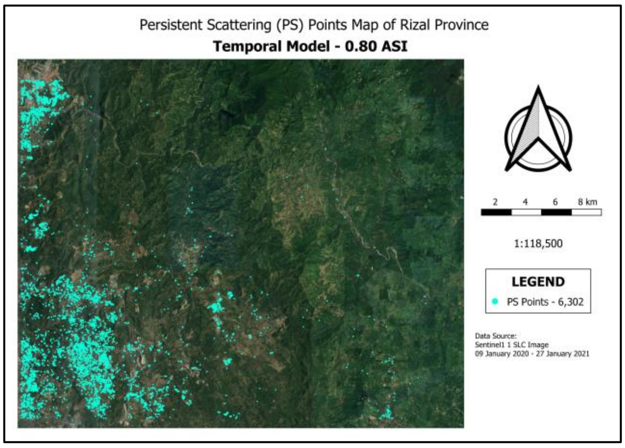

Figure 8. PS Points Map (0.80 ASI)

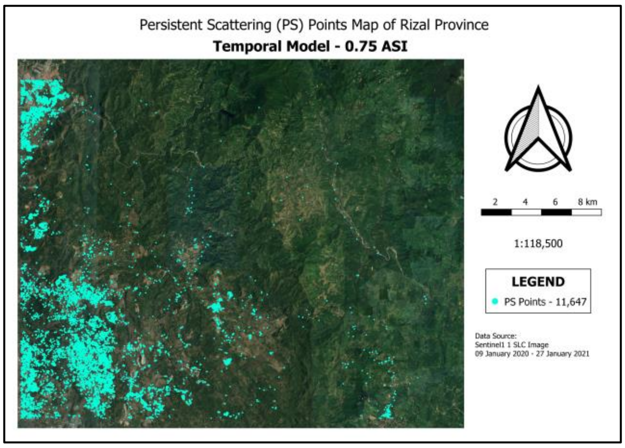

Figure 9. PS Points Map (0.75 ASI)

The key limitation of using the original Persistent Scatterer approach (Ferretti, 2001) is its inability to detect PS points within areas devoid of man-made structures. This is evident in the result that high vegetated and mountainous areas have very little PS points detected. With this, analysis of the displacement measurements in the mountainous region becomes limited due to the lack of PS points in the area.

3.2. Spatial Correlation Model Approach

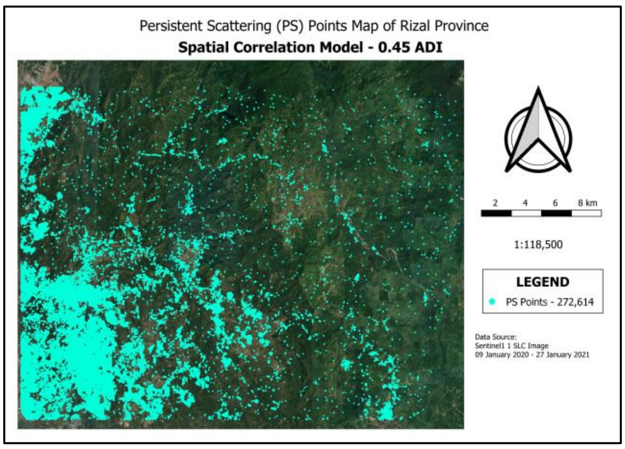

Figure 10. PS Points Map (0.45 ADI)

To overcome the limitation of the temporal model approach, another approach is utilized in the research. The spatial correlation model approach is an updated PSI technique developed to work on areas that are devoid of man-made structures. Figure 10 shows the result of the spatial correlation approach in detecting PS points

For the spatial correlation approach with 0.45 ADI value, a total of 272,614 PS points was detected. Based on these results, the use of spatial correlation approach is better suited in landslide hazard monitoring as it detects more PS points which are used to make ground measurements that translates to potential pre-failure movements. Aside from the number of detected PS points, the distribution of these points are equivalently important. The spatial correlation approach was able to detect PS points in the area with high landslide susceptibility. These measurements are crucial in monitoring landslide hazards as these areas pose the most risk in terms of potential slop failure.

One key limitation of the temporal approach is the assumption that the point moves in a steady state behaviour. Points that do not exhibit this property does not get detected using the temporal approach method. Points that belong in area with highly variability in terms of topography rarely exhibit these kinds of movement behaviour due to the presence of erosion and deposition in mountainous areas.

3.3. Field Measurement Validation

To verify the results of the displacement measurements from the PSI analysis, the derived values is compared to the displacement values from a reference Continuously Operating Reference Station (CORS). Displacement measurements were derived from daily GNSS solutions. The measurement pertaining to the date of acquisition was matched with that of the GNSS measurement and was plotted vs time (measured from days). For the study, the obtained measurements from the CORS station, StaMPS and SARPROZ are compared and a trendline is generated to determine which among the two approaches would provide the displacement measurement closer to the ground measurements.

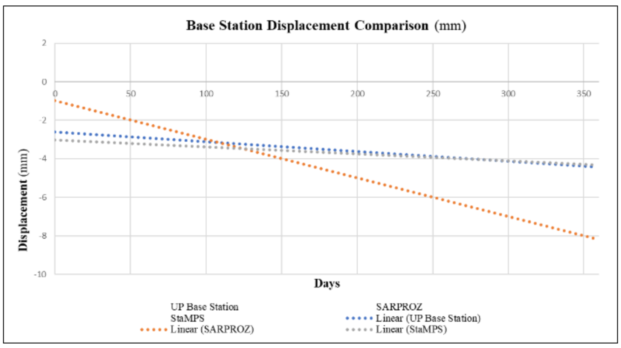

Figure 11. Displacement Comparison of SARPROZ, StaMPS and the CORS Receiver

Figure 11 show the trendline of the displacement measurements. From the same figure, it can be seen that the measured displacement using SARPROZ overestimates that of the GNSS measurement in terms of the overall trend by up to 4mm as it continues to exhibit a subsidence measurement at a much faster rate as compared to the GNSS measurement.

On the contrary, the displacements computed through StaMPS exhibit a good similarity to those acquired from the CORS GNSS, with an offset of less than a millimeter. The trendline of StaMPS measurements mirrors the behaviors observed in GNSS measurements. To quantitatively assess the relationship between these measurements, correlation coefficients were calculated for both SARPROZ and StaMPS in comparison to GNSS measurements. A correlation coefficient of 0.61 was determined for the relationship between SARPROZ and GNSS, while a robust correlation, with a coefficient of 0.83, was identified between StaMPS and GNSS. These findings strongly indicate that StaMPS displacement measurements bear a closer resemblance to GNSS measurements when compared to SARPROZ. This conclusion is further substantiated by the higher number of PS points detected using StaMPS, rendering it a more viable and reliable method for PSI processing within the scope of this study. The observed disparities in measured displacement can be attributed to the distinct PSI approaches employed by both methods.

The computed correlation coefficients can be attributed to the fact that only the Line-of-Sight (LOS) displacement dimension is compared to GNSS observations. While deformations can occur in three dimensions, the limitation arises from the lack of additional information regarding displacement. Consequently, only a one-dimensional LOS vector is compared. This limitation is inherent when employing a single-orbit SAR sensor, as it computes only one LOS value. Therefore, certain assumptions must be made to reconcile the GNSS observations with the measured LOS displacements to address this limitation.
The computed correlation coefficients can be attributed to the fact that only the LOS displacement dimension is compared to the GNSS observations. Deformations can happen in three dimensions, however due to the lack of additional information regarding the displacement, only a one-dimensional LOS vector is compared. This is one of the limitations of using only a single orbit SAR sensor wherein only one LOS value is computed therefore assumptions must be made to the GNSS observations and the measured LOS displacements to compensate for this limitation.

4. CONCLUSIONS

The study utilized a free and open SAR sensor (Sentinel 1) to aid in monitoring landslide hazard. The use of the traditional single pair InSAR measurement cannot be used in areas with high decorrelation and thus, no valid deformation measurement can be retrieved. To overcome this limitation, the use of Persistent Scatter Interferometry is introduced to stack multiple SAR images together referenced to a single master image to determine points on the ground that exhibit a stable phase behaviour and measurements can be retrieved per image acquisition. Two methods of PSI were tested in the study; Temporal approach and Spatial Correlation approach implemented in SARPROZ and StaMPS, respectively.

Both methods were able to detect PS points but the temporal approach detected mostly in areas with high urban development and little to no PS points in the mountainous areas where slope failure is crucial to be monitored. On the other hand, the spatial correlation approach was able to detect more than 18 times than that of the temporal approach. Majority of the points also lie in urban areas but PS point were also detected within the moderate to high landslide susceptibility. This makes the spatial correlation approach more viable for the purpose of the study – landslide monitoring as more points are located and measured in the hazard prone areas.

PS points are important to be determined as these are the points that serve as the actual ground measurement. These points provide deformation values without risking personnel safety and intensive field measurements. Determination of the number ans distribution of the PS points provided an important information to local monitoring agencies. Data-driven and science-backed decision making in disaster mitigation is aided by the presence and spatial distribution of the PS points. The effectivity of landslide monitoring systems will vastly improve when more PS points are detected on the ground.

REFERENCES

Aleotti, P. and Chowdhury, R. 1999. Landslide Hazard Assessment: Summary Review and New Perspectives. Bull Eng Geol Env 58, 21–44. https://doi.org/10.1007/s100640050066

Bueza, M. 2018. LIST: Deadly Landslides in the Philippines. Retrieved from: https://www.rappler.com/newsbreak/iq/212440-list-deadly-landslides-philippines/. Retrieved March 12, 2020.

Casagli, N. et. al. 2016. Landslide mapping and monitoring by using radar and optical remote sensing: Examples from the EC-FP7 project SAFER. Remote Sensing Applications: Society and Environment. 4 92-108. Elsevier.

Centre for Research on the Epidemiology of Disasters. 2018. Natural Disasters: 2018. Institute Health and Society. Université Catholique de Louvain.

Crozier, M. and Glade, T. 2005. Landslide hazard and risk: Issues, concepts and approach. Landslide Hazard and Risk. John Wiley and Sons Ltd. West Sussex. pp. 1–40

Crozier, M. 1989. Landslides: Causes, Consequences and Environment. Routledge, London

Crosseto, M. et. al. 2015. Persistent Scatterer Interferometry: A Review. ISPRS Journal of Photogrammetry and Remote Sensing. 115 p. 78 - 89.

Ferretti, A. et. al. 2001. Permanent Scatterers in SAR interferometry. IEEE Transactions on geoscience and remote sensing, 39(1), 8-20.

Hooper, A. et. al. 2004. A new method for measuring deformation on volcanoes and other natural terrains using InSAR persistent scatterers, Geophys. Res. Lett., 31, L23611.

Hoser, T. 2018. Analysing the Capabilities and Limitations of InSAR using Sentinel-1 data for Landslide Detection and Monitoring. Faculty of Mathematics and Natural Sciences. University of Bonn.

Hungr, O.et. al. 2014. The Varnes classification of landslide types, an update. Landslides. 11. 10.1007/s10346-013-0436-y.

Matsuoka, M. and Yamazaki, F. 2000. Interferometric characterization of areas damaged by the 1995 Kobe earthquake using satellite SAR images. Proceedings of the 12th World Conference on Earthquake Engineering, Vol 2.

Morales, E. et. al. 2001. The Cherry Hills Landslide Tragedy. The 2nd Civil Engineering Conference in the Asian Region, Tokyo, 2001.

Nikolakopoulos, K. et. al. 2015. Active landslide monitoring using remote sensing data, GPS measurements and cameras on board UAV. Proceedings Society of Photo-optical Instrumentation Engineers, 9644, 1–9.

Nikolakopoulos, K. et. al. 2005. Combined use of remote sensing, GIS and GPS data for landslide mapping. Proceedings. 2005

IEEE International Geoscience and Remote Sensing Symposium, 2005.

Perissin, D. et. al. 2011. SARPROZ InSAR Tool for Urban Subsidence/manmade Structure Stability Monitoring in China. Proc. of ISRSE. Sydney, Australia.

Schuster, R. and Highland, L. 2003. Impact of Landslides and Innovative Landslide-Mitigation Measures on the Natural Environment. USGS.

Victor, J. and Zarco, M. 2018. Multivariate Logistic Regression Approach for Landslide Susceptibility Assessment of Antipolo, Rizal. Philippine Engineering Journal. PEJ 2018; Vol. 39, No. 2: 27-40

https://doi.org/10.5194/isprs-archives-XLVIII-4-W8-2023-343-2024