InSAR ANALYSIS OF TERRAIN DEFORMATION DUE TO AN ONGOING SERIES OF COLLAPSE EARTHQUAKES IN THE CENTRAL HIGHLANDS OF SRI LANKA

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KEY WORDS: PS-InSAR, Collapse Earthquakes, Terrain Deformation

ABSTRACT: As series of collapse earth quakes in the central mountain region of Sri Lanka has hindered the daily life as well causing turmoil due to the placement of the country's highest altitude hydropower dam Victoria. Limestone quarrying, long time drilling to extract limestone creating cracks causing the areas to collapse due to water pressure, existing crack towards the eastern slope of the Mahaweli River, changes in soil layers in the interior of the earth could be the major causes for a continuous series of earth tremors. This study investigates the effects of the earthquakes for probable terrain deformation. PS-InSAR which is an extension of D-InSAR utilizing long time series SAR images with stable point like targets staying unchanged for a long period of time to detect slow movement was implemented in this study. PS-InSAR in mountainous terrains become challenging due to heterogeneous land scape, selection of the time series images, APS and phase unwrapping. A series of 34 Sentinel 1-A images in the ascending node from the year 2019 to 2021 was used. The results suggest possible movement along the line of sight (LOS) in the slant range at the maximum magnitude in the range 40mm/year. It was also observed that the areas in the main city shows more stable topography while the southern part of the Vitoria Dam are subjected to deformation. Eastern slopes of the Mahaweli river lying in the far range of the ascending swath with minimal fore shorting and layover effects has also shows deformation the range -29mm/year to -36mm/year.

1. Introduction

Sri Lankan is considered to lie in an aseismic region in the center of Indian Ocean. Earthquakes are not frequent in this region as a major disaster phenomenon. Contrary along lengthy historical significance, only a fewer number of small-scale earthquakes have been reported in the past making earthquakes a less important element to be studied at a national level disaster prevention. One main reason for this understanding is that Sri Lanka basement being a part of a stable Precambrian shield located very far from any active faults or plate margins and having a substantially thick old-cold curst does not provide a favorable site for occurrence of major/frequent earthquakes (GSMB report 2020. 09.04). Further due to this historical confidence, topographic changes in Sri Lanka have not been studied in detail utilizing satellite remote sensing, GNSS positioning or Levelling methods.

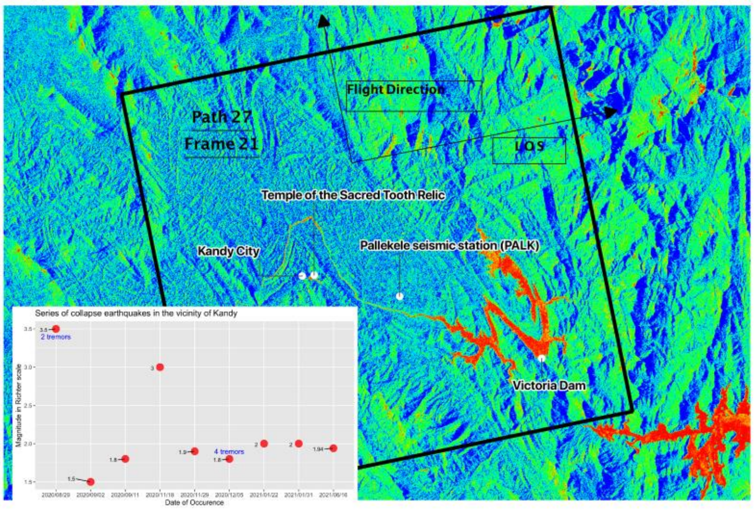

Figure 1 Series of collapsed earthquakes recorded at present from an ongoing series of events observed and the Sentinel 1A ascending path and the master area

In this backdrop, during the year 2020 a series of collapse earthquakes have been reported in the central province of the country, especially in the vicinity of Kandy city, the Hill capital of Sri Lanka (Figure 1). Consequences of these microearthquakes needs a detail investigation mainly because historically Kandy being the holy city of Buddhists all around the world and occupies highest population density in the central province of Sri Lanka (Vitanage, 1972, Berger and Jayasinghe, 1976, Cooray, 1994). Further as Kandy home to the country's tallest hydropower dam "Victoria Dam" a measurable seismic risk from an earthquake prone disaster could be terminal. Further to the recent seismic observations the earth quake history of Sri Lanka and the earliest Geological studies indicating a phenomenon called "Post-Precambrian uplift" in the geological formation of the country provide a reasonable need to conduct a study on its topography (Vitanage 1972). Finally we hypothise that the movement in the region are slow enough to be detected by using permanent scaterrer (PS-InSAR) (Ferretti et al 2000, Colesanti et al, 2003).

2. Study Area and Data set description

The study area is the region of Kandy, considered as the capital city of the hill country of Sri Lanka. Its situated in between northern latitude 7.10^0 N to 7.40^0 N and eastern longtitude 80.40^0 E to 80.90^0E. This region has a relatively wetter and cooler temperatures than that of the tropical climate of the rest of the island. As seen in Fig 2, the longest river of Sri Lanka "Mahaweli" takes an east to west turn from the north part of the Kandy city and boarders it from there sides. The average elevation of the kandy region is around 500m to 600m from the MSL, while the lowest elevation could be considered as 300m MSL. Further, Kandy is surrounded by Kadugannawa from the west, Hanthana from the south and Knuckles mountains from the north east and when entering the city, Balana, Balakaduwa, Galagedara, Ginigathhena & Hunnasgiri passes are met. The "Victoria Dam" is situated to the South East of kandy city. Recent Building collapses have been reported in the close proximity to the north east direction from the Kandy city center (newsfirst.lk/ 2020/09/20).

A time series SAR data stacks, covering the area of interest Kandy Sri Lanka have been used. It includes 35 ascending images acquired by the S-1A satellite path 27 frame 21 in IW mode during the period from 2019 to early 2021. The VV polarization is considered in all analyses. The master area selected for the analysis is around $25 \times 25Km^2$ area as shown in Figure 1. In this paper we report the results attained by ascending data only.

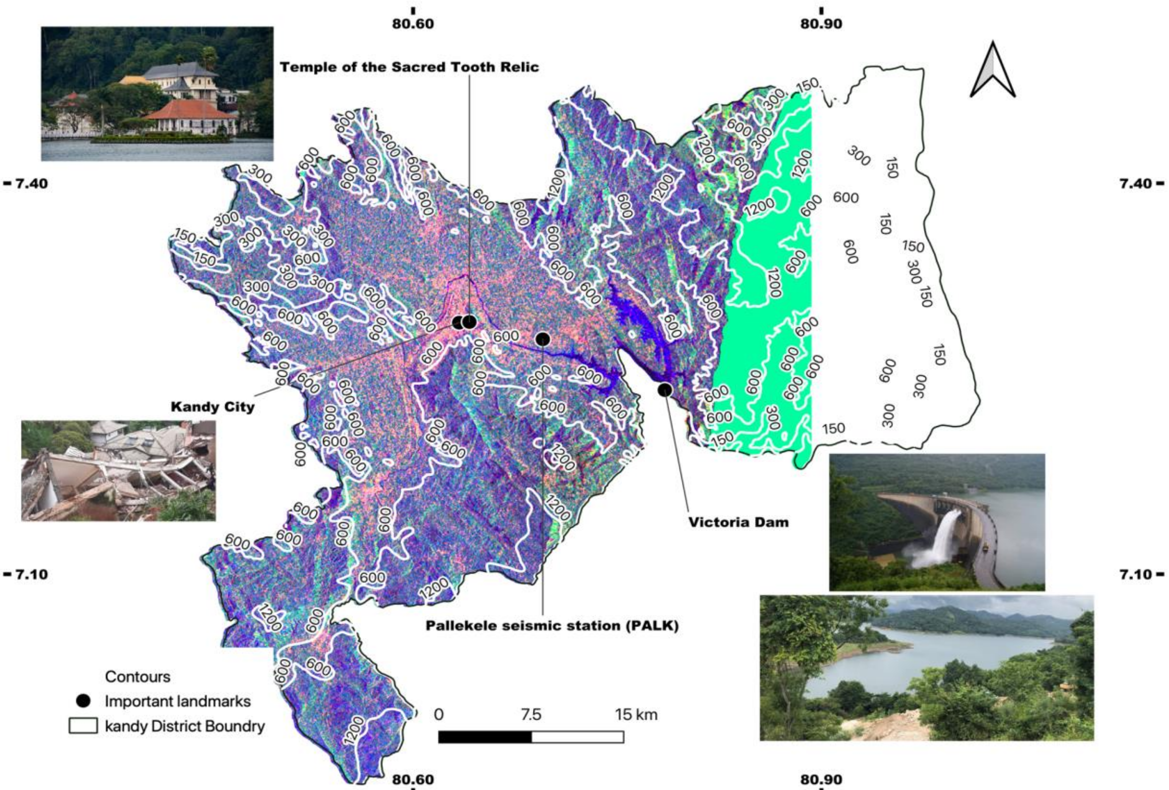

Figure 2 The study are Kandy and the Victoria Dam, the base image shows urban foot print of Kandy, mapped from two Sentinel 1A image stack acquired on 2020.01.09 and 2020.09.29 in IW2 burst 6 to 9, VV polarization with Red showing complex coherence, Green mean of the scattering coefficient (dB) and Blue difference of the scattering coefficient (dB) for the two days respectively, Contours are from the Levelling details of the central province from the Survey Department of Sri Lanka

3. Methodology, PS InSAR technique

The time series InSAR anlaysis method employed in this study fully utilizes the standard PS-InSAR methods introduced by Ferretti et al., 2001. The method uses a long time series stack of complex SAR images to detect point like targets (PS) with stable phase history, thus providing a network of control points to detect movement. Therefore, PS could be considered as the absence of temporal decorrelation in the SAR image stack. Though the PS method is well developed and robust, applying it in mountainous terrains is always a challenge. In this study for initial estimation of the ground deformation ESA SNAP 8.0 software has been used with SNAPHU phase unwrapping while the PS analysis was performed by using the SARPROZ software (Perissin et al., 2011, D. Perissin, 2009, D. Perissin, A. Ferretti, 2007). The SARPROZ is an extremely versatile software for processing time series InSAR data supported by MATLAB. The basic flow of the procedure is as follows, for more detailed description see F. Foroughnia et al 2019. Prior to the PS-InSAR analysis, two SAR images covering the main event on 29th August 2020 (Figure 1) with near zero-base line configuration was used determine the possible deformation signature of the area. A 2.03m normal base line between the acquisitions on 19th July 2020 and and 05th September 2020 was employed. Images were co-registered and the Enhance Spectral Diversity was performed. It is thus believing only the motion component is contained in the flatten differential interferometric phase ($\Delta\varphi$) represent by the following equation:

$$\Delta\varphi = \frac{4\pi}{\lambda} d_{LOS} \tag{1}$$

$$Where, \lambda - \text{Operational Wave Length}, d_{LOS} \text{Displacement along Line of Sight}$$

After the flat-Earth and topographic phase (using SRTM 30m DEM) removal the resulting interferometric phase was unwrapped and the displacement was deduced.

For the PS-InSAR, an InSAR stack was generated using a single master data. The Master data was selected, so that in the time series chain the spatial and the temporal decorrelation effects are minimal, which is quite useful in the selection of PS candidates later. Therefore, the image on 19th July 2020 was selected as the master image, while 34 slave images were co-registered using precise orbital information and the homologous points between the master and the slave images. After the removal of flat earth phase and the DEM phase the observation equation of the phase of flatten differential interferogram can be represented as:

$$\psi_{m,s} = \varphi_{m,s}^{topo\_res} + \varphi_{m,s}^{defo} + \varphi_{m,s}^{atmo} + \varphi_{m,s}^{orbit} + \varphi_{m,s}^{noise} \tag{2}$$

Where $\varphi_{m,s}^{topo\_res}$ is the DEM error derived by using R sensor target distance w.r.t master acquisition, $B_{\perp m,s}$ Normal baselines, θ local incidence angle.

$$\varphi_{m,s}^{topo\_res} = \frac{4\pi}{\lambda\, R\, Sin\theta} B_{\perp m,s} h_{PS} = B_{m,s} h_{PS} \tag{3}$$

Further if a linear displacement model is considered with velocity v, $\varphi_{m,s}^{defo} = T_{m,s} v$, thus the Eq. 3 could be written as:

$$\psi_{m,s} = B_{m,s} h_{PS} + T_{m,s} v + \varphi_{m,s}^{atmo} + \varphi_{m,s}^{orbit} + \varphi_{m,s}^{noise} \tag{4}$$

PS candidates (PSC) were selected using Amplitude Stability Index (ASI), which is a measure of the phase standard error. A small standard error indicates a higher phase stability. For the study we used an ASI$\leq$ 0.3. With the use of PSC, in the observation equation (4) $\varphi_{m,s}^{noise}$ could be neglected. A reference point is carefully selected from the selected persistent scatterers candidates (PSCs). Selection of this point is an important step in the process. The main character of the reference point is that it should be free from the deformation effect under investigation. For this study a reference point is selected from an area north east of Kandy at a road cross section. This point had a Temporal coherence of 0.98 and spatial coherence of 0.82. With the use of the reference point, PS method become a relative estimation considering the observation effects in the flattened differential interferograms (DInSAR). Therefore the Eq. 5 could be written considering the reference point as follows.

$$\Delta\psi_{m,s} = \psi_{m,s}^{ref} - \psi_{m,s} = B_{m,s}\Delta h_{PS} + T_{m,s}\Delta v + \varphi_{m,s}^{atmo} + \varphi_{m,s}^{orbit} \tag{5}$$

Where the contribution from atmosphere and the orbits could be written as $\varphi_{m,s}^{atmo} + \varphi_{m,s}^{orbit} = \frac{4\pi}{\lambda} r_{m,s} + \frac{4\pi}{\lambda} a_{m,s} = ko_{m,s}$ and Equation 5 Become:

$$\Delta\psi_{m,s} = \psi_{m,s}^{ref} - \psi_{m,s} = B_{m,s}\Delta h_{PS} + T_{m,s}\Delta v + ko_{m,s} \tag{6}$$

As it is now possible to consider that the atmosphere is similar for nearby PSC and $ko_{m,s}$ term could be neglected with the relative estimation setup. Hence the unknowns are the Δh_{PS} Elevation difference between PSC w.r.t the DEM and the difference in velocity as Δv. Delaunay triangulation (DT) was used to connect the PSC to form a spatial graph. Because the atmosphere is spatially correlated, its phase contribution between two adjacent pixels $(p_{i,j})$ is neglected (Hanssen, 2001). The unknown's height (Δh) and velocity (Δv) of each connection are estimated through maximizing the periodogram (Perissin and Wang, 2012)

$$\Gamma[\Delta h_{ps}, \Delta v_{ps}] = \frac{1}{N}\left|\sum_{s=1}^{N} e^{j}\,\Delta\psi_{m,s}(p_{i,j}).\, e^{-j}\left(\frac{4\pi}{\lambda}\Delta v(p_{i,j})T_{m,s} + \frac{4\pi}{\lambda R Sin\theta}\Delta h(p_{i,j})B_{m,s}\right)\right| \tag{7}$$

$T_{m,s}$, $B_{m,s}$ are the temporal and normal baseline respectively. The height of the peak of the periodogram can be considered as the likelihood of the estimate for $\Delta h_{ps}, \Delta v_{ps}$. This is also the process of maximizing the temporal coherence and minimizing the residual phase.

$$\{\widehat{\Delta h_{ps}}, \widehat{\Delta v_{ps}}\} = argmax\ \Gamma[\Delta h_{ps}, \Delta v_{ps}] \tag{8}$$

The estimated unknowns are integrated using the reference point selected to obtain the absolute values at each PS candidates. The atmospheric phase for PS candidate pixels are removed and the final PS pixels are selected using a higher threshold on the ADI criterion. The unknown parameters are estimated again for all pixels. This time, no spatial graph among PS points is formed and a periodogram for each point (Ferretti et al., 2001, Foroughnia et al, 2019) is maximized with respect to the previously taken reference point. Eventually, the PS points with high TC values are used to generate the subsidence map.

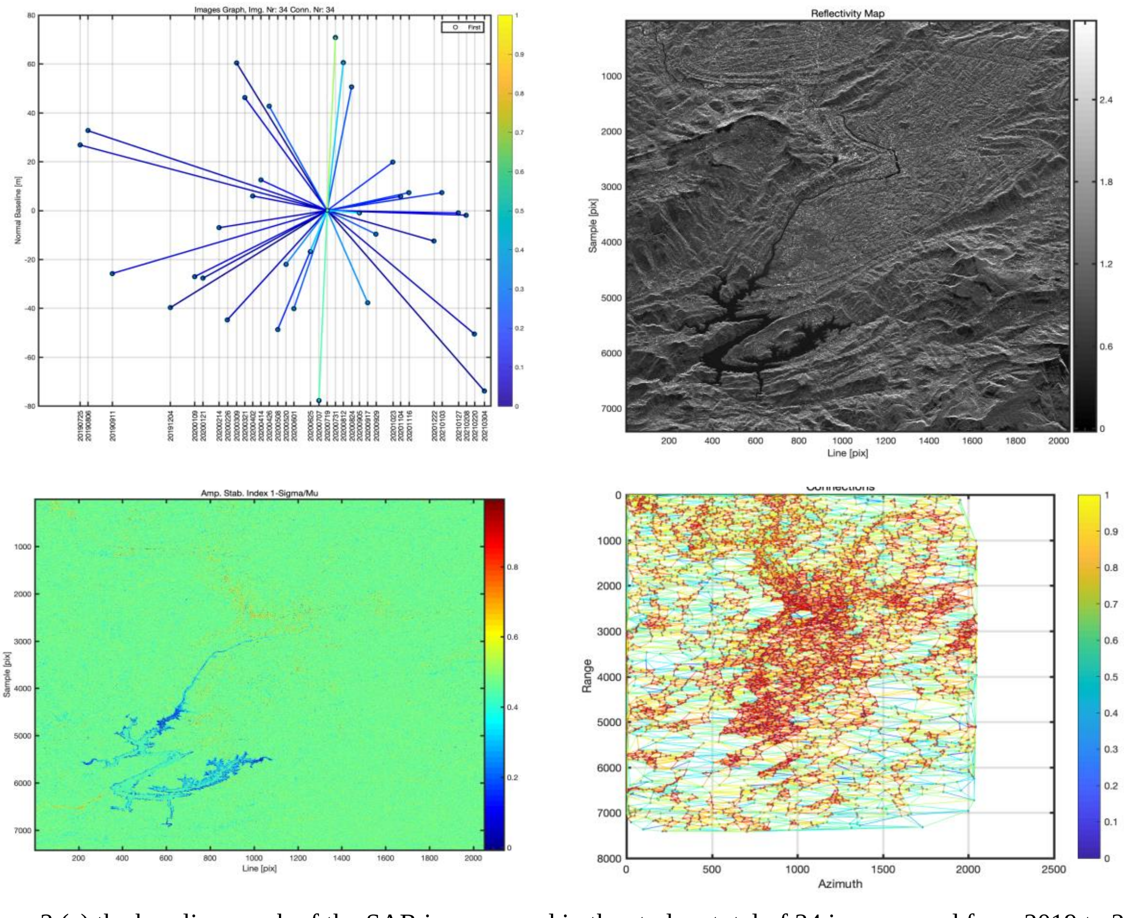

Figure 3 (a) the baseline graph of the SAR images used in the study a total of 34 images used from 2019 to 2021, the master image is on 2020/07/19 (b) Amplitude image of the study area using VV polarization (c) Inverse of the Amplitude stability index image generated using the phase stability of the pixels (d) the Delaunay triangulation on the using of the PSC points, points of 1-ASI>0.7 was used for the analysis

4. Results and Discussion

As short communication we provide a part of the study especially focused to the results from the ascending S1-A data. We first investigated the deformation foot print using a zero-baseline interferometric pair. This pair of images are from 19th July 2020 and 05th September 2020. It is possible to be come to conclusions that starting event with a magnitude of 3.5 on the Richter scale with two consecutive tremors, and the one with the highest magnitude to occur could have its influence recorded in these images. It is also important to mention that the master image chosen later with the Ps-InSAR is also the master image in this zero-base line interferometric analysis. From the available ascending data sets for the study this pair of images hold a normal baseline of 2.03 which we consider the best candidates for a near zero baseline analysis. By a zero-baseline analysis we consider the interferometric phase to have the deformation component only as with the zero-baseline configuration the topographic phase contribution has been removed. The interferometric phase was unwrapped prior to the derivation of displacement. Figure 4 shows the results. The overall analysis suggests that southern cross section running from Kandy towards Victoria dam signifies a movement away from the ascending sensor in a magnitude of 7mm. Isolated movement patterns could also be investigated in the slopes in the northern part of Kandy running towards "Mathale town" and in the eastern slopes as well.

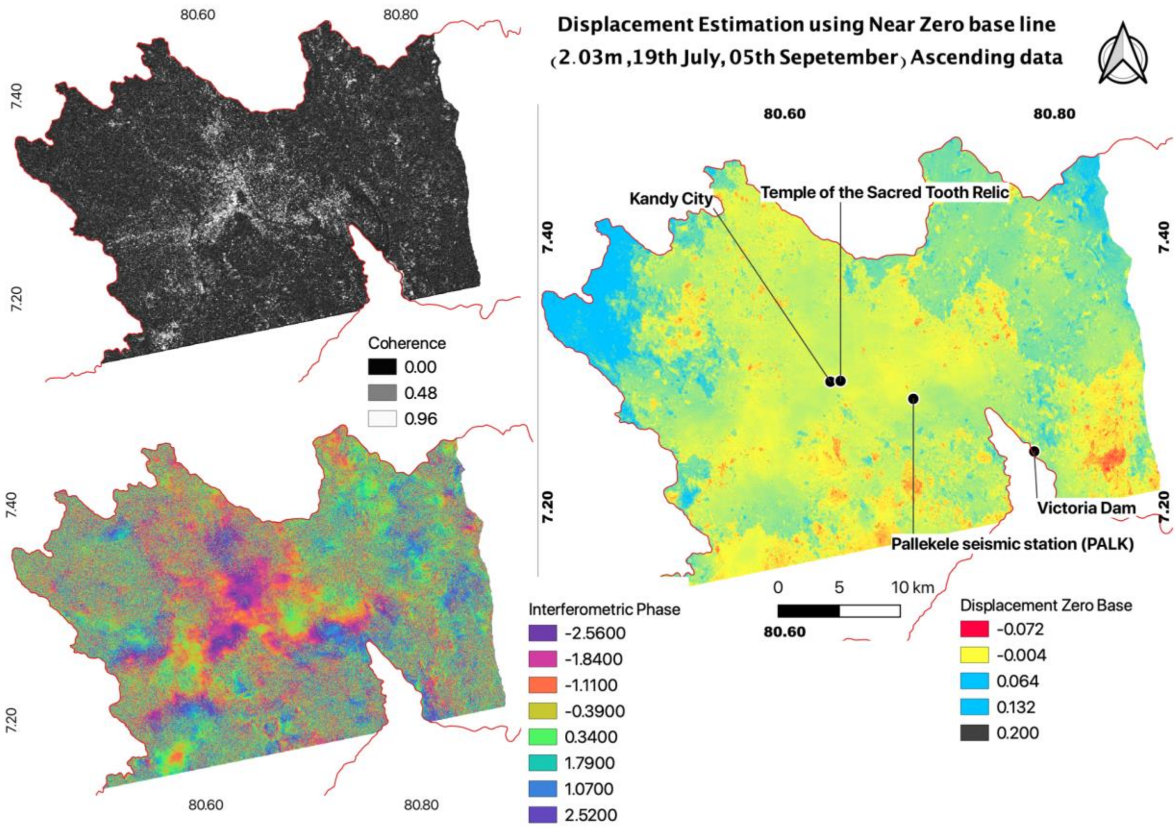

Figure 4. Zero base line deformation signal of the area, the master image chosen for the PS analysis on 19/07/2020 was one of the two images used along the zero baseline

Moving towards the PS-InSAR analysis results, Figure 5 and Figure 6 shows the PS points with temporal coherence> 0.92 with their linear velocity and the nonlinear cumulative displacement results respectively. Further number of PS points in the two images are 3927 and 3947 respectively. As indicated by the Zero-baseline interferometric pair the southern slopes running from Kandy towards the Victoria dam shows movements along the LOS direction. Especially on the southern part of the Victoria dam shows movements in the range of -30mm/year. This study was conducted using the images till the end of March 2021. During the study the latest movement on 06th June 2021 was also recorded directly in the southern part of the Victoria dam (News First local media).

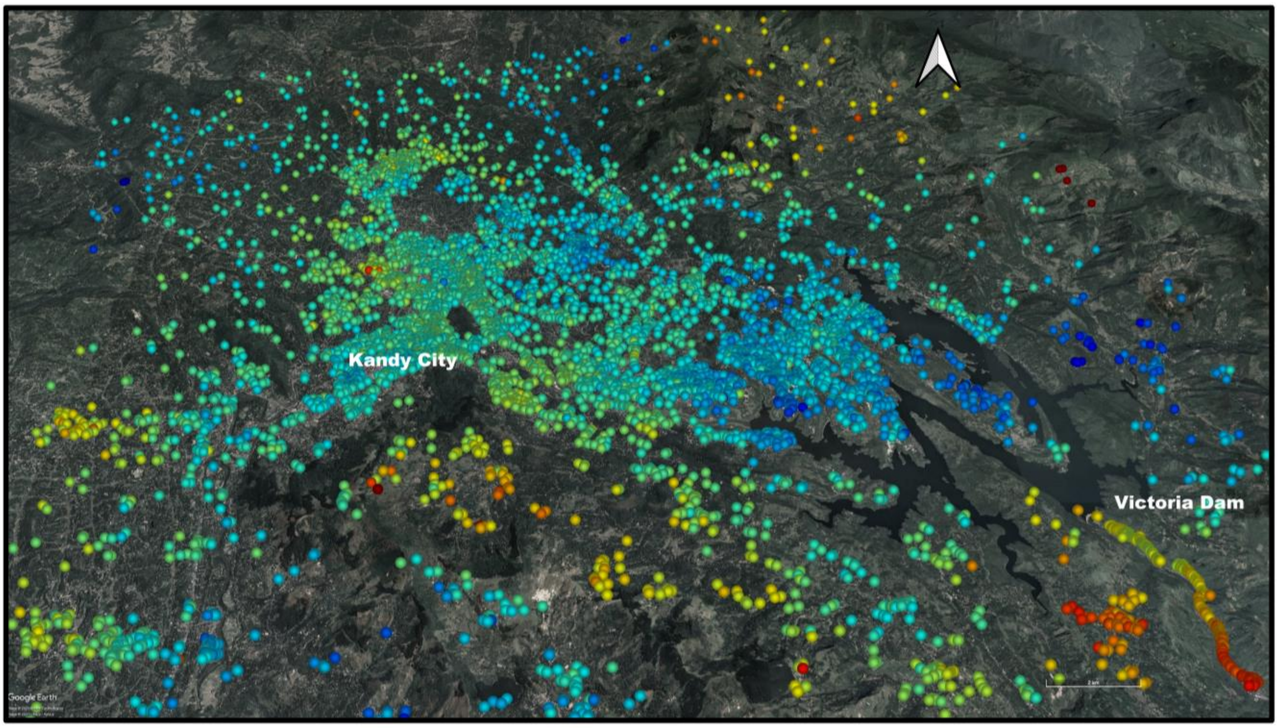

Figure 5 Lineal velocity estimation using the PS analysis, the southern part of the Kandy and the Victoria Dam shows considerable movement towards the south east direction along the LOS of the ascending path of the satellite.

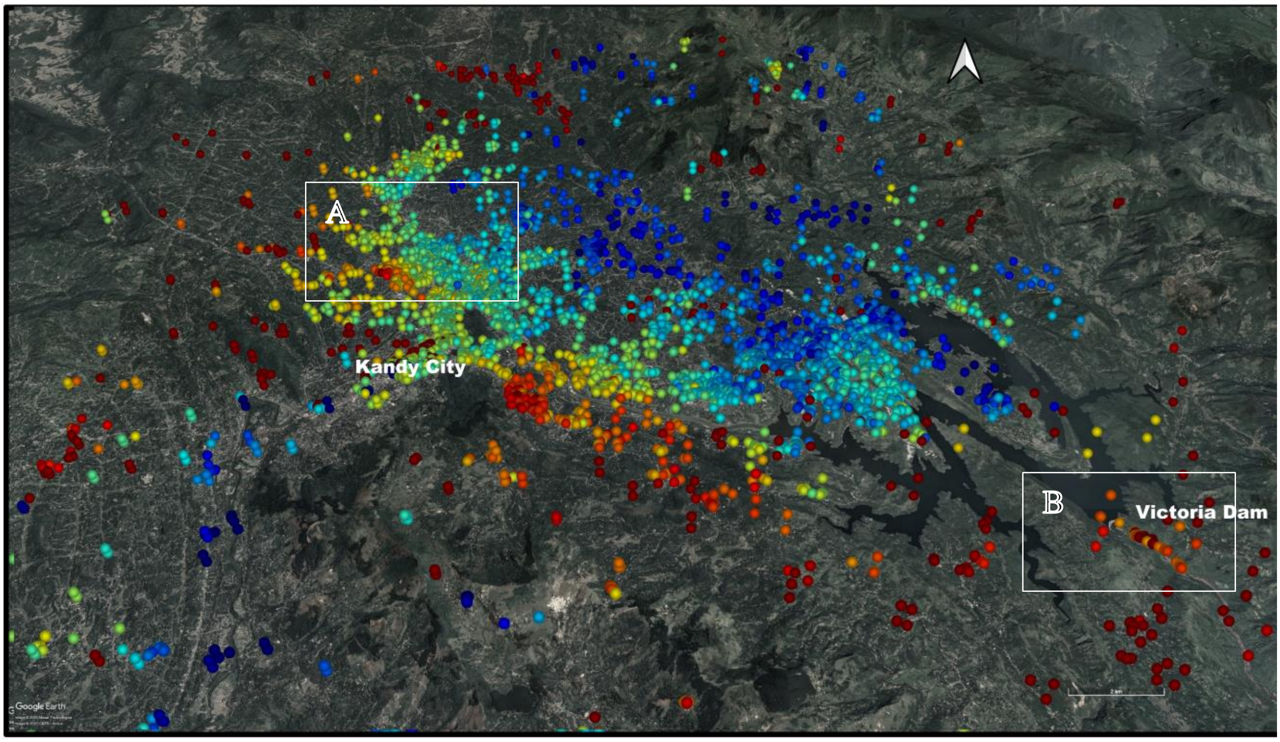

Figure 6 None Lineal cumulative displacement using the PS analysis, which follows the patterns out come from the linear model

The deformation pattern extracted by the linear velocity models are quite similar to the patterns identified by the nonlinear models for the movement. The cumulative movement along the LOS of the ascending image was around -40mm/year in the regions with maximum movements indicated. This general observation was made by looking at a large number of PS points which need to be investigated more closely with the possible geodetic leveling data for a more confirmed conclusion. In order to see closely this movement, we have selected three PS points in representing three sample areas of the whole study. They are around the Kandy Temple, Kandy Railway station and the western slopes of the Victoria Dam. The deformation represented by the velocity is shown in the Figure 7. The visuals pattern we have investigated earlier has quantified in this. Out of the three PS points the permanent scatterer near the Victoria dam indicate movement in the range of -15mm/year as this area is directly subjected to movements recorded by the ongoing series of minor earthquakes. On the contrary the other two points belonging to the city area shows reasonably stable topography. This is further elaborated by the Table 1.

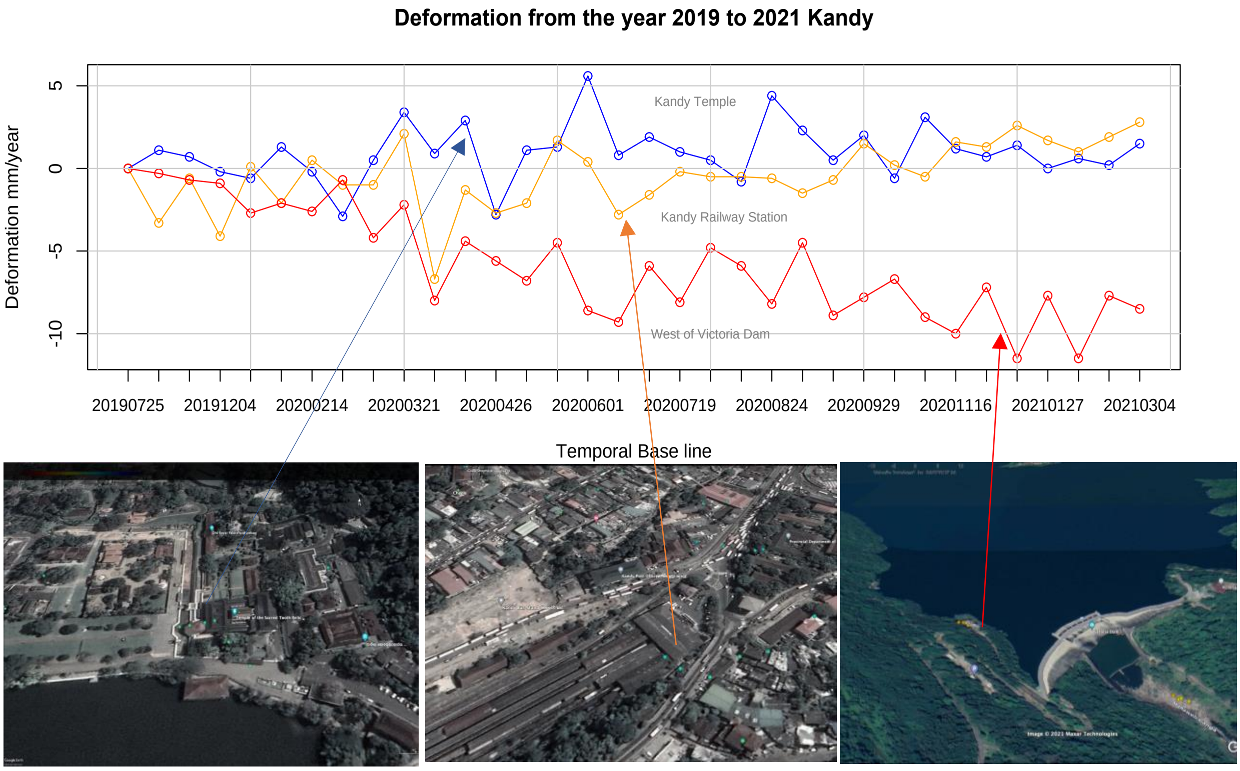

Figure 7 Three area of concern, Kandy Temple, Kandy Railway station and the Victoria dam, Selected PS pixels are shown in the respective sub images. PS pixel temporal coherence is ≥ 0.92. PS pixels towards west of Victoria dam shows movement in the range greater than 10mm/year, while Kandy city and its surrounding is more stable in its topography

Table 1 Average Deformation range for the area A and B Figure 6

Area	Average Deformation (mm)	Temporal Coherence
A	-10 (mm) to -40(mm)	>0.9
B	0(mm) to -20(mm)	>0.9

4. Conclusion and recommendation

This is an initial investigation of the effect of currently ongoing collapse earthquakes in the region of Kandy Sri Lanka. The results suggest that the area is subjected to deformation especially towards north east direction. The city area of Kandy could be considered to have more stable topography while the frequent earth quake occurring area near the Victoria dam shows more significant movements. This need further analysis with the possible use of levelling or GNSS data. PS-InSAR provide a good framework to study deformation patterns with the aid of stable scattered on the ground. The movements are highly related to the highest coherent point targets detected with the use of InSAR time series. The study area concerned in this investigation is exposed to limestone quarrying, long time drilling to extract limestone creating cracks causing the areas to collapse due to water pressure, existing crack towards the eastern slope of the Mahaweli River, changes in soil layers in the interior of the earth. As mentioned by (Vithanage, 1972) certain amount of movement towards the satellite showing the uplifting need further investigation. Part of the PS-InSAR analysis has been documented in this paper, while continued investigation with the ground truth will continue.

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