Angkor site monitoring and evaluation by radar remote sensing

Fulong Chen^{*a,b}, Aihui Jiang^{a,c}, Natarajan Ishwaran^b

^a Key Laboratory of Digital Earth Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, No. 9 Dengzhuang South Road, Haidian District, Beijing 100094, China; ^b International Centre on Space Technologies for Natural and Cultural Heritage under the Auspices of UNESCO, No. 9 Dengzhuang South Road, Haidian District, Beijing 100094, China; ^c College of Geomatics, Shandong University of Science and Technology, No.579 Qianwangang Road Economic & Technical Development Zone, Qingdao, Shandong, 266510, China

ABSTRACT

Angkor, in the northern province of Siem Reap, Cambodia, is one of the most important world heritage sites of Southeast Asia. Seasonal flood and ground sinking are two representative hazards in Angkor site. Synthetic Aperture Radar (SAR) remote sensing has played an important role for the Angkor site monitoring and management. In this study, 46 scenes of TerraSAR data acquired in the span of February, 2011 to December, 2013 were used for the time series analysis and hazard evaluation; that is, two-fold classification for flood area extracting and Multi-Temporal SAR Interferometry (MT-InSAR) for ground subsidence monitoring. For the flood investigation, the original Single Look Complex (SLC) TerraSAR-X data were transferred into amplitude images. Water features in dry and flood seasons were firstly extracted using a proposed mixed-threshold approach based on the backscattering; and then for the correlation analysis between water features and the precipitation in seasonally and annually. Using the MT-InSAR method, the ground subsidence was derived with values ranging from -50 to +12 mm/yr in the observation period of February, 2011 to June, 2013. It is clear that the displacement on the Angkor site was evident, implying the necessity of continuous monitoring.

Key words: Angkor site, ground subsidence, MT-InSAR, flood disaster

1. INTRODUCTION

Angkor, in the northern province of Siem Reap, Cambodia, is one of the most important world heritage sites of Southeast Asia¹. It is well-known for the Temple of Angkor Wat, Angkor Thom, the Bayon Temple and many other monuments of the different capitals of the Khmer Empire from the 9th to the 15th century. As the first stage, UNESCO has set up a wide-ranging programme to safeguard this symbolic site and its surroundings since 90s of last century. At present, the conservation measurement of this site has stepped into another stage; that is, the sustainable development focusing on the interaction of environment and human-being activities. Seasonal flood and ground sinking are two representative hazards in Angkor site, as illustrated in Figure 1. In recent three years, one severe floods hit this archeological site (occurred in 2011). Flood hazards cause physical damages and also aggravate the erosion process of ancient remains. Furthermore, the problem posed by both flooding and groundwater fluctuations initiates ground subsidence and in turn causes structural damage of ancient remains.

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Synthetic Aperture Radar (SAR) remote sensing has played an important role for the Angkor site monitoring and management². In this study, 46 scenes of TerraSAR data acquired in the span of February, 2011 to December, 2013 were used for the time series analysis and hazard evaluation; that is, two-fold classification for flood area extracting and Multi-Temporal SAR Interferometry (MT-InSAR)³ for ground subsidence monitoring.



Figure 1. Study site of Angkor (rectangle in red highlights the TerraSAR-X spatial coverage). This world heritage faces challenges from floods and collapses of ancient remains.

2. DATA AND EXPERIMENTAL SITE

2.1 TerraSAR data

TerraSAR-X is German Earth-observation satellite, successfully launched on 15 June 2007. Its aim is to create new, high-quality radar images of the Earth's surface using an X-band radar sensor with a range of different modes of operation, allowing it to record images with different swath widths, resolutions and polarizations. In this paper, the 46 scenes of 3 m resolution Stripmap SAR images in the acquisition from February, 2011 to December, 2013 were used, making a tradeoff between wide spatial coverage (30×50 square kilometers) and high spatial resolution (see Table 1). Those cycle-revisited Single Look Complex (SLC) data, in ascending orbit, HH polarization with incidence angle of 44.5°, cover the most region of Angkor World Heritage site, as marked by the red rectangle in Figure 1. The pixel spacing of images in range and azimuth direction is 1.364 m and 1.977 m, respectively.

No.	Acquisition	No.	Acquisition		
	(yymmdd)		(yymmdd)		
1	20110216	24	20120921		
2	20110310	25	20121002		

Table 1. The parameters of multi-temporal TerraSAR-X images applied in this investigation.

3	20110321	26	20122024		
4	20110401	27	20121104		
5	20110412	28	20121207		
6	20110504	29	20121229		
7	20110526	30	20130109		
8	20110617	31	20130120		
9	20110709	32	20130131		
10	20110720	33	20130211		
11	20111016	34	20130305		
12	20120225	35	20130316		
13	20120307	36	20130418		
14	20120318	37	20130429		
15	20120409	38	20130510		
16	20120420	39	20130521		
17	20120512	40	20130612		
18	20120603	41	20130623		
19	20120614	42	20130704		
20	20120706	43	20130908		
21	20120717	44	20131113		
22	20120819	45	20131124		
23	20120830	46	20131216		

2.2 Experimental site

Angkor is one of the most important archaeological sites in South-East Asia containing the magnificent remains of the different capitals of the Khmer Empire, from the 9th to the 15th century. The ruins of Angkor are located amid forests and farmland to the north of the Tonle Sap Lake and south of the Kulen Mountian, near modern-day Siem Reap city (13°24'N, 103°51'E), in the Siem Reap Province, Cambodia⁴, see Figure 1. UNESCO has set up a wide-ranging programme to safeguard this symbolic site and its surroundings. Up to now, many of the temples at Angkor have been restored, and together, they comprise the most significant site of Khmer architecture. However, the sustainable development of Angkor site are still facing challenges in aspects of flooding, temple collapses, deforestation, urbanization, over-tourism, and etc. Influenced by tropical climate (annual average temperature is around 24°C), the precipitation of Angkor site is approximately 2000 mm yr⁻¹; and 80% of that is contributed by the precipitation in the rainy season spanning from May to October. Consequently, flood hazards are always occurred during the rainy season in the site, not only influence the tourism and agriculture, but also accelerate the weathering process of the ancient ruins. Furthermore, the sandy soils under the monuments tends to instable induced by water-table dropping and seasonal ground water variation, resulting in crack, fissures and even collapses on ancient temples. The situation could be more serious due to the rocket rising of tourist (10,000 in 1993 increases to more than 3,000,000 in 2013), which leads to excessive pumping of ground water, particularly in dry seasons.

3. METHODOLOGY

3.1 Mixed-threshold for flood extraction

Generally, flood extraction on remote sensing images equals to a two-fold classification problem. Taking advantage of the merits of Otsu⁵ and two-dimensional maximum entropy⁶ approaches, in this study, a mixed threshold method was developed for the flood extraction. Owing to the introduction of neighborhood image textures, the classification capability of this method has been enhanced along with the suppressed noise-sensitivity in SAR images. Furthermore, in order to improve the computation efficiency, a three-step classification solution was proposed. Firstly, the two-dimensional maximum entropy approach was applied to derive an initial threshold t_0 for the classification of *water feature A* and *background B*. Second, the Otsu method was applied for the sub-classification of *A* and *B* respectively to derive *water feature A1*, *A2* and *background B1,B2*. In this stage, the *A1* and *B2* have been determined using the threshold of t_1 . Third, the Otsu method was again applied for the further confirmation of *A2* and *B1* to determine the

final optimal threshold of t_2 .

3.2 MT-InSAR for ground sinking monitoring

Owing to the development of spaceborne platforms, the spatial resolution of SAR data has increased by an order of magnitude from tens of meters to a meter (e.g. TerraSAR-X, Cosmo-SkyMed, Radarsat-2). High resolution is beneficial for detail information detection; however, several of key issues will be arisen, including the enhanced effects of layover, shadow and foreshorting, phase ambiguity and multi-route reflection, resulting in difficulties for phase unwrapping and signature discrimination. MT-InSAR, the advances of differential SAR interferemetry (DInSAR) technologies, including the Persistent Scatterers SAR Interferometry (PS-InSAR)⁷⁻⁸ and Small Baseline Subsuts (SBAS)⁹⁻¹⁰, are capable of deriving motion measurements as high as millimeters, due to the intrinsic limitations (e.g. spatial-temporal decorrelation and atmospheric disturbance) overcome by means of the phase analysis in the temporal domain. Generally, the procedure of MT-InSAR can be comprised by seven steps: 1) co-registration of multi-temporal SAR images, 2) interferogram combination and generation, 3) Reference image simulation and co-registration; 4) point targets identification and selection, 5) flattening and topographic phase removal, 6) velocity and residual height inversion, 7) deformation calculation and atmospheric delay isolation.

In this study, the PS-InSAR with the least square solution was developed for the ground deformation inversion covering the whole scene of TerraSAR-X. Compared with current PS-InSAR methods^{7-8,11}, the developed PS-InSAR has following improvements. 1)Assuming no phase ramp is existent for any neighboring target points, the differential phase analysis is employed in our model, analogical with the persistent scatterer method^{7-8,11}. The assumption holds on urban areas, particularly when high-resolution SAR data are involved due to the high spatial density of persistent scatterers. Then, the least square approach is used for increment components (velocity and height) estimation. It avoids phase ramps caused by the occurrence of multiple peaks using the periodogram method. 2) During the integration of increment components, an optimum routine searching algorithm is developed to avoid low-reliable neighboring points (e.g. connection with a long arc). That is, the integration routine is guided by the connection constructed by a minimum spanning tree.

4. RESULTS AND ANALYSIS

4.1 Flood monitoring and analysis

Flooding is one of significant hazards in the World Heritage of Angkor site. In this study, 28 scenes of TerraSAR-X images through the acquisition of 2011-2013 were selected for the water feature extraction and the flood monitoring. Taking the dry season acquisition of March 10 and flood season of October 16 in 2011, the performance of the three two-fold classification approaches mentioned in Section 3, including Otsu, two-dimensional maximum entropy and the mixed threshold, were firstly compared using the grey-level amplitude SAR images. The corresponding statistical results were summarized in Table 2. Compared with the result of Otsu (underestimation) and two-dimensional maximum

entropy (overestimation), it is clear that the mixed threshold approach derives a moderate classification. Extracted water features by the three approaches also shown the same phenomena, as illustrated in Figure 2. That is, omission detection of Otsu and false-alarm detection (e.g. swampy areas) of two-dimensional maximum entropy VS. an optimal estimation of the proposed mixed threshold method.

For the significant factor analysis, the mixed threshold approach was applied for the water feature extraction and then the time series analysis using the 28 scenes selected TerraSAR-X images. The relationship between the water body expansion/shrinkage and the precipitation was further investigated. Results demonstrated that the seasonal or annual variation of water bodies in Angkor was impacted by the precipitation, indicating a consistent trend for the water body expansion and the precipitation rising in flood seasons (e.g. July to October), as illustrated in Figure 3. After that, the linear regression model was applied for the quantitative analysis. Results shown that although not significant, there is a positive linear correlation between the variation of the monthly precipitation and the water bodies extracted, indicated by the R^2 coefficients of 0.077 in 2011, 0.132 in 2012 and 0.054 in 2013, respectively. This low correlation can be interpreted from two-folds. 1) It implied that there are other factors linked to the occurrence of floods in Angkor site, such as the downstream runoff of Mekong River and the water level rise of Tonle Sap Lake, apart from the local precipitation. 2) The difference of SAR and precipitation data in aspects of temporal sampling and spatial resolution induces measurement alias.

Acquisition	Otsu		Two-dimensional maximum entropy		mixed threshold	
	Grey Threshold	Extracted water body pixels	Grey Threshold	Extracted water body pixels	Grey Threshold	Extracted water body pixels
20110310	36	35885918	133	76884520	54	36443974
20111016	60	47552026	110	61524376	83	53679328

Table 2. Performance comparison of Otsu, two-dimensional maximum entropy and mixed threshold methods



Figure 2. Comparison of Otsu, two-dimensional maximum entropy and mixed threshold in water feature extraction using the dry and flood SAR images in 2011.



Figure 3. Correlation plot between water bodies (pixels) and the monthly local precipitation (mm) in temporal.

4.2 Deformation monitoring and analysis

Nowadays, the potential collapse of temples remains a potential threat to the conservation and sustainable development of Angkor site. One hypothesis widely supported by the staff of the Authority for the Protection and Management of Angkor and the Region of Siem Reap (APSARA) claims that on-going changes in the ground-water table, due to increasing demand for water to meet the needs of the management of Angkor as well as that of resident communities and a growing number of visitors, was a significant cause that increases the vulnerability of monuments to collapse.

42 scenes of TerraSAR data acquired in the span of February, 2011 to June, 2013 were used for the surface deformation estimation and time series analysis. The acquisition of June 3, 2012 was selected as the reference image for the PS-InSAR analysis to minimize the potential decorrelation induced by spatial-temporal baselines as well as the Doppler centroid difference. The corresponding interferogram formation was illustrated in Figure 4. Using the developed PS-InSAR with the least square solution, the surface subsidence was derived with values ranging from -50 to +12 mm/yr for the observation period, as illustrated in Figure 5. It is clear that displacement was evident in selected places in Angkor site and its surroundings, implying the relationship between monument collapses and the ground subsidence. Owing to the combination of high-resolution SAR images and improved PS-InSAR data procedures, the spatial distribution of detected PS have been enhanced, although the site locates in a tropical region with dense vegetations. The past field investigation conducted in June, 2014 confirmed that three primary factors induce surface deformation. Firstly, the structural instability along with the surrounding surface movement induced by the seasonal and annual variation of underground water levels, e.g. the ancient temples collapsed in subregion, as illustrated in Figure 5 (a). Secondly, the surface deformation induced by the urbanization, e.g. soil compression and compaction by the downward pressure from constructed buildings or traffic vehicles. Finally, the surface movement induced by the accelerated soil erosion after the vegetation was burned down, as illustrated in Figure 5 (b).



Figure 4 Interferogram formation in the proposed PS-InSAR data procedures. The acquisition image of June 3, 2012 was selected as the reference image.



Figure 5 PS-InSAR derived annual velocity rates of Angkor site using 42 scenes multi-temporal TerraSAR-X data in the observation span of February, 2011 to June, 2013. (a) Detected deformation linked to collapses of ancient temples; (b) deformation linked to the erosion deterioration of land surface after the vegetation was burned down.

5. SUMMARY

In this study, the flood and surface instability were monitored using 46 scenes of high resolution TerraSAR-X data in the acquisition from February, 2011 to December, 2013. A mixed threshold algorithm was developed for the fine extraction of flooding impacted regions, and results indicated its better performance than classical approaches, e.g. two-dimensional maximum entropy method. The seasonal and annually analysis indicated that the correlation between flood impacted areas and the precipitation is relatively low, implying the contribution of Tonle Sap Lake for the water supply from the downstream of Mekong River. The surface deformations derived by the improved PS-InSAR demonstrated that the sandy soil under the monuments at Angkor is instable jointly induced by the ground water over-pumping as well as the seasonal variation of its levels.

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