ENVIRONMETAL STUDIES

Radar interferometry offers new insights into threats to the Angkor site

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The conservation of World Heritage is critical to the cultural and social sustainability of regions and nations. Risk monitoring and preventive diagnosis of threats to heritage sites in any given ecosystem are a complex and challenging task. Taking advantage of the performance of Earth Observation technologies, we measured the impacts of hitherto imperceptible and poorly understood factors of groundwater and temperature variations on the monuments in the Angkor World Heritage site (400 km^2). We developed a two-scale synthetic aperture radar interferometry (InSAR) approach. We describe spatial-temporal displacements (at millimeter-level accuracy), as measured by high-resolution TerraSAR/TanDEM-X satellite images, to provide a new solution to resolve the current controversy surrounding the potential structural collapse of monuments in Angkor. Multidisciplinary analysis in conjunction with a deterioration kinetics model offers new insights into the causes that trigger the potential decline of Angkor monuments. Our results show that pumping groundwater for residential and touristic establishments did not threaten the sustainability of monuments during 2011 to 2013; however, seasonal variations of the groundwater table and the thermodynamics of stone materials are factors that could trigger and/or aggravate the deterioration of monuments. These factors amplify known impacts of chemical weathering and biological alteration of temple materials. The InSAR solution reported in this study could have implications for monitoring and sustainable conservation of monuments in World Heritage sites elsewhere.

INTRODUCTION

As the legacy from the past and the common wealth to future generations, heritage is essential for social development and transmission of cultural identity. Nowadays, sustainability of World Heritage sites faces a number of challenges from aggravated modern anthropogenic activities coupled with rapidly changing landscapes. Earth Observation technology provides a feasible platform for monitoring and conservation of heritage, considering its capability for synoptic and objective assessments.

Angkor, located in northwestern Cambodia, is famous for its ancient temple complex constructed in laterite blocks, sandstones, and bricks. As the remnant of the pinnacle of the ancient Khmer architecture, the site has attracted intensive research on archaeological mapping (*1*–*3*), safeguarding and preservation of monuments (*4*, *5*), and the search for other cities and monuments of the Khmer civilization within the broader Angkor heritage landscape (*6*, *7*). More recently, a new awareness of the role of the natural environment in the future conservation of Angkor has dawned among high-level officials of the Cambodian government [for example, the Authority for the Protection and Management of Angkor and the Region of Siem Reap (APSARA)] and a number of international partners collaborating with APSARA to ensure long-term safeguarding of the site for the benefit of current and future generations.

Collapse of monuments, a potential threat to the conservation and sustainable development of World Cultural Heritage sites (*8*, *9*), could be unforeseen and sudden. Field investigations demonstrate that deterioration of monuments is common and is often evidenced by the presence of cracks, fissures, and collapses (see fig. S1). Considering the risks to the authenticity of the monument posed by dismantling/reassembly and other interventions during restoration, careful assessments of threats to monuments and feasibility analysis of restoration are critical. The International Coordinating Committee for the Safeguarding and Development of the Historic Site of Angkor (ICC-Angkor) (*10*), established in 1993, has stressed the importance of research on a detailed understanding of the intrinsic causes of monument collapse and supported and encouraged preventive approaches that can support conservation of monuments and facilitate restoration efforts.

Nonetheless, the causes of structural instability and decay of monuments in the Angkor site are still poorly understood. A widely held hypothesis (*11*) postulates that the ongoing decline of the groundwater table, driven to a significant extent by an increasing demand for water to meet the needs of Angkor, resident communities, and a rapidly growing number of visitors (a 300-fold increase from 10,000 in 1993 to 3,000,000 in 2013), could increase the probability and frequency of collapse of monuments. However, data and analysis to test this hypothesis have not yet been available. In the past 10 years, some investigations in Angkor have focused on the surveillance of the structural instability of monuments using in situ measurements (*12*) and geotechnical analysis (*13*). Those studies have measured soil/stone decay and destruction due to overgrowth from trees, providing valuable information for the safeguarding and restoration of monuments. The Angkor site is well known for the Angkor Wat Temple, Angkor Thom, the Bayon Temple, and many other globally renowned monuments; their conservation is critical to the sustainability of the outstanding universal value of the Heritage site. Studies focusing on a single temple or components of the monument could lead to solutions that are partial and fragmentary and may not ensure the sustainable conservation of the entire monument zone. Moreover, structural motion anomalies could lead to the potential collapse of individual

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temples and increase the vulnerability of other monumental components in their immediate vicinity.

Resolving the kinetics of monument structural instability and movements of the surrounding lands by synthetic aperture radar interferometry (InSAR) (*14*) is highly feasible owing to the development of multitemporal SAR interferometry (MT-InSAR) (*15*–*19*), a powerful tool for monitoring subtle movements over a large surface area at millimeter-level accuracy. Recently, MT-InSAR has been successfully applied for the detection of anomalies in movement of monuments and for preventive diagnosis in the Olympic site in western Greece (*20*) and in the ancient monuments of Rome (*21*); however, results of these applications could be of limited value when detailed structural motion data and analyses are lacking. Tomography-based persistent scatterer InSAR (Tomo-PSInSAR) (*22*), an innovative methodology that combines the strengths of persistent scatterer InSAR (PSInSAR) and SAR tomography, addresses some of these defects and promises to be of crucial importance for future monitoring of monuments.

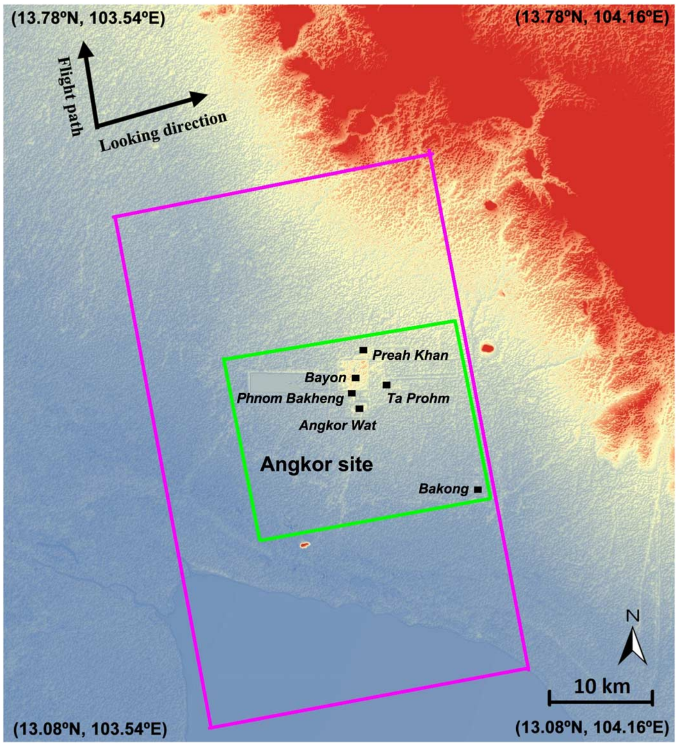

Fig. 1. The area covered by the TerraSAR/TanDEM-X SAR data is highlighted by the pink rectangle, and the area within the Angkor World Heritage site, where the detailed studies reported in this work were undertaken, is shown by the green rectangle (courtesy of the Shuttle Radar Topography Mission Digital Elevation Model data from the U.S. Geological Survey). The map was generated by ArcMap 10.0 (www.esri.com).

RESULTS

Traditional safeguarding and conservation in Angkor focus on monument restoration once susceptibility to collapse is observed by visual inspection, point-based measurement, or geotechnical analysis. However, inability to detect early-warning signs of deterioration over a sufficiently large area of the monument zone can result in collapse occurring at unexpected locations. Here, we report our efforts to detect movement of monuments and neighboring land surface of a 22 km × 18 km area within the Angkor World Heritage site (Fig. 1). We developed a two-scale Tomo-PSInSAR approach (see Materials and Methods) applied to 45 scenes of images from German twin Earth Observation satellites TerraSAR/TanDEM-X (a second and almost identical spacecraft to TerraSAR-X) (see the Supplementary Materials for description of data). Movements detected in the line of sight have profoundly improved our understanding of the vulnerability of monuments to collapse and thereby contribute to the long-term conservation of Angkor.

Regional-scale Tomo-PSInSAR

Using the reference point (highlighted by a white star in Fig. 2) located at the terminal building of the Siem Reap International Airport, regional-scale Tomo-PSInSAR results revealed no surface subsidence holes across the whole site (Fig. 2). However, mild to moderate values (−5 to −12 mm/year) of deformation were concentrated on the Siem Reap City (in particular the eastern subzone) compared to the relatively stable surface (within −4 mm/year) of the central archaeological zone of the Angkor site that is 5 to 7 km away north of Siem Reap. Urbanization has increased markedly since 2000, probably peaking during 2011 to 2013 (fig. S2). The rapid growth of Angkor tourism is a major contributor to the significant expansion of urban land cover. Urbanization has a significant impact on the short-term decline of groundwater tables because of the increasing water demand for infrastructure development as well as for residential and recreational facilities, resulting in the growing risk of potential irreversible sinking of surface on the sandy-clay soil that is already subject to the downward pressure of buildings. Hundreds or perhaps thousands of private wells (fig. S3) in the densely populated region contribute to mild surface subsidence in the city (Fig. 2). Groundwater is pumped out of public wells (fig. S3) located in the southwestern tip of the Siem Reap International Airport (black circles in Fig. 2). We did not detect surface subsidence in this region (measurements in the area approximately within −2 mm/year), implying that the volume of water being pumped out is within the threshold limits. Compared with other subzones, steady trends of ground surface occurred in areas near the Siem Reap International Airport, Srah Srang, and the Preah Khan Temple in the vicinity of water reservoirs (Barays) including the West Baray, North Baray, and Srah Srang. Apart from irrigation, Barays are generally used to recharge groundwater by direct infiltration and are assumed to facilitate sustainable water supply for temple moats. Year-round availability of water in moats can help to stabilize the moisture content of the sand layer, which provides the foundation of most monuments. Since 2005, APSARA has launched several hydrological projects for the Angkor site; one project involves maintaining or raising the water level of reservoirs, such as those in the Srah Srang, Angkor Thom, and Angkor Wat moats, all of which have been restored to their maximum water-holding capacity. North Baray, which had long been dry, was rehabilitated by collecting 700,000 m^3 of water in 2008, 2,980,000 m^3 in 2009, and 3,678,000 m^3 in 2010, reaching its maximum capacity of 5,000,000 m^3 in 2011 (*23*). These measures have most likely contributed to surface stability observed around the Preah Khan Temple, west of Angkor Wat, and other monuments around Srah Srang (Fig. 2). The groundwater table beneath the airport region can be replenished by the water supply from West Baray as well as from moats of Angkor Thom and Angkor Wat. Observation data from 15 boreholes (marked by pink squares in Fig. 2) surrounding the central monument zone, as illustrated in Fig. 3, indicated significant seasonal variations (ranging

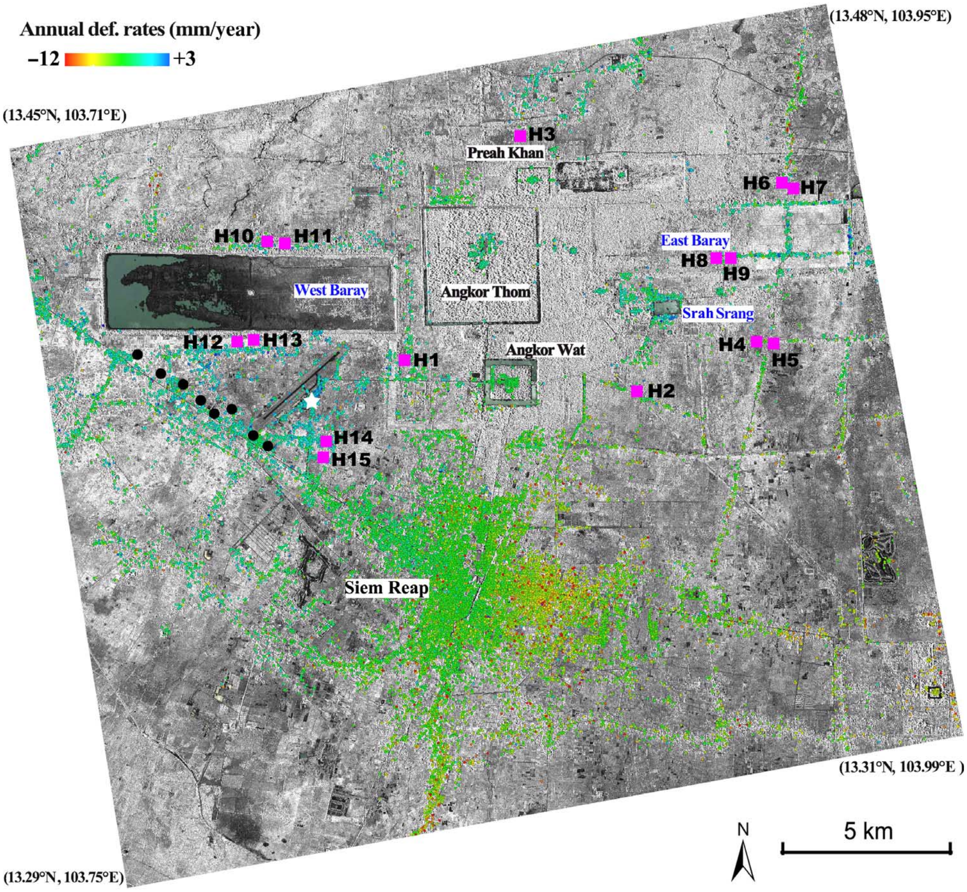

Fig. 2. Regional-scale Tomo-PSInSAR–derived annual deformation rates around the Angkor site (reference point is located at the terminal building of the Siem Reap International Airport, shown by the white star) for the 2011–2013 observation period (overlapped on the averaged amplitude of SAR imagery). Surface stability and/or mild subsidence was observed (less than −4 mm/year) surrounding the central archaeological zone, including the Preah Khan Temple, west of Angkor Wat, and other monuments around Srah Srang, which can be attributed to not only the restoration of the ancient hydraulic system but also maintaining or raising the water level of reservoirs. The locations of public groundwater pumping wells and observation boreholes are indicated by the black circles and pink squares (indicated by H1 to H15), respectively. Urbanization surrounding the densely populated areas was rapid, leading to a mild to moderate (−5 to −12 mm/year) surface subsidence in the Siem Reap City region. TerraSAR/TanDEM-X data were provided by Deutschen Zentrums für Luft- und Raumfahrt (DLR; http://sss.terrasar-x.dlr.de/) under the General AO project (CAL2073).

from a depth of 4 to 0.5 m relative to the ground surface) as well as a steady annual trend of groundwater tables from the shallow aquifer during the 2009–2014 observation period. APSARA has the authority to regulate the rate of pumping out of water in public and private wells. Consequently, APSARA and local authorities must collaborate to keep installation of public or private wells a safe distance away from the World Heritage monument zone to prevent potential ground subsidence (such as the mild to moderate values evident in Siem Reap urban regions) from affecting areas in and around the monument zone.

Monument-scale Tomo-PSInSAR

By extracting overlaid PS points as well as an estimation of the thermal expansion and/or contraction of materials, monument-scale Tomo-PSInSAR was designed for detection of structural motion anomalies (relative to a stable reference point in the vicinity of the monument monitored) (see Materials and Methods). Spatial motion heterogeneities were evident in a representative sample of ancient temples, including Preah Khan, Bayon, Phnom Bakheng, Ta Prohm, Angkor Wat, and Bakong (fig. S4), with values ranging from −3 to +3 mm/year. However, the surface surrounding those temples was generally stable (Fig. 2). These monument- or component-scale measurements can signify structural instability and diagnose emerging problems by identifying susceptible locations of evident motion velocity or inconsistent motion trends. Taking the Angkor Wat Temple for instance, the motion anomalies (Fig. 4) could be easily detected with an internal precision of 0.2 mm/year (statistical significance of results included in the Supplementary Materials) and an accuracy of approximately 1 mm/year, as reported by Ferretti *et al.* (*15*, *16*). Cracks or manual repairs were found in monuments in those "hot spots" during the field investigation conducted in 2014. In combination with appropriate on-site confirmation of deformation anomalies (the heterogeneity of motions and thermal amplitudes) detected via Tomo-PSInSAR, their implication for the conservation of World Heritage monuments and the sustainable development of surrounding regions could be objectively assessed and evaluated.

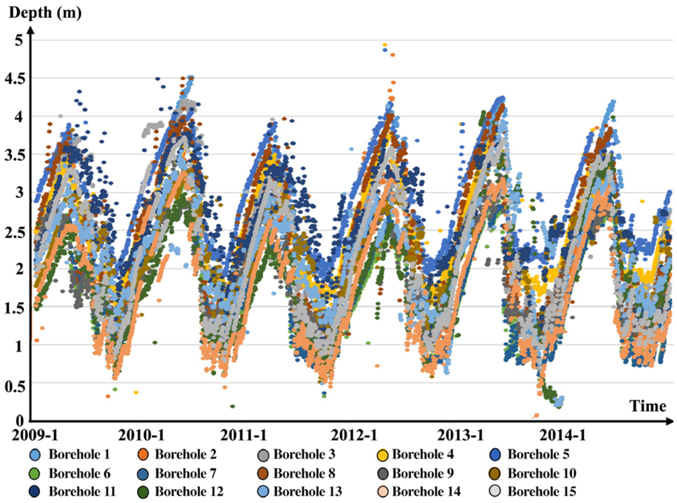

Fig. 3. Groundwater data on 15 boreholes observed in the vicinity of the central monument zone of the Angkor site (pink squares in Fig. 2), indicating a steady condition of the shallow aquifer system during 2009 to 2014. Seasonal variations of groundwater tables were significant and were modulated by the wet-drought monsoonal climate with values ranging from a depth of 4 to 0.5 m relative to the ground surface.

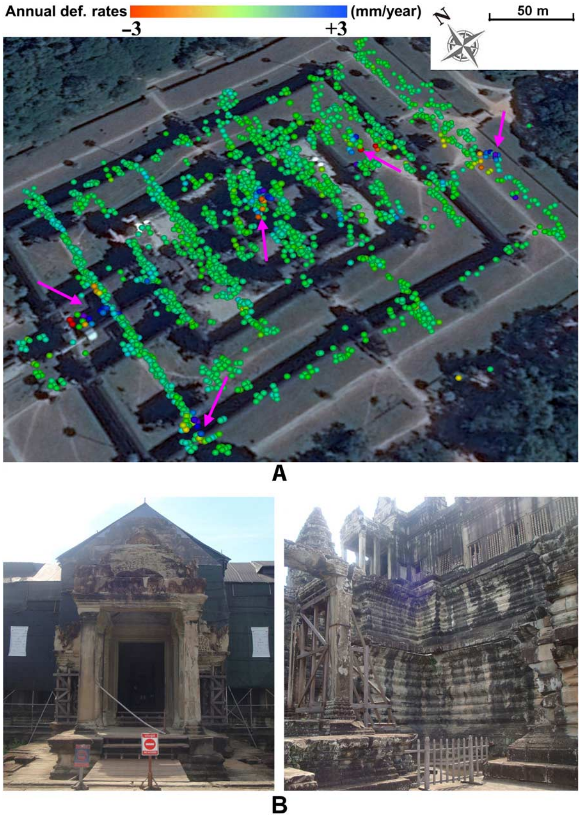

Fig. 4. Monument-scale Tomo-PSInSAR–derived results in Angkor Wat for the 2011–2013 observation period. (**A**) Annual deformation rates show the spatial motion heterogeneity (overlaid on a QuickBird imagery provided by DigitalGlobe, www.digitalglobe.com/). (**B**) Two examples of vulnerable monuments [marked by pink arrows in (A)] with cracks and where maintenance work was under way, as seen during field investigations in 2014. Photographs were provided by F.C. from the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences.

Implications

In general, the detection of motion anomaly on ancient temples in the Angkor site is a challenging task considering the imperceptible (for example, millimeter level) scale of changes that occur in a vegetated landscape. The two-scale Tomo-PSInSAR solution that we developed was effective in detecting surface movements linked to the structural instability of monuments. Note that subtle (−3 to +3 mm/year) structural movements may be ignored in the short term, but their cumulative impacts, particularly in the context of continuous uneven structural kinetics over decades resulting in cracks that are centimeters to decimeters wide, could accelerate deterioration significantly. Hence, those defective monuments need to be stabilized immediately to prevent the said structural movements from compounding other factors that contribute to future collapse.

DISCUSSION

The most significant contribution of this TerraSAR/TanDEM-X InSAR study is that it provided a new solution to resolve the decline of monuments in the Angkor site. The Angkor basin, a Quaternary alluvial floodplain (Fig. 5) with sand and clay deposits, was formed by the sedimentation of the eroded sandstone from the Kulen Mountain. A drill core conducted in 1994 revealed that the near-surface geology in the Angkor site is a substrate of ancient and impermeable sandstone overlaid by an approximately 80-m depth of highly permeable

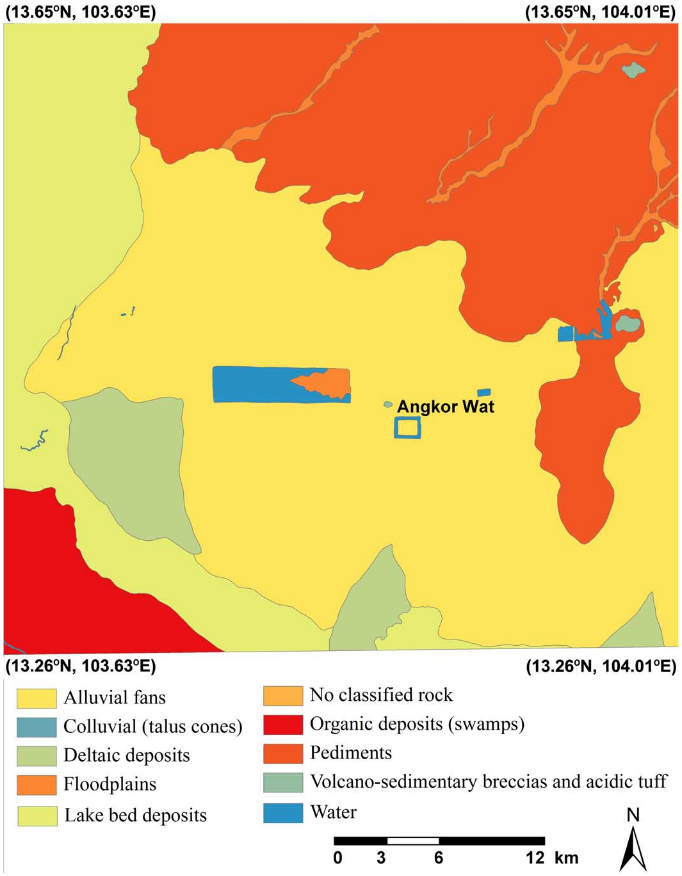

Fig. 5. Geology map of the Angkor site. The map was generated by ArcMap 10.0 (www.esri.com).

Quaternary sedimentation (*24*). From a geological aspect, sandy-clay soils under the monuments can be destabilized by groundwater overexploitation as well as by seasonal groundwater variation. The prevalent notion for monument collapse (*11*) claims that the ongoing decline of the groundwater table due to increasing water extraction by resident communities and a rocketing number of visitors negatively affect monument stability in Angkor. Regional-scale Tomo-PSInSAR–derived results imply a decline in groundwater tables, particularly those in the densely populated region of Siem Reap City where rapid urbanization, which occurred during the period of observation (fig. S2), was accompanied by the installation of thousands of private water pumps. However, no direct, location- or monument-specific destructive signs of groundwater depletion that could affect monument stability were detected (for example, uniformly stable surface of the temples illustrated in Figs. 2 and 4 and fig. S4) within the World Heritage site. During the study period between 2011 and 2013, groundwater exploitation in the Angkor site was under control because there appears to be sufficient replenishment due to abundant rainfall characteristic of the tropical monsoonal climate (annual precipitation around 1200 mm; see Fig. 6A) and the overall improvements to the hydrological regime of the area put in place by APSARA through restoration of the water-holding Barays or reservoirs within the Heritage site (*23*). These restoration efforts have also stored the remaining water in the moats and water-holding structures longer, thereby further stabilizing the groundwater tables within the World Heritage area (validated by the stable annual groundwater tables during 2009–2014, as shown in Fig. 3). However, water demands are highest during the dry season when water replenishment potential is at its lowest. The cumulative impacts of rapid urbanization, explosive growth in visitor numbers, tourism and hospitality infrastructure, and continuing deforestation in the Kulen Mountain (the source of Puok, Siem Reap, and Roluos rivers that feed the Angkor hydraulic system and that supply the needs of residents of and visitors to

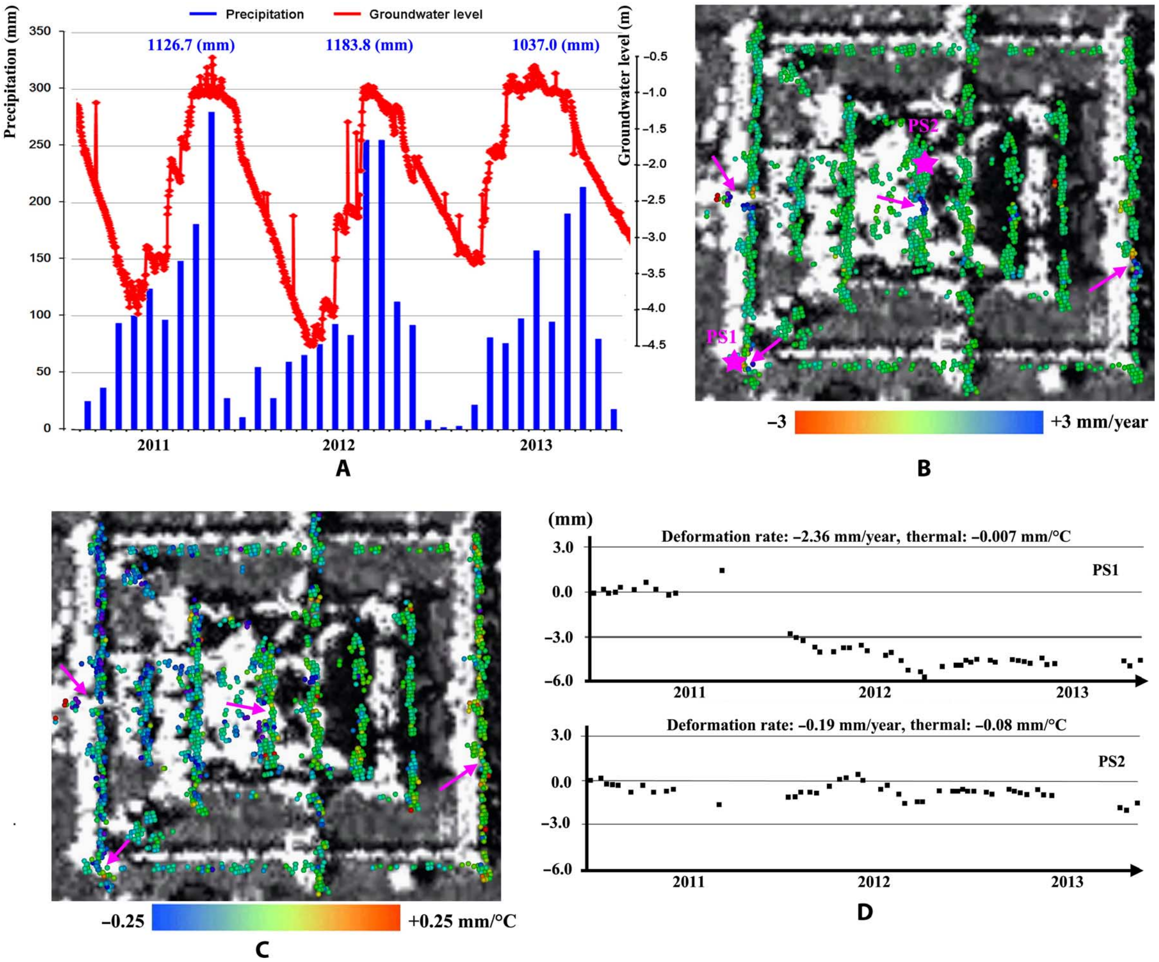

Fig. 6. Observed triggering evidences of seasonal groundwater tables and the thermodynamics of stone materials. (**A**) Correlation between groundwater level and precipitation. An intense seasonal variation in groundwater level (–4.5 to –0.5 m), coupled with annually steady groundwater table, was seen detectable in the central archaeological zone of Angkor after the restoration of the Barays, which stabilized groundwater tables despite a decrease in annual precipitation from 2012 to 2013 (that is, 1183.8 mm in 2012 dropping to 1037.0 mm in 2013). (**B**) Annual deformation rates of the Angkor Wat Temple, indicating irregular fragmentary motions with values ranging from –3 to +3 mm/year; (**C**) thermal amplitudes in SAR line of sight direction, indicating spatial differences with values ranging from –0.25 to +0.25 mm/°C (overlaid on the averaged amplitude of SAR imagery); and (**D**) deformation time series of two representative PS points, PS1 with mild subsidence and PS2 with a steady trend, marked by pink stars on (B). A positive correlation between the seasonal variation of the groundwater table and the nonlinear motion of PSs was detectable. The co-occurrence of structural instabilities and thermal amplitude dispersions was also observed [highlighted by the pink arrows in (B) and (C)]. TerraSAR/TanDEM-X data were provided by DLR (http://sss.terrasar-x.dlr.de/) under the General AO project (CAL2073).

the Angkor World Heritage site) are nevertheless significant causes for concern that may affect the future balance of the groundwater table. Moreover, any climate change trend that may extend the dry season (and thus shorten the rainy season) and disrupt the evenness of the distribution of precipitation during the rainy months will heighten future risks to maintaining current balance in the groundwater table and monument collapse.

We also investigated the impact of seasonal groundwater variations and material thermodynamics using the monument-scale Tomo-PSInSAR–derived motion time series (see Materials and Methods) of the Angkor Wat Temple together with monthly precipitation [raw data of precipitation and daily temperatures were obtained from World Weather Online (*25*)] and geological data.

We first observed a highly positive correlation between groundwater levels and seasonal precipitation during the 2011–2013 period (Fig. 6A). The deterioration of the structural instability of monuments was supported by deformation rates ranging from −3 to +3 mm/year (Fig. 6B). Angkor Wat combines two basic components of Khmer architecture: three rising rectangular galleries and the central temple towers. Owing to the uniform nature of soil-bearing capacity (at monument scale under homogeneous geological conditions; see Fig. 5), we did not detect diverse fragmentary motions at gallery levels. We then analyzed the thermal amplitude of the stone material of monuments (Fig. 6C). With values ranging from −0.25 to +0.25 mm/°C (corresponding to a linear thermal expansion coefficient of 5.0×10^{-5} to 6.0×10^{-5}, which is in agreement with physical property of sandstones), the temple shows a spatial heterogeneity of thermal expansion and/or contraction, up to ±2 mm, calculated from multiplying thermal amplitudes by temperature amplitudes of seasonal variations (8° to 9°C; table S1). We also observed the anomalous co-occurrences of motion and thermal amplitude values (highlighted by pink arrows in Fig. 6, B and C), which suggest the contribution of thermal effects to the vulnerability of monuments. Field measurements (*26*) indicated that the groundwater level around the World Heritage site is right at the surface during the rainy season but drops 5 m during the dry season. We postulated that, apart from known driving forces, such as chemical weathering (*5*, *13*, *27*) and biological alteration of stone materials (*28*), the seasonal variation in groundwater level can be another imperceptible factor that could contribute to the long-term decline of Angkor monuments. Swelling-shrinking movements (on the order of submillimeters to a few millimeters; for example, approximately 1 mm in this case) of sand layer foundations beneath monuments can trigger staggered pressures on structural instability during wetting-drying cycles (Fig. 6B and fig. S4), as observed by motion time series of the Tomo-PSInSAR measurements (Fig. 6D; PS1 with a mild subsidence and PS2 with a stability trend), pointing to sinusoid or semi-sinusoid seasonal motion trends. These movements could be caused by high porosity and permeability of the Quaternary sediment that lies above bedrock (located 80 m below the surface), particularly due to elastic kinetics induced by the variation in shallow parts of the aquifer (less than 5 m depth. Soluble salts from the subsurface reinforce the chemical weathering process of foundation rocks (*13*) as well as the structural instability of monuments, driven by the up-and-down dynamics of groundwater tables in a wet-dry seasonal cycle. Therefore, rehabilitation of the ancient hydraulic system in the Angkor site is thoroughly beneficial for the sustainable conservation of monuments because it could contribute to stabilizing the groundwater table, particularly in the context of potential future changes in rainfall distribution and intensity resulting from climate change.

We further explored the links between groundwater variation, thermodynamics of materials, and monument stability by modeling the deterioration process of Angkor ruins to explain the decline in the stability of Angkor monuments (Fig. 7). The combination of seasonal variations in groundwater and thermal amplitude of materials triggers and aggravates a natural deterioration process of the monuments because of heterogeneous structural motions. An entire rigid motion of monuments predominated initially, after completion of construction; but, with the progress of time (that is, tens to hundreds of years), this bulk motion turned into irregular fragmentary motions, and monuments became weak because of the combination of material decay and other impacts. The interaction of material decay, thermodynamics, and seasonal surface motion caused a progressive mild to severe structural instability over the long term, finally leading to monument collapse.

CONCLUSION

This study highlights the need (which has been prioritized by the ICC for Angkor since 2012) to shift the management of the Angkor World Heritage site from reliance on traditional temple-based conservation methods to use of environmental approach that regulates activities of communities and institutions in the landscape surrounding the site. In an entire geo-ecological system, the impacts of geology, hydrology, climate change, and anthropogenic activities interact and combine with one another, whether these systems are near-natural ones, such as those in the Amazon (*29*, *30*), or significantly altered and built environments, such as Angkor (*31*). Using the two-scale Tomo-PSInSAR monitoring scheme, the factors that could trigger the potential decline and eventual collapse of monuments in the Angkor site have been illustrated by the detection of quantitative precursor movement anomalies. Conventional monitoring approaches, such as in situ

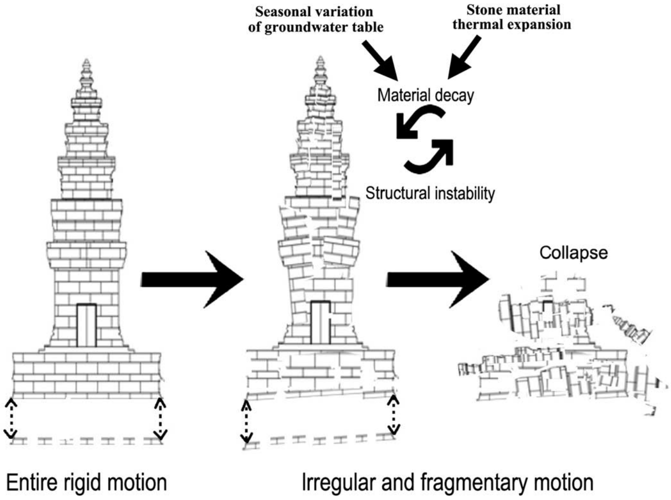

Fig. 7. Deterioration processes affecting ancient monuments because of the interaction of material decay, material thermodynamics, and seasonal variations of the groundwater table. The model shows that an entire rigid motion dominant in the early stages immediately after a temple had been constructed gradually gives way to irregular and fragmentary motions over the long term (for example, hundreds of years) due to variability in seasonal fluctuations of groundwater tables and thermal expansion of stones, which together trigger and/or aggravate structural instability and decay, increasing the risk of monument collapse.

measurements (*12*) and geotechnical analysis (*13*), may have to be significantly supplemented by Earth Observation techniques and tools, because of the significant advantages offered by the latter in terms of large-area coverage, high spatial resolution, frequent revisit cycles, and noninvasive detection approaches.

This study has clearly shown that pumping of groundwater either in public or in private wells does not cause an immediate region-wide surface subsidence that threatens the sustainability of monuments. This conclusion has been substantiated with data and analysis up to the 2013 completion date of this study. However, imperceptible influence of seasonal variations in the groundwater table and thermal expansion of temple materials are newly recognized contributory factors to the long-term deterioration of monuments, which is normally driven by other natural causes, such as sandstone weathering (*13*, *27*) and biological alteration (*28*). Consequently, (i) maintenance of groundwater table stability by increasing replenishment sources and structures that can hold water throughout the year in areas surrounding the temples should be seen as an approach that would minimize seasonal groundwater variations and their medium- to long-term impacts on structural motion of monuments; and (ii) use of materials with a uniform thermal property would be an advisable measure in the ongoing restoration of monuments to avoid variability of structural motions that could be triggered by diverse thermodynamics of heterogeneous materials. In future work, we intend to investigate the impacts of the growing tourism industry on local geology underneath the temples and their immediate surroundings.

MATERIALS AND METHODS

The detection of movement anomalies using spaceborne InSAR was targeted to a 22 km × 18 km area, including south (core monument of the Bakong Temple) and central (core monument of Angkor Thom) areas of the Angkor archaeological park (Fig. 1). Our aim was to extract millimeter-level deformation variations of surface soil and structural instability of monuments through a two-scale monitoring scheme using four-dimensional (*22*, *32*) and extended four-dimensional (*33*) Tomo-PSInSAR methods. By exploiting amplitude information in addition to phase information, Tomo-PSInSAR slightly outperforms PSInSAR (*15*, *16*) in the detection of PS points (*34*).

Forty-five scenes of TerraSAR/TanDEM data (from 103.54°E to 104.16°E and from 13.08°N to 13.78°N), in the Stripmap mode with a ground spatial resolution of 3 m, and the corresponding temperature values at 10:00 a.m. local time (1 hour and 15 min before the acquisition of SAR imagery) were acquired for the period from February 2011 to December 2013 and were used for movement calculation and modeling.

We developed a four-dimensional (estimating both the elevation and linear deformation rate by reconstruction tomography in the space-time domain) Tomo-PSInSAR with a two-tier network for parameter estimation. In the first-tier network, we integrated beam forming with an M-estimator (*35*) at the arcs of the Delaunay triangulation network of reliable single PSs (SPSs) and then applied a ridge estimator (*36*) for network adjustment based on one reference point (located at the terminal building of the Siem Reap International Airport) for the whole area. Because of the densely vegetated landscape, a relax arc distance (for example, 1200 m) was applied to construct a uniform network covering the whole Angkor World Heritage site. In this case, atmospheric artifacts between two PS points connecting an arc cannot be ignored. Consequently, we introduced an additional procedure to normalize the motion velocity field for the removal of the low-frequency atmospheric artifacts in the spatial domain. By comparing motion parameters on overlapping SPSs estimated from the relax scheme with the rigorous experimental one (arc distance within 400 m), indicating a statistical difference of less than 1 mm/year, we validated the robustness and accuracy of the relax scheme used. In the second-tier network, we detected the remaining SPSs by constructing local star networks referring to SPSs detected in the first-tier network. For the atmospheric artifacts and unmodeled nonlinear motions, we applied a high-pass filter and a low-pass filter, respectively, to the time series residual signal at each arc (subtracting the height and linear motion components) and then integrated them. Finally, we derived the final accumulated time series deformations with reference to the first acquisition by combining linear and nonlinear motions.

Although it was feasible to identify subsidence holes and hot spots with significant surface motions in the regional-scale Tomo-PSInSAR, the results express averaged movements of PS targets, at approximately every 9 m^2 or less, with an assumption of one SPS in one pixel. Taking unfavorable shadowing/layover on SAR images into account, the spatial density of measured SPS points was relatively sparse, particularly on the tower-shaped temples with multiterraces in Angkor. The motion anomaly in this vertical direction is undetectable using the regional-scale method, although it is critical for the structural instability monitoring and defect diagnosis. Considering the capability of separating multiple PS points in overlaid areas, in the monument-scale monitoring, we made an extension for the Tomo-PSInSAR model (*33*). First, we extracted the overlaid double PSs by using a local maximum ratio method in the second-tier network construction as well as for parameter calculations. Second, we introduced the extended four-dimensional model to estimate geophysical parameters of elevation, linear deformation velocity, and thermal amplitude to assess the impact of thermal expansion and/or contraction of materials on the vulnerability of monuments. Note that the preliminary removal of atmospheric phase screen is not needed for the developed Tomo-PSInSAR method owing to the two-tier networks strategy that was applied. For more technical issues in the application of this strategy, please refer to the study by Ma and Lin (*37*).

Here, unknown parameters in Tomo-PSInSAR models were calculated simultaneously, causing the concurrence of high-accuracy or low-reliability inversion of motion and heights. Consequently, the validity of height estimates (for example, the comparison of estimated values with field-measured heights) can, to some extent, validate the estimates of motion (deformation velocities and thermal amplitudes), particularly in case of unavailable ground-based motion data. The robustness of the Tomo-PSInSAR model was qualitatively verified by the estimated tower-shape heights and quantitatively compared with ground-truth height values from the terrace gallery of the Angkor Wat Temple (fig. S5); the robustness of the internal precision of the Tomo-PSInSAR model was validated by a statistically significant motion error of 0.2 mm/year. Moreover, the linear thermal expansion coefficients of temple materials (for example, sandstone with values around 5.0×10^{-5} to 6.0×10^{-5}) estimated by the Tomo-PSInSAR model further validated the accuracy of InSAR results quantitatively.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/3/3/e1601284/DC1

Supplementary Materials and Methods

fig. S1. Collapsing monuments in Angkor site.
fig. S2. Extension of urban land use estimated by the comparison of multitemporal Landsat images for the period 1985–2013.
fig. S3. Field photos of wells for pumping groundwater.
fig. S4. Monument-scale Tomo-PSInSAR–derived annual deformation rates in ancient temples (overlaid on the averaged amplitude of SAR imagery).
fig. S5. Validation of Tomo-PSInSAR–derived motions using the PS heights confirmed by field investigations undertaken in 2014.
table S1. Parameters of acquisition and interferogram formation of TerraSAR/TanDEM-X SAR images and the corresponding temperature data (10 a.m. local time) used in this study; the acquisition of 4 November 2012 (marked by the star) was selected as the reference image.

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