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Preliminary Result

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Integration of satellite subsidence and sea-level data for evaluating the mean high-water line in the Bangkok region: Preliminary result

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***Abstract*— The provinces of Bangkok, Samut Prakan, Samut Sakhon, and Nakhon Pathom in Thailand are experiencing subsidence caused by land subsidence, tectonic activity, and sea-level rise. INSAR result from 2015-2022 show that Bangkok and nearby provinces subsided up to 3 cm/yr in the past 20 years. GNSS results show absolute subsidence rates (below 20 m) up to 5 mm/yr in the past 25 years. According to satellite altimetry data, Bangkok is currently experiencing a sea-level rise of up to 5 mm per year in the Gulf of Thailand. Ground water pumping also play an important role on land subsidence.**

Keywords-Land subsidence, Tectonic motion, Sea Level Change

The combination of land subsidence and sea-level rise poses a significant threat to the residents of Bangkok's coastal areas in Thailand; the main contributor to subsidence is groundwater extraction for drinking water, industry and food. Subsidence in this region is monitored using in-situ leveling, Global Navigation Satellite System (GNSS) observations, and Interferometric Synthetic Aperture Radar (InSAR) analysis. An extensive network of tide gauges is combined with satellite altimetry to monitor sea-level changes; groundwater levels are measured in observation wells. Forecasting subsidence is complicated by uncertainties in model state and parameters, secondary effects such as consolidation of clay, and the lack of in-situ data coverage.

I. Historical background

River deltas provide a living place to more than 500 million people, and many of these deltas are sinking[1-3]. This subsidence increases their susceptibility to flood hazard which is further amplified by global sea-level rise[4]. The societal impact of flood hazards was starkly evident during the 2011 Thailand floods, which involved the Chao Phraya River, the primary waterway flowing through Bangkok into the Gulf of Thailand. Human-induced changes in land use and groundwater extraction have been identified as likely contributors to this flood event[5]. By studying how groundwater extraction affects subsidence and how this combined with the sea-level changes affects the mean high water line, we expect to better understand the influence of groundwater extraction and expected sea-level change on flood hazard. The dramatic event of the 2011 flood, which led to a total of 815 deaths and a total economic damage and loss estimated to be 45.7 billion US dollars[6], underpinned the importance of understanding flood hazard and monitoring sea-level and subsidence, especially in densely populated areas such as Bangkok. This equally true for Ho Chi Minh City, Jakarta, Guangzhou, and other coastal urban areas. Land subsidence can result from natural processes like sediment loading, compaction, and tectonic activity. It can be further exacerbated by human activities, particularly groundwater extraction [3,7]. Historically, studies of land subsidence rely on point measurements, but with the availability of interferometric satellite aperture radar images (InSAR, see Fig. 1),

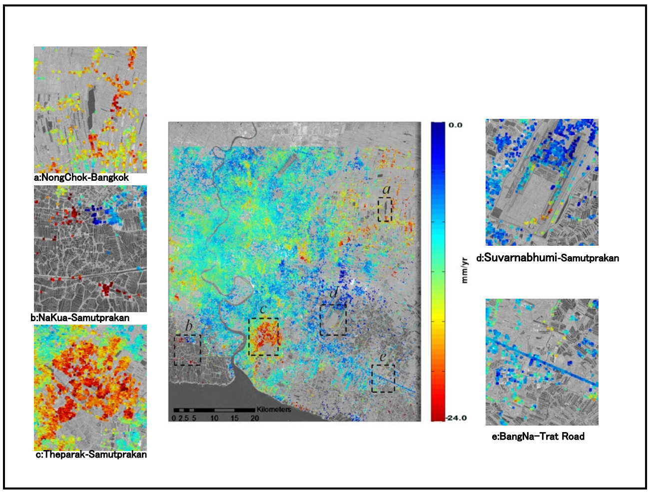

Fig. 1. the most recent published InSAR results (Aobpaet et al, 2013) for the Bangkok area using RADARSAT SAR images in between 2005 and 2010. It shows land-subsidence in Bangkok both at the east and west Chao Phraya river banks, with the maxima occurring mostly in new urban areas and coastal area

the combination of scattered GPS observations, borehole extensometer observations and levelling data with InSAR can provide meaningful analyses e.g.,[7]. Surge-driven water levels are likely to increase as sea level rises [8]. World tide-gauge records show that global mean sea level (GMSL) rose 3.2 ± 0.4 mm/yr between 1993 and 20109, with a strong impact on coastal zones [4]. For the Gulf of Thailand, the 1993-2009 sea level rising rates are in the range of 3 to 5.5 mm/yr [10]. By the year 2100, GMSL are expected to reach levels of 0.43 m to 0.84 m higher than today [9]. Any land subsidence in Bangkok, currently sinking at a rate of 2-3 cm/yr [11,12] will locally increase this number further. The high-water or high-tide line, the line that that marks the limit of the rise of the medium tides of the sea between the spring and neap tides, can be used to locate the coastal boundary [13]. This demarcation will also increase with an increase in sea-level. To examine the mean high-water lines across a broad range of coastal areas, a global digital elevation model (DEM) can be utilized in conjunction with sea level estimates and local one-year return level heights (RL1) derived from the Global Tides and Surge Reanalysis [8,14]. Even with deep cuts to carbon emissions, by 2100, areas in Thailand now home to 17 % of its people may face high-water lines higher than land, not considering episodic flooding events [14]. Since the 1970s, the main contributor to subsidence in the Bangkok area is considered to be the pumping of groundwater for drinking water, industry and food [15]. In addition to these human causes, crustal deformation can also cause vertical land motion[15]. While Global Isostatic Adjustment (GIA) amounts from +0.50 to +0.65 mm per year depending on location, much larger vertical displacements are associated with the 9.1 Mw 2004 Sumatra-Andaman earthquake [10,16]. In addition to the vertical land motions, coastal erosion occurs as a result of the complex interaction of human-induced shoreline changes and natural processes [2,17]. In theory, changes in atmospheric variability and increased rainfall can also increase the likelihood of a flooding event, but in the case of the 2011 Thailand flood, the changes in hydrography of the river Chao Phraya, as well as human-induced changes in land use, specifically groundwater extraction, have been identified as more likely contributors [5].

Satellite and In-situ observations of land subsidence

Land subsidence, with an annual amplitude ranging from a few millimeters to several centimeters, can be precisely monitored using geodetic techniques based on Global Navigation Satellite Systems (GNSS), such as the Global Positioning System (GPS). Between 1994 and 1998, land movement in Thailand was systematically observed through GPS stations established under the Geodynamics of South and Southeast Asia (GEODYSSEA) project [18,19]. In particular the CHON GPS point of this campaign is of relevance for subsidence in the Bangkok area. It has been re-occupied at least annually since 2001 by the Royal Thai Survey Department (RTSD) after the GEODYSSEA ended in 1998. After 1999 the BNKK station provided continuous GNNS data, and the same in 2005, 2008 and 2011 respectively, the RTSD, CUSV, SPKN stations followed to provide continuous monitoring in Bangkok. Additional GPS stations in the region provide complimentary data [16,20]. In addition to these observations, annual levelling campaigns have been conducted since 1978 by the Royal Thai Survey Department (RTSD) [12,21]. Since 2009, these levelling campaigns have been combined with Interferometric Synthetic Aperture Radar (InSAR) analyses for a spatial coverage of subsidence.

Satellite and in-situ observations of local sea level change

Since the 1980s, satellite radar altimeters have provided continuous observations of sea surface heights across the global oceans. This technological advancement has facilitated a broad range of scientific investigations. Researchers have explored diverse topics, including ocean circulation and marine plate tectonics. Specific areas of focus have encompassed planetary-scale waves, interannual climate phenomena such as El Niño, oceanic boundary currents, coastal circulation patterns, tides, and surface waves. Additionally, studies have addressed variations in mean sea level, marine gravity and geoid, bathymetric features, and lithospheric processes, significantly enhancing our understanding of oceanic and geophysical systems. The processing of altimeter observations has advanced tremendously leading to cm accuracy, and since global coverage has increased with the advent of new altimeter missions, the technique has become very valuable for the study of coastal areas, such as Bangkok. Tide gauges observe sea level and fluctuations thereof. As most gauges are installed on land, vertical land motion will need to be corrected for when using tide-gauge observations for sea-level analysis [22]. In addition to in-situ observations of sea level, satellite-borne altimetry has been instrumental in the global analysis of sea level variations since the early 1990s. The data set has well-distributed precise sea-level measurements, unaffected by vertical land motion. Based on a decade of multi-satellite altimetry short-term variability in sea-level is not always geographically uniform [23]. In order to evaluate local sea-level changes, the combination of altimetry and tide-gauge observations can thus prove to be valuable. An analysis conducted from 1940 to 2004, incorporating data from tide gauges and satellite altimetry, reveals significantly higher sea level change trends in the northern region of the Gulf of Thailand compared to the global average. Specifically, the rates at Sattahip and Ko Sichang are estimated at 5.0 ± 1.3 mm/year and 4.5 ± 1.3 mm/year, respectively. These values notably exceed the global sea level change rate derived from tide-gauge data, which stands at 1.8 ± 0.3 mm/year over a comparable observation period from 1950 to 2000 [24]. Two other tide-gauges stations are located in the vicinity of Bangkok: the Pom Phrachunlachomklao and Bangkok Bar. These tidal stations do not have a foundation on the bedrock, and trend lines of the position of these gauges strongly suggest an influence of the settling of the sand layers on which the supporting piles stand. While the influence of vertical land motion of these tide gauges caused them to be excluded from the earlier sea-level analysis of the Gulf of Thailand [10], their observations may be valuable for monitoring ground motion. Observational analyses of sea-level change can be complimented with dynamic models of the ocean circulation. While regional models for tides [25] and waves [26] exist, for long-term sea-level rise, projections are generally taken from ocean climate models [27].

Groundwater Studies

Land subsidence is commonly driven by excessive groundwater extraction. However, accurate simulation of subsidence is often hindered by limited data availability, particularly with regard to input forcings, driving factors, and calibration datasets. In this study, an ensemble-based data assimilation method is employed to enhance the accuracy of land subsidence estimates in Bangkok, Thailand. This is achieved through a coupled data-driven and physics-based modeling approach. Despite the constraints of limited groundwater and subsidence measurements and an approximate estimate of basin-wide groundwater pumping, the methodology proves effective.

This research integrates sparse and noisy groundwater head and subsidence observation data into the Ensemble Smoother with Multiple Data Assimilation (ESMDA) algorithm. This assimilation process leads to improved predictions and more robust uncertainty quantification for groundwater heads, localized pumping rates, and model parameters. The ESMDA framework refines subsidence estimates by constraining the compaction of each modeled geological layer, which is computed based on groundwater drawdown and the specific properties of the layer. Ultimately, the cumulative land subsidence at a well nest is determined as the sum of the compaction across all model layers, aligning with established methodologies [28]. This integrated approach demonstrates the potential to address data scarcity challenges while providing reliable insights into subsidence dynamics in data-limited regions.

II. Preliminary Result

A. Land subsidence

InSAR result also shows relative land-subsidence takes places at rates up to 3 cm/yr in the past 20 years (Fig.2).

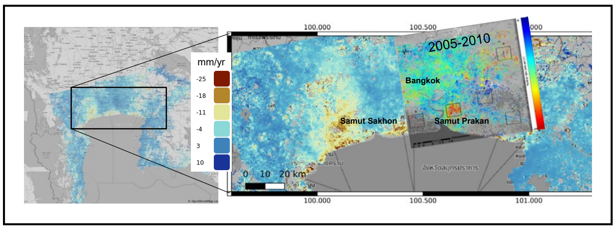

Fig. 2. show subsidence rate in (mm/yr) from 2015-2020 InSAR (Sentinel-1) time series analysis (preliminary / low resolution / based on line-of-sight velocities – vertical component still needs be fully extracted) so subsidence of Bangkok seems to be stabilizing, details from high resolution analysis.

B. Land motion

GNSS result shows absolute subsidence rates (below 20 m) up to 5 mm/yr in the past 25 years (Fig.3).

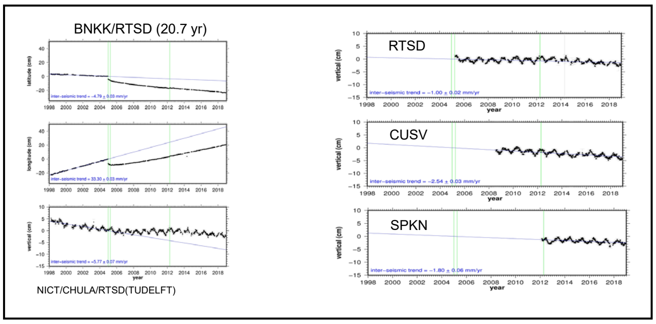

Fig. 3. The station position time series (weekly averaged from 1998 to 2021, based on the IGS14 reference frame) and linear velocity estimates are presented for the RTSD, CUSV, and SPKN stations located in Bangkok, Thailand. The velocities are analyzed in three directions: northward (latitude), eastward (longitude), and vertical (upward). The observation period spans 3.3 to 4.1 years, with position and velocity uncertainties expressed as one-sigma values, representing a confidence level of 68%. For the SPKN station, a position shift (indicated by a green line) was detected in March 2019, attributed to a slight displacement (~1 cm to the southwest) of the antenna pillar after being impacted at the pier.

C. Sea level Changes

The tide gauge near Bangkok indicates relative sea-level rise rates of up to 15 mm per year over the past 60 years, reflecting the combined effects of sea-level rise and land subsidence. Satellite altimetry data estimate the absolute sea-level rise in the Gulf of Thailand to be between 3 and 5 mm per year (Fig.4.).

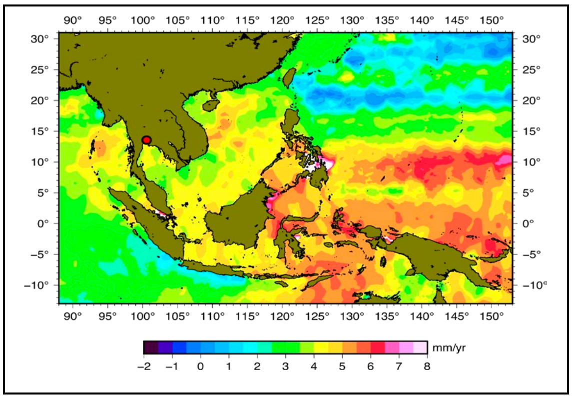

Fig.4. Absolute Sea level Change in Southeast Asia

D. Groundwater studies

ESMDA analysis for Annual rates of land subsidence from 1980 – 2012 are between 0-10 cm/yr which is almost linear since 1990 due to ban for ground water pumping has been active.

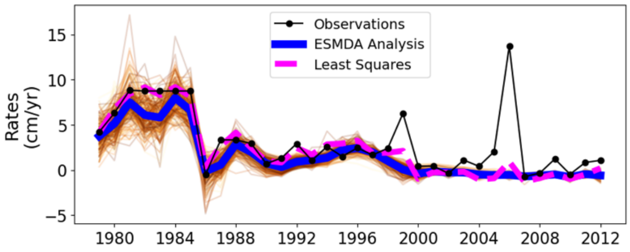

Fig.5. Simulated annual rates of land subsidence at well nest BKK005 compared to benchmark levelling from 1980-2012

III. CONCLUSION

Absolute sea level rise due to climate change is undeniable and SALT shows Bangkok is presently facing a rate of up to 5 mm/yr in the Gulf of Thailand. Whether this is an even bigger threat is depending on what the land is doing:

- GNSS result shows absolute subsidence rates (below 20 m) up to 5 mm/yr in the past 25 years.
- InSAR result shows relative land-subsidence takes places at rates up to 3 cm/yr in the past 20 years.
- TG near Bangkok show relative sea-level rise rates up to 15 mm/yr in the past 60 years (combined effect of sea-level rise plus land-subsidence)
- Subsidence : RMSE of well nest BKK006 decrease from 2.9 to 2.1 cm/yr after implementing ESMDA

The simultaneous use of multiple observation techniques allows for the calibration of different measurement systems. Tectonic subsidence resulting from the 2004 magnitude 9.2 mega-thrust seismic event could raise the relative ocean surface height in the Bangkok area by up to 10 cm in the coming decades. Groundwater pumping and sea-level rise increases flood risk in this area. If no appropriate measures are taken, the Greater Bangkok Region faces progressive coastal land loss and increased/permanent flooding during the next decades. Mostly the ground soil level is affected as buildings with deeper foundations subside at lower rates.

It is clear that the relative sea level change needs to be continuously monitored to get awareness of its possible threat to Bangkok. For this we need to continued GNSS, SALT, InSAR, and TG data. Cooperation between TU Delft, Thai universities and government agencies started in previous EU-ASEAN projects is ongoing and will be extended with additional Thai partners. It is important to seek national and international funds for realizing and sustaining this unique scientific research efforts. The results from this study can be utilized by policy makers and stakeholders for planning in order to prevent Bangkok from gradually becoming an underwater city in the near future.

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