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Cumulative Land Subsidence in Populated Asian Coastal Cities

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Abstract

In contrast to sea-level rise, which is often associated with climatic and environmental changes, land subsidence has largely been overlooked in discussions regarding future adaptation to higher sea water levels. In order to articulate the critical contribution of this phenomenon, this short paper provides a reliable chart that details the historical progression of land subsidence in densely populated East and Southeast Asian coastal cities. The causes of subsidence at these locations are also discussed based on existing literature. Land subsidence was observed to be one or two orders of magnitude faster than sea-level rise caused by anthropogenic global warming, and can continue unabated unless its root causes are addressed through clear policies at the municipal level. Subsidence is clearly a localized problem, and is thus easily overlooked by regional or national governments. Nevertheless, once subsidence takes place it cannot be reversed, and hence it is crucial to rapidly formulate appropriate countermeasures when it is identified. The examples of these Asian cities demonstrate that, if subsidence is recognized and adequate policies are put in place and implemented, it can be brought under control in a fairly short period of time.

Keywords

Asian coastal cities, Land subsidence, Long-term observations, Subsidence rate, Sea-level rise, Flood

1 Introduction

The Intergovernmental Panel on Climate Change 6th Assessment Report projected global mean sea level rise (SLR) by 2100 to be between 0.63 m – 1.01 m higher than the 1995 – 2014 period under the RCP 8.5 scenario (Fox-Kemper et al., 2021). Expert judgement estimates that for a 2ºC degree warming, global mean SLR (GMSLR) could be between 0.36 m – 1.26 m by 2100 (Bamber et al., 2019). Such drastic changes in sea levels could have serious impacts on human development and infrastructure along the coastline.

Low-lying coastal areas are the most vulnerable to flooding induced by SLR. Currently, almost 900 million people (accounting for 11% of the population of the world) are living in coastal areas that are lower than 10 m in elevation above mean water levels (Haasnoot et al., 2021), which could grow to 1 billion people by mid-century (Oppenheimer et al., 2019). Vulnerability assessments have indicated that the possible damage induced by SLR to 136 major coastal cities by midcentury could be $1.6 trillion under RCP 8.5 and that 1.13 billion people would be exposed to the impacts of SLR and 100-year floods, with the highest proportion of vulnerable people concentrating in Asia (Neumann et al., 2015). China, India, Bangladesh, Indonesia and Vietnam are the countries most burdened, in terms of exposed population, and would remain so in the future (Neumann et al., 2015). After the middle of this century, vulnerable coastal cities, especially those in developing countries, would have limited time to adapt to the impacts of SLR (Jevrejeva et al., 2016).

In addition to SLR, coastal deltaic cities are prone to various hazards that can result in flooding, including fluvial and pluvial flooding due to heavy rains and a concentration of human settlement on the flood plains, coastal flooding, or storm surges due to tropical or extra-tropical cyclones. Moreover, many of their inhabitants are becoming increasingly vulnerable as a result of sediment compaction or consolidation owing to the removal of oil, gas and water from the delta's underlying sediments, and the trapping of sediment in reservoirs upstream, in combination with SLR (Syvitski et al., 2009). In particular, many Asian deltaic cities are relying heavily on pumping groundwater for both domestic and industrial uses, which has led to rapid land subsidence (Kaneko and Toyota, 2011). The IPCC Special Report on the Ocean and Cryosphere in a Changing Climate indicated that land subsidence is the most important cause of relative SLR (Oppenheimer et al., 2019). The latest IPCC Sixth Assessment Report (AR6) continued to highlight that land subsidence is among the most important drivers of coastal hazards in all coastal archetypes (Glavovic et al., 2022). Globally, the observed rates of land subsidence induced by urbanization range from 6 – 100 mm per year (Bucx et al., 2015; Higgins, 2016), which is at least twice the rate of GMSLR over the same period (Higgins, 2016; Tessler et al., 2018). However, since land subsidence is still a gradual process, residents themselves may not be fully aware of the threat (Takagi et al., 2021).

Therefore, it is crucial to understand current land subsidence trends in populated deltaic coastal cities and to inform people of such challenges. Besides, looking at case studies of areas that have experienced land subsidence can also provide valuable insights for adaptation to future SLR (Jamero et al., 2017; Esteban et al., 2019). Even in the event of frequent flooding due to the ground being lowered as a result of severe land subsidence, local residents still prefer incremental adaptation measures to relocation (Jamero et al., 2017). Esteban et al. (2019) provided evidence that coastal cities chose hard protection measures as responses to relative SLR and, as people living in such low-lying areas have traditionally lived with seasonal flooding, there is a certain resilience to minor floods. However, in the near future, due to the combined effects of SLR and land subsidence, floods could occur in any season of the year and become more serious (Wang et al., 2012; Takagi et al., 2016; Cao et al., 2021). If subsidence is not taken into account when formulating adaptation strategies, not only will seawalls become ineffective in the future, but they would also turn entire cities into water reservoirs when overtopped (Takagi et al., 2017), requiring much effort to pump the floodwater out. Therefore, special attention should be paid to this issue to promote preparedness for possible major flooding events in the near future.

This short communication presents a comparison of the cumulative land subsidence that has taken place in some of the most populated Asian deltaic coastal cities, including a brief historical overview and what mitigation measures were implemented. The relevance of the paper lies mostly in the compilation of one figure that will give readers an immediate understanding of the magnitude of the problem. Although similar figures in the past have been widely quoted in academia, some of those presented in available literature seem both out of date and/or have untraceable data used in their elaboration. The authors are releasing this figure into the public domain, given that it is important for researchers working on SLR and land subsidence issues to have reliable and up-to-date figures.

2 Methodology and Data

To analyze the time history of land subsidence in Asian coastal cities, the authors scrutinized observation records for the 11 sites listed in Table 1 (the location of which is shown in Figure 1). The references cited include peer-reviewed academic journal articles, books, and reports published by government agencies. The data are typically the result of long-term ground level surveys at particular points, but recent data may include some results from GPS (GNSS) surveys. The cumulative subsidence and the maximum subsidence rate based on the extracted data are indicated. As the cumulative subsidence represents a total value for a given observation period, including in some cases (relatively) short-term observations, the actual displacement may be higher. The maximum subsidence rate also depends on the frequency of measurements, as it is calculated by dividing the increment of subsidence by the corresponding period of time[1]. Therefore, the more frequently that observations were made, the larger the maximum subsidence rate that is in some cases measured. Since the beginning of the 21st century, remote sensing technologies such as interferometric synthetic aperture radar (InSAR) have been used with increasing frequency to determine the spatial distribution of land subsidence, but this paper does not include any results from such technology.

Table 1: List of the data sources used in the analysis.

City	Location	Data period (Year)	Cumulative subsidence (m)	Maximum subsidence rate (cm/yr)	Reference
Tokyo	Koto Ward	1918–2018	4.52	19.6	Tokyo Metropolitan Government (2018)
Shanghai		1921–2013	2.0	10	Xue et al. (2005), Chai et al. (2004), CCOP (2013)
Bangkok		1933–2003	1.65	30.5	Kaneko and Toyota (2011)
Osaka	Konohana Ward	1936–2017	2.93	16.4	Osaka City (2019)
Taipei		1955–1998	1.88	9.1	Kaneko and Toyota (2011)
Niigata	Nishi Ward	1957–2020	2.87	53.3	Niigata Prefecture (2021)
Nagoya	Minato Ward	1962–2020	1.33	24.7	Aichi Prefecture (2021)
Manila		1964–2002	1.15	6	Kaneko and Toyota (2011)
Tianjin		1971–2013	1.68	10.9	Gong et al. (2018)
Jakarta	Pluit	1974–2013	4.0	10.9	ITB (2016)
Yunlin		1992–2019	1.68	10.9	Information for Prevention and Monitoring of Land Subsidence in Taiwan (2018)

[1] The maximum subsidence rate presented here was calculated by the authors based on long-term observation data. Therefore, exact values may not be identical to those presented in other literature. For example, Endo et al. (2001) indicate 23.89 cm/yr as the maximum rate for Nishi-Kasai, Edogawa-ku in Tokyo.

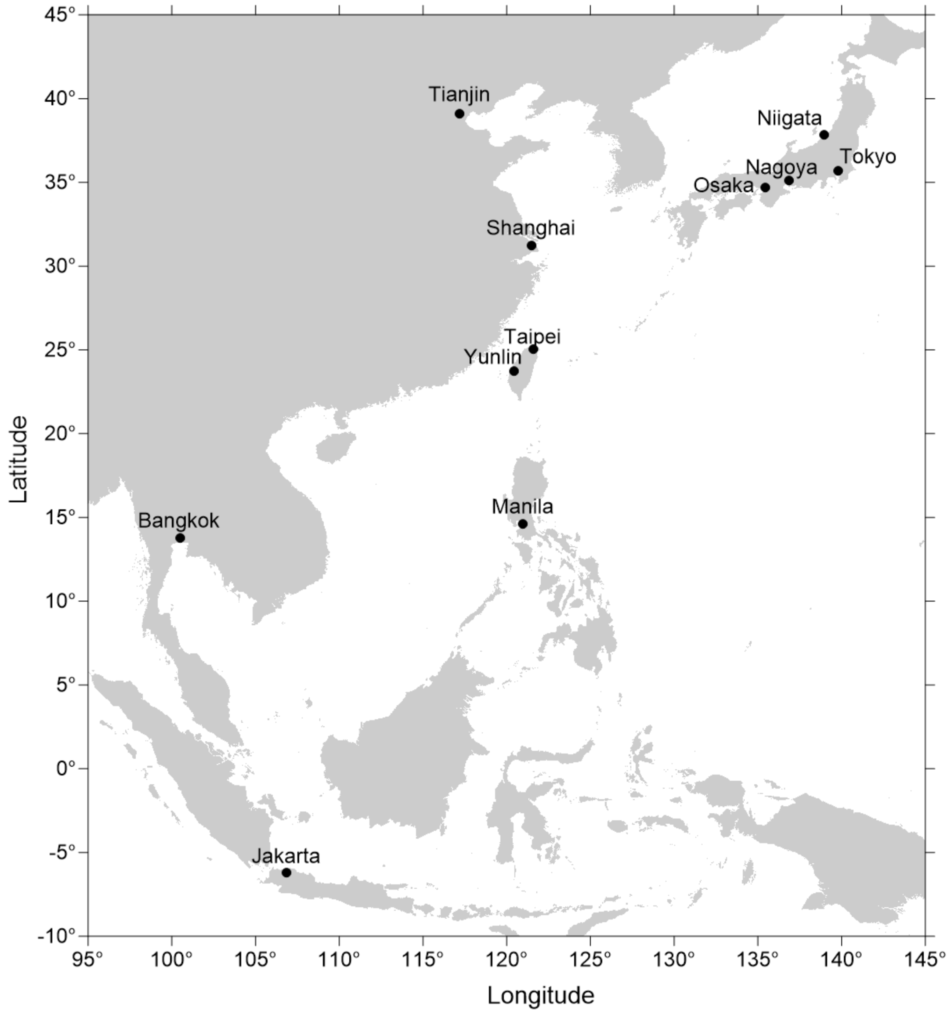

Figure 1: Location map of the 11 cities scrutinized in this study.

3 Results and Discussion

Figure 2 shows the historic progression of land subsidence, created based on the data shown in Table 1. Historical observations for Tokyo were the oldest among the 11 sites, with records dating back to 1918, followed by Shanghai in 1921 and Bangkok in 1933. The figure also shows Global Mean Sea Level Rise (GMSLR) based on long-term tide records and satellite radar altimeters (since 1993) (Church and White, 2011; Veng and Andersen, 2020). Land subsidence is 10 to 100 times greater than GMSLR. In contrast to GMSLR, which has been steadily rising over the last century, the trend in land subsidence shows characteristic phases e.g. periods when the rate of subsidence is mild, very steep, or suddenly flattens out. Nevertheless, it is important to note that once subsidence occurs it is irreversible, even if the root cause is removed.

One reason for the early recognition of land subsidence in Tokyo was the frequent ground level surveying that took place following the Great Kanto Earthquake of 1923. In 1933, a 35-meter observation well was installed in Koto Ward to scientifically verify land subsidence in the layer of Holocene deposits (Inaba et al., 1969). The reason for the lull in subsidence in Tokyo and Osaka recorded in the 1940s resides in the cessation of industrial economic activity during World War II (Endo et al., 2001). During postwar period there was rapid economic growth in the 1950s and 1960s, and as a result large amounts of groundwater were extracted for industrial use and building heating and cooling systems, which caused rapid subsidence (Aihara et al., 1969, Tsuchiya 2014). However, it should be noted that groundwater was not only used for industrial purposes, but also for domestic water supply (for example in the Taipei Basin since about 1895, see Hwang and Wu, 1969).

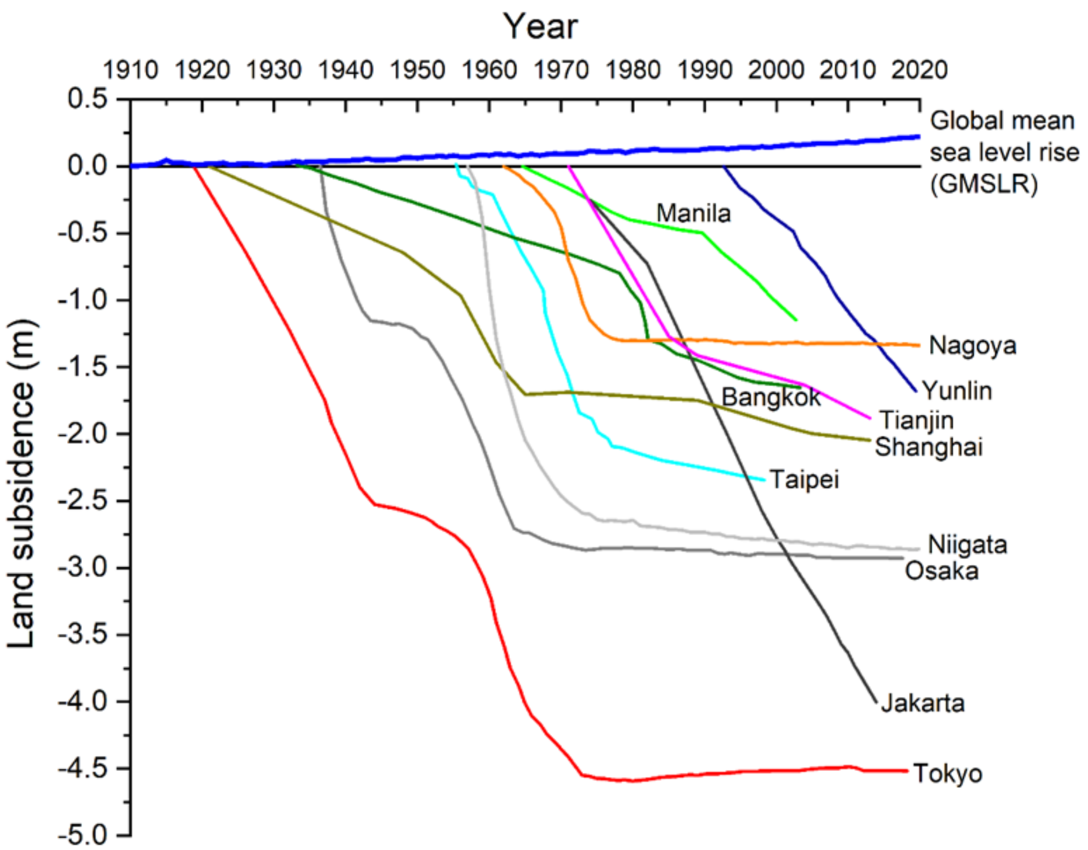

Figure 2: Cumulative land subsidence in Asian deltaic and coastal cities2.

Shanghai and Tianjin represent significant examples of land subsidence in China, although more than 50 major cities are affected by it in the country. Since 1950, the total estimated financial losses due to land subsidence in China amount to approximately 72.8 billion USD, with direct damage to assets being approximately 145.7 million USD annually (Yin et al., 2006). Shanghai, situated in the Yangtze River Delta, began sinking at about the same time as Tokyo due to extensive groundwater pumping. In both cities, land subsidence almost ceased by the 1970s due to regulations on groundwater extraction. However, for the case of Shanghai subsidence once again re-started in the 1990s due to the expansion of groundwater exploitation and urbanization, especially the construction of high-rise buildings (Xue et al., 2005). Annual land subsidence data for Tianjin is only available from 1971, though it started as early as 1923. From 1958, land subsidence gradually increased from several millimeters to 20 mm/year before rapidly increasing in 1970s (Hu et al., 2002; Xue et al., 2005). Similar to Shanghai, land subsidence in urban areas of Tianjin slowed down due to regulations on groundwater extraction established in 1986. However, land subsidence is still happening in suburban areas (Xue et al., 2005, Gong et al., 2018).

The subsidence rate in Niigata was particularly fast, with an annual rate of over 50 cm observed in 1959. In addition to the softness of the Echigo Plain, where Niigata is located, the pumping of groundwater for natural gas extraction (as methane gas was dissolved in water) was thought to be the main reason for the subsidence. Gas extraction companies initially denied that their activities were having any effect on subsidence, but investigations revealed it to be a major factor (Momotake, 1996). Subsequently, regulations were put in place to control extraction, and by the 1970s the rate of subsidence had slowed considerably.

In the last two decades the sinking of Jakarta and Yunlin (Taiwan) has been remarkably fast and shows no sign of abating. As for Jakarta, recent land subsidence has slightly slowed, but still the GPS survey results for 2015-2019 show that the northern coast is sinking at a rate of 6.2 cm per year (Abdullah et al., 2021). In Yunlin, the risk of coastal

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disasters is rapidly increasing due to a combination of ongoing land subsidence and coastal erosion (Wei-Po et al., 2022). In Bangkok, pronounced land subsidence started in the 1970s and reached its most critical state in the early 1980s, when it was as high as 12 cm/year (Phien-wej et al., 2006).

As a consequence of land subsidence, the risk and consequences of flooding can increase, and such visible effects are likely to prompt an investigation into land subsidence. In fact, land subsidence was recognized as a major issue in Osaka, Niigata, and Nagoya due to the increase in recorded damage from coastal flooding caused by storm surges due to typhoons or winter storms (Osaka Prefecture, 2004; Momotake, 1997; Ministry of the Environment, 2020). The historic flood in Jakarta in January 2013 was exacerbated by land subsidence, which was estimated to have increased the inundation area by 17.6% (Moe et al., 2016). However, in areas like Jakarta, where residents are accustomed to fluvial floods, communities might not necessarily recognize the effect that subsidence is having on aggravating risks, even when their houses are actually sinking rapidly and, consequently, the municipal government may fail to take significant action (Takagi et al., 2021). For Manila, the sea-level change recorded by tide gauges can be explained only by regional SLR before 1965, but the changes after 1965 cannot be explained without including coastal subsidence (Zoysa et al., 2021). However, most sectors of the government are oblivious or ignore the fact that subsidence is taking place (Rodolfo and Siringan, 2006). Thus, it is important to increase awareness amongst municipal authorities as well as normal citizens, in order to formulate adaptation pathways that can mitigate land subsidence and future SLR, with the long-term aim of improving the resilience of coastal communities and reduce their risk to future disasters.

4 Conclusion

This short communication provides a chart that details the progress of land subsidence of 11 coastal cities in East and Southeast Asian countries, along with the global mean sea level rise. This severe land subsidence took place in parallel with economic development, and was typically caused by urban development and groundwater extraction. Land subsidence was found to be one to two orders of magnitude faster than sea level rise. While land subsidence has stopped in Tokyo, Osaka, and Nagoya, and slowed down in Niigata, Shanghai, Taipei, and Tianjin, it is still ongoing in Jakarta, Manila, Yunlin, and Bangkok.

Land subsidence may be occurring in many other places where urban development is progressing rapidly and groundwater is extracted for domestic and industrial purposes. However, in many areas it is probably unrecognized, as there are few places where fixed-point precise observations of ground elevation are being carried out. Once land subsidence occurs the ground level cannot be returned to its original level. However, the examples discussed in this communication indicated that, if land subsidence is identified and dealt by through regulations, it can be slow down or stopped relatively quickly. Hence, the authors hope that the figure provided will lead city planners and disaster risk management practitioners to seriously consider the fundamental challenges posed with land subsidence to sustainable urban development.

Author contributions (CrediT)

Hiroshi Takagi[1]: Conceptualization, Data correction and analysis, Literature analysis, Visualization, Writing – original draft. Anh Cao[2]: Conceptualization, Data correction and analysis, Literature analysis, Writing – review & editing. Miguel Esteban[3]: Conceptualization, Data correction and analysis, Literature analysis, Writing – review & editing.

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