Recent measurements of subsidence in the Ganges-Brahmaputra Delta, Bangladesh

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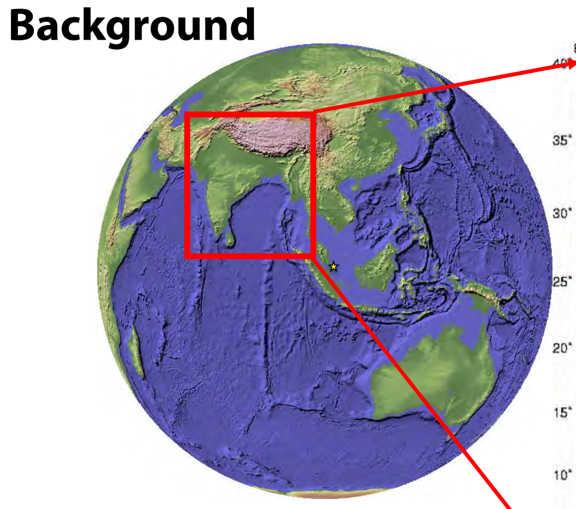
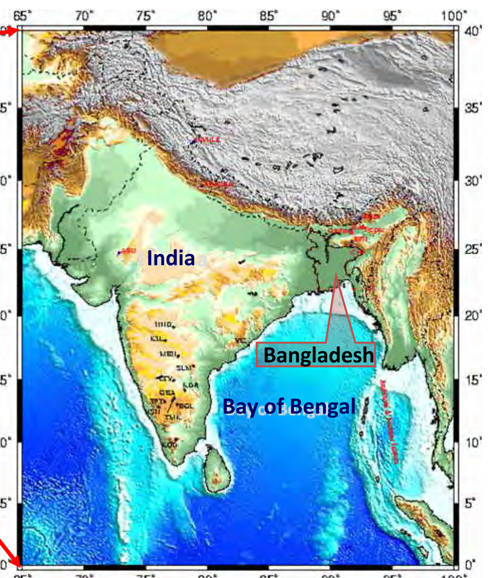
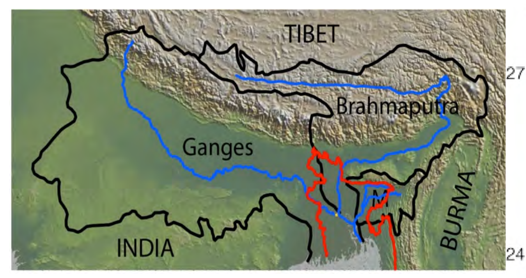
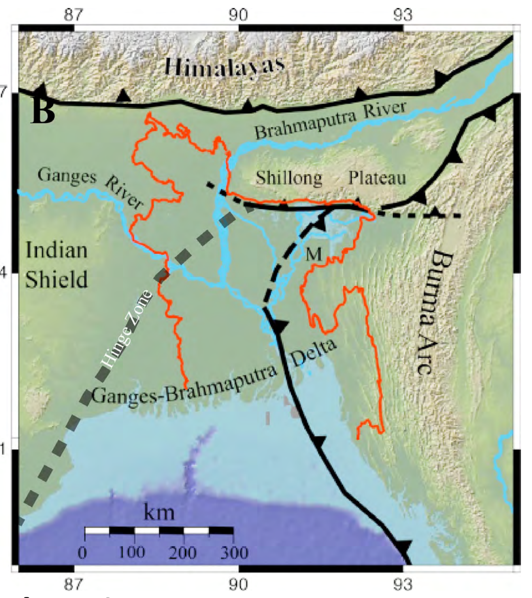
This poster represents a summary of our efforts to understand the variations in subsidence of the Ganges-Brahmaputra Delta (GBD), both spatially and with depth. The GBD, the world's largest, like all deltas, is sinking due to compaction, isostasy, tectonics and human interventions. Its future is dependent on understanding the balance between sea level rise, land subsidence and sedimentation.
We focus on measurements of subsidence using multiple methods. The columns present our recent results using continuous GPS sites of subsidence, campaign GPS reoccupation of geodetic monuments installed 18 years ago, Rod Surface Elevation Tables and Marker Horizons to measure shallow elevation changes and sedimentation, hand-drilled stratigraphic wells for Holocene subsidence rates, historic sites for centennial subsidence rates and an optical fiber compaction meter system installed in a suite of wells to directly measure compaction.
Results show an increase in subsidence from NW to SE and a decrease in compaction with depth. Combining different sets of measurements, we can differentiate between moderate average Holocene subsidence rates and higher current subsidence rates. We can also distinguish between shallow and deeper contributions to subsidence. Results are still very preliminary and should improve as we continue our efforts.

Background

Bangladesh is located in the NE corner of the Indian subcontinent. It is the lowlands between the Indian craton, the Himalayas and the Indo-Burma Ranges





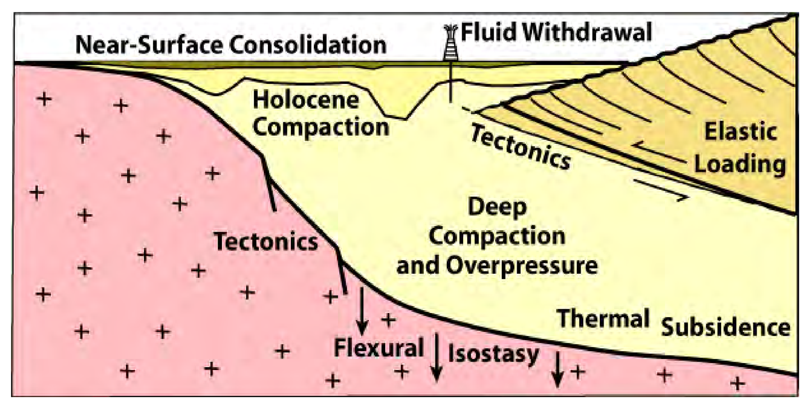
The Ganges and Brahmaputra Rivers drain 3/4 of the Himalayas and supply over 1000 megatonnes of sediment to the GBD every year. The GBD is being overthrust by the Shillong Plateau from the north and the IndoBurma subduction zone from the east. In the west, the Hinge Zone marks the transition from the Indian Craton to the thin crust and thick sediments of the Bengal Basin, reaching up to 20 km.

Dynamic Balance of Delta Elevation

$$\Delta_{REL} = \underbrace{\Delta E}_{\text{Sea Level Rise}} + \underbrace{C_n + C_A + M}_{\text{Subsidence}} - \underbrace{A}_{\text{Sedimentation}}$$

Δ_{REL}	=	Vertical change in delta surface elevation
ΔE	=	Eustatic Sea Level Rise
C_n	=	Natural Compaction
C_A	=	Accelerated Compaction
M	=	Crustal Vertical Movement
A	=	Aggradation Rate

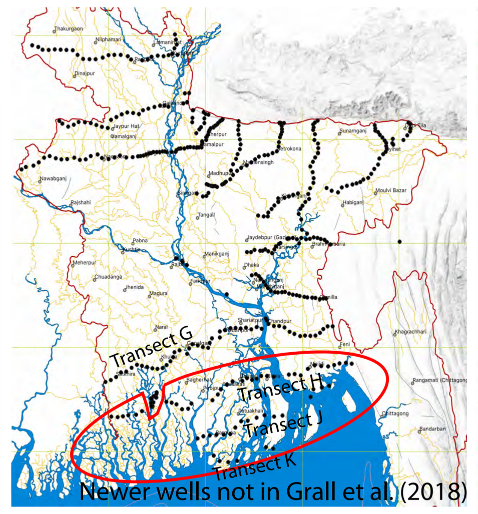
Modified from Syvitski et al. (2007)

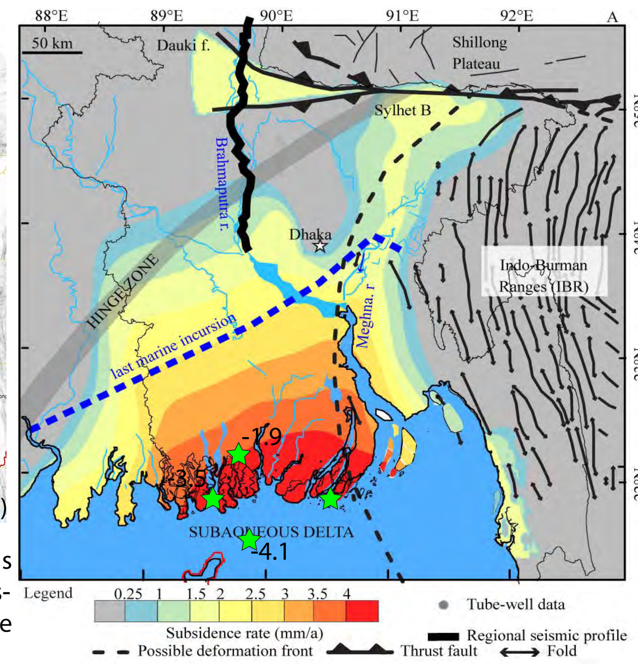


The future of the GBD depends on the balance between subsidence, which increases relative sea level rise, and sedimentation, which counters it by depositing new land.

Many processess contribute to subsidence in the GBD, including tectonics and elastic loading in the east, fluid withdrawal, particularly water pumpingg at Dhaka, multipl processes of sediment consolidation and compaction and isostatic loading by the weight of the sediments. We use multiple types of measurements to determine the rates of ongoing subsidence.

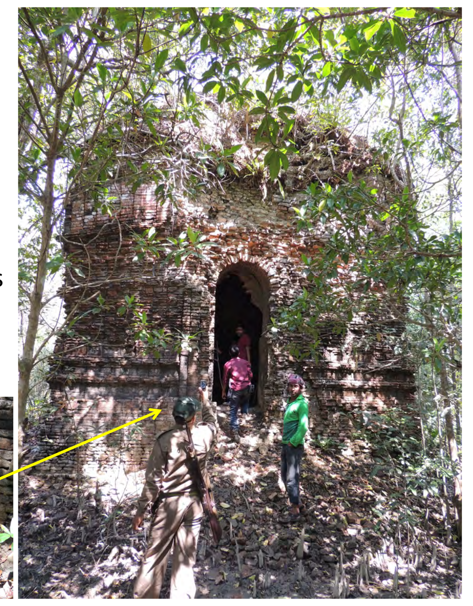
Wells and Historic Sites



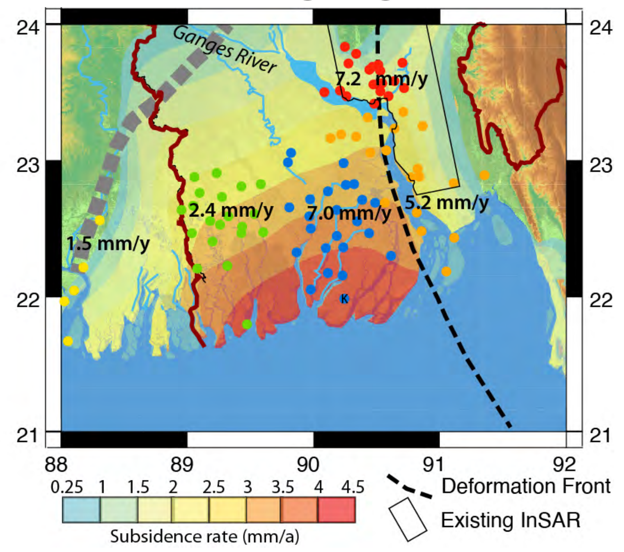


Grall et al. (2018) used over 400 tube wells drilled by Vanderbilt University and a seismic profiles to construct a map of average Holocene subsidence rates. Results show a seaward increase in subsidence from the Hinge Zone, the edge of the Indian craton, to ~4.5 mm/y near the coast.

The figure also shows historic sites that are 3-500 years old (green stars). Hanebuth et al. (2013) determind a 4.1 mm/y rate at a salt kiln near the coast. Sarker et al. (2012) studied 4 historic sites, two mosques and two Hindu temples. However, we reinterpret the plinth level of the temples since Hindu temples, as the home of a god or goddess, have raised entrances. We revisited the Shakher Temple where we found a lower ridge that we interpret as the plinth level. Augering found a brick layer that we interpret to be the base of the platform at 1.5 m depth. Together they indicate a subsidence rate of -3.5 mm/y.



River and tide gauges

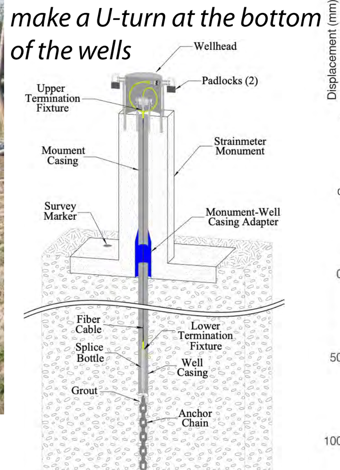
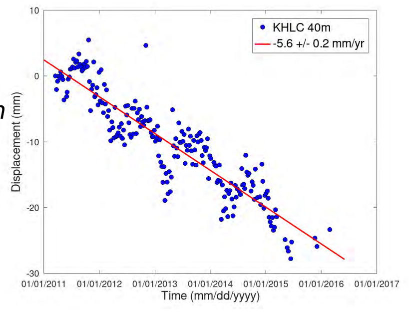


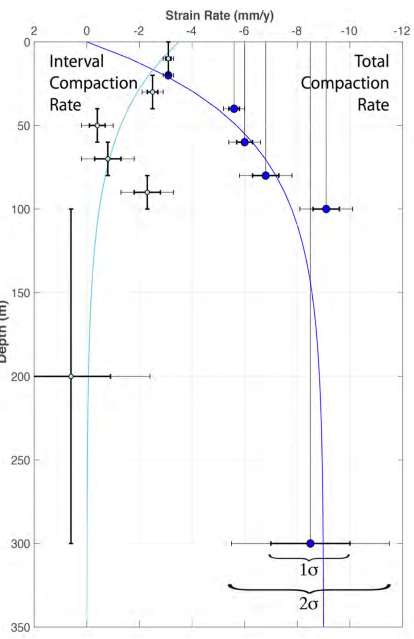
Although we have found individual tide gauges to not be reliable, Becker et al. (2020) used more detailed analysis of groups of river and tide gauges to estimate subsidence increasing the the SE away from the Hinge Zone. Grall et al. (2018) and Becker et al. (2020) obtained similar patterns of subsidence, but the modern rates are a little higher than Holocene rates. We note that in the region affected by tectonics east of the deformation front (orange dots) the -5.2 mm/y rate is significantly higher than the holocene rates as it reflects interseismic subsidence rather than the net rate including uplift ffrom past earthquakes.

Compaction Meter

Photo of the KHLC compaction meter well nest and nearby river

Design of the individual wells. two pairs of fibers make a U-turn at the bottom of the wells

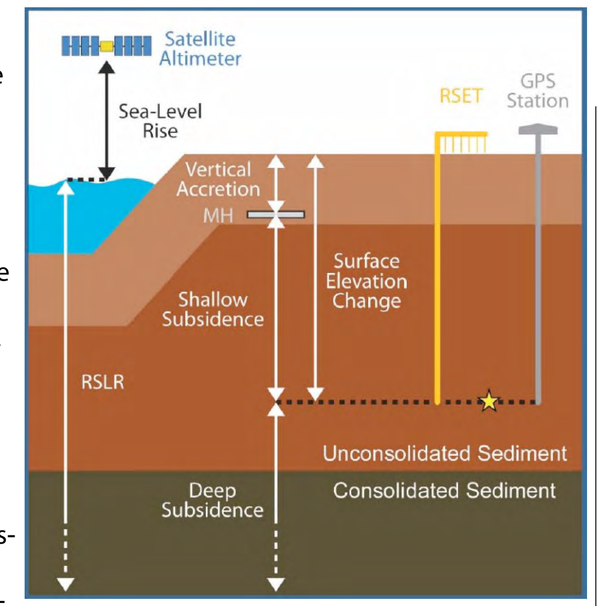



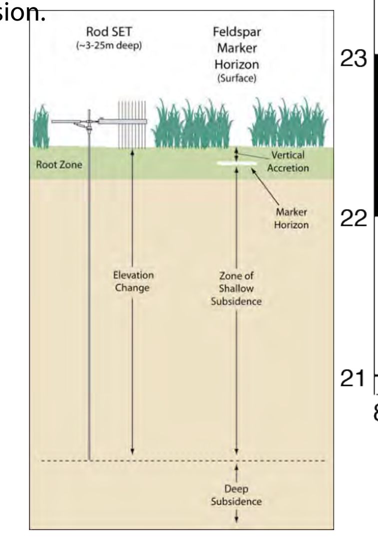


We installed two wells nests with vertical optical fiber strain meters to directly measure sediment compaction in Bangladesh. The one in the coastal zone had 6 PVC lined wells ranging from 20 to 300 m depth (photo). The length of optical fibers was measured weekly using an EDM (Electronic Distance Meter). Example in upper right. Unfortunately, the adjacent river was dredged in 2015 leading to the collapse of the site. All of the fiber measurements show a strong seasonal and net shortening of the fibers. The ensemble results so the compaction rate decreased with depth with a total compaction rate of ~9 mm/y.

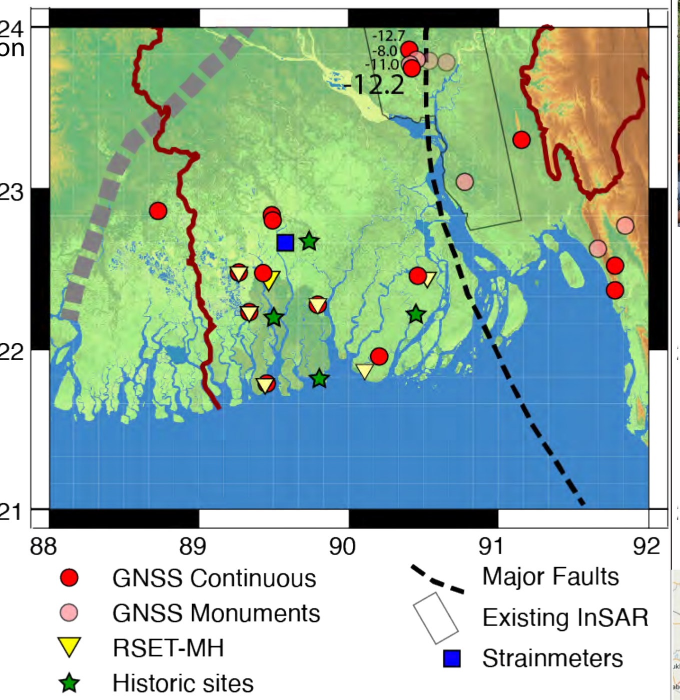
Continuous GNSS and RSET-MH

As illustrated in this figure from Keogh and Tornqvist (2018), GNSS (GPS and other space geodetic systems) and RSET-MH (Rod Surface Elevation Tables-Marker Horizons) make a powerful combination for measuring subsidence. GNSS measures the total subsidence rate of the antenna. RSET measures elevation relative to a rod driven to refusal or 80' deep to get shallow subsidence above the rod base of the rod. MH measures sedimentation rate. The difference yields the shallow subsidence. Together GPS and RSET can separate shallow and deep componenets of subsidence.
In 2019, with support from the Bangladesh Water Development Board (BWDB) as part of the project "Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone (Sustainable Polders Adapted to Coastal Dynamics)" we installed and/or refurbished co-located GNSS and RSET-MH systems in the GBD. Details on the RSET-MH installation and measurements are given in the presentation by Wilson et al. (2021) in this session.

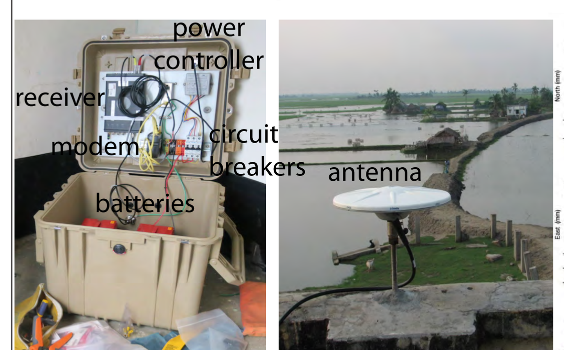


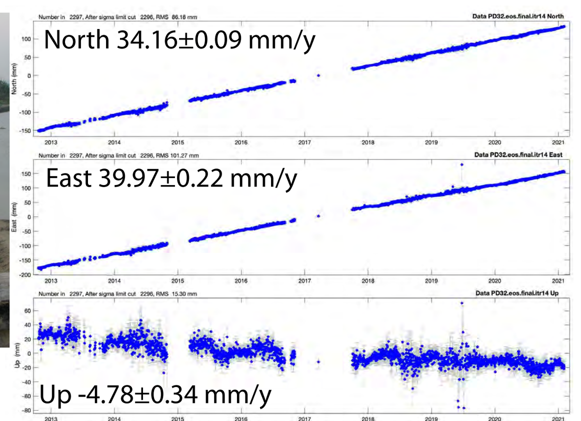


Callaway et al. (2013)

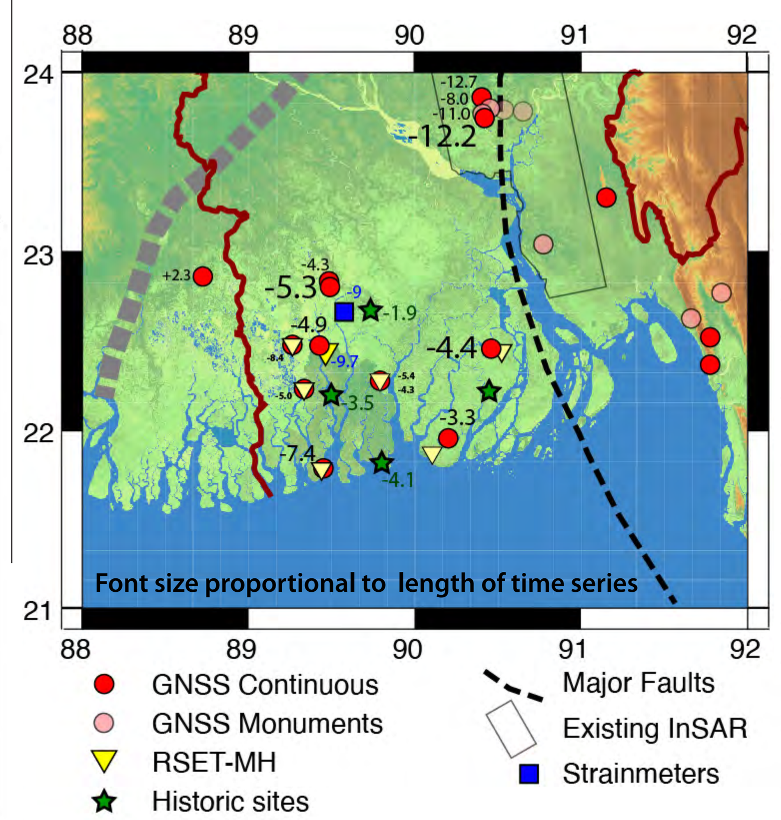


Photos from the fieldwork in 2019 of the M/V Kokilmoni, used to travel around, UNAVCO engineer John Galetzka installing GNSS antenna and M. Steckler with an installed equipment box.





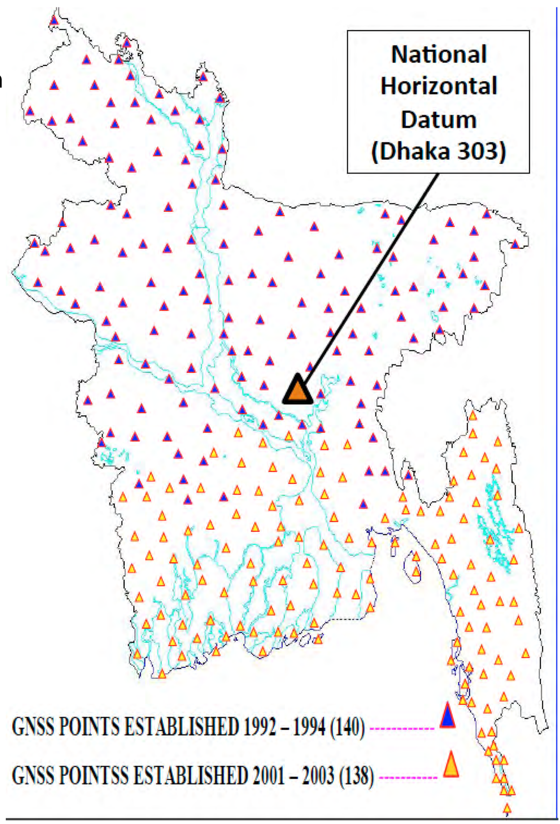
Photos of GNSS installations and results for station PD32 installed in October 2012.



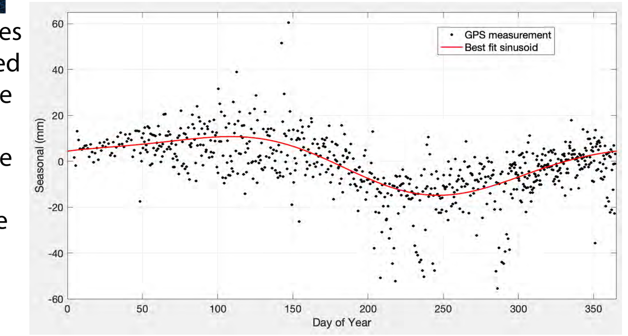
Results:
1)Continuous GNSS yield rates from +2 to -7 mm/y of subsidence. Sites installed in 2019 are not yet reliable.
2) The historic sites (-1.9, -3.5, -4.1) and the sites in the eastern part of the field area (-4.4, -3.3) yield rates similar to the average Holocene rates.
3) Stations farther west (-4.3, -5.3,-4.9,-7.4) yield slightly higher rates similar to tide gauges. We believe muddier sites farther from large rivers, and perhaps having thicker Holcene sediments, contribute to greater compaction at these sites.
4) RSET-MH (Bomer et al., 2019) and KHLC (DeWolf et al., in prep.) include very shallow compaction to the surface and yield high sediment compaction rates.

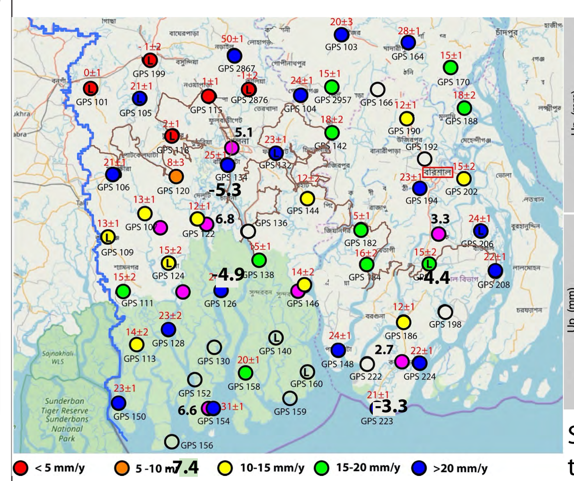
Campaign GNSS

The Survey of Bangladesh (SoB) has installed geodetic monuments throughout Bangladesh in conjunction with JICA. We identified 55 monuments in our field area of coastal Bangladesh. Most of them were installed and surveyed by GPS in 2002 with a 4 hour occupation. We remeasuring them with a campaign GPS survey in early 2020, providing an ~18 year time difference for estimating subsidence. This effort was also supported by the BWDB as part of the CEIP-1 project "Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone (Sustainable Polders Adapted to Coastal Dynamics)". Our field team consisted of people from Columbia University, Barishal University, Iinstitute for Water Modeling, SoB, Dhaka University, and La-Rochelle University.

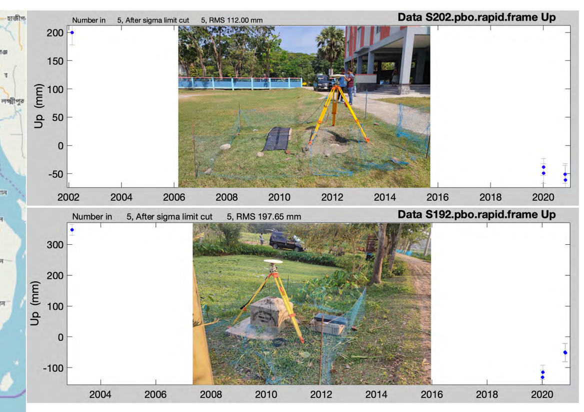


We were able to reoccupy 48 of the 55 sites with observations of 1-5 days. We obtained the original GPS observation files from the 2002 measurements from the SoB with 4 hour observations. We processed all of the data using GAMIT (Herring et al., 2018) to obtain subsidence rates. We corrected the subsidence rates for seasonal elevation changes based on the continuous GPS at Hiron Point (HRNP).

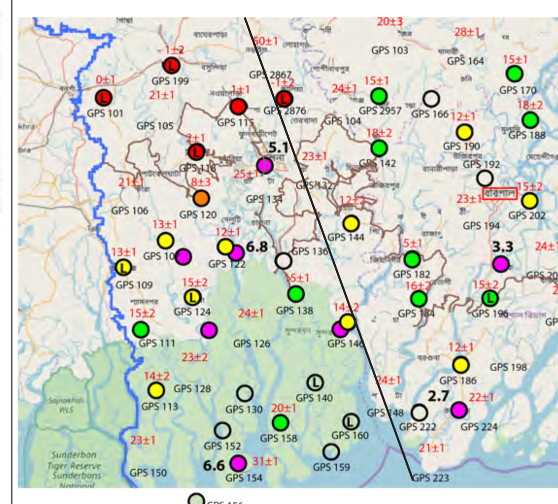


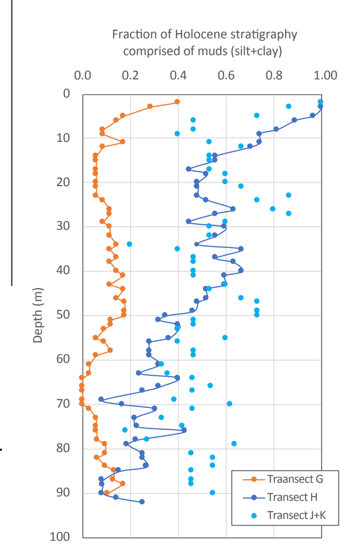


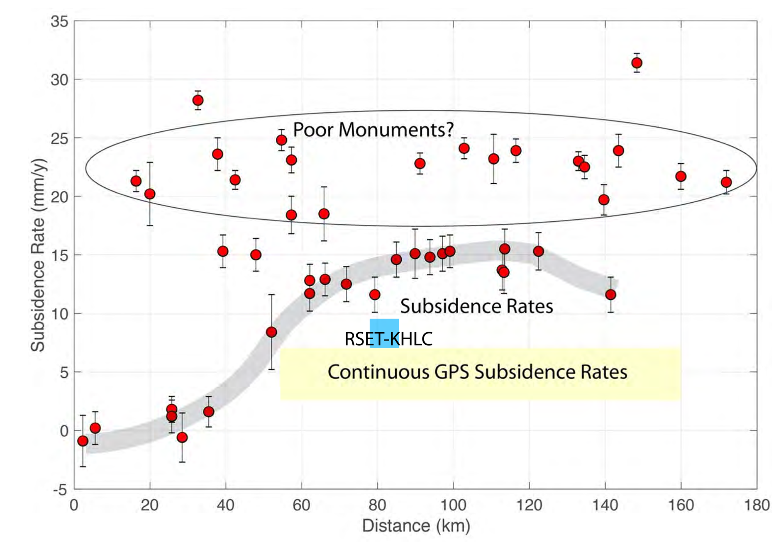
Map of the subsidence rates obtained from the repeat survey of SoB monuments in Bangladesh. Open circles are monuments that could not be located or measured. L indicates GPS was set up nearby and leveled to monument due to tree cover.



Some sites yielded very high rates (20-50 mm/y) that we suspected of instability. At the end of October 2020, we resurveyed 4 sites near Barishal (red box). Two sites, GPS 190 and GPS 202 yielded subsidence rate of 13-14 mm/y over those 10 months indistinguishable from the 2002-2020 rate. The two other sites, GPS192 and GPS 194, showed uplift or little subsidence. This supports the inference that the high subsidence rates are due to instability of the monument, perhaps including clay expansion or poroelastic effects as seen in the compaction meter. The map at right shows the results with the high rates excluded.
Below is a projection of the rates along a profile perpendicular to the Holocene subsidence contours. We find very low rates in the NW corner of the field area where wells indicate sandy strata (lower left). Rates increase to the SE to slightly higher than the RSETs at Polder 32, and significantly higher than seen by continuous GPS on buildings (gray band). The higher rates at suspected poor monuments are seen above this trend.

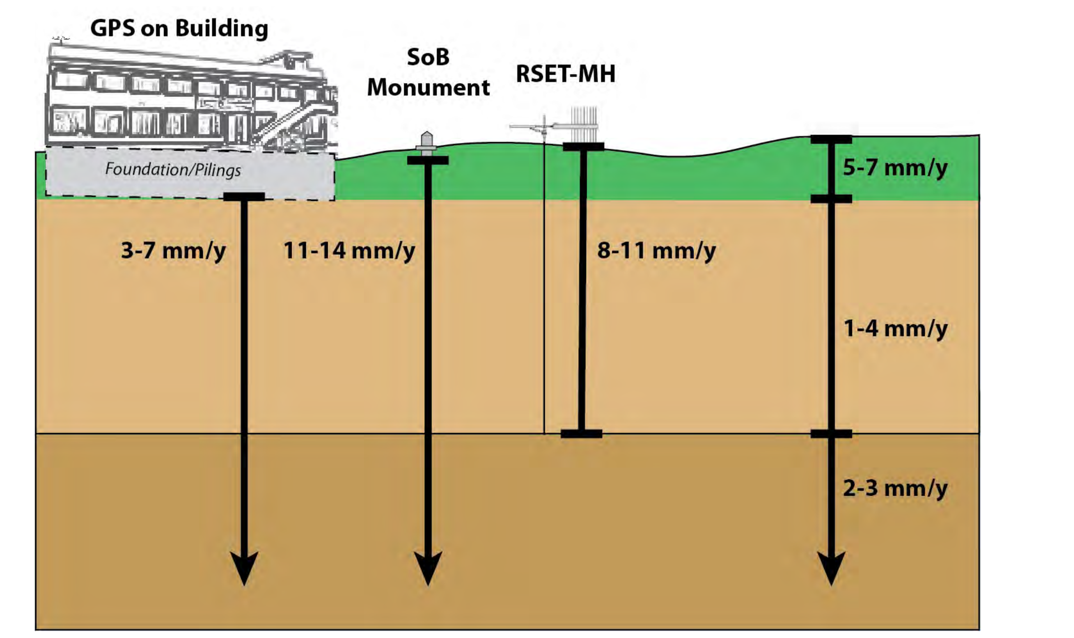






Conclusions

The collection of subsidence measurements using different methodologies exhibit variation that show systematic patterns both spatially and with depth. Holocene averaged subsidence rates (Grall et al., 2018) increase from the Hinge Zone of the early Cretaceous passive margin seaward. The rates from the 300-600 year old historic sites Sarker at etl., 2012; Hanebuth et al., 2013; Chamberlain et al., 2020) are similar to the Holocene rates, perhaps providing a timescale for sediment compaction.
The devices measuring shallow subsidence, the RSET-MH and vertical strainmeters, show much higher rates of 9-10 mm/y. These instruments, in sites of active sedimentation, include shallow subsidence that is not recorded by river gauges and GNSS. The depth of anchoring of the river gauges in Bangladesh is unknown, however Keogh and Tornqvist (2018) note that in the Mississippi Delta they average 20 m. Any compaction above this depth is not recorded. Most of the GNSS sites are installed on reinforced concrete buildings. The depth of pilings for the foundations of the buildings are unknown. Furthermore, the ground is compacted before construction and there is no young sedimentation. Again, shallow subsidence above some significant depth is not measured. They do include deep subsidence below the base of the RSET or strainmeters. This indicates that there is a considerable amount of ongoing shallow sediment subduction.
The campaign survey reveals low rates of subsidence in the NW, close to the Hinge Zone where sediment thicknesses are less and deposits are sandier. Farther seaward rates are much higher (11-15 mm/y). These measurements include both shallow campaction and deep subsidence. Using these still limited measurements, the figure below provides a first cut at the variation of subsidence with depth. We estimate that there is 2-3 mm/y of subsidence from compaction and isostasy (e.g., Karpytchev et al., 2018, Krien et al., 2019). The measurement also suggest significant very shallow subsidence related to sediment consolidation and organic matter degradation, perhaps reaching 5-7 mm/y. The remaining subsidence is related to compaction at intermediate depths. However, we note that the compaction meter suggests the this compaction occurs on a larger depth scale than the other measurements.



Summary figures showing the range of subsidence measurements from the different methods used here and a preliminary interpretation of their variation with depth.

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