Analisis Pemenuhan Kebutuhan Air Baku Akibat Pengaruh Antropogenik Untuk Penurunan Muka Tanah di Pulau Jawa, Indonesia

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Abstract

Jakarta faces long-term land subsidence and cumulative surface deformation, compounded by sea-level rise. Space-geodetic techniques, particularly Interferometric Synthetic Aperture Radar (InSAR), have mapped displacement velocities and bowl-shaped subsidence patterns. Yet velocities describe motion, not the underlying deformation. Assessing deformation mechanisms and infrastructure risk therefore requires analysis of spatial velocity gradients in the strain rate domain. Spatially averaged InSAR East and North velocities are inverted at 450 m × 450 m resolution using a finite-element framework with Tikhonov regularization to estimate the two-dimensional horizontal strain-rate field and its invariants. In addition to six previously known bowls, four new subsiding regions are identified, along with corridors of maximum shear indicating localized, non-tectonic deformation within soft coastal alluvium. Maximum principal strain rates range from **−7.2** to **+9.5** ***με***/yr, corresponding over 10.7 years and 450 m to cumulative strains of ∼80–100 ***με*** (35–46 mm), implying progressive strain accumulation and approach to structural cracking and functional damage thresholds within half a century under sustained rates. Interpreting Jakarta's subsidence in the strain rate domain reveals its kinematic complexity, moving beyond mapping motion to quantifying deformation and informing risk assessment.

Keyword: Deformation, geodesy, InSAR, GNSS

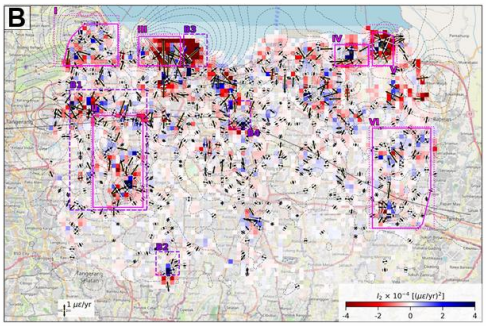
Introduction

Jakarta, the world's largest coastal megacity [1], has experienced decades of significant land subsidence, making it among the fastest-sinking urban areas globally. Land subsidence observations began in 1926 with precise leveling surveys [1–3] documenting for the first time vertical ground settlement across the city. Geodetic monitoring developed in the 1980s–1990s through repeated leveling [3, 5] and later GNSS campaigns [5–7], improving spatial coverage but remaining limited by sparse benchmarks, monument instability [7], and discontinuous survey intervals.

Most recent InSAR studies rely on line-of-sight (LoS) velocities projected onto the vertical (PoV) or 2D decomposed velocities projected onto the East-Up plane assuming no north-south motion. These studies have successfully quantified subsidence rates and cumulative vertical displacement, revealing coherent bowl-shaped patterns. However, velocity alone does not capture deformation that is, changes in shape or area. If all points within a region move at the same velocity, the motion reflects rigid- body translation without strain. Deformation arises only from spatial variations in velocity, which are captured by the symmetric part of the velocity-gradient tensor, that is, the strain rate.

Research Method

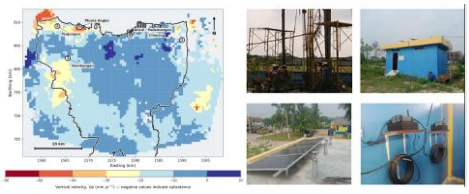
To estimate a continuous two-dimensional (2D) horizontal velocity field, $\mathbf{x}$ˆ, and derive a kinematically compatible strain rate field, ˆ$\boldsymbol{\varepsilon}$˙ , we follow a finite-element Tikhonov inversion approach using InSAR-derived RUM-averaged velocity observations. Each RUM provides average East ($v_E i$) and North ($v_N i$) velocities over a defined foot-print (e.g., 450×450 m) with an associated 2×2 variance–covariance matrix capturing measurement uncertainties and correlations. The inverse problem is formulated as a Tikhonov-regularized weighted least-squares minimization



Picture 1. Horizontal strain rate invariant field over Jakarta derived using the finite- element Tikhonov inversion framework

The GNSS network functions as a combined geodetic and hydro-geomechanical observatory. Surface GNSS measures total land motion relative to a global reference frame, while the three deep reference assemblies partition deformation by depth. The primary scientific value derives from the differential measurements, as these distinguish shallow consolidation from deeper aquifer-system compaction and from motion below the deepest reference.

Five stations are documented: two constructed in 2021, two in 2022, and one in 2023. All are identified in the inventory as built by DSDA. The network provides east-west coverage along northern Jakarta but exhibits limited north-south coverage and lacks stations in the southern basin margin or on independently verified stable bedrock. The three nominal intervals are 0-50 m, 50-100 m, and 100-150 m, conceptually separated by aquitards at approximately 50, 100, and 150 m.



Picture 2. Jakarta InSAR velocity and GNSS Extensometer Monitoring Stations, Photographic evidence of the monitoring infrastructure. The images show drilling and construction activity, protected shelters, rooftop solar panels, internal vertical assemblies, electronic enclosures, and signal or power cabling for the monitoring system

Discussion & Result

Although three-dimensional-averaged velocities are available, we restrict the finite-element Tikhonov inversion to the horizontal components. The vertical component is an order of magnitude larger (σ7.25 mm/yr; minimum 81 mm/yr) than the horizontal velocities, while its covariances with East and North are negligible, reflecting the small vertical tilt angles inherent to the ENU strapdown decomposition. Hence, horizontal and vertical motions are effectively uncorrelated. Including the vertical velocity could pull the Morozov discrepancy toward the dominant vertical signal, potentially shifting the optimal regularization parameter α and altering horizontal smoothness without improving the estimation of horizontal strain rate invariants. Vertical velocities would only contribute additional information if coupled through a physically motivated volumetric constraint linking horizontal divergence to vertical compaction. Such coupling requires assumptions about stratigraphy and layer thicknesses that lie beyond the scope of this study. We therefore restrict the present analysis to a purely horizontal inversion, leaving the implementation of physically motivated coupling within the inversion framework to future investigations.

Conclusion

The strain rate fields reveal previously unresolved features beyond the six known subsidence bowls including four new subsiding regions. All ten regions display compaction-driven bowl kinematics, with inward contraction at centers, shear along flanks, and lateral dilatation at edges. In addition, three corridors of maximum shear strain rate are identified, showing predominantly uniaxial, non-tectonic deformation resulting from compaction-driven bowl-flank deformation, shallow subsidence, or combined effects of nearby subsidence bowls. Regionally, the northern half of Jakarta, underlain by soft coastal alluvium, accommodates most deformation, including areas with the largest areal contraction and shear, whereas the southern half, on stiffer alluvial fan deposits, contains only two localized bowls and minor river-channel shearing.

These results provide the first spatially resolved dataset of horizontal deformation in Jakarta, capturing both bowl kinematics and previously unresolved deformation features. The dataset enables improved interpretation of subsidence mechanisms, assessment of infrastructure risk, and can serve future hydrological, geomechanical, and mitigation studies.

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