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3-D Voxel Modeling of Near-Surface Sediments: Insights into Depositional Environments and Geotechnical Properties- A Case Study of Barishal Town and its Surroundings, Bangladesh

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Abstract: Geology is a natural science focused on understanding the Earth's composition, structure, and processes. 3D geological modeling effectively visualizes complex surface and subsurface conditions, geological settings, and geomorphic processes. This technique provides near-realistic representations of geological features, making them easier to understand for both professionals and the public compared to traditional maps and diagrams. This study integrated geological, geotechnical, and special datasets within a GIS framework for statistical analysis. Key datasets include sand-silt-clay percentages, SPT-N values, litho-coarseness curves, core photographs, geomorphological features, and depositional domain maps. The geomorphic features of Barishal town and its surroundings are characterized by complex and dynamic fluvial-deltaic systems. 97 geotechnical boreholes, covering approximately 94 km^2, which were analyzed to construct a 3D geological model down to a depth of 30 meters. 3D indicator kriging, a geostatistical method, was used to create a voxel-based geological model (100m x 100m x 0.50m). Each sediment layer was assigned to cluster IDs for a second round of 3D indicator kriging, visualizing sediment-type clusters, sequences, and depositional stages from younger to older sediments. The domain map provides additional insights into the depositional history. The voxel model can be explained through thickness maps, unit-wise visualization, and depth-wise slicing. The thickness map shows sediment accumulation and depletion. The unit-wise voxel model presents six depositional sequences in the study area from younger to older stages with lithological assemblages. The sediment assemblages could be displayed in six different depth levels: at the surface, 5m, 10m, 15m, 20m, and 25m, relative to mean sea level (*MSL*), showing a fining-up trend. Automatically generated cross-sections clarify lithological variations and sediment interlayering. 3D model enhances scientific understanding and improves communication among engineers, planners, and non-specialists by translating complex geological data into intuitive visuals. This approach supports informed decision-making and resilience planning while aiding geoscientists in analyzing subsurface conditions related to groundwater quality, pollution, and paleo-flood predictions.

Keywords: ***3D indicator kriging, Geostatistical approach, Litho-coarseness curves, Core photographs, Voxel models.***

Introduction

Geomorphic processes are dynamic agents that continuously reshape the Earth's surface, forming diverse landforms that are strongly influenced by depositional environments, sediment transport, and distribution patterns. Understanding these processes is critical for a wide range of applications, from natural hazard assessment to urban planning and sustainable resource management. Traditional geological techniques, including two-dimensional (2D) maps, cross-sections, and borehole data, have long provided foundational insights into subsurface conditions. However, interpreting these datasets is often challenging for non-specialists due to the inherent spatial variability, heterogeneity, and complexity of near-surface sediments.

In recent years, three-dimensional (3D) geological modeling has emerged as a transformative tool in modern geoscience, offering a powerful means to visualize and analyze the subsurface in ways that were previously unattainable. By employing 3D voxel modeling, geoscientists can accurately represent complex lithological successions and stratigraphic relationships, producing a near-realistic depiction of the subsurface architecture. This approach not only facilitates the identification and interpretation of sedimentary facies but also enables detailed analysis of structural features, depositional patterns, and potential geotechnical risks.

The integration of 3D geological models into engineering and environmental workflows significantly enhances decision-making processes. It supports infrastructure development, such as tunneling, road construction, and urban expansion, by providing a reliable understanding of subsurface conditions. Additionally, it informs environmental management strategies, groundwater resource assessment, and natural hazard mitigation. By bridging the gap between geological science and engineering practice, 3D modeling fosters a more informed and proactive approach to land use planning, resource utilization, and sustainable development. Overall, this methodology represents a paradigm shift in how complex subsurface systems are analyzed, interpreted, and applied in multidisciplinary contexts.

Geomorphology, subsurface analysis and geostatistical modeling

Barishal Town is located on the active Ganges-Brahmaputra deltaic plain (Goodbred and Kuehl, 2000). The geomorphic setup of Barishal town is a complex fluvial-deltaic system, offering insights into subsurface structures and sediment dynamics. In an area of approximately 94 sq. km., 97 boreholes have been drilled to record the geotechnical properties of the subsurface. The Geomorphic Map, Digital Terrain Model (DTM), serves as a base map during data analysis.

The litho-coarseness curve, core photos, and geotechnical data (such as SPT curve shapes) are analyzed together to identify geological units by examining changes in sedimentary sequences and trends. In Barishal study area, five (05) geological units are identified within the upper 30 meters of subsurface. The lithological assemblages of units 1 and 2 exhibit significant similarities, and their bases are underexplored. For this reason, they are presented together to simplify the modeling process. Five (05) sediment cluster IDs/classes have been identified by the K-means method, and these are utilized in the 3-D voxel model of the study area.

This study integrates statistical and geostatistical analysis. A Geographic Information System (GIS) serves as a platform for managing, analyzing, and evaluating statistical data. A geostatistical approach using 3D indicator kriging was used to generate litho-depositional models.

Voxel model calculation

Subsurface Viewer (R) MX 8.5 is used to arrange data, analyse, and develop the voxel model of the study area. It can perform 3-D indicator kriging operations and visualizing sediment changes and deposition stages.

The voxel model is built using 3-D kriging interpolation (Deutsch et al., 2005). Geological units are assigned to xyz positions and treated as indicator variables, such as core photos, grain-size data, depositional stages, and sediment clusters. These inputs are used in 3-D indicator kriging to create a geostatistical layer model. The smooth layer boundaries are adjusted into realistic geological structures through isoline modeling and converted into triangulated irregular networks (TINs). Modeling is calculated from younger to older deposits, with corrections made where layers extend above the digital terrain model (DTM). Each layer is refined with sediment cluster IDs, and the kriging operation is repeated. The final voxel model (100 × 100 × 0.5 m) is visualized in Subsurface Viewer, showing sedimentary sequences, clusters, and depositional stages.

Results

The voxel model of Barishal town (Figure 1) visualizes the lithological assemblages in two distinct ways, and by the cross-sections.

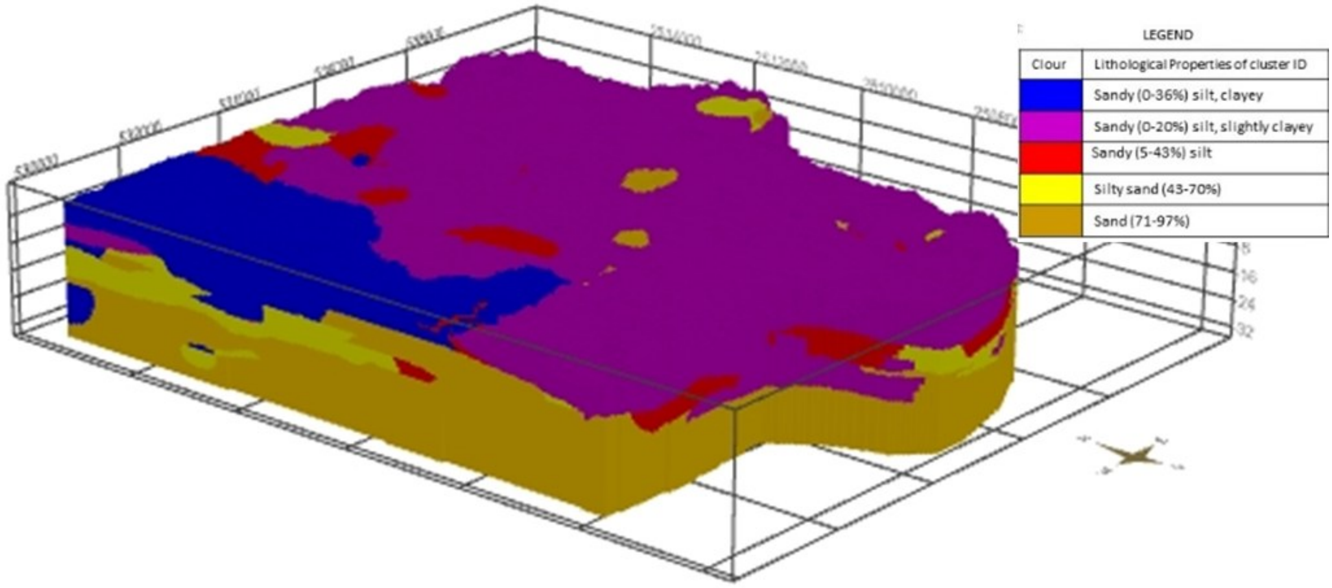

Figure 1, Voxel model of the Barishal study area.

Depth-wise slicing

The model can be explained according to depth levels beneath the surface. In this context, six different depth levels have been extracted in the study area: i) from the top to -5 m, ii) -5 m to -10 m, iii) -10 m to 15 m, iv) -15 m to -20 m, v) -20 m to -25 m, and vi) greater than -25 m.

Unit-wise slicing

It is based on SPT N-value and sedimentary sequences; it explains six depositional sequences in the study area from younger to older stages. The thickness map is the result of the top surface calculation, showing relative sediment accumulation and depletion. Areas with a greenish color indicate higher sediment accumulations, while yellow to red colors indicate areas with erosion or low deposition, including lithological assemblages of the respective model units.

Cross-section

This is another technique to visualize subsurface data. It illustrates how subsurface sediments change dynamically in terms of nature, condition, distribution, and depositional energy along the specified direction. It also shows the lateral variation and interlayers of fine sediment. Figure 2 illustrates a cross-sectional view along the east-west direction of the study area. The presence of finer sediments suggests they were deposited during periods of decreased or fluctuating fluvial energy. In contrast, the coarser sediments found in the lower part indicate higher-energy conditions at the time of deposition.

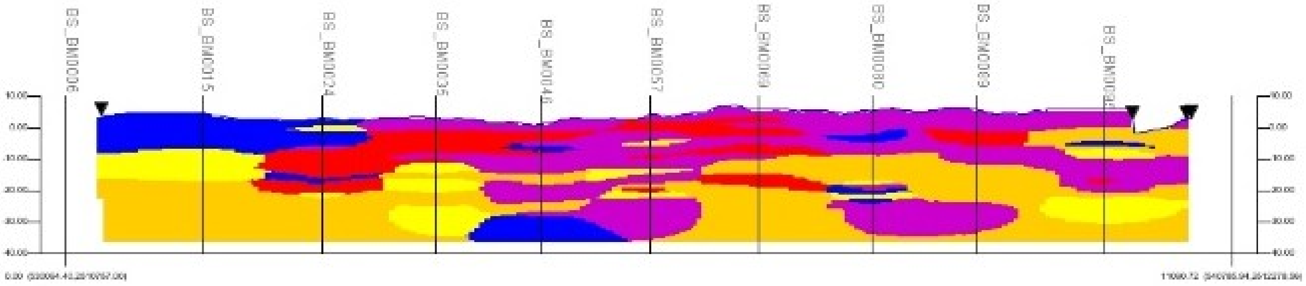

Figure 2, Cross-sectional view along E-W direction.

Discussion

The deposition domain map, generated by grouping geotechnical logs based on coarseness curves, provides an initial interpretation of the local depositional history. In Barishal town, the domain map reveals a dynamic depositional environment with varying drainage positions and energy conditions, characteristic of a deltaic plain.

The 3D voxel model further illustrates a fining upward trend in sediments, with sandy deposits replacing silty ones in the western part of the study area due to reduced depositional energy associated with the Ganges Brahmaputra basin. Fine and sandy sediments observed at deeper stratigraphic levels indicate the transport and deposition of finer material derived from the Ganga delta system. The model effectively captures lithological variability and sediment interlayering, thereby improving the understanding of subsurface heterogeneity and stratigraphic continuity. It also clarifies the relationships between different geomorphic features, which can be systematically interpreted through both longitudinal and transverse cross-sectional views.

Furthermore, the voxel model enables the automatic generation of cross sections along borehole alignments and also allows the creation of customized sections based on specific user defined requirements. This capability provides a clearer representation of spatial and temporal variations in depositional energy conditions across the study area. In addition, the geomorphic units identified on the geomorphic map, such as high floodplains, low floodplains, and marshy areas, provide independent support for the observed depositional trends. These units collectively confirm the interpreted variations in sedimentation patterns and energy regimes over time, thereby strengthening the overall geological interpretation derived from the model.

Conclusion

The 3D voxel model is a powerful tool for analyzing and visualizing subsurface depositional history while assessing geotechnical properties such as lithology, layer thickness, and sediment variability. By transforming traditional 2D maps, cross-sections, and borehole data into a three-dimensional framework, it provides a more accurate and detailed understanding of complex subsurface conditions. The model captures sediment interlayering, fining-upward trends, and variations in depositional energy, which are often difficult to interpret from 2D data alone. In Barishal town, it reveals dynamic depositional environments typical of delta plains, with sandy sediments replacing silty layers in low-energy zones. It can generate cross-sections along borehole lines automatically or in customized ways, facilitating easy interpretation. The voxel model improves communication among engineers, planners, and non-specialist stakeholders through intuitive visualizations. This supports informed decision-making in infrastructure development, urban planning, and hazard mitigation. Overall, 3D voxel modeling promotes sustainable construction, efficient resource management, and a deeper understanding of geomorphic and sedimentary processes.

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References

Deutsch, C. V., and Neufeld, C. (2005). New software for fitting indicator covariances and for indicator kriging/simulation (12 p.). University of Alberta, Edmonton, AB, Canada.

Goodbred, S. L., and Kuehl, S. A. (2000). The significance of large sediment supply, active tectonism, and eustasy on margin sequence development: Late Quaternary stratigraphy and evolution of the Ganges–Brahmaputra delta. Sedimentary Geology, 133(3–4), 227–248. https://doi.org/10.1016/S0037-0738(00)00041-5