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Enhancing Urban Tunnelling Efficiency through Real-Time Geotechnical Parameter Analysis, a Case Study at Kolkata East West Metro Project, KMRCL-1674

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ABSTRACT
The exponential increase in urbanization has heightened the demand for a systematic and rapid mass transportation system in developing countries. One efficient solution has been the construction of underground networks of tunnels using Tunnel Boring Machines (TBMs). Urban tunnels, however, require careful attention to minimizing ground disturbances to avoid adverse impacts on existing infrastructure.

The current study focuses on a parametric investigation based on observed trends from the Kolkata East West Metro UG1 project. It undertakes numerical regression to establish correlations, aiming to investigate geotechnical parameters derived from observed operational parameters during tunnel advancement. This correlation allows for the determination and validation of considered geotechnical parameters in real-time, thereby facilitating the optimization of operational parameters.

By establishing correlations, the study examines and validates the effect of geotechnical parameters on observed settlement. In conclusion, the consideration of tunnel operational parameters and subsequent establishment of geotechnical parameters can potentially automate the functioning of mechanized tunnelling, leading to more efficient and effective tunnel construction processes.

Keywords: Tunnelling, Ground Parameters, Geotechnical Assessment, Tunnel Operational Parameters, Numerical Regression

I. INTRODUCTION

The dimensional limitations of surface infrastructure have led to a significant increase in the development of underground infrastructure, particularly through the construction of networks of tunnels in urban areas. Underground tunnelling poses inherent challenges and uncertainties due to the complexities of varying geologies. Despite numerous investigations, uncertainties persist during tunnelling operations, often arising from differences in geology or variations in investigated ground parameters.

The current study aims to compare and establish potential trends for geotechnical parameters based on tunnel operational parameters. This assessment seeks to enable the determination of actual observed ground conditions in real-time, facilitating the optimization of tunnelling operational parameters and potentially automating them. By identifying and analysing these trends, the study endeavours to enhance the efficiency and effectiveness of tunnel construction processes in urban environments.

II. PROJECT BRIEF& DESIGN CONSIDERATIONS

Project Brief

An Underground Transit Rail Metro project was proposed to connect Kolkata and Howrah via a tunnel underneath the Hooghly River. This pioneering project holds immense significance as the first of its kind in the country. The Project UG1 (Figure 1) encompasses a 3.8 km underground tunnel, including three underground stations and a ventilation shaft.

The section provides a comprehensive overview of the geotechnical conditions, parameters, and tunnel operational parameters considered for tunneling. This information serves as a crucial foundation for understanding the complexities and challenges inherent in executing such an ambitious undergroundinfrastructure project.

Figure.1 Kolkata East West Metro UG1 Tunnel Alignment

DESIGN CONSIDERATIONS

Figure 1 illustrates the plan of the tunnel alignment. As the Tunnel Boring Machine (TBM) progresses, tunnel linings are installed within the tail shield of the TBM, adjacent to the previous segmental ring. The adopted lining thickness is 275 mm, with an internal diameter of 5550 mm. These tunnel linings are pre-cast concrete segmental linings comprising five large segments and one key segment for the construction of each ring. During tunnel advancement, segments are meticulously aligned and placed adjacent to each other with millimeter precision.

Hydro-Geological circumstances

The geological context primarily consists of an alluvial formation comprising silt, clay, peat, and sand. The depth of the tunnel along the alignment varies from 12-33m below ground level. Considering the existing geological conditions, Earth Pressure Balance Tunnel Boring Machines (EPB TBMs) were chosen. Along the alignment, the tunnel traverses varying geological contexts, encountering both clayey silt and occasional sand lenses.

Figure 2 illustrates the typical geological profile along with the vertical tunnel alignment. The geological profile is divided into four units:

Unit 01: This upper soil layer (1-3 meters below ground level) primarily consists of filled-up soil.

Unit 02: Beneath Unit 01 lies soft dark greyish clayey silt with N-values ranging from 2-8 and extending up to 15-18 meters below ground level. This layer is considered very weak with low permeability ranging from 10^-8 to 10^-9 m/sec.

Unit 03a: Stiff Yellowish grey Clayey Silt with N-values ranging from 20 to 30 underlies the soft clayey silt (Unit 02) typically down to 45 meters below ground level. This soil is relatively stiff and comprises discrete sand lenses (a water-bearing patch) sandwiched within. Permeability ranges between 10^-8 to 10^-9 m/sec.

Unit 03b: Dense sandy soil (fine sand) is observed as discrete sand lenses (a water-bearing patch) sandwiched in the Unit 3a stratum. This is a water-bearing stratum with relatively higher permeability ranging around 10^-5 m/sec.

Groundwater Table: Short-term measurements indicate the groundwater table in the range of 1-4 meters below ground level, while long-term measurements using standpipe piezometers show the water table at 7 to 10 meters below ground level.

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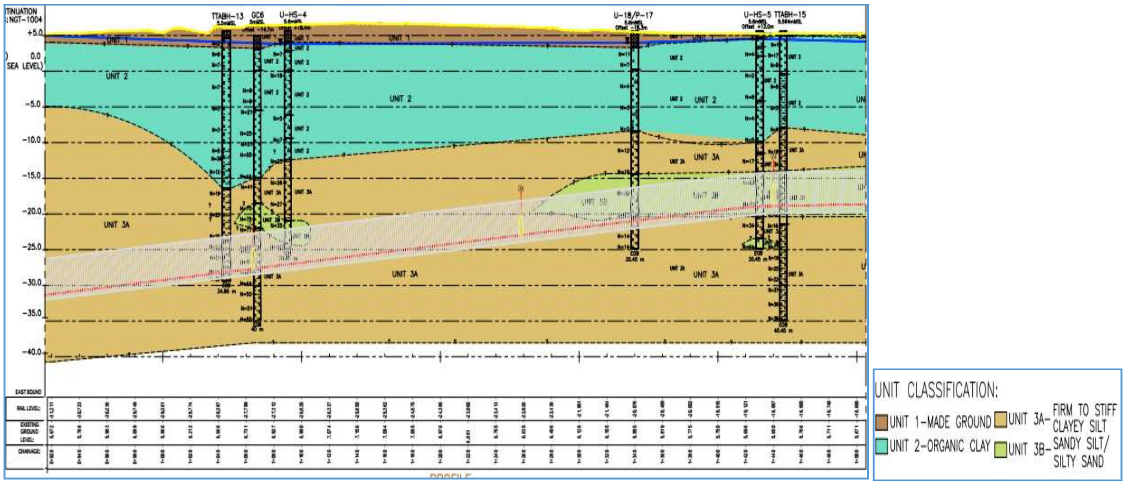

Figure.2 Typical geological conditions observed in tunnel alignment

III. EVALUATING GEOTECHNICAL PARAMETERS USING TBM OPERATIONAL PARAMETERS

Tunnel Boring Machines (TBMs) utilize thrust cylinders to propel forward, drawing reaction from the installed concrete segment linings. These thrust cylinders are typically equipped with load cells to measure the reaction force during advancement. In the Kolkata Metro UG1 project, observed thrust forces during TBM advances have been compared with geotechnical properties such as N-value and Young's Modulus of soil, revealing a strong correlation between them. The figures below illustrate the observed trends of TBM thrust in relation to geotechnical properties.

The significant degree of correlation observed in these trends facilitates a tentative assessment of the geotechnical properties of the ground being tunneled through during TBM advances. This tool can be effectively utilized for validation and optimization of various tunnel operational parameters, as they heavily rely on the considered design parameters.

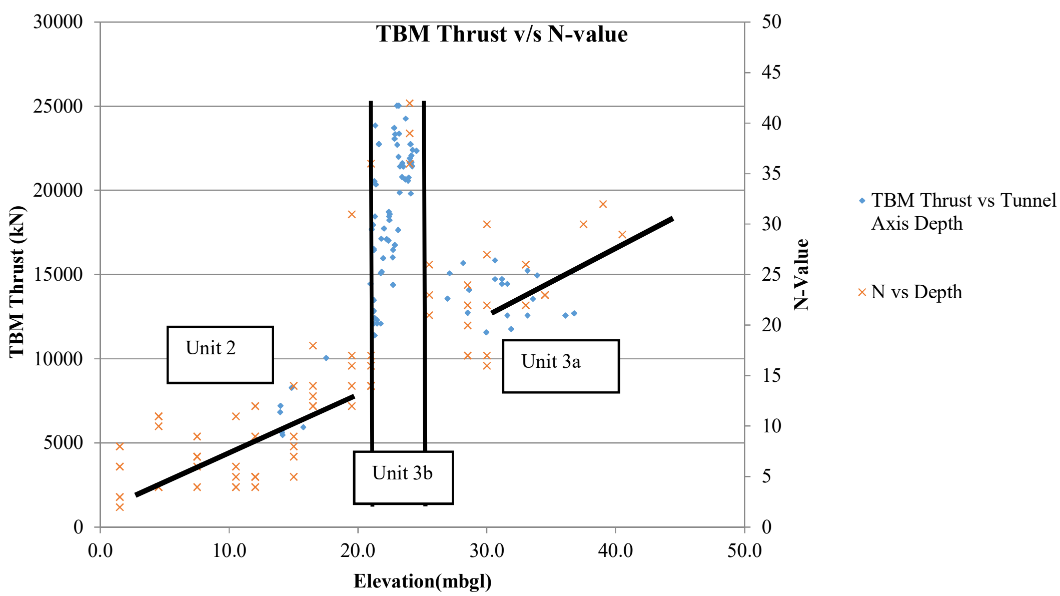

Figure.3 Comparative TBM Thrust v/s N-value in context with elevation

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Based on the observed similitude, a comparison between the soil properties (stiffness of soil as obtained from field & lab results) & TBM thrust has been undertaken.Soil young's modulus has been conservatively correlated with N-value using correlation suggested by CIRIA R143 & correlations based on laboratory triaxial & consolidation tests.

E'/N=1(MPa)

1.

A relation between the stiffness of soil i.e. young's modulus & the TBM thrust has been established and mentioned below i.e. Equation.1. Further a multi variableregression analysis has been undertaken to establish the degree of correlation between the observed thrust during TBM advance and geotechnical properties.

$$E' = T * \frac{k*g}{\pi*\frac{d2}{4}*Ar}$$

2.

where. E' = Soil Modulus of Elasticity (kPa),
T = TBM Thrust (kN),
d = Tunnel Diameter; 6.1 for the current case,
Ar = Area Ratio of TBM cutter head i.e. 40% for the current case,
g= force to mass conversion factor; 9.81,
k = Soil Co-efficient (2 for soft clay, 2.3 for stiff clay&2.2 for silty sand)

The value k is a constant defined as co-efficient for soil and is found to vary for different soil types for generating a regression fit. The value of k can is found nearing to co-efficient of passive earth pressure of soil for long term or effective stress condition.

Figure.4 depicts a scatter plot showing the comparison between the young's modulus of soil in context with depth.

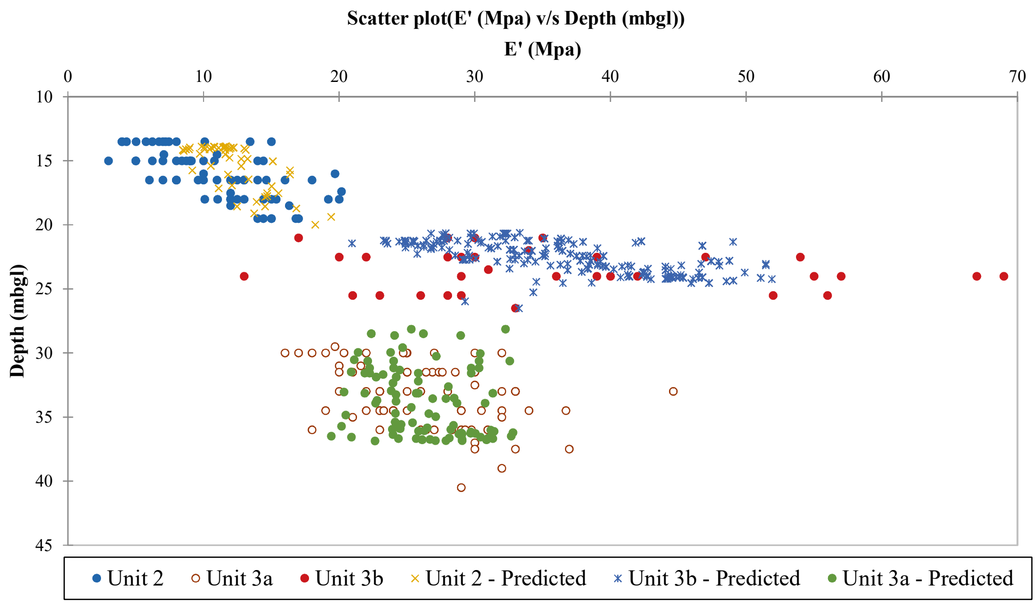

Figure.4 Scatter plot of E' (Field & Lab Tests)& E'-Predicted (TBM Thrust) with respect to elevation

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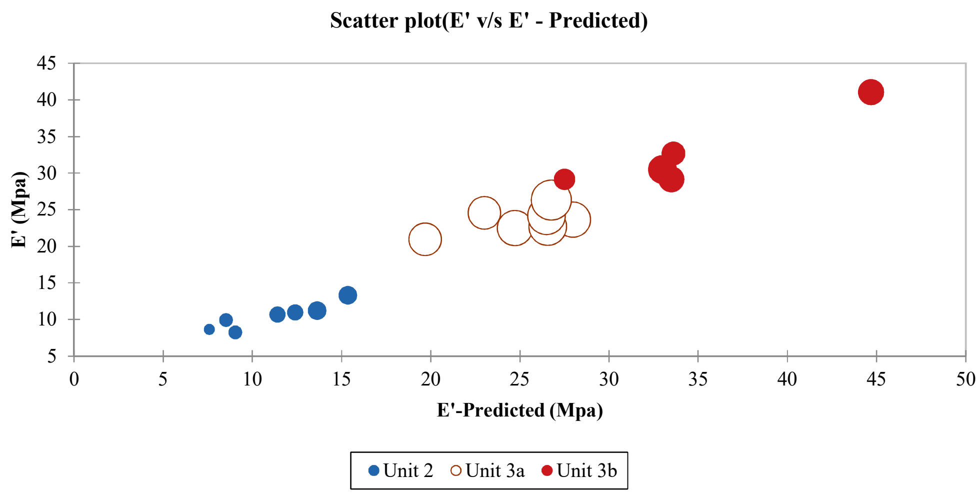

Figure.5 Comparison of E' – Avg (Field & Lab Tests) v/s E' – Avg (Predicted from TBM Thrust)

Figure.5 plots the average E' values obtained using field and laboratory test results with average predicted E' from TBM thrust using Equation.2 for respective soil types at respective depths. Evident from the figure, the scatter is found to form a good fit.

The results of regression analysis are further sensitized and are presented in Figure.6 & 7. R-square value of 0.962 was found for the established correlations between the TBM thrust and soil stiffness (E') mentioned in Equation.2.

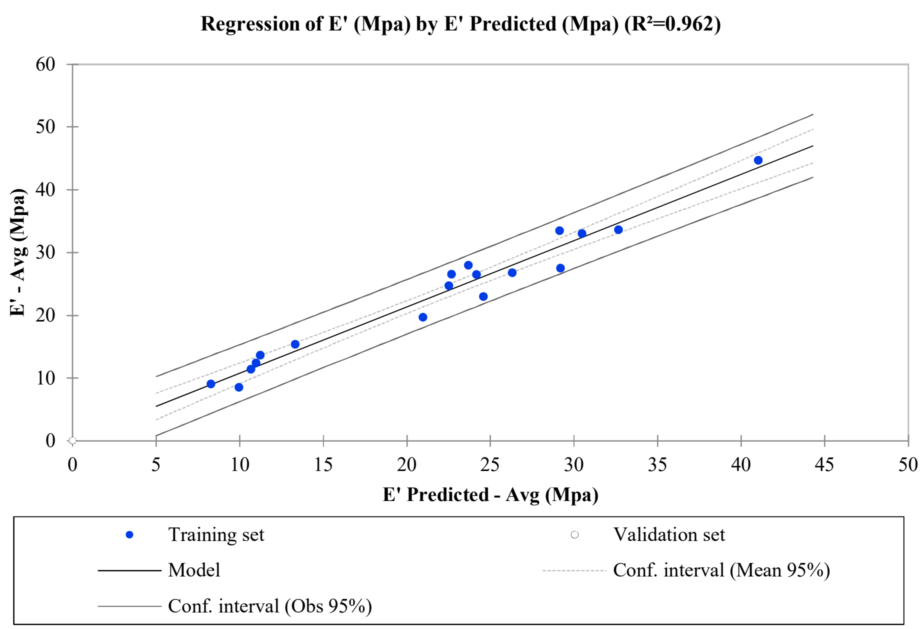

Figure.6 Regression Analysis of E' – Avg (Field & Lab Tests) v/s E' – Avg (Predicted from TBM Thrust)

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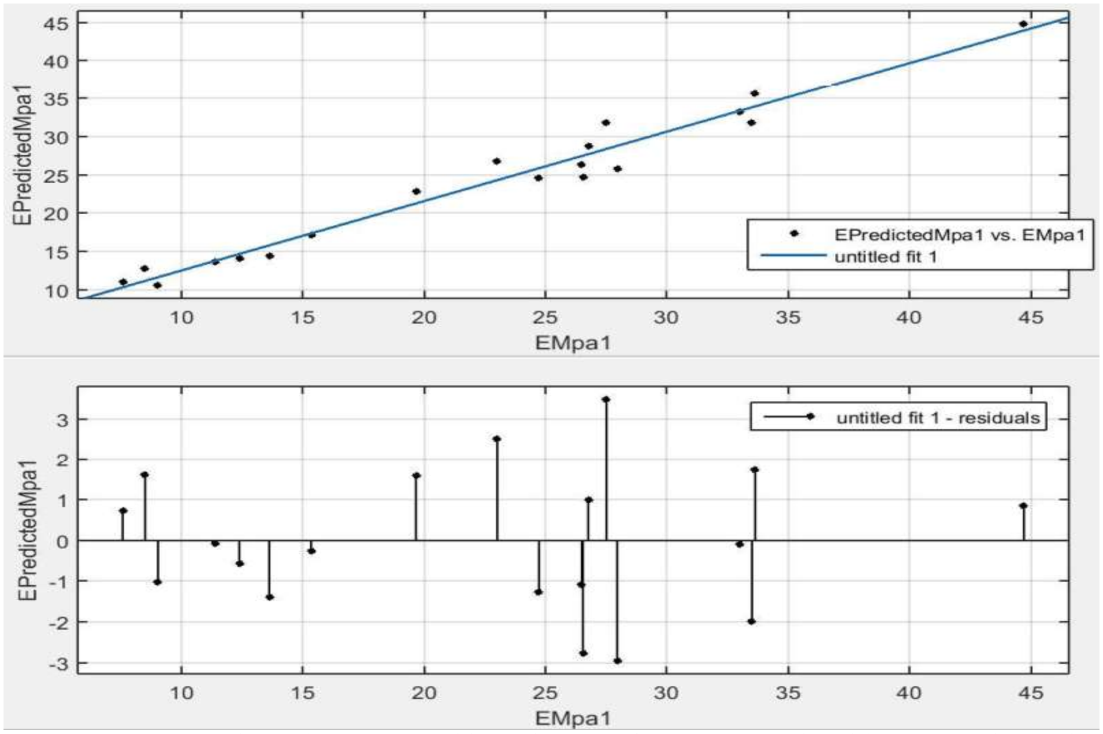

Figure.7 Regression Analysis of E' – Avg (Field & Lab Tests) v/s E' – Avg (Predicted from TBM Thrust) along with Residual plot -2D using MATLAB

Figure.8 shows a 3-D plot of E' predicted v/s E'-(lab & field tests) with respect to elevation. The observed residuals are also found to be within threshold of 2MPa and hence can be considered as a good fit.

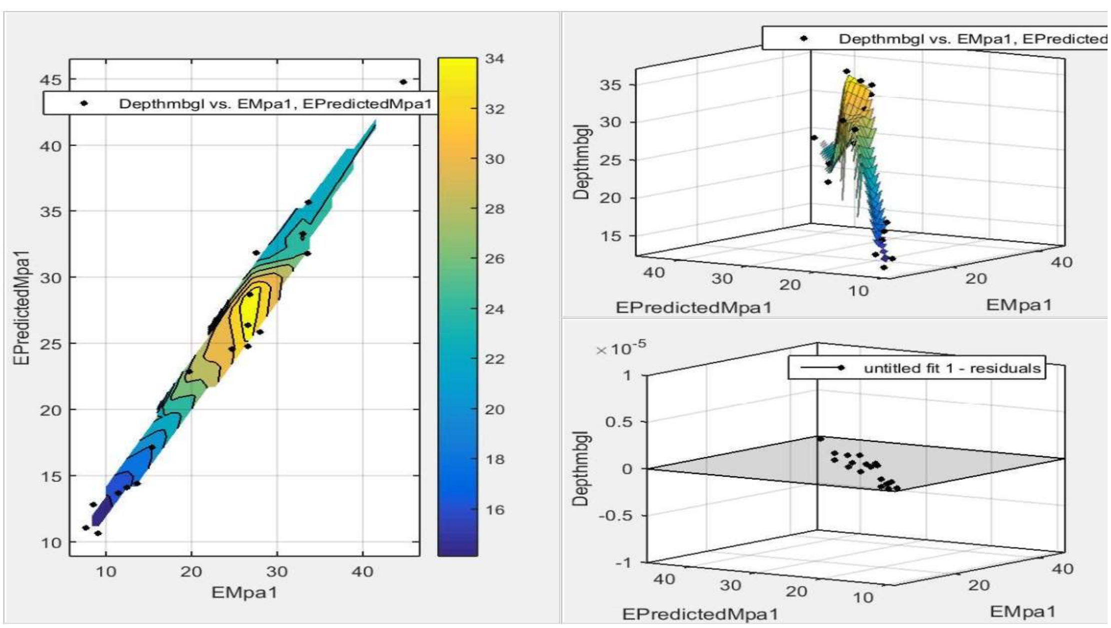

Figure.83Dplot of E' – Avg (Field & Lab Tests) v/s E' – Avg (Predicted from TBM Thrust) with respect to depth (mbgl) along with Residual plot using MATLAB

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Real time back-Calculation of geotechnical properties can enable us to validate the considered geotechnical parameters and can be further utilized for amending/modifying the tunnel operational parameters accordingly as they rely heavily on the considered design geotechnical parameters. Several instances have been put forward in literatures whereby the predicted geology doesn't correspond to the observed geology. The mathematical tool can efficiently enable us to derive geotechnical properties for further correlations. Although it can be suggested that project bound sensitization be undertaken.

In order to further validate the derived correlation suggested in Equation.2, the E' values from Ahmedabad Metro (as correlated from N-values using Equation.1 correlation) were compared to the Predicted E' derived from TBM parameters using Equation.1.

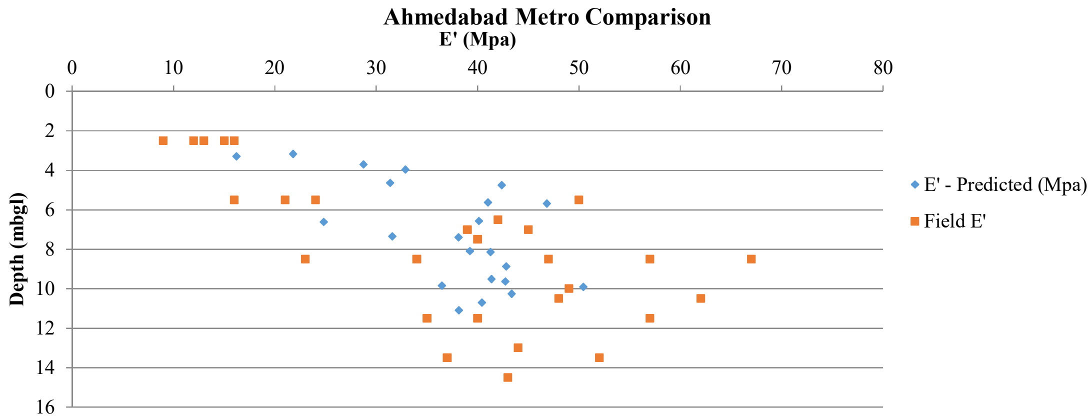

Figure.9 Scatter plot of E' (Field Tests) & E'-Predicted (TBM Parameters) with respect to elevation – Ahmedabad Metro

Evident from Figure.9, the E' values derived from Field Tests form good correlation with the predicted E' derived from TBM parameters using Equation.2.

IV. CONCLUSION

Based on the observed correlation between TBM thrust and Soil Young's Modulus, a methodology has been developed to compute Soil Young's Modulus from TBM thrust. This correlation enables the assessment of geotechnical properties based on observed TBM parameters. The comparison of results demonstrates that a precise range of ground parameters can be determined from operational parameters, facilitating the validation of investigated parameters.

In the absence of geotechnical parameters, these correlations can be utilized to determine ground parameters using TBM parameters, thus enabling further refinement through iteration and back-calculation to obtain accurate ground parameters. The consideration of assessing ground parameters from operational parameters allows for the precise determination of existing ground conditions and the iterative adjustment and optimization of operational parameters.

There remains a wide scope for research and application of this method across diverse geological settings to determine ground parameters using operational parameters, enabling even more precise determinations. Further development of this method on a larger scale may ultimately enable a degree of automation in TBM operations, wherein the TBM could maintain required operational parameters such as face pressure and grout pressure, as well as adjust soil conditioning based on observed TBM parameters such as diameter and thrust.

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