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Analysis of EPB Shield Tunneling–Induced Ground Settlement in Inclined Layered Soil

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ABSTRACT

Ground settlement is a critical concern in Earth Pressure Balance (EPB) shield tunneling. Most existing studies have focused on homogeneous or horizontally layered soil conditions, where the strata remain uniform along the excavation direction. However, in practice, inclined layered soil beyond the excavation face can influent the pattern and magnitude of ground settlement. Thus, this study investigates ground settlement induced by EPB shield tunneling in inclined layered soils, focusing on how strata orientation ahead of the excavation face affects settlement. The influence of inclined layers with varying dip angles and distances from the excavation face is examined using FLAC3D. The results highlight that inclined soft soil layers ahead of the excavation face increase ground settlement, especially as the face approaches the layer interface. The stiffness of the lower stratum has the greatest impact on settlement, while the effects of upper layer stiffness and dip angle are comparatively minor. Distance to the inclined interface is a critical factor, with higher dip angles causing greater deformation when soft soil lies above the tunnel.

1. INTRODUCTION

With the rapid pace of urbanization, the demand for underground space in densely populated cities is increasing. Earth Pressure Balance (EPB) Tunnel Boring Machines (TBMs) are particularly advantageous in urban environments due to their minimal impact on surrounding infrastructure, as well as their enhanced safety and operational efficiency. However, EPB TBMs can still induce ground settlement—a critical concern in urban settings where surface deformation must be tightly controlled (Shen et al., 2014; Di et al., 2016; Zheng et al., 2025). Many studies have examined the influence of shield tunneling on surface settlement, but the majority have focused on homogeneous or horizontally layered ground conditions (Broere, 2001; Tiwari & Kumawat, 2014; Alagha & Chapman,

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2019). In practice, however, tunneling often encounters inclined stratified soils (Liu et al., 2022; Wang et al., 2024; Tu et al., 2024; Cui et al., 2025). The inclined layer beyond the excavation face can alter the behavior of the ground during the excavation. Hence, this study aims to investigate ground settlement induced by EPB shield tunneling in inclined layered soils, with particular emphasis on how the geological strata in front of the tunnel face affects surface settlement.

2. METHODOLOGY

A finite difference method (FDM) numerical analysis of tunnel-induced ground settlement is performed using FLAC3D. The ground consists of two soil layers: a stiffer lower layer and a softer upper layer, which is inclined over the stiffer stratum. The tunnel is excavated from the stiff soil layer toward the soft soil. The TBM is modeled using shell elements, while the concrete lining is represented using liner elements. Ground settlement is monitored as the distance from the excavation face (L) increases in 10-meter increments. The geometry and material properties of the ground are provided in Table 1. The model dimensions are set to minimize boundary effects, and the full geometry of the model is illustrated in Fig. 1.

Table 1. Ground properties

Geometry		
Tunnel Diameter, D	10m	
Tunnel Cover Depth, C	20m	
Ground Properties	Soft Soil	Stiff Soil
Friction angle, φ (°)	25	35
Cohesion, c' (kPa)	35	0
Density, ρ (kg/m^3)	1600	1800

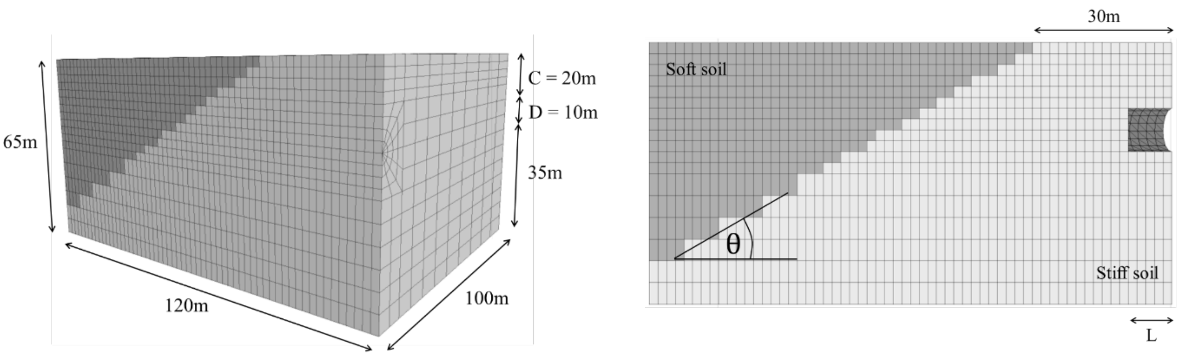

Fig. 1 Model Dimension

The influence of the inclined soil layer ahead of the excavation face is investigated by comparing the ground settlement observed in an inclined layered soil profile with that in a homogeneous ground profile, which possesses the same properties as the stiff soil layer. The effects of elastic modulus and dip angle of the inclined strata on settlement behavior are analyzed. The ground properties used in each simulation case are summarized in Table 2.

Table 2. Simulation cases

Variables	Stiff Soil Elastic Modulus (MPa)	Soft Soil Elastic Modulus (MPa)	Dip Angle
Homogeneous	E = 100, 20, 10		
Elastic Modulus	E_{stiff} = 100, 20, 10	E_{soft} = 5, 1	θ = 30°
Dip Angle	E_{stiff} = 20	E_{soft} = 1	θ = 20°, 30°, 40°

3. RESULTS

Fig. 2 presents the settlement profile for an inclined stratified ground condition, where the lower soil layer has an elastic modulus of E = 10 MPa and the dip angle of the strata is θ = 30°. The results indicate that the presence of an inclined soft layer ahead of the excavation face leads to greater ground settlement compared to a homogeneous ground with the same properties as the stiff soil. The influence of the inclined layer becomes more pronounced as the excavation face approaches the interface between the soft and stiff layers. Also, a soft soil layer with a lower elastic modulus (E = 1 MPa) results in greater settlement compared to one with a higher elastic modulus (E = 5 MPa).

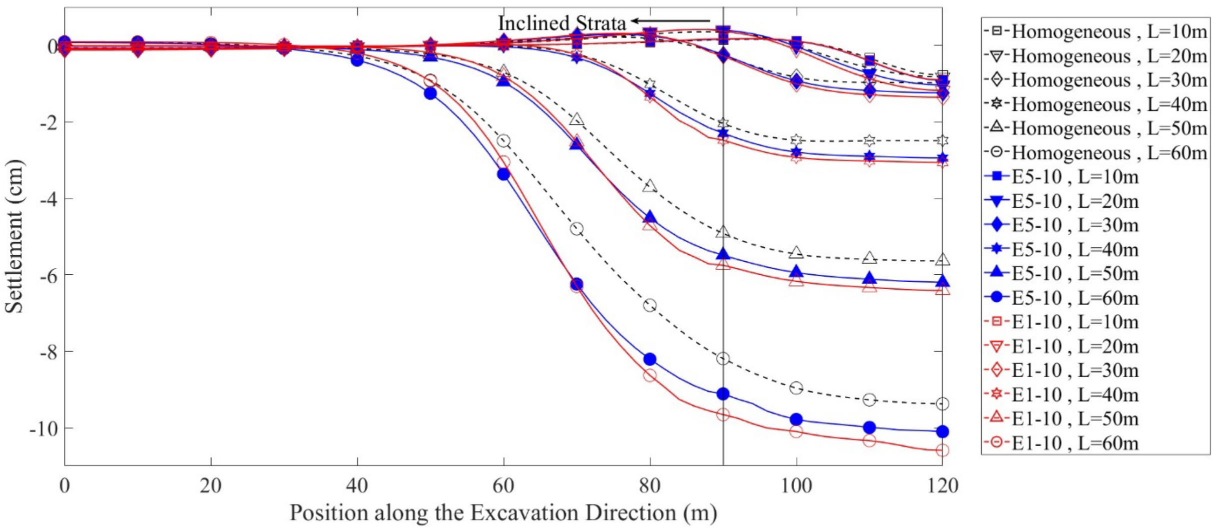

Fig. 2 Settlement profile of the excavation with lower strata E=10MPa

Fig. 3 and 4 show the settlement profiles for ground conditions where the lower strata have elastic moduli of E = 20 MPa and E = 100 MPa, respectively. Across different stiffness values of the lower stratum, the presence of an inclined layer still results in greater settlement compared to the homogeneous ground. However, as the elastic modulus of the lower strata increases, the overall ground settlement decreases, and the influence of the inclined layer becomes less significant. These findings suggest that the stiffness of the lower stratum—where excavation occurs—has a considerably greater impact on settlement behavior than the elastic modulus of the upper inclined strata.

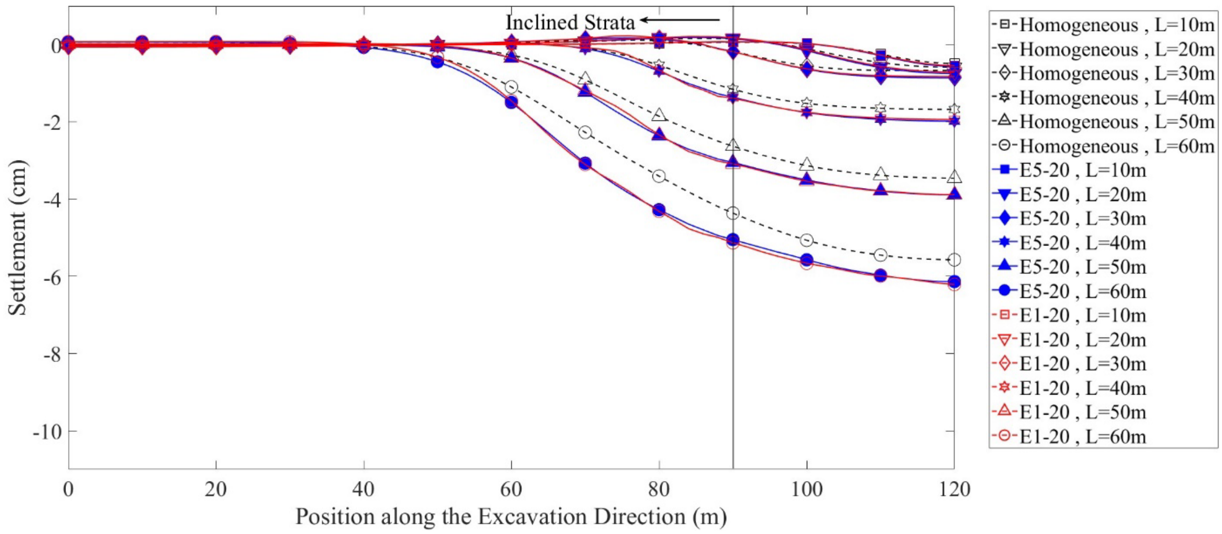

Fig. 3 Settlement profile of the excavation with lower strata E=20MPa

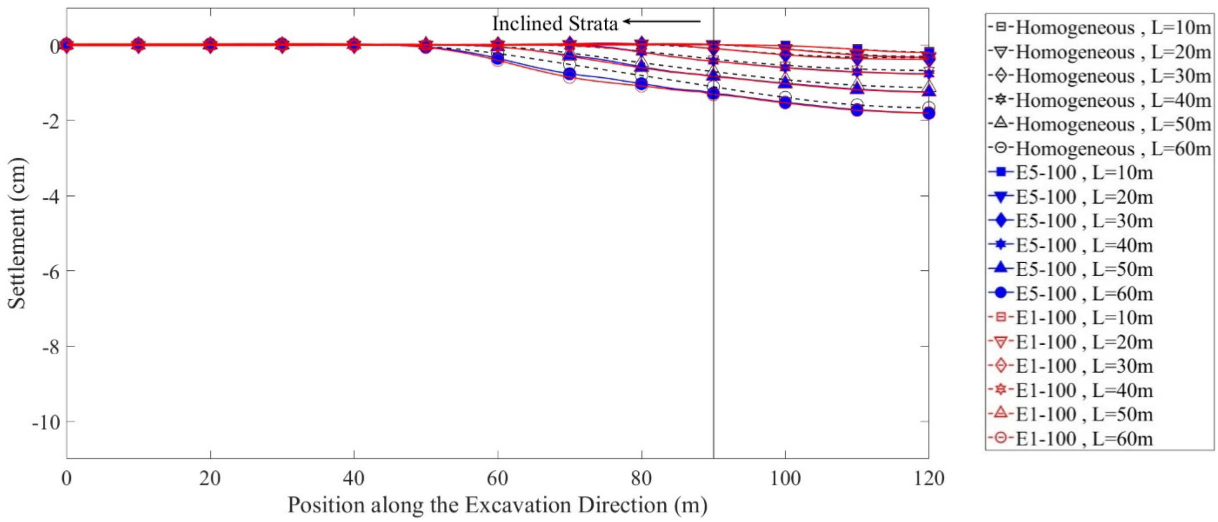

Fig. 4 Settlement profile of the excavation with lower strata E=100MPa

Figures 5 and 6 illustrate the incremental settlement observed in inclined layered ground conditions—where the upper layer has elastic moduli of E = 1 MPa and E = 5 MPa, respectively—relative to the corresponding homogeneous ground cases. The results show that when the excavation face is distant from the inclined layer interface, the influence of the inclined strata on settlement is negligible, with differences approaching zero. However, as the excavation face advances toward the inclined interface, the impact of the inclined layer on settlement becomes increasingly pronounced. In this region, the elastic modulus of the lower layer becomes a more dominant factor in controlling settlement. Similarly, the influence of the upper layer—located ahead of the excavation face—on settlement also becomes more noticeable, particularly as its stiffness varies. Nevertheless, its effect remains substantially less significant compared to that of the lower stratum, which directly hosts the excavation. Importantly, the distance from the inclined interface has a greater effect on ground settlement than the elastic modulus of the soft soil strata.

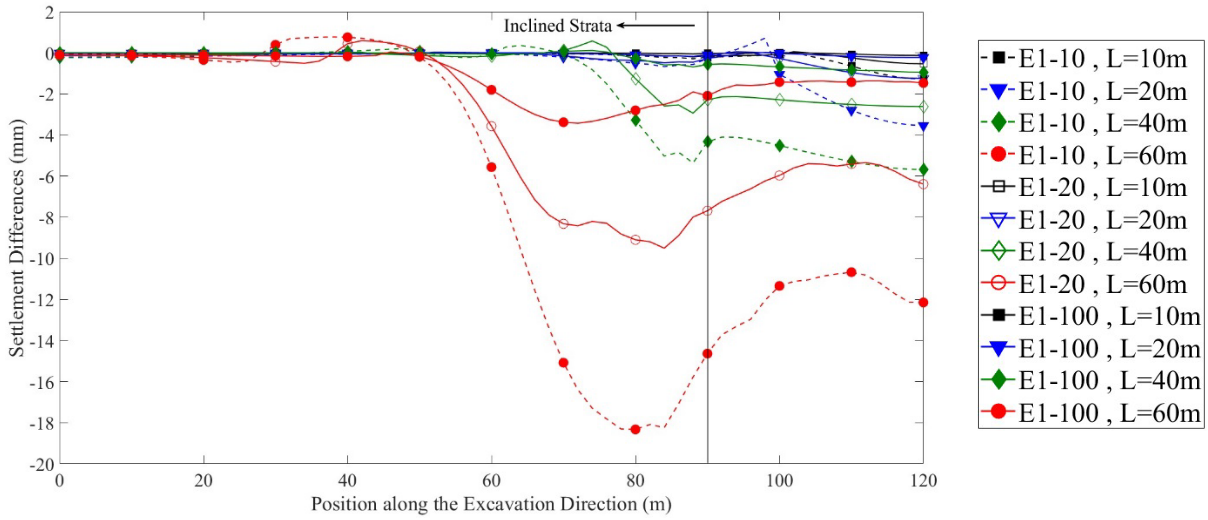

Fig. 5 Settlement difference between inclined strata with soft soil layer E = 1 MPa and different stiff soil layer elastic modulus, and homogeneous ground

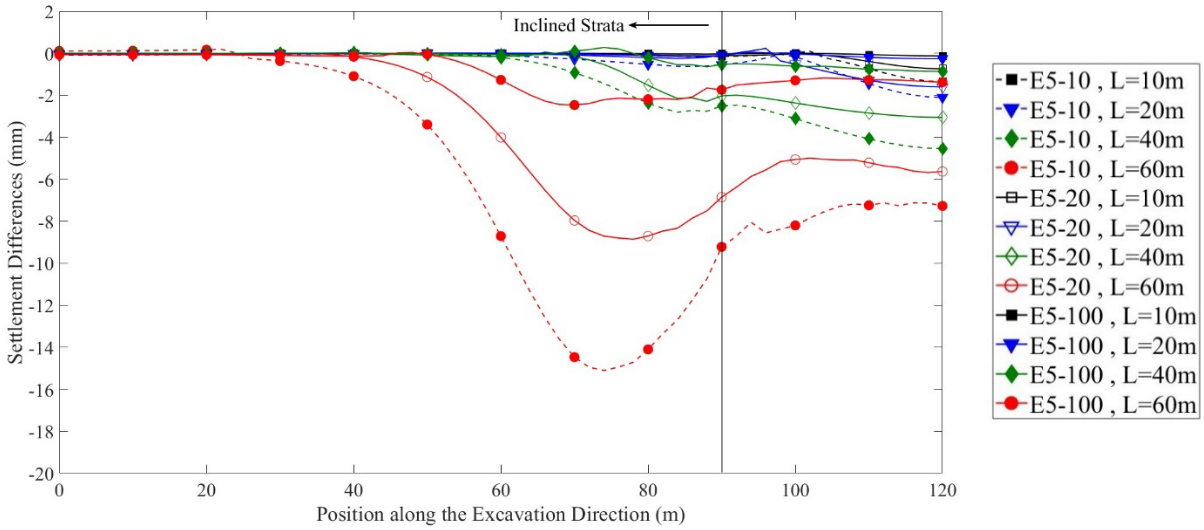

Fig. 6 Settlement difference between inclined strata with soft soil layer E = 5 MPa and different stiff soil layer elastic modulus, and homogeneous ground

Fig. 7 presents the settlement profiles for inclined stratified ground with an upper layer elastic modulus of E = 1 MPa and a lower layer modulus of E = 20 MPa. Settlements resulting from different dip angles are compared with those in a homogeneous ground condition with E = 20 MPa.

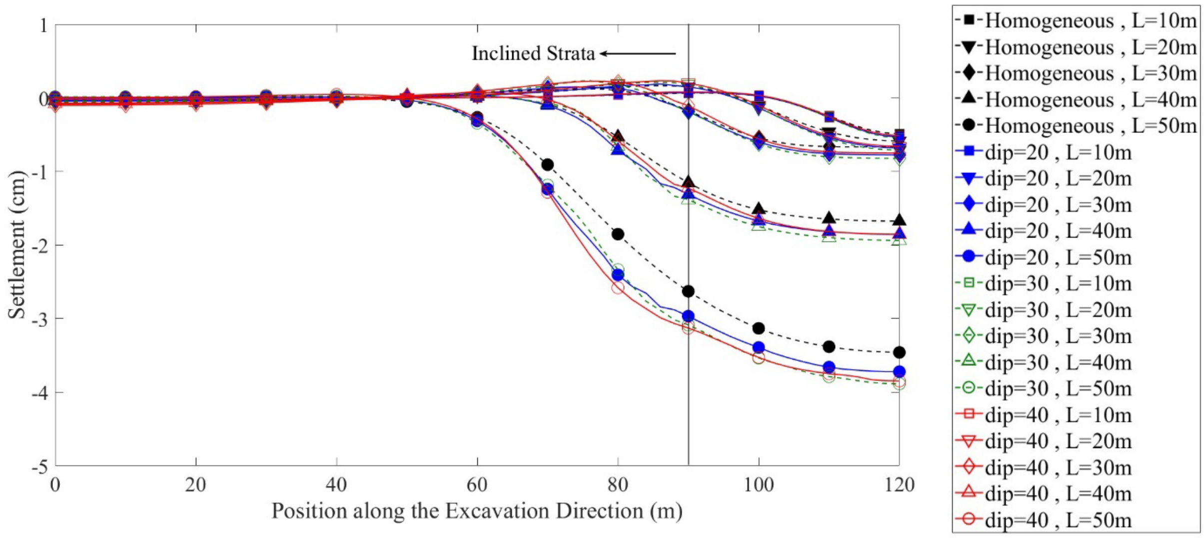

Fig. 7 Settlement profile of the excavation with different strata dip angle

Fig. 8 shows the corresponding settlement increments due to varying dip angles, relative to the homogeneous case. The results indicate that the influence of dip angle becomes more significant as the excavation face approaches the interface between the soil layers. In particular, a dip angle of 40° results in substantially larger settlements compared to dip angles of 20° and 30°, as a greater volume of the soft soil lies not only ahead of the excavation face but also directly above it. This vertical positioning amplifies the deformation response.

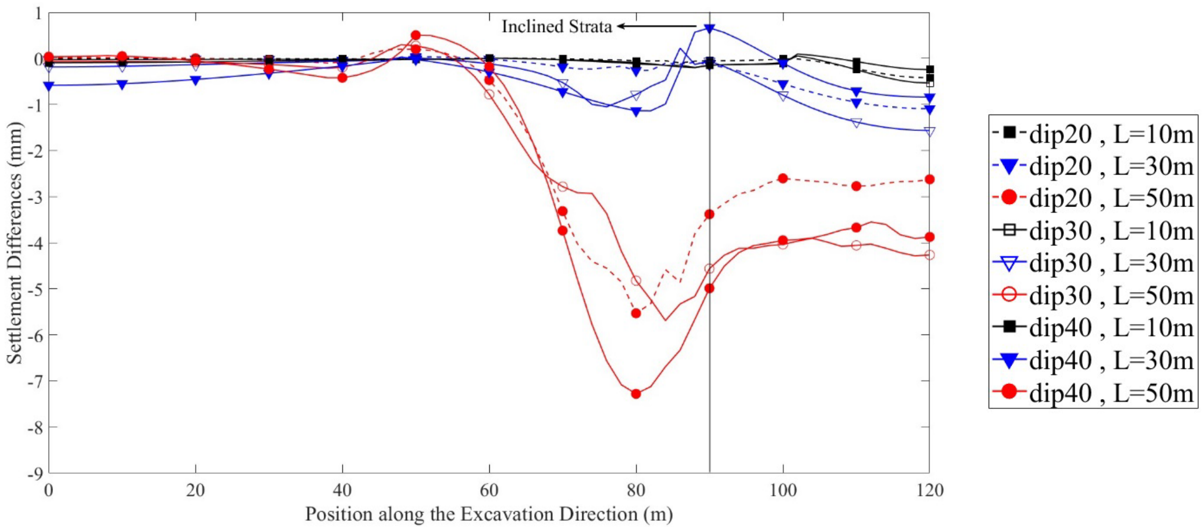

Fig. 8 Settlement difference between inclined strata with different dip angle and homogeneous ground

Similar to the trends observed with variations in the elastic modulus of the upper layer, the dip angle of the strata has a less pronounced effect on settlement compared to the proximity of the excavation face to the inclined interface. This highlights the dominant role of excavation face distance in influencing ground deformation behavior.

4. CONCLUSION

The results revealed that the presence of an inclined soft soil layer ahead of the excavation face increases ground settlement compared to homogeneous ground conditions. This effect becomes more pronounced as the excavation face approaches the interface between the soft and stiff soil layers. Among the factors studied, the elastic modulus of the lower strata—where excavation takes place—was found to have the most substantial influence on settlement magnitude. Although variations in the elastic modulus of the upper soft layer and the dip angle of the inclined strata do affect the settlement pattern, their impact is relatively minor in comparison.

Notably, the distance from the inclined interface proved to be a critical parameter. Settlement differences remained negligible when the excavation face was far from the interface but increased sharply as it approached. This trend was consistent regardless of changes in upper layer stiffness or dip angle. Moreover, higher dip angles (e.g., 40°) caused greater settlement due to a larger portion of the soft soil lying vertically above, rather than just ahead of, the tunnel face.

In conclusion, the findings highlight the importance of considering both stratigraphic orientation and spatial positioning of inclined layers in tunneling design. Accurate assessment of the distance to the inclined interface and stiffness contrast between soil layers is essential to predict and control ground deformation.

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