

Chapter 1

Incorporation of Surrounding Rock Layer Presence in the Design of Underground Cut and Cover Box Structure



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Introduction

Underground construction is generally carried out by two methodologies, namely: tunneling and cut and cover. Depending on ground conditions, tunneling methodology is subdivided into Tunnel Boring method and New Austrian Tunneling method, whereas cut and cover methodology is subdivided into top-down and bottom-up construction. In top-down construction, temporary and permanent support can be integrated into one earth retaining structure. On the other side, bottom-up construction requires separate temporary earth retaining structural arrangement to provide support during excavation and construction period. Top-down construction with diaphragm wall is mainly chosen when there is presence of soil strata. Bottom-up construction is mainly preferred in mixed ground condition or if there is presence of rock layer [1]. In a metro corridor in congested locations, soldier and secant piled walls are mainly provided as temporary earth retaining arrangement due to limited space availability [2]. Bottom-up construction with soldier pile support arrangement is generally chosen when water table is below base slab level. Secant pile support arrangement is chosen when water table is at shallow depth. Waler and strut or ground anchor system is further provided to support soldier piled and secant piled walls laterally. Thus, bottom-up construction, as earth retaining arrangement, requires additional time and activities leading to higher costs. Hence, it is necessary to have an innovative practice beyond the common and conventional methods in design/construction with site-specific considerations and design input parameters. Structural design of a cut and cover station situated in mixed ground condition of

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Chennai Metro Project Phase-II alignment corridor has been referred for the present case study. Construction of underground station in mixed ground condition is quite tough, uneconomical, and time consuming with conventional methods. Grade (IV) or better charnockite rock is encountered within the excavation depth of Thiruvanmiyur station. Due to difficulty of excavation in hard strata as well as self-standing nature of rock, diaphragm walls with shear pins embedded into rock strata have been adopted. This arrangement reduces the requirement of temporary earth retaining support arrangement like soldier pile, secant pile, etc. Therefore, it helps to save time, manpower and material costs by 15–20%. Due to varying rock level along the station alignment, diaphragm walls, cast in panels, terminate at different depths. The above-mentioned arrangement has been adopted to ensure adequate stability. Furthermore, stitch walls have been provided as connection between station diaphragm wall and station base slab using open excavation method. Entire sequence of construction has been modeled and analyzed in PLAXIS 2D [2] software for checking of structural design, stability, ground deformation, etc. On the other hand, service stage model has been developed in STAAD.Pro V8i [3] to check for serviceability criteria of the structure.

Project Location and Station Description

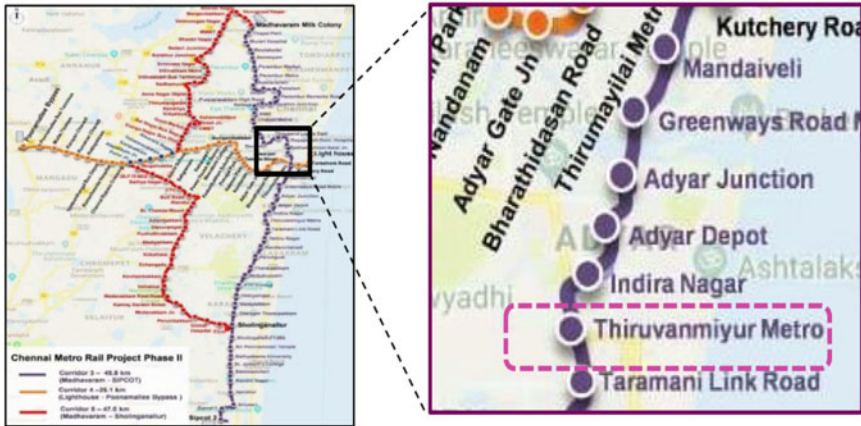
The city of Chennai is situated near 13° North Latitude and 80° East Longitude and stretches over a length of 19 km along the Coromandel Coast with an area of 172 km². Entire Phase-II work of Chennai Metro Rail Limited (CMRL) is divided into three lines, i.e., Corridor 3, Corridor 4 and Corridor 5. Thiruvanmiyur station (Ch. 24,804.002) lies in Chennai Metro Phase-II Corridor 3. AECOM is the Detailed Design Consultant (DDC) for CMRL Corridor 3. The horizontal alignment for Thiruvanmiyur station is shown in Fig. 1.1.

Thiruvanmiyur metro station comprises three levels of slabs supported on two diaphragm walls on both sides. Length of the station is 152 m, height is 16.5 m, and width of the station varies from 20.35 m in the middle of station to 24.05 m at the ends. Three-dimensional (3D) view of the entire station box for Thiruvanmiyur station is shown in Fig. 1.2.

Geotechnical and Geological Conditions of Project Location

The geology of Chennai comprises mostly sand deposits, clay, granite, gneiss, and traces of shale and sandstone. The city is classified into three regions based on geology i.e., sandy areas, clayey areas, and hard rock areas.

For the Thiruvanmiyur station, the subsurface strata at the site consist of cohesionless soil, cohesive soil, and weathered rock. Depth-wise and strata-wise summary



(A) CMRL Project Phase II Corridor

(B) Location of Thiruvanniyur station

Fig. 1.1 Location plan of Thiruvanniyur underground metro station

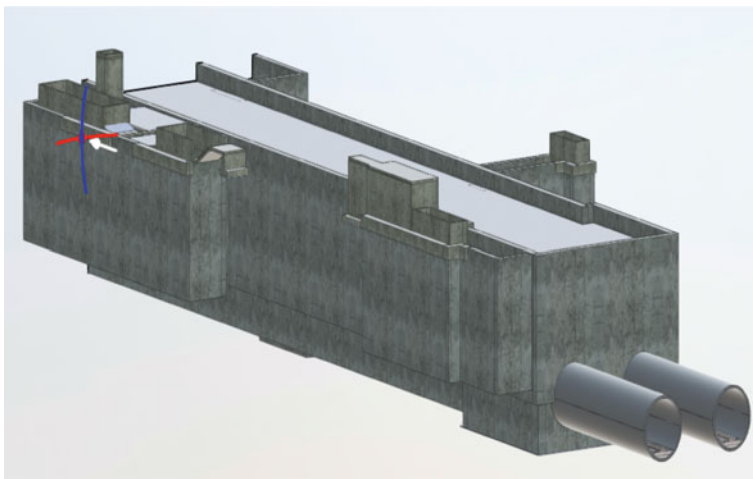


Fig. 1.2 3D view of the entire station box for Thiruvanniyur station

of station design parameters (SPT: standard penetration test, C' : effective cohesion, Φ' : effective angle of internal friction, Y : bulk density, E' : drained modulus, E_{rm} : rock modulus, ν : Poisson's ratio) for soil and rock are presented in Table 1.1. Geotechnical profile's longitudinal section with superimposed station box outline for Thiruvanniyur station is shown in Fig. 1.3.

Ground water level observations during drilling of boreholes indicate that the ground water table varies from 1.25 to 4.4 m ground level.

Table 1.1 Depth-wise geotechnical parameters for Thiruvanniyur station

Soil type	Depth m	SPT	C' kPa	Φ' deg	γ kN/m ³	E' kPa	E_{rm} MPa	ν
Filling material	0–1.5	12	–	30	18.0	18,000	–	0.3
Medium silty sand	1.5–12.0	30	–	32	19.0	27,500	–	0.3
Charnockite G(V)	12.0–15.0	–	61	48	20.0	–	348	0.3
Charnockite G(III)	15.0–27.0	–	252	67	24.0	–	4665	0.2
Charnockite G(II/I)	27.0–40.0	–	758	71	25.0	–	19,890	0.15

Model of the Case Study

Due to varying rock layer along the station alignment, the following conditions are considered:

- Case 1 (rock layer at base level): diaphragm wall terminates at least 3 m below base slab
- Case 2a (rock layer more than 3 m below concourse slab): diaphragm wall terminates above base slab and more than 6 m below concourse slab
- Case 2b (rock layer within 3 m below concourse slab): diaphragm wall terminates within 6 m below concourse slab.

Shear pin is required in Case 2a and Case 2b. A reinforced concrete stitch wall is further provided as a connection between diaphragm wall and station base slab. Diaphragm walls (D-Walls) with shear pins embedded in rock strata and stitch wall connections with diaphragm wall for Thiruvanniyur station are shown in Fig. 1.4.

Construction Stage Analysis

Top-down stations are supported by temporary 2 levels of conventional steel strutting system and permanent slabs during excavation. The entrances/shafts are constructed with bottom-up sequence. The entrances/shafts are supported by temporary 2 levels of conventional steel struts during excavation. To reduce the effect of unbalanced load, entrance excavation should commence only after concourse slab of station is constructed. Different stages of construction sequence of typical top-down station with entrance modeled in PLAXIS 2D [4] are shown in Fig. 1.5. The constitutive model contains simple graphical inputs for different stages of construction. Mohr–Coulomb method of soil model is used in finite element-based software PLAXIS 2D [4].

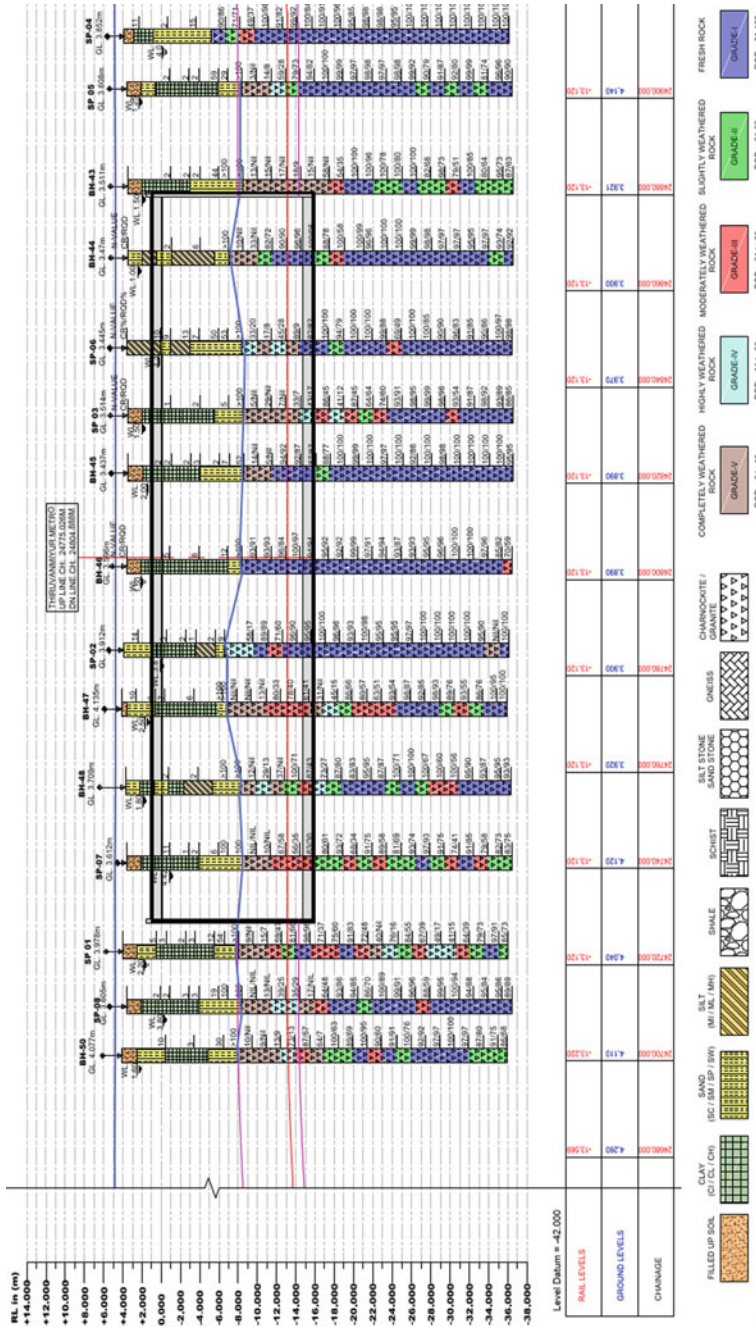
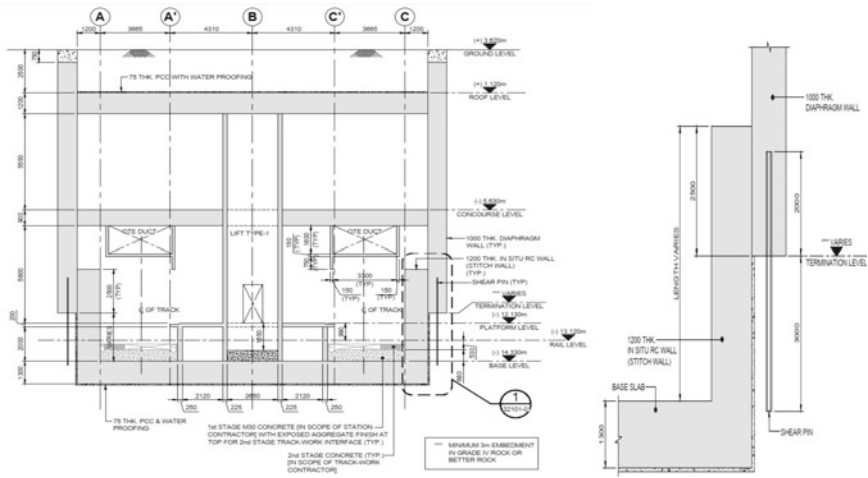


Fig. 1.3 Geotechnical profile longitudinal section with superimposing station box



(A) Station typical Cross Section

(B) D- wall with shear pin and stitch wall

Fig. 1.4 Diaphragm wall with shear pin and stitch wall connection for Thiruvanniyur station

Service Stage Analysis

The diaphragm walls are modeled as two-dimensional frame elements supporting the roof slab, concourse slab, and base slab which in turn provide lateral restraint to the diaphragm walls. The crack width on the external and internal faces of the diaphragm walls has been limited to 0.25 mm for serviceability limit state. Besides this, it has also been checked against ultimate limit state. The thickness of diaphragm walls has been taken as 1000 mm for main station and 800 mm for entrances/shafts. To incorporate the varying nature of rock layer, two extreme cases have been considered, namely Case 2a and Case 2b. In both the cases, minimum overlap of 2.5 m between the D-Walls and the stitch walls has been considered for the connection. The details are illustrated in Fig. 1.6. The crack width on the external and internal faces of the 1200-mm-thick stitch walls has been limited to 0.25 mm and 0.3 mm, respectively [5]. Three-dimensional, (3D) cross-sectional view of the station showing connection between D-Wall with stich wall from Revit BIM [6] structural model is shown Fig. 1.7.

Stability Analysis

The complete cut and cover station structure has been checked against flotation considering water table at ground level. Toe stability has also been checked from PLAXIS 2D model. Factors of safety for both flotation and toe stability have been

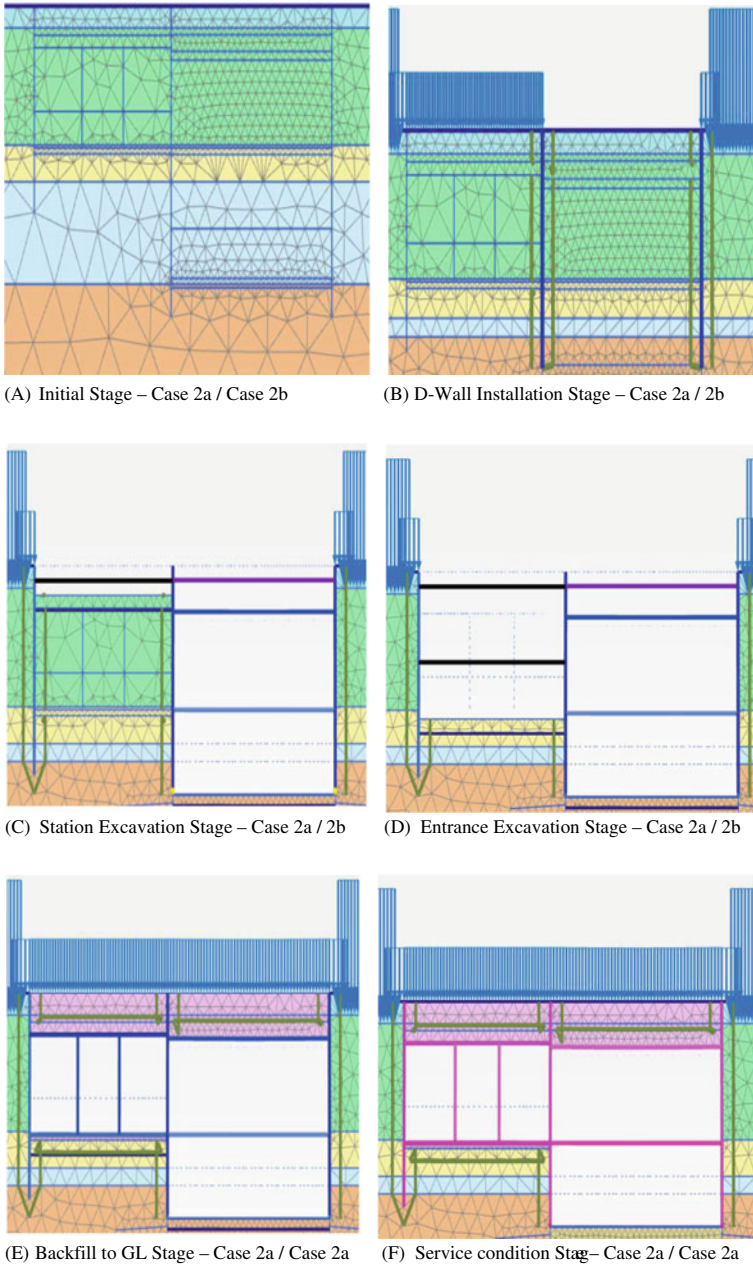


Fig. 1.5 PLAXIS model cross section for top-down station with entrance

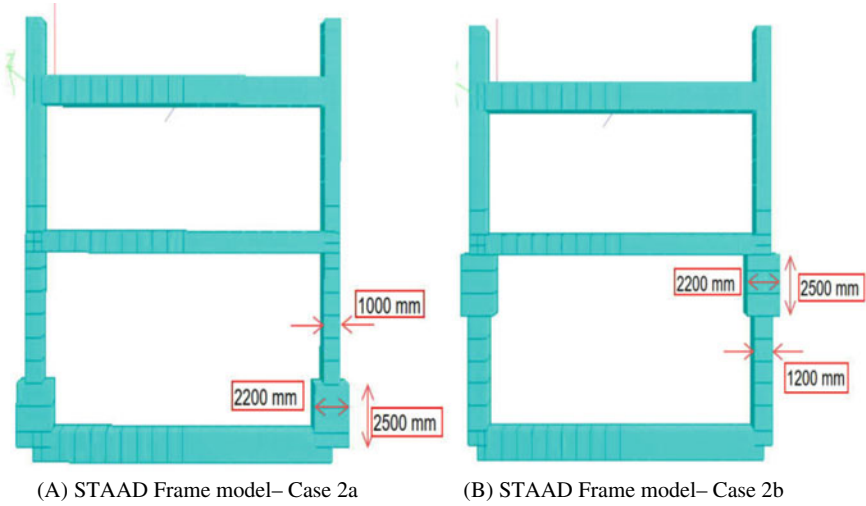


Fig. 1.6 STAAD two-dimensional frame models showing case 2a and case 2b

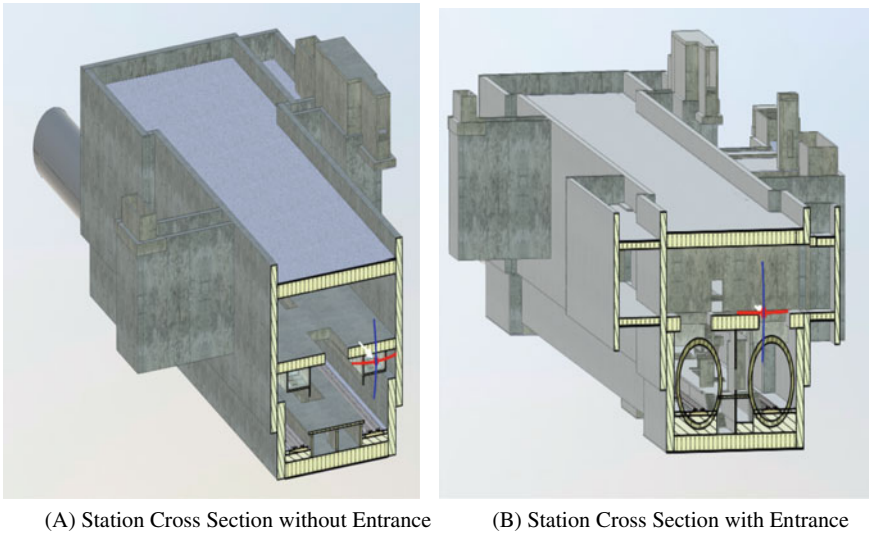


Fig. 1.7 3D cross-sectional view of station from Revit BIM service model

found well within the limiting values. Toe stability factor curve from output envelop of PLAXIS 2D model is shown Fig. 1.8.

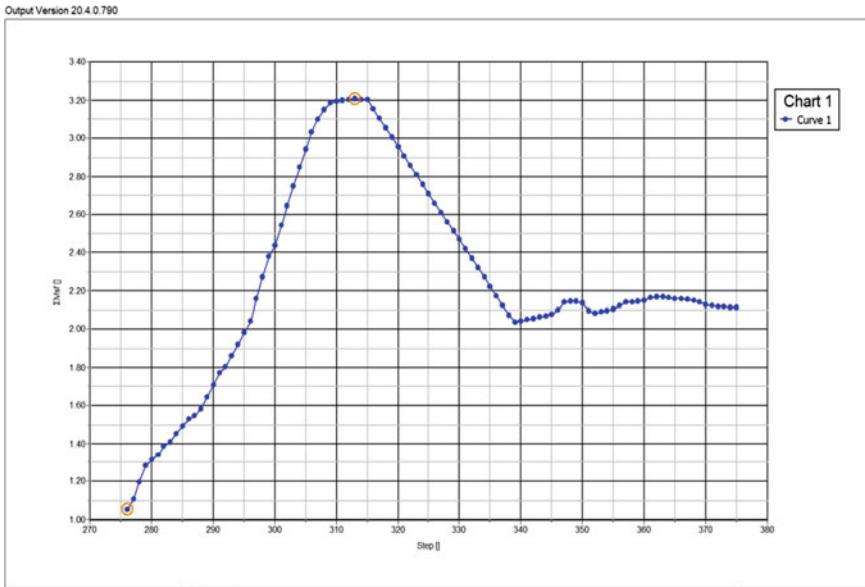


Fig. 1.8 Toe stability factor curve from PLAXIS 2D model

Discussion on Analysis and Results

As outcomes of model analysis, ground settlement, lateral deformation of diaphragm walls, bending moments, and shear forces of diaphragm walls have been estimated. Ground stability has been ensured by checking ground surface settlements with respect to the limiting value. Ground settlement curve from output envelop of PLAXIS 2D model is shown Fig. 1.9.

Horizontal deflection of diaphragm walls in different stages of excavation at different depths of the diaphragm wall has been plotted. Stability and safety of adjacent structures have been ensured by checking deflection of diaphragm walls and by performing a building damage assessment which is beyond the scope of this paper. Figure 1.10 shows the sequential deflection curve of diaphragm wall for different stages of excavation till final excavation level (FEL), strut levels, and slab levels.

Bending moment and shear force diagrams of diaphragm walls have been plotted for different stages of excavation, backfill, and service condition. Structural reinforcement concrete design of diaphragm walls has been done with respect to the envelop for different stages. Figure 1.11 shows the bending moment and shares force envelop for different stages of excavation till final excavation level (FEL), strut levels, and slab levels.

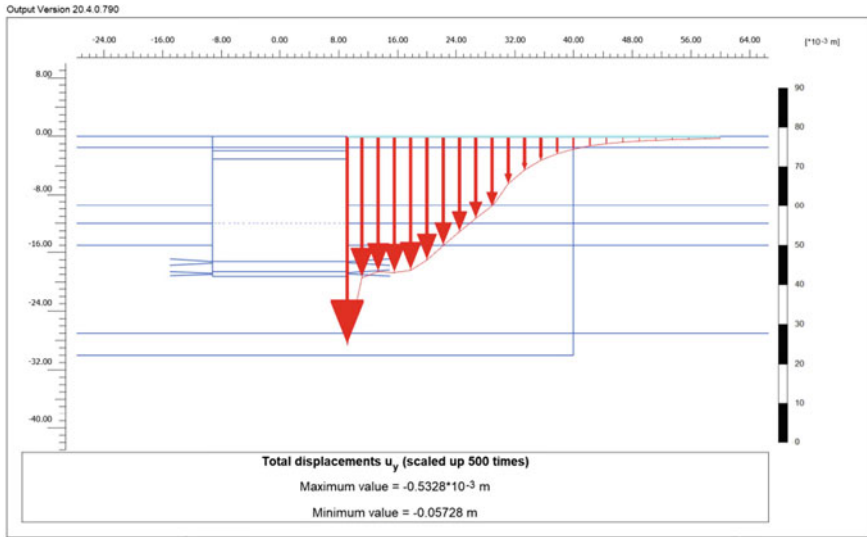


Fig. 1.9 Ground settlements curve from PLAXIS 2D model

Conclusion

Construction of underground cut and cover box structure in mixed ground condition is quite difficult, uneconomical, and time consuming with current conventional methods. The present case study describes an unconventional approach in design and construction of underground cut and cover box structure in mixed ground condition. Unconventional and innovative technical solutions many times save project from long standstills.

Structural design of Thiruvanmiyur station which falls in mixed ground condition of Chennai Metro Project Phase-II alignment corridor has been referred here. Due to difficulty in excavating hard rock strata, an arrangement of shallow diaphragm walls (terminated above base slab level) with shear pins embedded into rock strata with stitch walls has been adopted. This arrangement reduces the requirement of temporary earth retaining supports like soldier piles, secant piles, etc. Therefore, it helps in saving time, manpower, and material costs of temporary earth retaining supports.

Entire sequence of construction stages has been analyzed in finite element-based numerical model for checking of structural design, stability, ground deformation, etc. The present case study may be useful to the practicing engineers as a good reference for similar situations and to simplify the design.

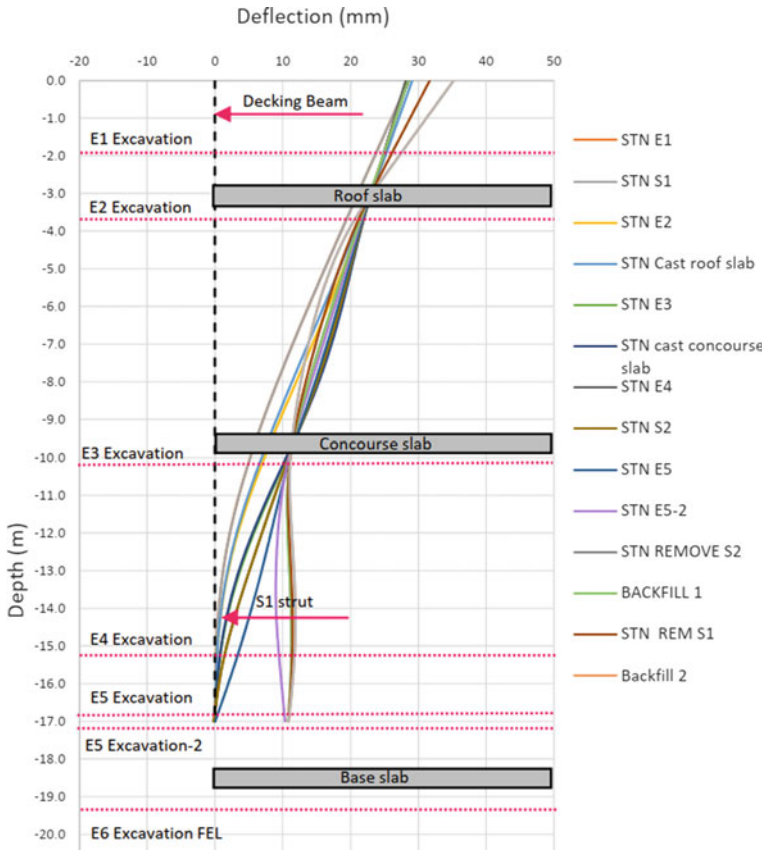
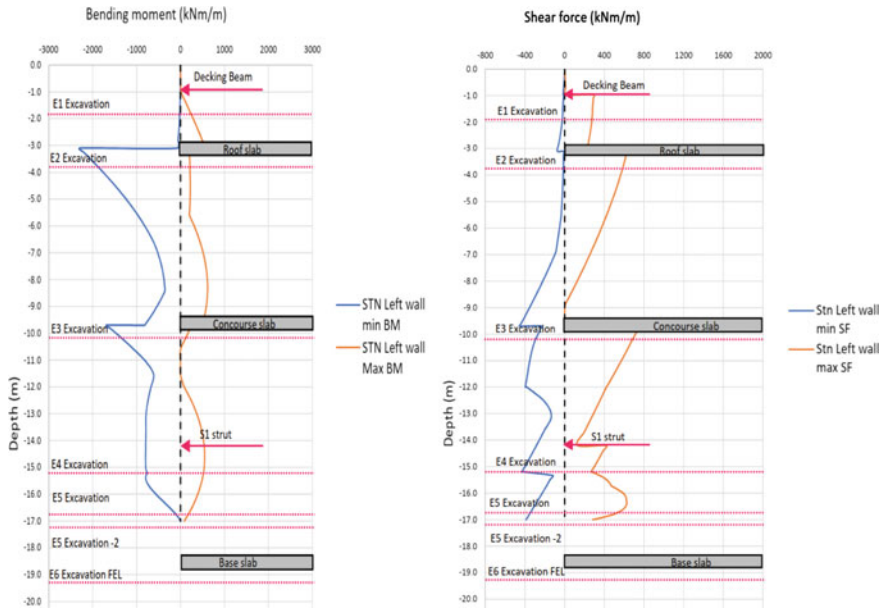


Fig. 1.10 Deflection of diaphragm wall for different stages of excavation at different depths



(A) Bending moment diagram of D-Walls

(B) Shear force diagram of D-Walls

Fig. 1.11 Bending moment and shear force diagram of D-walls for different stages of excavation, backfill, and service condition

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