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Analysis and Design of Diaphragm Wall in Sandy Soil Conditions

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Abstract - *In developing countries like India, the requirement of transit infrastructures is inevitable in highly urbanized locations. The new rapid transit infrastructures, so called "Metro" has been introduced in major cities in India such as Bangalore, Chennai, Delhi, and Mumbai etc. and witnessed quite successful in financial as well as environmental aspects. There is a huge potential in metro sector in India and worldwide, and many organizations are constantly engaged with getting into the metro projects. A metro corridor can be either elevated or underground (UG) or combination of both. The underground metro system is quite useful for congested areas where land & property acquisition are big concern for the authority. This technical paper discusses the construction methodology, structural analysis, and detailed design of a diaphragm wall. Parametric study has also been carried out for three different thicknesses of diaphragm wall to understand the structural behavior.*

Key Words: Diaphragm wall, construction stage, permanent stage, vehicular loading, soil-structure interaction

1. INTRODUCTION

There are various codes of practices [1-7] available on the general guidelines for the various earth retaining structural systems (ERSS). Diaphragm wall also known as "Dwall" is a well-established method of construction which is commonly used as ERSS for deep excavations. Dwall are cast in place embedded retaining walls which provides high structural stiffness, consisting of individual panels excavated from existing ground levels [3-4]. These panels are typically in the range of 2.5m to 4m wide and vary in thickness from 0.8m to 1.2m, depending on strength and serviceability requirements. Dwall panels in metro systems are constructed typically in the range of 25 m to 30 m depth and even more, depending on subsoil conditions, ground water table and structural requirements etc. There are various literatures available on the various considerations associated with the construction of Dwall [8-10]. Few researchers also studied the effects of installation of Dwall to surrounding soil and adjacent buildings [11-12].

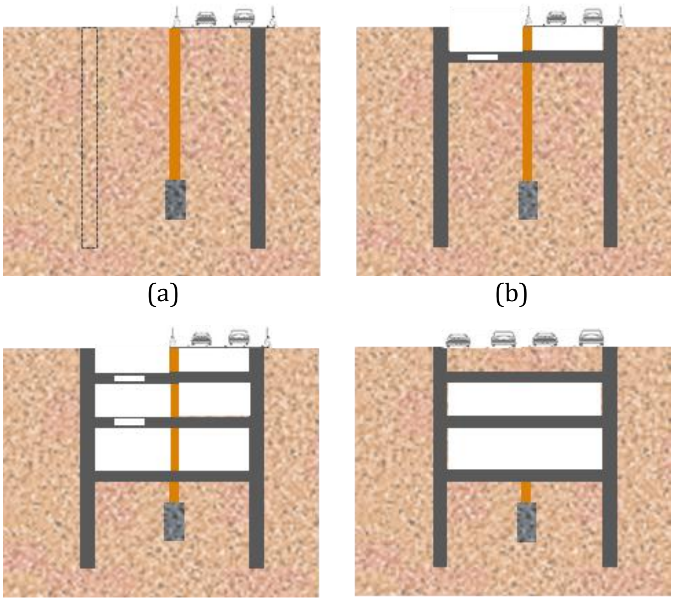
Dwall has many advantages over other earth retaining structural systems such as secant bored pile (SBP) wall, contiguous pile walls, hence it is widely used in practice these days. Dwall is considered as the 'highly effective watertight' earth retaining wall due to the low and defined number of construction joints and the option to seal the joints with 'water-bars'. Water-stops are installed in between the individual panels to provide enhanced water tightness. Another major advantage of Dwall in cut-and-cover structures is, it can be used as a temporary support system during construction stage and as a permanent structural system during operation/service. As there is no separate ERSS requirement, the Dwall can be considered as a cost-effective solution in cut-and-cover structures; however, it requires more attention during construction (for example to maintain the verticality within the prescribed limits). Few researchers carried out the studies on various factors affecting the Dwall design [13-16]. The objective of the present study is to explain the procedure for analysis and design of Dwall with practical example. The sandy soil conditions of Chennai city are considered for the case study with actual geotechnical parameters. In addition, the parametric study has also been carried out for three different thicknesses of diaphragm wall to understand the structural behaviour and variation in horizontal deflection and design forces such as bending moment and shear force.

1.1. Construction of Dwall

Construction of Dwall is virtually a blind operation where a deep and narrow trench is excavated under bentonite or polymer slurry. Heavy reinforcement cages are lowered into the trenches and concrete is placed afterwards. Before constructing Dwall panels, reinforced concrete (RC) guide walls are constructed to maintain the horizontal alignment and continuity. Once guide wall achieves sufficient strength, individual Dwall panels are constructed. Reinforced capping beam on top of Dwall are constructed at later stage which connects all individual Dwall panels. The main purpose of the capping beam is to provide lateral support for the topsoil layer during excavation and distribute the earth/surcharge pressure uniformly along its length. Based on the total height & weight of reinforcement cage for a single panel, crane lifting capacity, working space etc., multiple reinforcement cage units are adopted with lapping to facilitate construction.

1.2. Construction Sequence

There are two methods of construction sequence adopted for construction of cut-and-cover structures using Dwall as an ERSS, i.e. top-down method and bottom-up method of construction. The selection of construction method depends on several factors such as land availability, space constraint, traffic congestion etc. Instrumentation (settlement markers, piezometers, inclinometers etc.) and monitoring to be carried out properly at site. Monitoring shall be carried out on a day-to-day or more frequent basis depending upon the importance of the existing building structure (EBS). Monitoring shall begin prior to commencement of the works to enable instrument base-line values to be determined accurately and shall continue until all movements and distortions to the ground and EBS, and changes to the groundwater table. Following Fig. 1 shows the construction sequence in top-down approach.

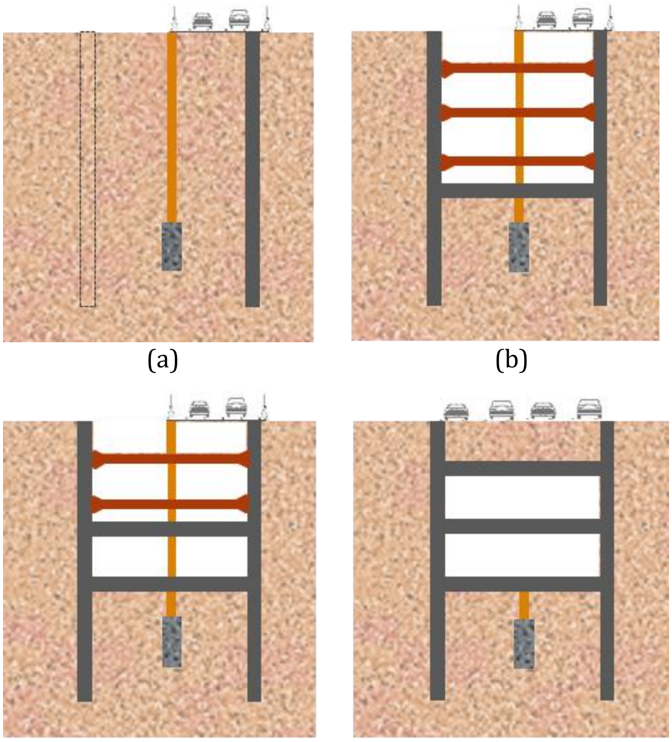


(a) (b) (c) (d)

Fig -1: Construction sequence: Top-down method

Traffic deck arrangements supporting on Dwall and temporary plunge column are installed for movement of the traffic on one side. Water table are gradually lowered to the desired level (inside the cut-and-cover structure) with the suitable pumping arrangements in such a way that there should not be any loss of ground or ground water occurs at any part of the structure nearby. RC slabs are constructed with temporary openings (for muck disposal) after the excavation reaches its required level. Temporary strut/waler beam arrangement are to be provided between the intermediate levels if wall deflection exceeds the permissible limits. The temporary structures will be removed once slabs achieve its sufficient strength.

Fig. 2 shows the construction sequence in bottom-up approach. Traffic deck arrangements for movement of the traffic are provided like top-down approach. Water table are gradually lowered to the desired level and reach the final excavation depth with installing temporary strut/waler arrangement at different levels (depend on structural requirements). RC base slab is constructed, and the temporary supports will be removed once slabs achieve its sufficient strength. Similarly, other slabs are constructed followed by removal of temporary support.



(a) (b) (c) (d)

Fig -2: Construction sequence: Bottom-up method

1.3. Design Methodology

Unlike other ERSS, the structural design of Dwall is complex because, it acts both temporary as well as permanent structural system in cut-and-cover structures. So, the structural analysis of Dwall in cut-and-cover structures requires two types of analysis: (1) construction stage analysis, and (2) permanent stage analysis.

Construction stage analysis

Construction stage analysis is carried out by using geotechnical software such as WALLAP or PLAXIS to capture the soil-structure interaction effects as per the construction sequence and to obtain the design forces in Dwall for construction induced loads (such as construction or vehicular surcharge, building surcharge and differential hydrostatic pressure etc.). In construction stage analysis, the horizontal deflection of Dwall and settlement of soil behind Dwall are in general limited to 30mm to 40mm and 25mm [17], respectively as per client requirements to avoid damage to EBS. Fig. 3 shows the WALLAP model used for the present study.

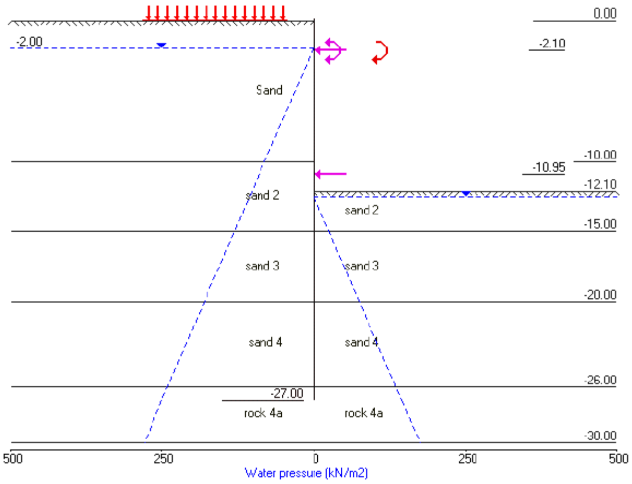


Fig -3: Typical Dwall analysis in WALLAP

Permanent stage analysis

Permanent stage analysis is carried out by using structural analysis software such as STAAD Pro or SAP 2000 to calculate the design forces in Dwall and structural slabs (i.e. roof, concourse and base slab) for permanent loads (such as self-weight, soil backfill weight, earth pressure, water pressure, uplift, public live load, vehicular live load, train live load, derailment load and earthquake loads etc.) during operation/service. The structure is analysed for various critical load combinations as per IS:456 [18] for both ultimate limit state (ULS) and serviceability limit state (SLS) conditions. For the present study, the permanent stage analysis is carried out by using STAAD Pro as shown in Fig. 4.

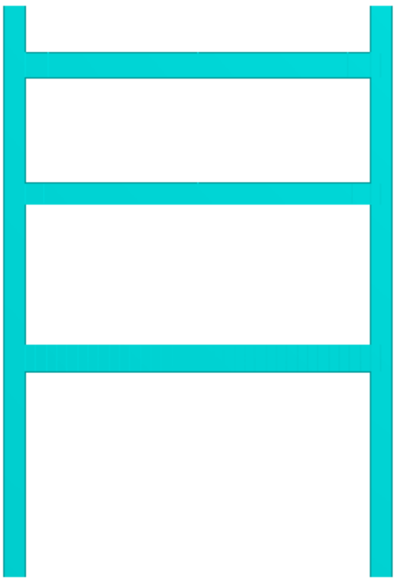


Fig -4: Typical cut-and-cover structure model in STAAD

2. CASE STUDY

In this study the procedure for analysis and design of Dwall is discussed with following practical example. In this case study, a typical two-level cut-and-cover structure is considered. The sandy soil conditions of Chennai city are considered with actual geotechnical parameters obtained from the bore hole tests.

Structural parameters:

The schematic representation of a typical two-level cut-and-cover structure with geometric dimensions is shown in Fig. 5. Concrete Grade of M40 is adopted for Dwall and slabs. The thickness of structural components considered for the present study is given below.

- Base slab thickness 1.3 m
- Roof slab thickness 1.2 m
- Concourse slab thickness 1.0 m
- D-wall thickness 1.0 m
- Clear width of station 16.5 m

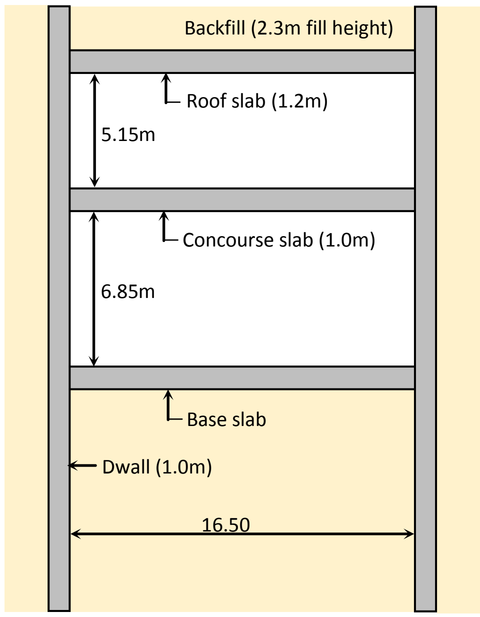


Fig -5: Geometry

Soil parameters:

Based on the bore hole information in coastal area of Chennai city, the following soil parameters are considered for the present study.

Table -1: Soil parameters

Depth from GL (m)	Soil type	γ_{sat} (kN/m³)	E_s (MPa)	υ_s	ϕ (deg)
1.5	Filled up soil	19	8	0.35	28
10	Silty sand	19.5	12	0.38	31
15	Silty sand	19.5	15	0.38	31
20	Silty sand	19.5	25	0.38	31
25	Silty sand	21	75	0.38	39
27	CWR	22	200	0.26	45
-	SWR	26	5000	0.22	65

Where, γ_{sat} is saturated unit weight of soil; E_s is modulus of elasticity of soil; υ_s is Poisson's ratio of soil; ϕ is angle of internal friction of soil. CWR and SWR are completely and slightly weathered rock, respectively.

2.1. Construction stage analysis

In this study, the construction stage analysis is carried out by using WALLAP to capture the soil-structure interaction effects as per the construction sequence and to obtain the design forces in Dwall under construction induced loads. Top-down construction methodology is adopted, and the various construction stages used in the modelling are given Table 2.

Table -2: Construction stages

Stage	Description
1	Application of surcharge
2	Dewatering till -5m
3	Excavation till -4m
4	Installation of roof slab at -2.9m
5	Dewatering till -8m
6	Excavation till -7m
7	Installation of temporary strut at -6.5m depth
7	Dewatering till -11m
8	Excavation till -10m
9	Installation of concourse slab at -9.15m
10	Dewatering till -16m
11	Excavation till -15m
12	Installation of temporary strut at -14.5m depth
13	Dewatering till -19m
14	Excavation till -18m
15	Installation of Base slab at -17.15m

In this analysis, 2UB610 type temporary struts are used at two different elevations (i.e. at -6.5m and -14.5m) as given in the Table 2. In this analysis, the water table is considered at ground level, conservatively. Also, the surcharge load of 20kPa is applied behind the Dwall. The variation of bending moment and shear force in ULS conditions along Dwall depth are shown in the Figs. 6-7. The variation of horizontal deflection in SLS conditions along Dwall depth is shown in the Fig. 8.

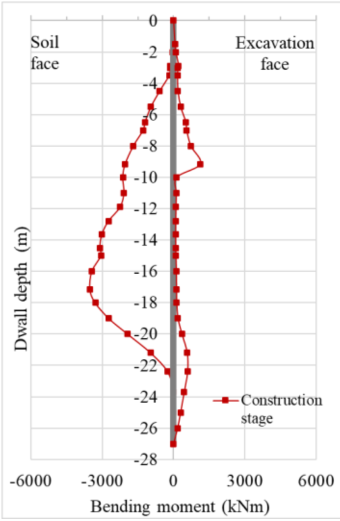


Fig -6: Bending moment (ULS) envelope

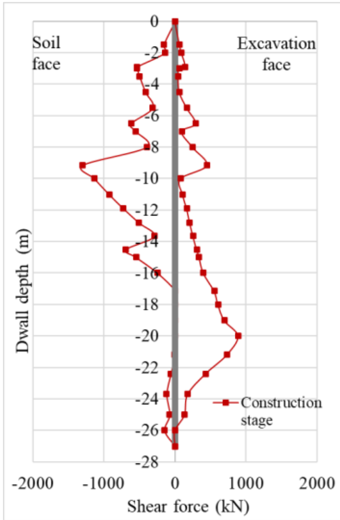


Fig -7: Shear force (ULS) envelope

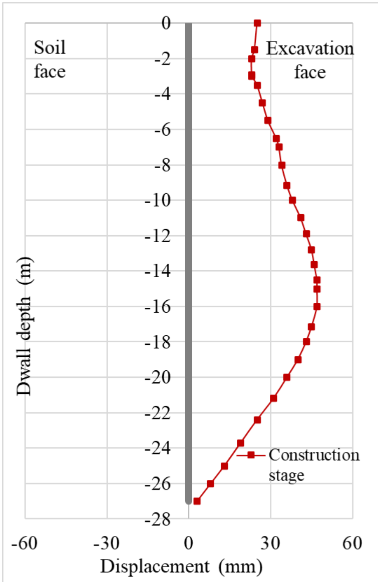


Fig -8: Displacement (SLS) envelope

2.2. Permanent stage analysis

In this study, the permanent stage analysis is carried out by using STAAD Pro to calculate the design forces in Dwall and structural slabs under permanent loads during operation/service. Following primary loads are considered for the permanent stage analysis of cut-and-cover structure.

1. Dead load: Self-weight of the structure is considered as dead load and unit weight of 25kN/m³ is considered for RC members.
2. SIDL: Super imposed dead load of 4.4kPa is considered on concourse slab which includes finishes, ceiling, and partition.
3. Live load: Public live load of 6kPa is considered.

4. Soil backfill: Soil backfill of 50kPa is considered over roof.
5. Lateral earth pressure: Lateral earth pressures are considered for both saturated and submerged soil conditions. The coefficient of earth pressure at rest condition (k_0) is considered as 0.48 and at active condition (k_a) is considered as 0.32.
6. Vertical surcharge: Vehicular surcharge of 20kPa is considered over roof slab.
7. Lateral surcharge: Lateral surcharge of 10kPa is considered on both sides of Dwall.
8. Water pressure: Lateral water pressure and uplift pressure are calculated based on the assumption that the water table is at ground level. The unit weight of 10kN/m^3 is considered for water.

The load combinations are derived based on worst possible situations such as (a) minimum vertical and maximum horizontal loads, (b) maximum vertical and minimum horizontal loads, and (c) maximum vertical and maximum horizontal loads. The load factors are considered as per IS:456 [18]. The effect of seismic loads is not considered.

Support conditions

The soil-structure interaction for the cut-and-cover structure in STAAD Pro is modelled by using ground reaction springs. The vertical springs on base slab (linear, compression only) and horizontal springs on Dwall below base slab (linear) to represent the soil strata has been calculated by using the available geotechnical parameters. The vertical spring value has been calculated based on Vesic equation [19] and the calculations are given in Table 3. As there is no unbalanced lateral load condition in the structure, hence lateral springs on Dwall above base slab are ignored.

Table -3: Vertical spring stiffness

Parameter	Unit	Value
Grade of concrete	MPa	40
Elastic modulus of concrete	kPa	3.2E+07
Thickness of base slab	m	1.30
Width of base slab	m	1.00
Poisson's ratio of soil	-	0.38
Elastic modulus of soil	kN/m^2	25000
Moment of inertia of slab	m^4	0.183
Subgrade modulus	kN/m^3	12065

The variation of bending moment and shear force in ULS conditions obtained from the STAAD analysis are shown in the Figs. 9-10.

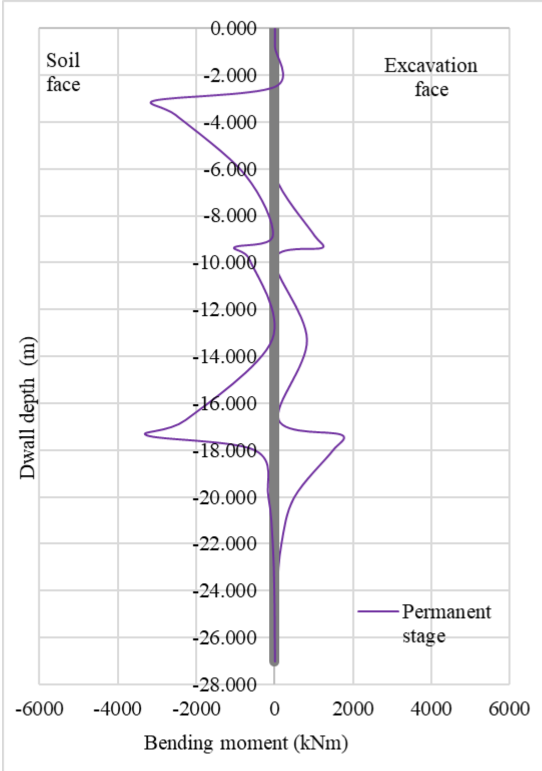


Fig -9: Bending moment (ULS) envelope

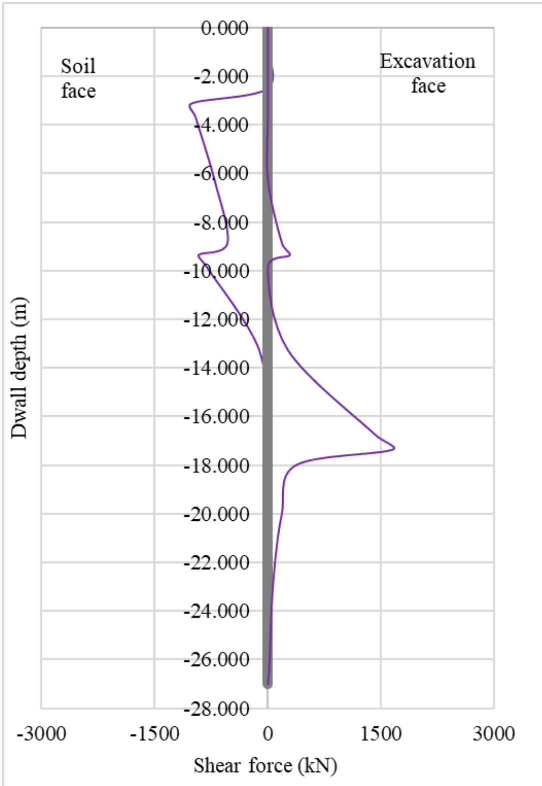


Fig -10: Shear force (ULS) envelope

2.3. Structural design of Dwall

The design forces (such as bending moment and shear force) are obtained on both faces (i.e. soil face and excavation face) of Dwall from construction stage as well as permanent stage analysis at various levels for ULS and SLS conditions.

Following design parameters are considered for Dwall design.

- Design cover = 80mm
- Nominal cover for crack width = 45mm
- Allowable crack width = 0.25mm

During the construction of Dwall, the concrete is to be placed under the slurry (bentonite/polymer). In such cases, the design compressive strength and shear strength of structural concrete shall be reduced in comparison to the adopted concrete grade. Hence for the proposed Dwall design, the characteristic strength of the compressive and shear stress is considered as 80% of the characteristic strength of the adopted concrete grade (i.e. M40). The capacity charts are produced for bending moment and shear force for different reinforcement ratios for the given Dwall thickness and checked against requirements as shown in the Figs. 11-13.

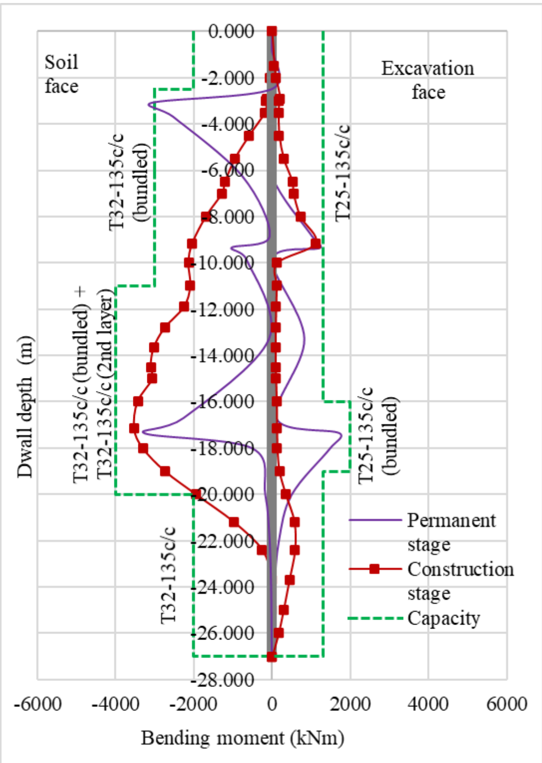


Fig -11: Bending moment (ULS) - demand vs capacity

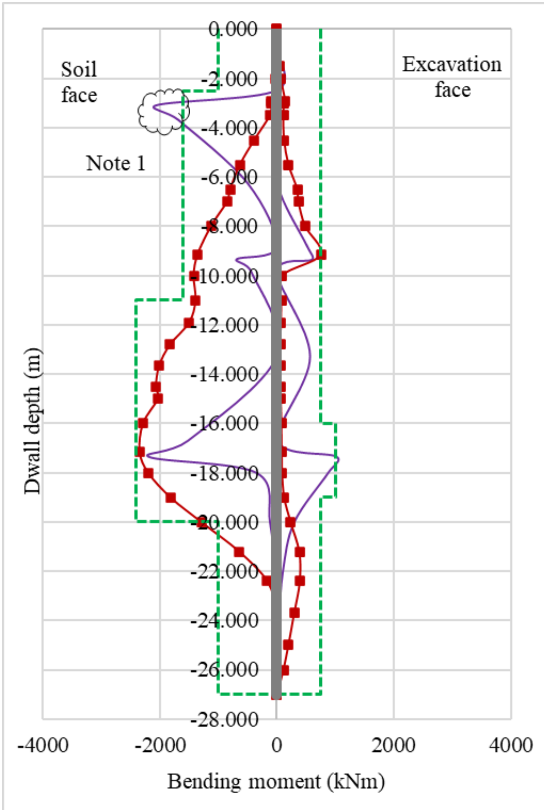


Fig -12: Bending moment (SLS) - demand vs capacity

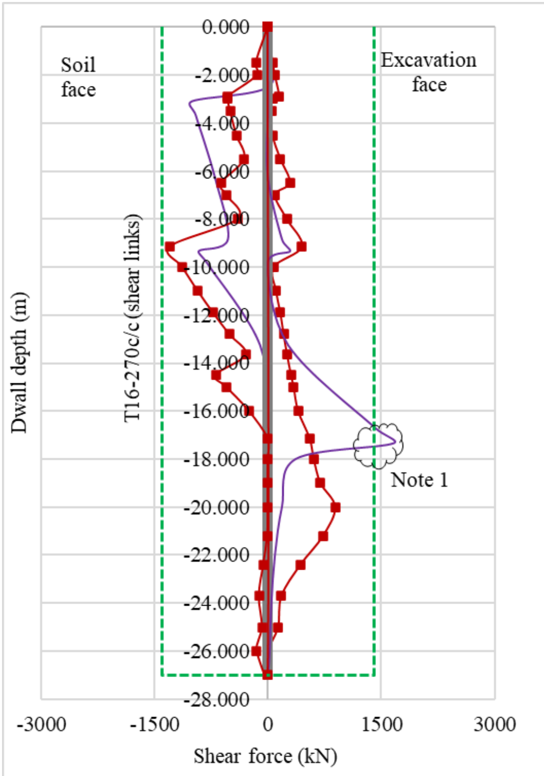


Fig -13: Shear force (ULS) - demand vs capacity

Note 1 - Design forces are considered at face of slab, hence local peaks are ignored.

From the Figs. 11-13, it is observed that the construction stage results are governing the Dwall reinforcement in soil face except at roof level. However, the permanent stage results are governing the Dwall reinforcement in excavation face. In addition, it is also observed that SLS conditions govern the Dwall design (both in soil and excavation face), as the limitation of crack width is stringent.

3. EFFECT OF DWALL THICKNESS

Analyses have been carried out with three different Dwall thickness values i.e. 0.8m, 1.0m and 1.2m and the results obtained from the construction stage and permanent stage are presented in Figs. 14-16 and Figs. 17-18, respectively. The peak design forces from the construction stage analysis is summarized in Table 4.

Table -4: Peak design forces from construction stage analysis

Peak values	0.8m	1.0m	1.2m
Bending moment (kNm)	2715	3513	4305
Shear force (kN)	1181	1297	1458
Displacement (mm)	57	47	40

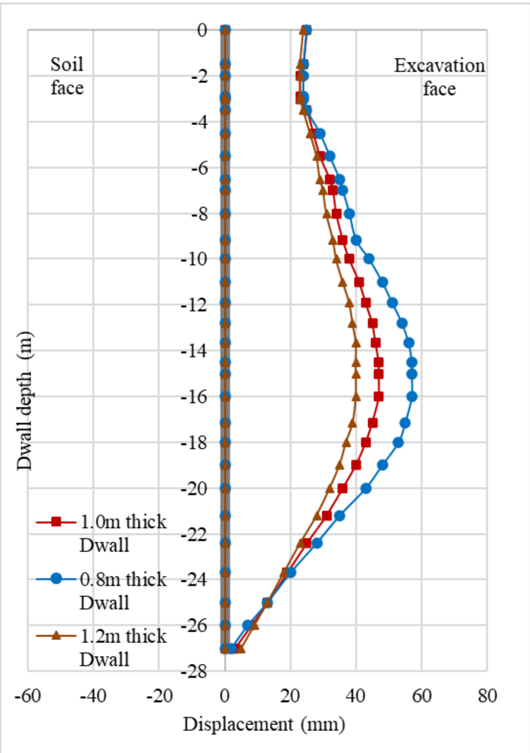


Fig -14: Deflection profile (SLS) envelope from construction stage

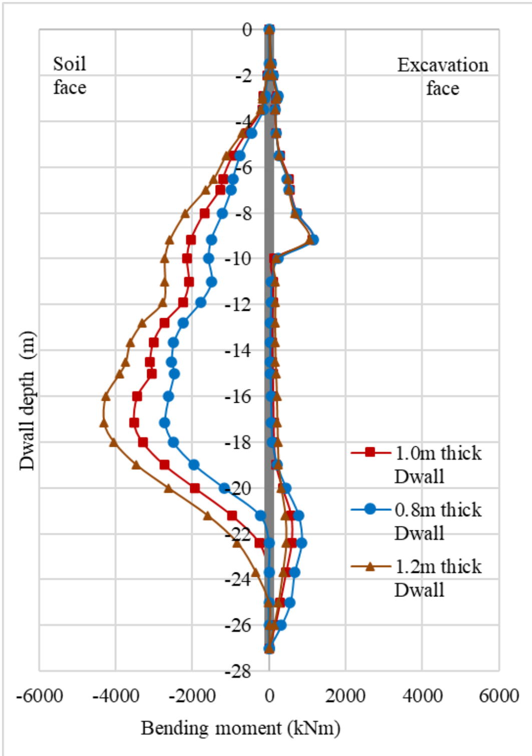


Fig -15: Bending moment (ULS) envelope from construction stage

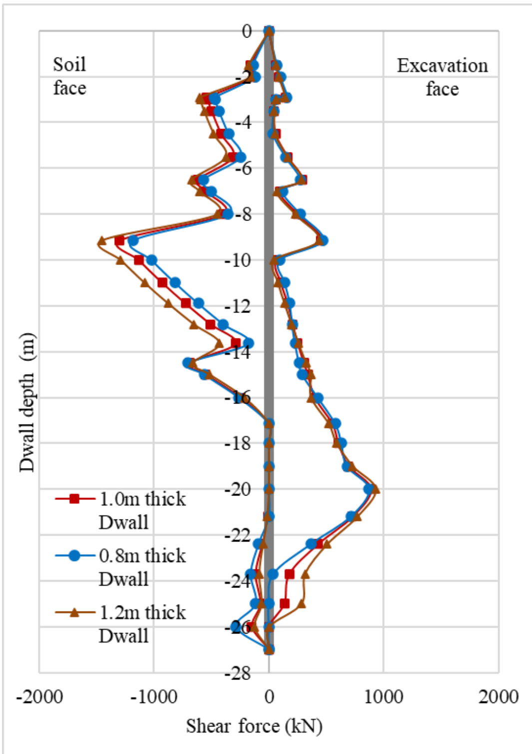


Fig -16: Bending moment (ULS) envelope from construction stage

As anticipated, Fig. 14 and Table 4 shows that increase in Dwall thickness greatly reduce the horizontal deflections. By using 1.0m thick Dwall, the horizontal deflection can be reduced to 18% comparing 0.8m thick Dwall. Similarly, by using 1.2m thick Dwall, the horizontal deflection can be reduced to 43% comparing 0.8m thick Dwall. So even with the 1.0m thick Dwall, the horizontal deformations in Dwall exceeds the permissible value (i.e. 40mm is considered as permissible in this study). However, the horizontal deformations in Dwall are within the permissible value if we use 1.2m thick Dwall (Table 4).

On contradictory, increase in Dwall thickness leads to significant increase in bending moments which in turn increases the reinforcement quantity (Figs. 15-16 and Table 4). The increase in bending moment is 29% in case of 1.0m thick Dwall and 59% in case of 1.2m thick Dwall in comparison with 0.8m thick Dwall. Similarly, the increase in shear force is 10% in case of 1.0m thick Dwall and 23% in case of 1.2m thick Dwall in comparison with 0.8m thick Dwall. Hence, an optimum thickness must be chosen based on allowable horizontal deflection criteria without compromising reinforcement quantity much. The horizontal deflections can be reduced by providing addition temporary struts.

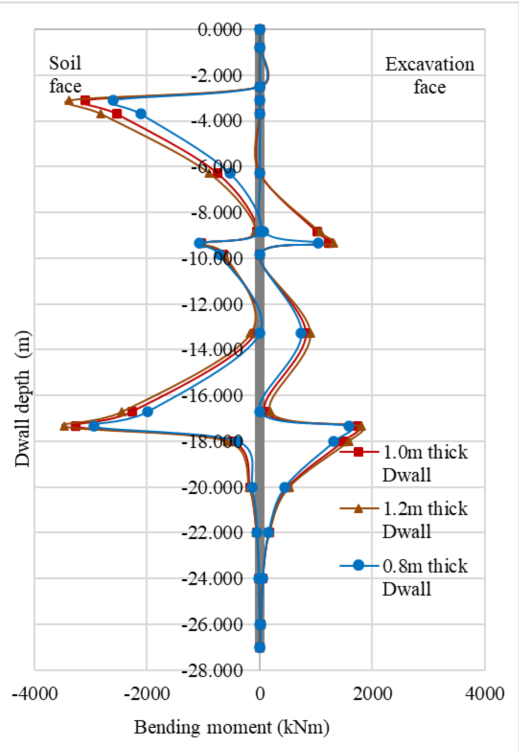


Fig -17: Bending moment (SLS) - demand vs capacity

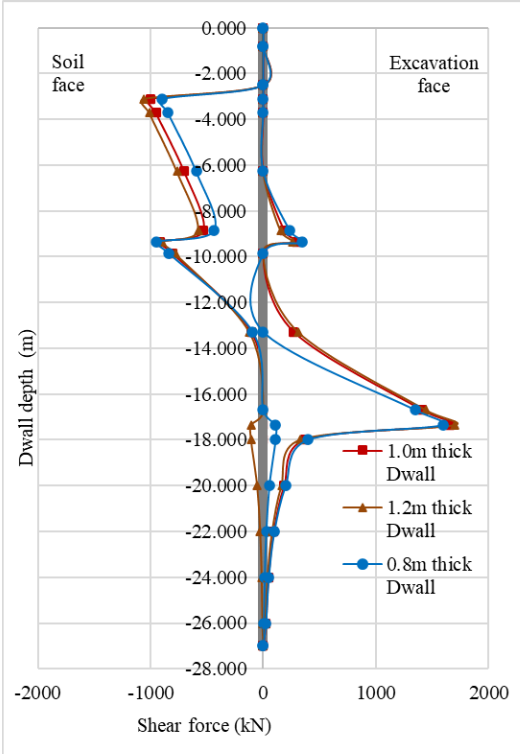


Fig -18: Shear force (ULS) envelope from permanent stage

The bending moment and shear force envelope obtained from the permanent stage analysis is plotted in Figs. 17-18. The peak design forces from the permanent stage analysis are also summarized in Table 5. From Figs. 17-18 and Table 5, it is observed that the increase in Dwall thickness leads to increase in bending moments and shear forces. The increase in bending moment is 11% in case of 1.0m thick Dwall and 18% in case of 1.2m thick Dwall in comparison with 0.8m thick Dwall. Similarly, the increase in shear force is 4% in case of 1.0m thick Dwall and 6% in case of 1.2m thick Dwall in comparison with 0.8m thick Dwall.

Table -5: Peak design forces from permanent stage analysis

Peak values	0.8m	1.0m	1.2m
Bending moment (kNm)	2950	3270	3470
Shear force (kN)	1600	1660	1700

It is also inferred from Table 4 and Table 5 that, the increase in bending moment and shear force is significant in construction stage analysis in comparison with permanent stage analysis.

4. CHALLENGES

The following challenges are involved in design and construction of cut-and-cover structure using Dwall as an ERSS. Damage assessment of adjacent properties/assets to be made and suitable mitigation measures to be proposed before the start of excavation. Maintaining the actual water level behind the Dwall during dewatering process is also crucial task. Suitable dewatering methods to be adopted to maintain the existing water table level behind the Dwall to minimize the settlement, distortion, or loss of ground adjacent to EBS. Dwall verticality and coupler dislocations etc. are also the major concern during construction. Inaccurate/insufficient soil investigation and uncertainty in the ground conditions will make more complications during design stage as well as construction stage. The reinforcement requirement in Dwall is huge due to stringent crack width criteria to meet the serviceability requirements.

5. CONCLUSIONS

In this paper, the detailed discussion on construction methods, advantages, and limitations of Dwall are discussed. A case study has been performed for two-level cut-and-cover structure located on sandy soil conditions. Detailed procedure for construction stage and permanent stage analysis of Dwall is also presented in this paper. Parametric study has also been carried out for three different thicknesses of Dwall to understand the structural behavior. From the above parametric study following conclusions are being made.

(1) Construction stage analyses govern the Dwall reinforcement in soil face. However, the permanent stage analyses govern the Dwall reinforcement in excavation face.
(2) SLS conditions govern the Dwall design (both in soil and excavation faces) as the limitation of crack width is stringent.
(3) Increase in Dwall thickness significantly reduces the horizontal deflection. By using 1.0m thick Dwall the reduction in horizontal deflection is in the range of 18% and by using 1.2m thick Dwall the reduction is in the range of 43% comparing 0.8m thick Dwall.
(4) Increase in Dwall thickness leads to significant increase in bending moment and shear force. By using 1.2m thick Dwall, the increase in bending moment is in the range of 59% and increase in shear force is in the range of 23% comparing 0.8m thick Dwall in construction stage analysis.
(5) The increase in bending moment and shear force with respect to Dwall thickness is significant in construction stage analysis compared to permanent stage and hence the construction stage analysis is crucial for Dwall design.

6. LIMITATIONS

The effect of seismic loads is not considered as the site in this study is in Seismic zone III. However, it would be interesting to study the effect of seismic loads. Moment restraints for RC slabs are not considered in construction stage analysis. The conclusions arrived from this paper are based on sandy soil conditions of particular site, which may differ depending on structural and geotechnical parameters.

ACKNOWLEDGEMENT

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REFERENCES

[1] British Standards Institution. "British Standard: Execution of Special Geotechnical Works - Diaphragm Walls". BS EN 1538:2000, London.

[2] British Standards Institution. "British Standard: Code of Practice for Earth Retaining Structures". BS 8002:2015, London.

[3] Bureau of Indian Standards. "Code of Practice for Design and Construction of Diaphragm Walls". IS 9556:1980, New Delhi.

[4] Bureau of Indian Standards. "Design and Construction of Diaphragm for under Seepage Control – Code of Practice". IS 14366-1996, New Delhi.,

[5] Canadian Geotechnical Society. "Canadian Foundation Engineering Manual. 4th edition". 2006, Canada.

[6] European Committee for Standardization. "European Standard: Eurocode-7 Geotechnical Design Part 1: General Rules". EN 1997-1:2004, Brussels.

[7] Standards Australia. "Australian Standard: Earth Retaining Structures". AS 4678-2002, Sydney.

[8] R.V. Davies, "Special Considerations Associated with Constructing Diaphragm Walls in Marine Deposits and Residual Soils in Southeast Asia', Proceedings of 2nd Conference on Diaphragm Walling Techniques, CI-Premier, Singapore, 1-12, 1982.

[9] A. Rahman and M. Taha, "Geotechnical Performance of Embedded Cast-in-situ Diaphragm Walls for Deep Excavations", Slovak Journal of Civil Engg., 3, 30 –38, 2005.

[10] I. Hanjal, J. Marton and Z. Regele, "Construction of Diaphragm Wall", A Willey Inter-science Publication, 2011.

[11] M. Emilios, M.C. Papadopoulou and G.K. Konstantinidis", Effects from Diaphragm Wall Installation to Surrounding Soil and Adjacent Buildings, Computers and Geotechnics, 53, 106-121, 2013.

[12] K.N. Dinakr and S.K. Prasad, "Effecto Deep Excavation on Adjacent Buildings by Diaphragm Wall Technique Using PLAXIS", Journal of Mechanical and Civil Engineering, e-ISSN: 2278-1684, p-ISSN: 2320-334X, 2013.

[13] N.M. Ilies, V. Farcas and Marius, "Design Optimization of Diaphragm Walls", 8th International Conference Interdisciplinarity in Engineering, 2014.

[14] P.D. Shah and B.A. Vyas, "Parametric Study of Diaphragm Wall, International Journal of Science Technology & Engineering, Issue No 11, ISSN (online): 2349-784X, 2015.

[15] V.M. Ashok, Babu Kurian, Merin Mathews and Anu James, "Section Optimization of Diaphragm Wall", International Journal for Research in Applied Science & Engineering Technology, Issue No 12, ISSN: 2321-9653, 2015.

[16] Luis Segura-Castillo, Antonio Aguado, and Alejandro Josa, "Bi-layer diaphragm walls: Experimental and

numerical structural analysis", Engineering Structures, 2013.

[17] D. Twine and H. Roscoe, "Temporary Propping of Deep Excavations-Guidance on Design, Construction Industry Research and Information Association, CIRIA Publication C517, 1999.

[18] Bureau of Indian Standards. "Code of Practice for Plain and Reinforced Concrete". IS 456:2000, New Delhi.

[19] J.E. Bowles, "Foundation Analysis and Design", McGraw-Hill Book Company, Fifth Edition, 1997.