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Effect of Earth Pressure Coefficient on Underground Metro Station

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ABSTRACT: Structural design of underground station is mainly influenced by critical external loadings like earth pressure, backfill on the roof slab and water pressure. The ground enforces formidable design challenges due to geological complexities, induced stresses. In initial stages of the project, the limited geotechnical information is available. Further during detailed design phase, the additional investigations, geological formation is assessed through geotechnical interpretative reports. However, designer has to assess the lower bound and upper bound range of earth pressure coefficient and compliant design has to be produced. Hence, it is important to study the effect of earth pressure coefficient on the underground metro stations. This paper presents the sensitivity of earth pressure coefficient on the cut and cover stations having soil cover of 2m and 10m on the roof slab. The wide range of earth pressure coefficient covers all the geotechnical conditions across cities in India. 3D Finite element models are modelled and analyzed applying these variation in earth pressure coefficient. The resulting design bending moments at critical locations are presented graphically. The sensitivity analysis benefits for optimization, reducing risk due to uncertainties and to establish the preliminary structural analysis with respect to lower bound and upper bound parameters.

Keywords: Earth Pressure coefficient; Sensitivity analysis; Soil Cover; Underground Metro.

Abbreviations: EPh, earth pressure; WP, water pressure; EPv, backfill; SW, self-weight; SIDL, superimposed dead load; LL, live load; Ts, traffic surcharge; TL, train load; Bs, building load surcharge; BWJ, base wall junction; LWM, lower wall mid span; WCJ, wall concourse junction; UWM, upper wall mid span; WRJ, wall roof junction; Ko, earth pressure coefficient at rest.

I. INTRODUCTION

The underground infrastructure is becoming popular due to space congestion in urban areas like Mumbai, Chennai, Delhi and Calcutta. The underground metro is an integrated public transport which reduces the pressure at surface transport. It also reduces noise and improves air quality by leaving more green areas in the city centre. The underground metros are one of the most popular and most efficient means of urban transportation [1]. The Planning Commission's proposal for the Twelfth Five-Year Plan for urban transport has recommended that all Indian cities with a population in excess of 2 million shall start planning rail transit projects, and cities with a population in excess of 3 million start constructing the metro rails and proposed estimate is USD 26.1 billion [3].

Underground construction faces many geotechnical challenges during pre-tender design, detailed engineering and construction of structures. The challenges are geological complexities due to induced stresses, geological formation history etc. The mechanization demands better integration of engineering to ensure safety, sustainability, speedy construction and optimization. Mostly the geotechnical interpretation data is prediction based on the tests and experience. However, the cost and feasibility of the underground structures is governed by geology [2]. It is vital to study effect of earth pressure and deformation for underground structures [6]. The paper presents the effect of earth pressure coefficient on underground metro station which is missing in the literature.

II. RESEARCH SIGNIFICANCE

The structural analysis and design is carried out based on available geotechnical investigations, which are mostly limited during the initial concept stage and could vary during the detailed engineering. It is significant to understand the influence of the varying geotechnical parameters to reduce the risk in design and cost. The sensitivity check is required so as to assess the variation in design forces for upper and lower bound parameters. The developed parametric influence graphs becomes useful tool for the designers and authorities to assess the impact due to unforeseen changes during design developments, execution and service life.

III. METHODOLOGY

As per study carried out, the wide range of geotechnical parameters are identified across the major cities across India [4]. The range of earth pressure coefficient at rest (ko) varies from 0.25 to 1.0. The effect of these geotechnical parameters are analyzed on the design of underground cut and cover metro station having shallow depth with soil cover of 2m and deep stations with 10m cover. The influence of earth pressure coefficient becomes critical for lower ground water table and even below base slab. 3-D Finite element models are modelled and analyzed using Autodesk Robot Structural analysis software and influence on structural forces such as bending moment, axial force and shear force are studied at the key points [10]. The methodology includes,

– Structural Modelling - Geometry, load and support arrangement.
– FE analysis - Non-linear FE Analysis.
– Summarizing bending moments at key points.
– Result assessment.

Table 1: Load Specifications.

Load	Parameters	
Earth Pressure and backfill	U_d=20 kPa U'=10 kPa	Ko = 0.25-1.0 Soil cover =2m and 10m
Water Pressure	U_w= 10 kPa	Below base level as critical case
SIDL	5 kPa	On concourse and platform
Live Load	5 kPa	On concourse and platform
Traffic Surcharge	20 kPa	Above and adjacent to station at grade
Building load surcharge	50 kPa	Adjacent to station at grade

A. Structural Modelling

Typical cut and cover underground metro station has three levels as under-croft which is under platform, platform and concourse level based on the functional requirement. Typical sectional elevation is shown in Fig. 1 [5].

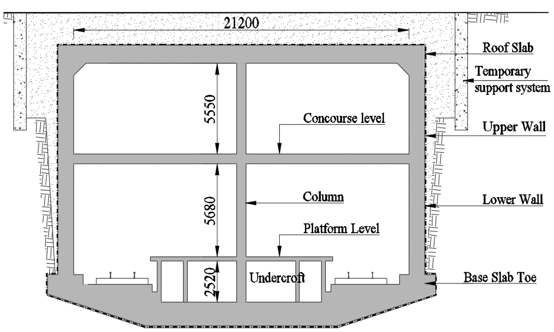


Fig. 1. Underground Station– typical Elevation.

B. Load Application

The governing design loads are earth pressure (EPh), water pressure (WP), backfill (EPv) along with typical basic loads such as self-weight (SW), superimposed dead load (SIDL), live load (LL), traffic surcharge (Ts), train load (TL), building load surcharge (Bs). The typical basic loads considered for the design are generally presented in the Indian Standards [8] and Euro Code [9] and are presented in Table 1 which are shown indicatively in Fig. 2 [5].

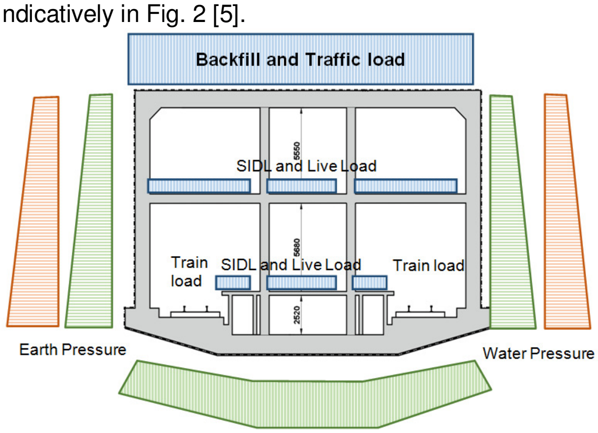


Fig. 2. Loading Diagram.

C. Support Condition

The underground metro station is surrounded with ground and is modelled with compression-only springs along the walls and base slab.

The toe is provided at the base level to resist against the uplift pressure through the shear friction in the ground, and modelled as bi-directional springs support. The support arrangement is shown in Fig. 3. [5]. The average bedding spring stiffness at the base slab is 100000 kN/m^2/m.

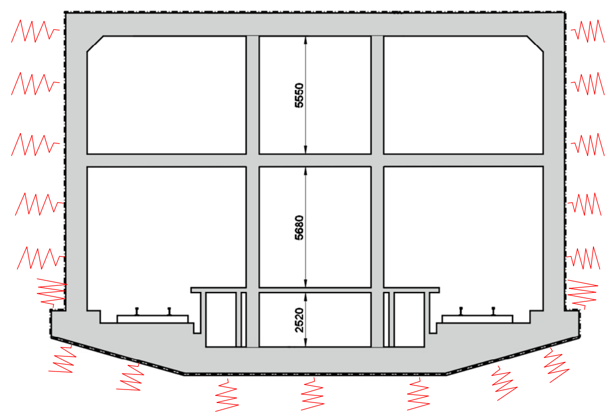


Fig. 3. Support Arrangement.

C. Finite Element Modelling

The 3-D finite element model is modelled in Autodesk Robot Structural Analysis software and as shown in Fig. 4. The models are updated with the earth pressure coefficient varying from 0.25 to 1.0, with interval of 0.25 (i.e. 0.25, 0.5, 0.75 and 1.0). The ground water level is considered below ground level. The average spring stiffness applied 100000 kN/m^2/m.

D. Uplift Criteria

As the ground water level is below base level as a critical case to derive variation of earth pressure coefficient, there is no uplift.

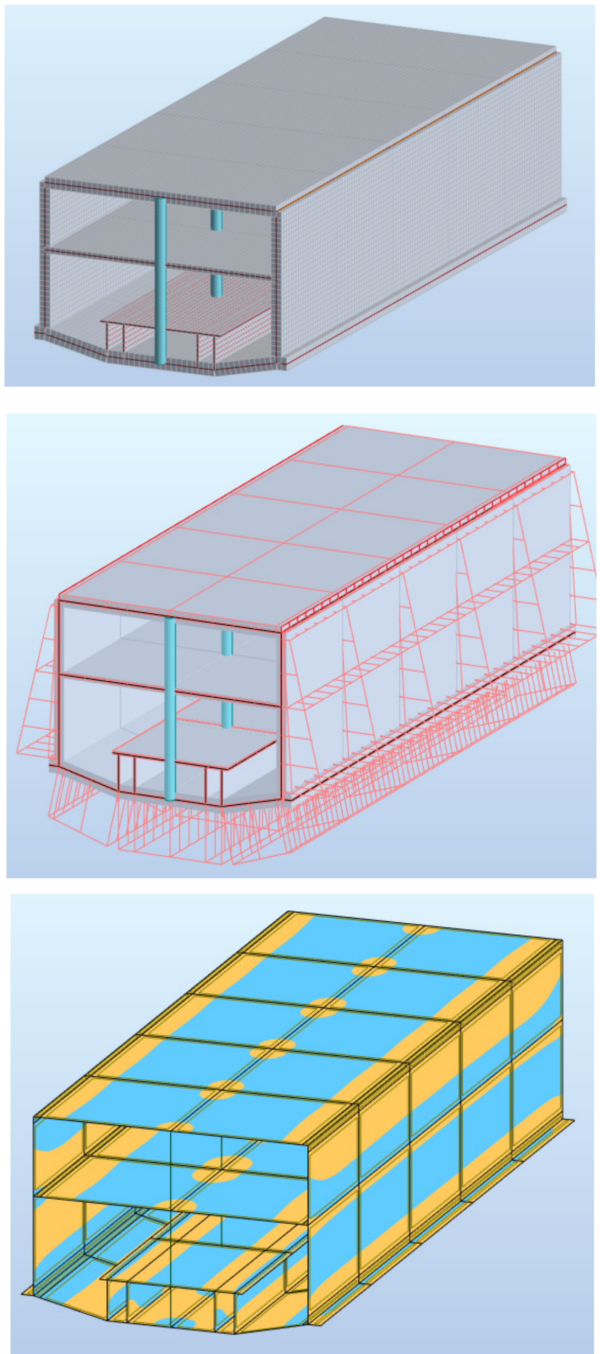


Fig. 4. FE Model, Load Application and results.

E. Analysis Approach

The 3-D FE models are analyzed with static-linear analysis. The models are statistically verified with respect to load application, reactions and axial forces in the section. The walls and slab elements are discretized with mesh size of 0.5m × 0.5m size with four-noded square elements [5].

The underground station structural design is governed by the stringent crack-width criteria of Servicability limit state (SLS). The structural model is analyzed for the loads as presented in Table 1. The earth pressure sensitivity is presented at key points shown in Fig. 5 and Table 2.

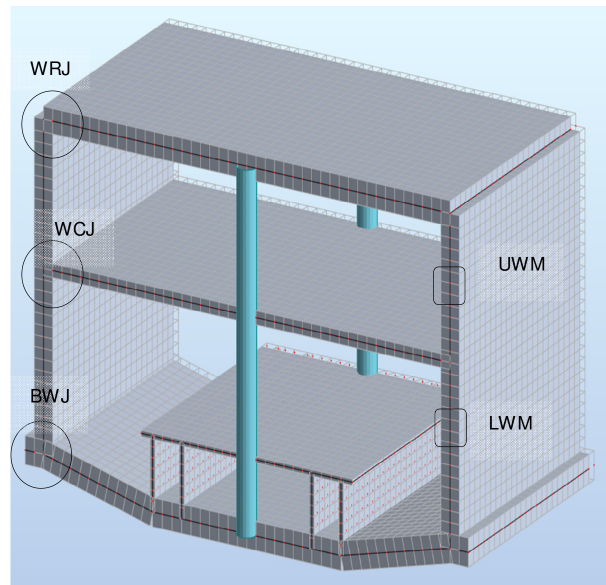


Fig. 5. Key locations.

Table 2: Key Points.

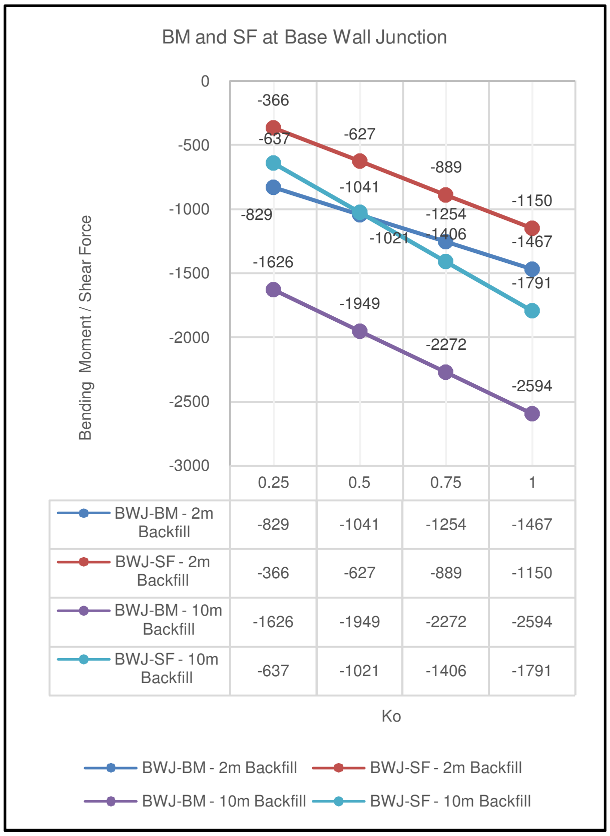
Member	Key location
Side Walls	Base Wall Junction (BWJ)
	Lower Wall-Mid span (LWM)
	Wall Concourse Junction (WCJ)
	Upper Wall-Mid span (UWM)
	Wall Roof Junction (WRJ)

The bending moment and shear force sensitivity is carried out and presented at the critical key points.

IV. RESULT ANALYSIS

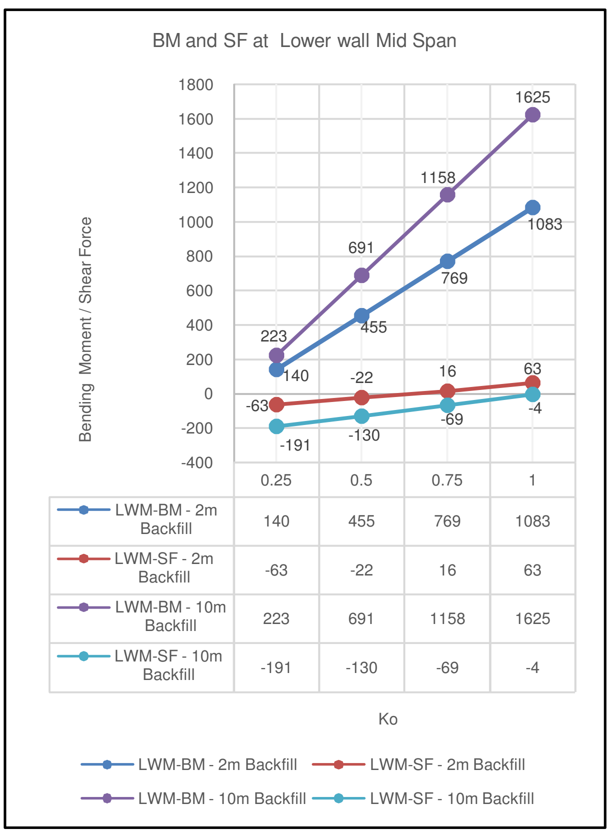
The earth pressure coefficient (Ko) imposes variation in lateral earth pressure and lateral surcharge due to traffic. It influences the bending moments critically on the wall such as at the wall base junction, lower wall mid span, wall concourse junction, upper wall mid span and the wall roof junction. The results at these critical junctions are discussed.

The variation in bending moment and shear forces as shown in Fig. 6 to 10 is observed as linear variation for 2m and 10m backfill on roof slab.



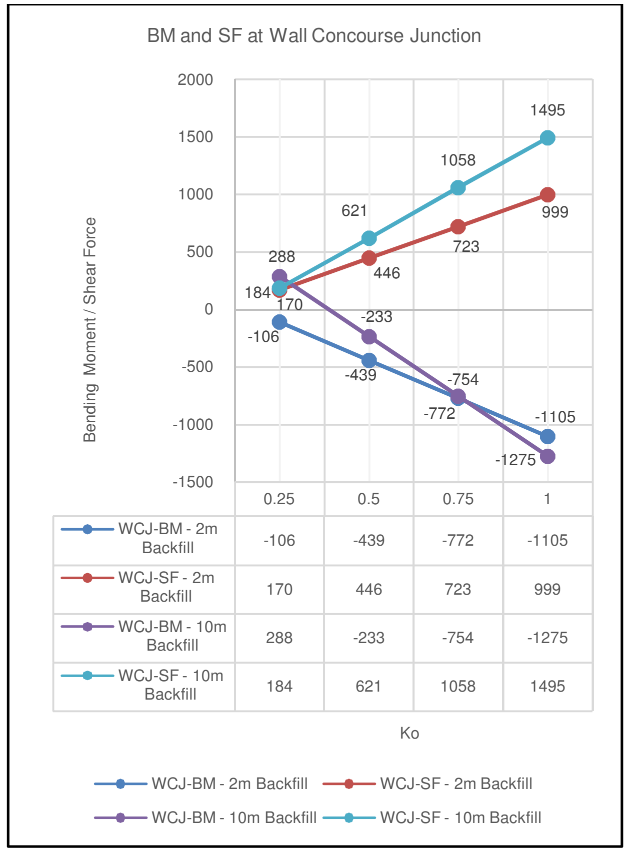
Ko	0.25	0.5	0.75	1
BWJ-BM - 2m Backfill	-829	-1041	-1254	-1467
BWJ-SF - 2m Backfill	-366	-627	-889	-1150
BWJ-BM - 10m Backfill	-1626	-1949	-2272	-2594
BWJ-SF - 10m Backfill	-637	-1021	-1406	-1791

Fig. 6. BM and SF at BWJ.



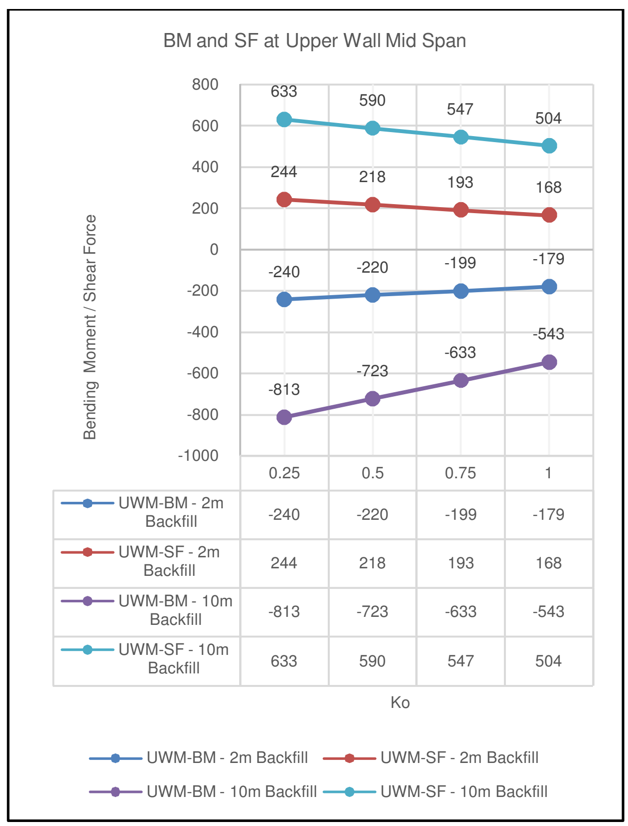
Ko	0.25	0.5	0.75	1
LWM-BM - 2m Backfill	140	455	769	1083
LWM-SF - 2m Backfill	-63	-22	16	63
LWM-BM - 10m Backfill	223	691	1158	1625
LWM-SF - 10m Backfill	-191	-130	-69	-4

Fig. 7. BM and SF at LWM.



Ko	0.25	0.5	0.75	1
WCJ-BM - 2m Backfill	-106	-439	-772	-1105
WCJ-SF - 2m Backfill	170	446	723	999
WCJ-BM - 10m Backfill	288	-233	-754	-1275
WCJ-SF - 10m Backfill	184	621	1058	1495

Fig. 8. BM and SF at WCJ.



Ko	0.25	0.5	0.75	1
UWM-BM - 2m Backfill	-240	-220	-199	-179
UWM-SF - 2m Backfill	244	218	193	168
UWM-BM - 10m Backfill	-813	-723	-633	-543
UWM-SF - 10m Backfill	633	590	547	504

Fig. 9. BM and SF at UWM.

Table 3: Variation Gradient in Radian for Bending Moment and Shear Force for 2m and 10 m backfill.

Key point	BM-2m	SF-2m	BM-10m	SF-10m
BWJ	-1.56962	-1.56984	-1.57002	-1.57015
LWM	1.57000	1.56485	1.57026	1.56678
WCJ	-1.57005	1.56989	-1.57032	1.57022
UWM	1.55858	-1.56095	1.56802	-1.56499
WRJ	-1.56462	1.56658	-1.56685	1.56898

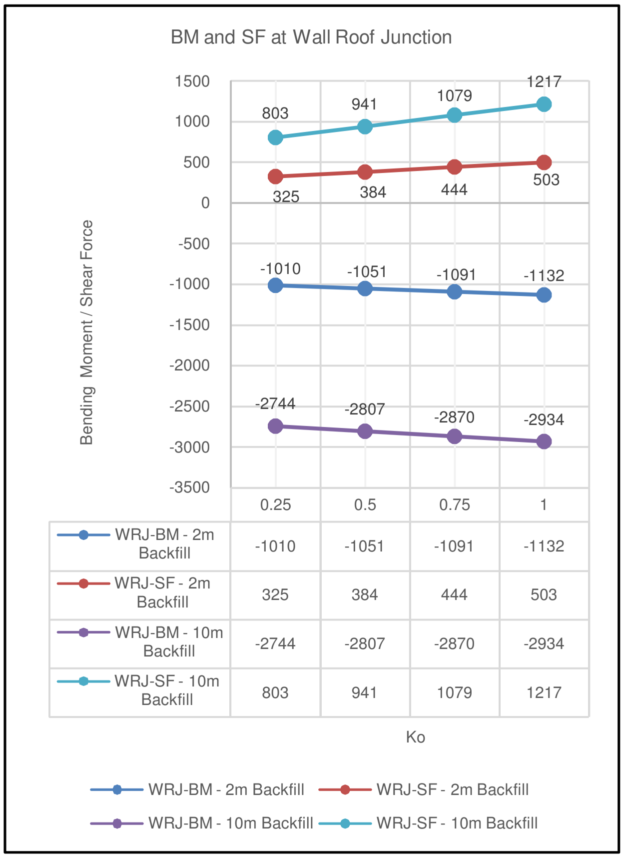


Fig. 10. BM and SF at WRJ.

The variation gradient presented in Table 3 is consistent and ranges between 1.56-1.57 Rad.

V. CONCLUSION

Study presents the effect of earth pressure coefficient for critical case of ground water level below base slab and backfill cover of 2m and 10m. Following conclusions are derived,

– The variation in bending moment and shear forces are observed as linear variation for 2m and 10m backfill on roof slab.

– The variation gradient is consistent and ranges between 1.56-1.57 Rad.

– The bending moment and shear force increases by 50% for 10m backfill compared with 2m backfill.

VI. FUTURE SCOPE

Effect of ground water table and bedding stiffness along with the effect of earth pressure coefficient shall be studied.

Conflict of Interest. On behalf of all authors, the corresponding author states that there is no conflict of interest.

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