Finite Element Modelling and Design of Underground Metro Station

Madan Magdum, Bilavari Karkare

Abstract**:** ***Underground metro stations are influenced by critical external loads such as earth pressure, hydrostatic pressure, bedding spring stiffness and backfill soil cover. Optimization, constructability and sustainability is a need, which demands thorough critical analysis and design. The variation in design parameters like ground water level (GWT), bedding spring stiffness (ks) and earth pressure coefficient (ko) needs to be covered through the analysis. Accordingly, design demands the upper bound and lower bound parameters considerations for finite element analysis. This paper presents, best practices for finite element modelling approach such as mesh configuration, loading, geometry, support arrangement; analysis approach such as analysis parameters, solvers and design idealization of critical forces such as bending moment, shear force and axial force at wall slab junction and slab column junction based on the international codes such as Euro-code and Indian codes. Also paper compares the behavior of 2D and 3D finite element modelling of underground metro station.***

Keywords: Analysis and Design approach, Finite Element Modelling,Underground-metro,

I. INTRODUCTION

India, the underground space is gradually becoming popular due to space restrictions at ground in cities like Mumbai, Delhi, Bangalore and Kolkata. The underground metro is preferred as integrated public transport to release the pressure from the surface transport by enabling usage of underground space for public transport. The underground metros are one of the most popular and most efficient means of urban transportation. [1].An estimated investment for the development of metro rails in Indian cities is USD 26.1 billion [3]. Underground construction faces many geo-mechanic challenges during tender design, detailed design and construction of structures. However, the cost and feasibility of the underground structures is governed by geology [2] and optimized design. Beadman discussed about the geotechnical challenges and gains for design of underground metro based on Euro-codes [6].

The finite element method is commonly used to analyze and design the reinforcement in structural concrete elements of underground metro stations.

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In order to simplify the analysis, the critical load combinations are analyzed with uni-directional compression-only bedding springs. For ultimate limit state (ULS), the strength criteria is evaluated to ensure the safety of users and structures. While the Serviceability Limit State (SLS) checks are carried out for deformations affecting appearance, vibrations causing discomfort and cracking affecting durability and functioning of the structures. For metro structures presented in Fig.2, the plate elements used in analysis are subjected to out of plane loading and a non-linear analysis is performed in order to determine the load effects. However in order to obtain a relevant basis for design, a proper modelling, interpretation and idealization of the FE results are required. For a concrete slab monolithically cast together with a supporting wall, the relevant moments in the slab are those at the face of the supporting wall where a failure mechanism occurs. These considerations influence the way in which the actual support is represented in the FE model and the mesh density around the support nodes. In addition, in linear models, unrealistic concentrations of moments occur due to necessary simplifications in the model. In order to obtain an economical design these concentrations need to be distributed over a certain width, here denoted as distribution or strip width.

II. SIGNIFICANCE

The metro stations are designed for stringent crack-width criteria due to exposure class, durability criteria and design service life of 100-120 years. Optimization, constructability and sustainability is a need, which is fulfilled through critical analysis and design assessment. The variation in design parameters such as ground water level (GWT), bedding spring stiffness (ks) and earth pressure coefficient (ko) needs to be critically evaluated in analysis. Accordingly, design demands the upper bound and lower bound parameters considerations for Finite element analysis [4, 5]. However, best practices for the Finite Element analysis and application to structural design of underground metro station along with modelling approach, analysis principles are presented withreference to Euro codes and Indian codes.

III. METHODOLOGY

3D Finite element models are developed and analyzed using Autodesk Robot Structural analysis software (Version 2018). The methodology includes:

- Modelling approach - Defining structural geometry, material, discretization, loading and support parameters.

- Analysis approach – Analysis parameters, idealization of design forces.
- Validation of FE Model - Static checks and verification of results.
- Idealization of design forces – Assessment of results at critical points and idealization of peak forces.

IV. FE MODELLING APPROACH

The modelling approach includes the geometrical parameters, discretization, loading and support parameters.

A. Geometrical Parameters

A typical cut and cover underground metro station consists of three levels, undercroft which is under platform, platform and concourse level based on the functional requirement, as presented in sectional elevation Fig. 1. The columns are generally placed at 11m spacing.

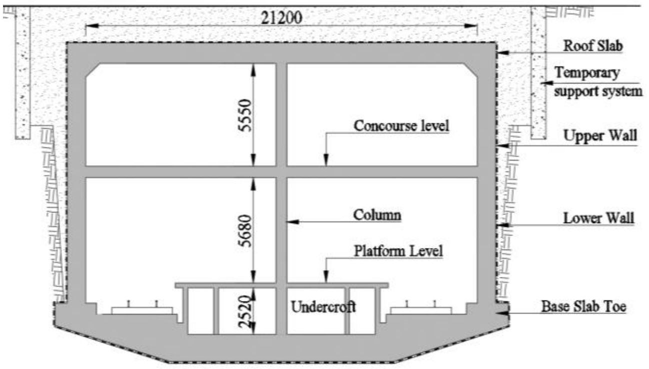

Fig. 1. Typical Sectional elevation of metro station

B. Modelling Approach – 3D FE Model

The 3D model shows realistic behavior based on the element stiffness, applied load resulting two way behavior along transverse and longitudinal direction in the slabs. 3D FE models are analyzed using Autodesk Robot Structural Analysis [7]. The wall and slab elements are defined as plate elements, while the column elements are defined as bar element as shown in Fig. 2.

A comparative study carried out to derive optimum size of mesh. The plate elements are discretized with mesh size of 1.0m x1.0m, 0.5m x 0.5m and 0.25m x 0.25m as shown in Fig.3a, Fig.3b and Fig.3c respectively. It is noted that 0.5m x 0.5m mesh size shows acceptable results and variation. The integral value summary is shown in Table VII and discussed under results analysis section.

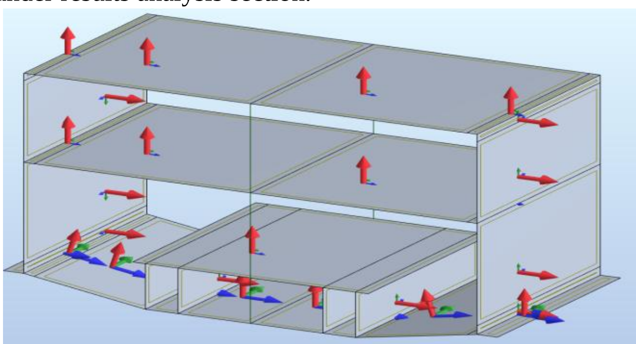

Fig. 2. 3D FE Model and Local axis

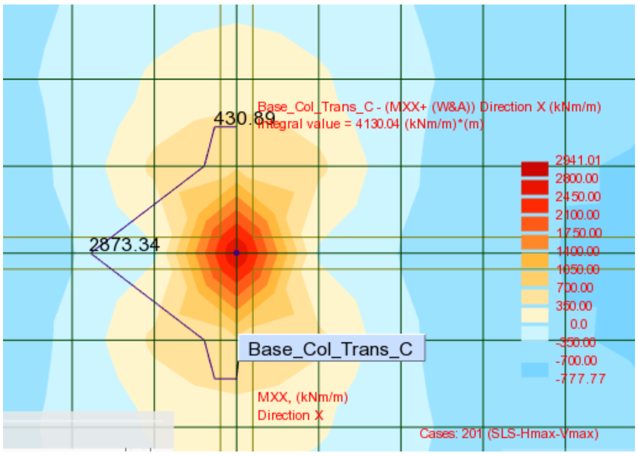

Fig. 3a. Mesh size 1m x 1m

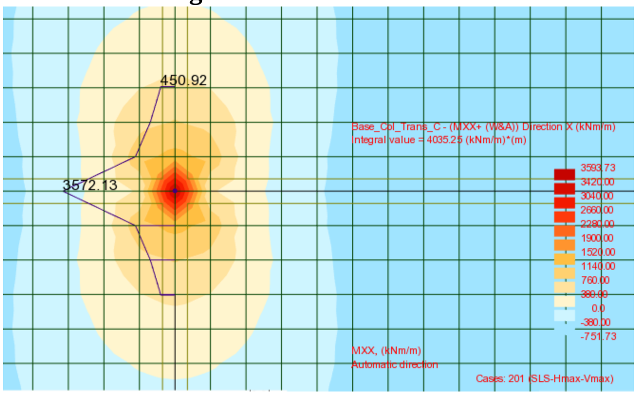

Fig. 3b. Mesh size 0.5m x 0.5m

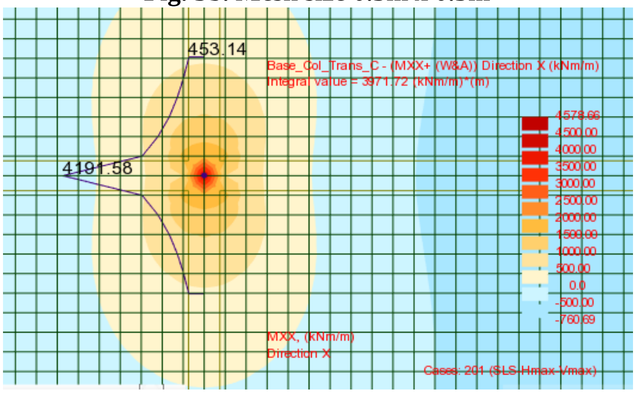

Fig. 3c. Mesh size 0.25m x 0.25m

C. Modelling 2D and 3D

Simplified 2D model is prepared for unit length and analyzed for same loading to compare results with 3D FE model. It is observed that 2D models does not present the realistic behavior due to intermittent columns and one way behavior as shown in Fig. 7a and Fig. 7b. The bending moments at critical location are summarized in Table-VI and discussed under result analysis section.

D. Joint Modelling

Generally, the analysis is used as basis for detailed design. Rombach examined different ways to model a wall support and column support with and without rigid links. It was concluded that wall has to be included in the FE model to get the rotational stiffness of the joint and to derive corresponding moment at the joint. The rotational stiffness of the wall provides a reasonably accurate support condition for the slab.

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For the case of a monolithic connection between the column and the slab, modelling alternatives were studied. Modelling alternative with a stiff coupling (rigid link) applied at the column top over a rigid joint. This modelling alternative gives results in good agreement with a continuum model [8], otherwise the results has to be averaged over distribution width. Autodesk Robot structural analysis has in-build tool to consider the reduction of forces at the support junction such as column and wall locations. The concept is explained in detail in Fig.6a and Fig. 6b.

E. Loading Parameters

For underground structures, 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 (IS 875: 1987) and Euro Code (EN 1991-1-1) and are presented in Table I which are shown indicatively in Fig. 4a. The suction and pressure load due to piston effect are ignored as they are very small and act against the external loads. Also, the draught shafts are provided to release the piston effect.

Table- I: Load and Support Specifications

Load	Parameters
Earth Pressure (EPh) and backfill (EPv)	Ko as per Geotechnical Interpretation. Backfill as per soil cover on roof slab
Water Pressure (WP)	Variation in ground water table.
Super imposed dead load (SIDL)	On concourse and platform
Live Load (LL)	On concourse and platform
Traffic Surcharge (Ts)	Above and adjacent to station at grade
Building load surcharge (Bs)	Adjacent to station at grade

The base slab, roof and external wall elements are thick elements to resist the critical external loads, which are generally in the range of 1.0- 1.25m. The FE centerline modelling of underground metro results in larger spans compared to clear span and increased extent of loading over this increased span. However, the bending moment becomes high due to increased span and higher extent of the loading inside the thickness at the junction. Hence, the loading extent is idealized and reduced till the inside face of the junction as realistic span, while point load and corresponding moment is applied at the junction especially at roof and base slab junction as shown in Fig.4a as best approach. Separate 2D comparison carried out for increased extent of loading and idealized load application as shown in Fig. 4a. It shows reduction up to 6% bending moments compared to increased span bending moments as shown in Fig.4g. for shallow underground metro station.

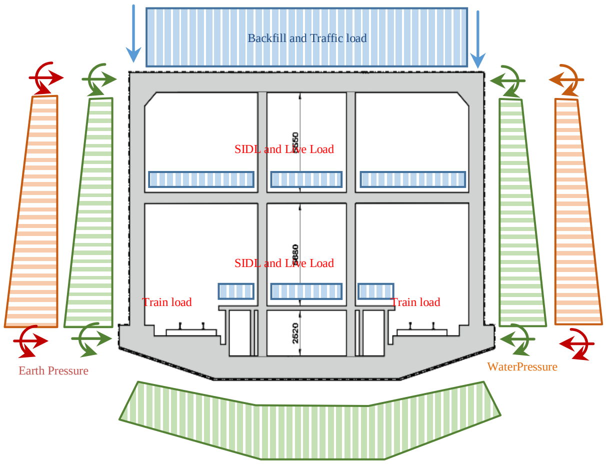

Fig. 4a. Schematic load application

The typical load applied in the FE model are presented in Fig.4b-4f.

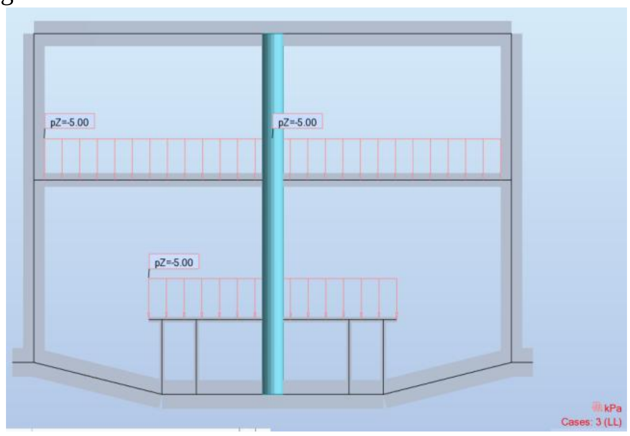

Fig. 4b. SIDL and LL application

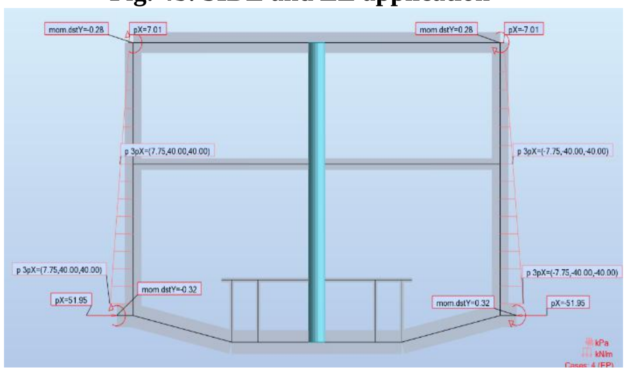

Fig. 4c. Lateral earth pressure application

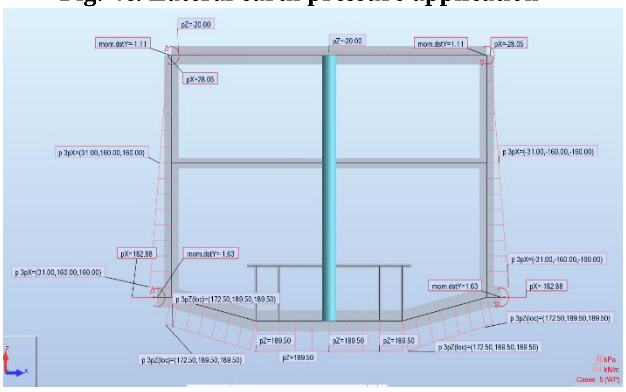

Fig. 4d.Water pressure application

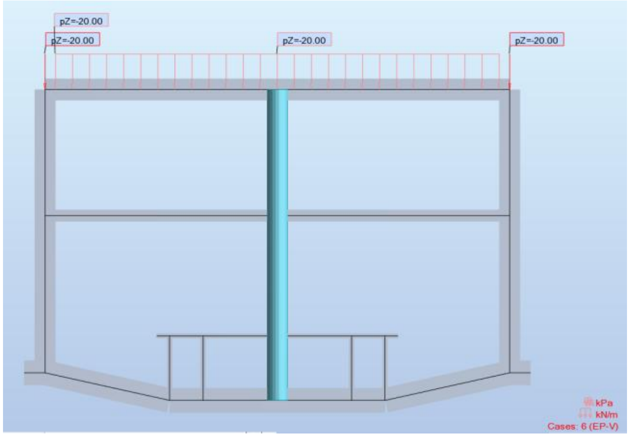

Fig. 4e. Backfill and traffic Surcharge

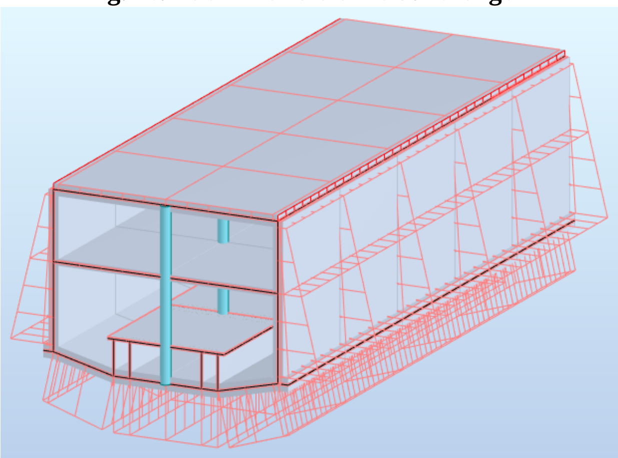

Fig. 4f.Loads in SLS Combination

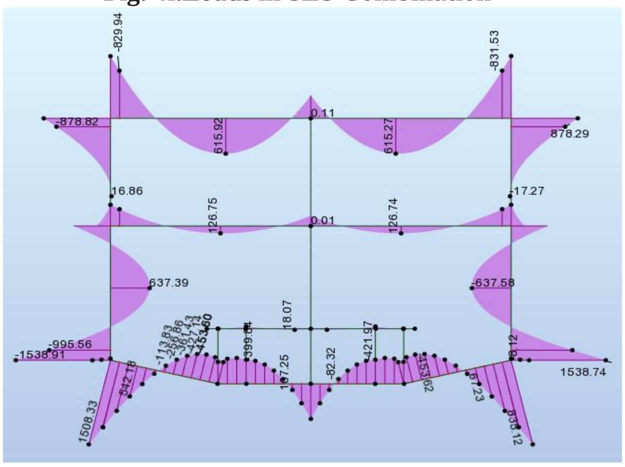

Fig. 4g-(a) Bending moment for idealized loading

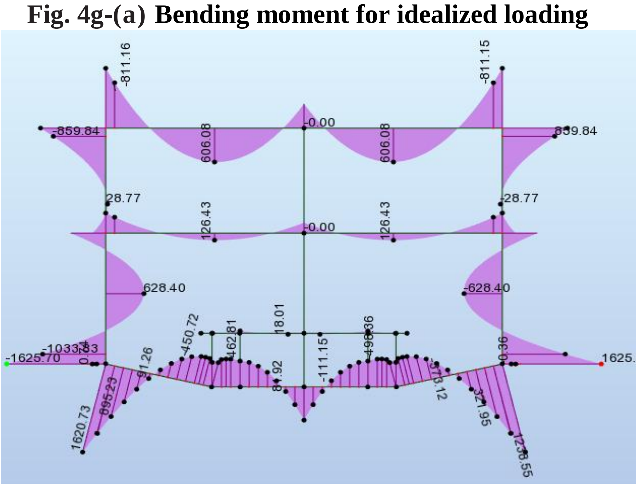

Fig. 4g-(b) Bending moment for increased extent of loading

F. Support Parameters

The underground structures are surrounded with ground and modelled with compression-only springs supports along the walls and base slab. The bedding springs provided at base slab become active in case of non-uplift condition, where the downward force higher compared to uplift pressure. Wall springs become active in case of lateral unbalanced forces.

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.5.

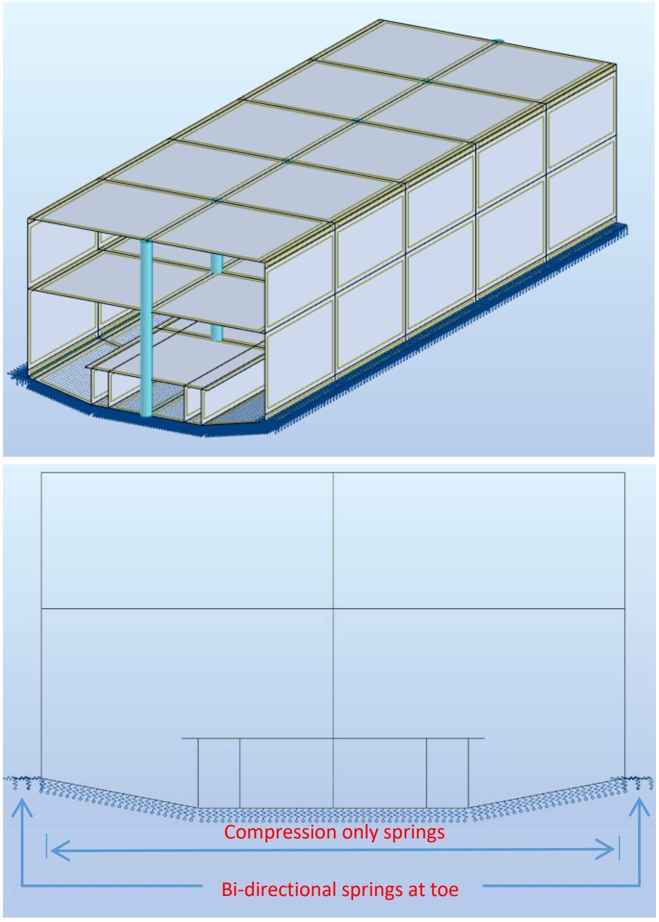

Fig. 5. Support arrangement in Structural Model

G. Uplift Behavior

In case of uplift, upward water pressure becomes higher compared to downward pressure due to self-weight and backfill. However, the compression-only springs becomes inactive for uplift and compression only springs in case of non-uplift scenario.

V. FINITE ELEMENT ANALYSIS APPROACH

The 3D FE model is analyzed with static-nonlinear analysis considering support non-linearity of compression-only bedding springs.

A. Non-linear Behavior

The structure includes non-linear elements such as unilateral compression-only supports, calculations are performed using incremental method in Autodesk Robot Structural Analysis Software.

In incremental method, the load vector is divided into equal increments. A consecutive load increment is applied to the structure once the state of equilibrium for the previous increment is achieved. The norm of unbalanced forces is specified for each step, allowing for monitoring of the structure force-deformation relations. The load increment is used when dividing a load into smaller segments. For complex structures where the impact of non-linear effects is considerable, it is possible that calculations do not converge if the analysis for the value of a load is applied in one step. The number of load increments influences the number of calculation iterations. The greater the number of increments, the greater the probability for the calculations to reach the point of convergence.

B. Structural Model Validation

The models are validated as geometrical validation and loading validations.

- Geometrical Validation: The geometrical validation is carried out by overlaying the structural model DXF format on the Autodesk Revit -3D model to verify the geometrical layout.
- Load Validation: The applied loads and reactions are validated to confirm the load applied for each load case as presented in the Table -II.

Table- II: Load Validation

Load Type	Load	Validation
Gravity Loads	Self-weight, SIDL, LL, Backfill, Traffic Surcharge	Total reaction at the base slab
Lateral pressure	Lateral Earth Pressure, Lateral Traffic Surcharge, Lateral Building Surcharge	Total pressure shall be equal to sum of axial force in base slab, concourse and roof slab for the individual load case.
Water Pressure	Water Pressure on wall and Uplift pressure on the base slab	Total lateral water pressure shall be equal to sum of axial force in base slab, concourse and roof slab. Uplift pressure on the base shall be equal to the reaction at the toe.

C. Idealization of Forces

The FE structural model shows peak bending moments at the critical junctions such as wall slab junction and slab column junction. These FE peak forces at the junctions needs to be idealized considering the infinite stiffness of the junction and shall be designed for the face bending moments. The idealization is presented as,

i) Wall and slab junction – The bending moment at the face of support would be either idealized as square ratio of spans or as per the structural model. The bending moment at the face of monolithic junction shall be not be less than 0.65 of fixed bending moment at the centre of the support (EN. 1992-1-1, 5.3.2.2).

ii) Slab and column junction – The bending moment at the centre of support shows peak. The bending moment above column shall be averaged over width of (b+2d), where, b is width of column and d is effective depth of slab. The bending moment at the face shall be maximum of average bending moment at face or (Mc-Pb/8) as shown in Fig.6a. Also presented in Euro code, regardless of the method of analysis used, where a slab is continuous over a support which may be considered to provide no restraint to rotation, the design support moment, calculated on the basis of a span equal to the centre-to-centre distance between supports may be reduced by an amount Pb/8. (EN. 1992-1-1, 5.3.2.2.).

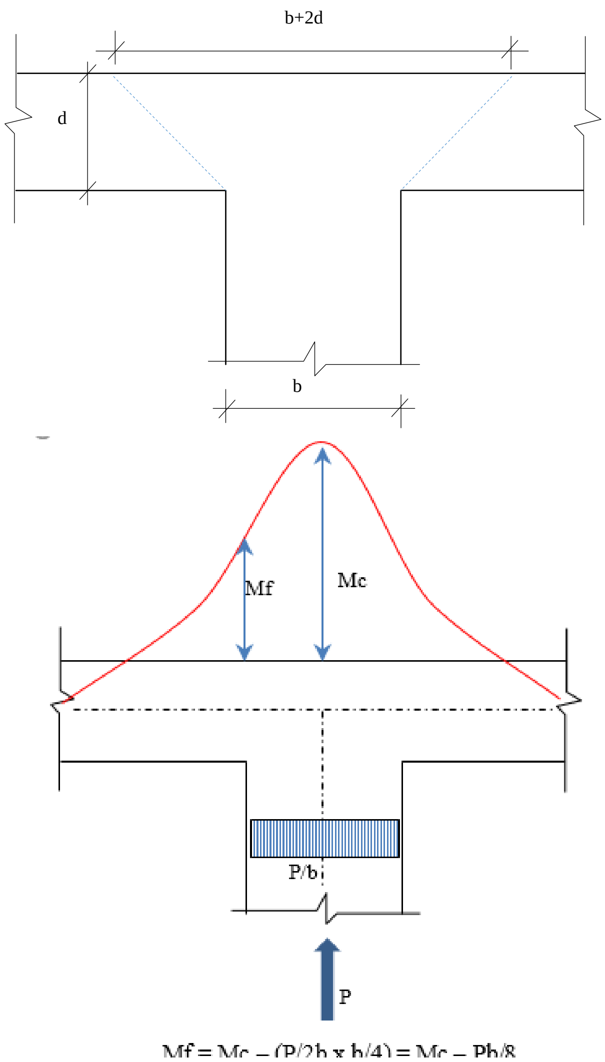

Fig. 6a Idealization of bending moment at the slab-column junction

Autodesk Robot Structural analysis software has in-built tool to reduce the forces at the support such as columns and walls as shown in Fig. 6b.

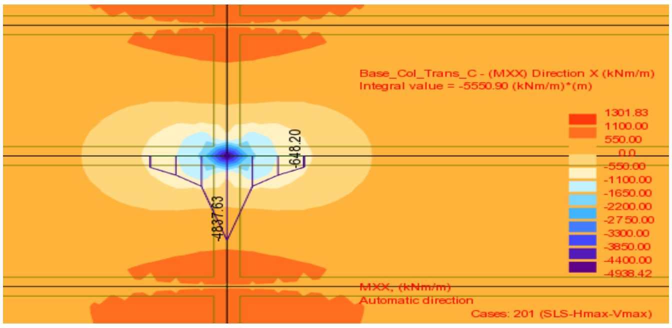

Fig. 6b- i) Bending moment at column junction

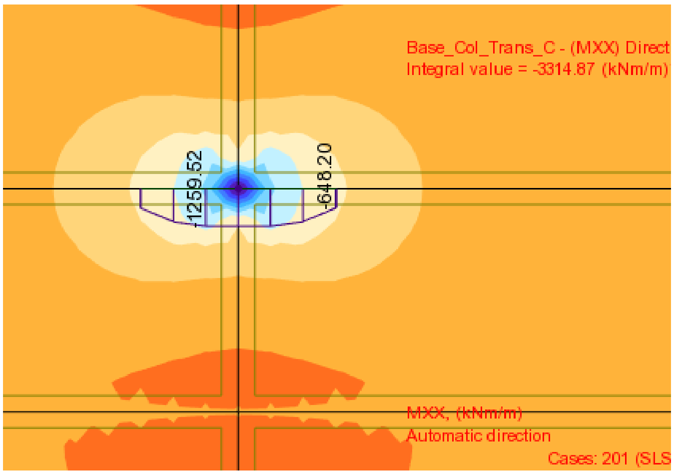

Fig. 6b- ii) Reduced bending moment at the column support

VI. RESULT ANALYSIS

Underground metro station are structurally designed for service life of 100-120 years. The reinforcement cover and grade of concrete shall be determined based on the exposure class and durability assessment. Based on Euro-codes, the structures are designed for four design situations such as persistent, transient, accidental and seismic cases as shown in Table-III (EN 1990:2000 +A1:2005, Section-6).

Table- III: Design situations for ULS based on EN 1990-2002+A1:2005

Design Situation		Verifications
Persistent	Service stage	ULS and SLS
Transient	Temporary conditions during construction, maintenance or repair etc.	ULS and SLS
Accidental	Service or construction stage – accidental	ULS
Seismic	Service or construction stage – seismic	ULS

A. Ultimate Limit State (ULS)

The ultimate limit state (ULS) design includes check for strength criteria to ensure the safety of users and structures. This is checked through EQU – Loss of equilibrium, STR – Structural internal failure, GEO – Excessive deformation of ground and FAT – Fatigue failure of structures. Underground structures are generally checked for STR – Strength criteria of structural elements and GEO- Ground failure. Other two checks for EQU – Loss of equilibrium and FAT-Fatigue generally does not governs the design, due to support exerted by the ground around the station to achieve the equilibrium criteria and less amount of live load compared to dead load for fatigue. UPL-Uplift checks are carried out as part of structural stability.

Reliability differentiation is related to the consequences of failure or malfunction of the structure. The KFI is factor for actions applied based on reliability class of RC3 used for consequence class CC3 for important building structures wherein the extended supervision from third party is not possible as mentioned under supervision class of DSL3 for RC3 (EN 1990:2002 + A1:2005, Section-B3).

Table – IV Load Factor for ULS based on 1990-2002+A1:2005 and IS:456-2000

Load	EN 1990:2002+A1:2005			IS:456-2000
	Load Factor (favorable / unfavorable)	*Reliability factor (KFI)*	*ULS Factor (favorable / unfavorable)*	*ULS Factor (favorable / unfavorable)*
Self-Weight	1.0 /1.35	1.1	1.0/1.49	1.0/1.5
SIDL	1.0/1.35	1.1	1.0/1.49	1.0/1.5
LL	0.0/1.50	1.1	0.0/1.65	0.0/1.5
Earth Pressure	1.0/1.35	1.1	1.0/1.49	1.0/1.5
Water Pressure	1.0/1.35	1.1	1.0/1.49	1.0/1.5
Traffic Surcharge	0.0/1.5	1.1	0.0/1.65	0.0/1.5
Train Load	0.0/1.5	1.1	0.0/1.65	0.0/1.5

For ULS, the bending and shear checks are carried out for critical load combinations.

B. Serviceability Limit State (SLS)

The Serviceability Limit State (SLS) checks are carried out for deformations affecting appearance, vibrations causing discomfort and cracking affecting durability and functioning of the structures. SLS load combinations are mainly classified as characteristic combination, frequent combination and quassi-permanent combinations as presented in Table-V (EN 1990:2002+A1:2005).

Table – V: Design Combinations for SLS based on EN 1990-2002+A1:2005

Design Combination		Verifications
Characteristic	Irreversible limit states	Tensile stress in reinforcement and compressive stress in concrete. Irreversible deformations.
Frequent	Reversible limit states	Decompression is checked for pre-stressed members. Reversible deformations.
Quassi-Permanent	Normally used for long term effects	Crack-width and long-term deformations including creep.

For underground metros, the characteristic and quassi-permanent load combinations are generally used.

While, the quassi-permanent combination governs the design due to stringent crack-width limitations for underground structures.

C. Comparison of 2D and 3D Models

The 3D FE models shows realistic behavior and 2D model does not consider the longitudinal behavior due to intermittent columns located at the spacing of 11m.

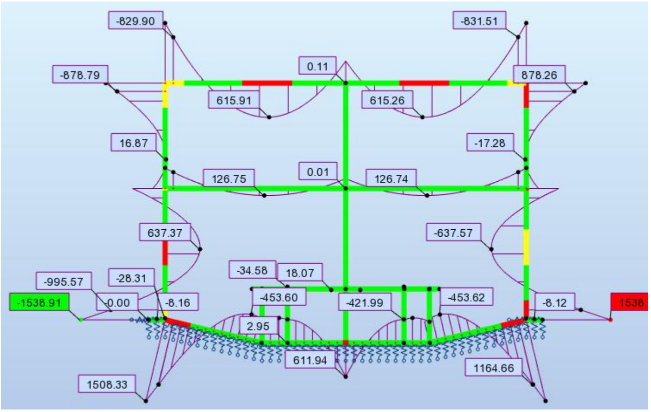

Fig. 7a. 2D Model – Bending Moment

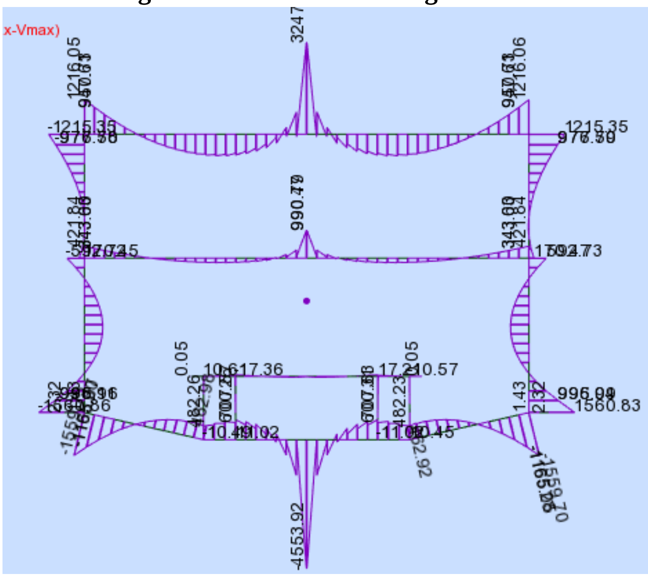

Fig. 7b. 3D Model – Bending Moment

The comparison results at key points are listed in Table –VI.

Table- VI: 2D and 3D Models Bending Moment Summary

Location	2D Model Bending Moment (kN.m/m)	3D Models Bending Moment (kN.m/m)
Wall base Junction	-1538	-1560
Base Column Junction	-612	-1809
Lower wall mid span	638	620
Wall Concourse Junction	-594	-590
Wall Roof Junction	-1084	-1217
Roof Column Junction	-398	-1202

D. Idealization of Mesh

The assessment presented in Fig. 3a, Fig. 3b and Fig. 3c, variation in integral value is between 4130 kN.m/m to 3970 kN.m/m. as shown in Table VII.

Table- VII: Mesh size and results

Mesh Size	Peak Value	Integral Value
1.0m x 1.0m	2873	4130
0.5m x 0.5m	3572	4035
0.25m x 0.25m	4191	3971

It is observed that 0.5m x 0.5m fine mesh shows the acceptable variation in results at the supports like walls and columns with minor variation in integral values. Hence it is appropriate to consider mesh size of 0.5m x 0.5m to derive optimum number of elements, fast processing and smooth variation of contours.

E. Effect of loading extent

As per assessment presented in Fig.4g, the bending moment at the base junction is about 6%, while variation is small at the roof and concourse junction for shallow underground metro station.

VII. CONCLUSION

The paper presents the simplified approach for modelling, analysis and design of underground metro structures using finite element approach. Following conclusions are derived,

- The underground stations has to be modelled as finite element 3D models for realistic behavior compared to 2D models.
- The wall, columns and slabs should be included in the FE model to get the rotational stiffness at joint and to derive corresponding moment at the joint. The joints should be modelled with rigid links.
- Mesh size of 0.5m is optimum size to derive at smooth variation in results.
- The design bending moment at the face of monolithic slab wall junction should not be less than 0.65 of fixed bending moment at the centre of the support.
- The design bending moment at the face of slab column junction should not be less than Mc-Pb/8.
- The extent of loads has to be applied on the clear span while the point load and corresponding moments can be applied at the support for the extent of load over junction thickness. This showed about 6% reduction in bending moments for shallow underground metro stations.
- Euro-codes allows 10% lower load factors for ULS condition compared with Indian codes as a part of third party supervision as mentioned in class DSL3.

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