SOIL-STRUCTURE INTERACTION ANALYSIS OF THREE DIMENSIONAL UNDERGROUND RAILWAY PASSAGE

K. S. R. Anusha¹, S. Madhuri², M. G. Muni Reddy³

EXTENDED ABSTRACT

An underground railway passage (UGRP) is a structure which is constructed under the ground surface and connects different locations in a city. An underground railway passage is mostly chosen where land area is minimal and to reduce the disruption in traffic. As the underground railway passage is constructed beneath the ground surface at several meters of depths, the structure interacts with soil. Hence, Soil-structure interaction analysis is performed for three dimensional model of underground railway passage. The clear width of the railway bridge without any platform is considered as 10.4m with two tracks having a side clearance from outer rail to the edge of the side wall as 2.012m. The clear height of the passage is considered as 6.4m. The road surface on the ground level above top slab of underground passage is assumed to be used as footbridge only. The depth of top and bottom slab is taken as 0.6m and the thickness of side walls is considered as 0.5m. The dimensions of the UGRP are adopted as per Indian Railway Standard Board. The structure is assumed to be at a depth of 20m below the ground surface. A soil stratum with six different soil layers is considered. Analysis is carried out for two trains passing on tracks at a time. Dead load, live load, moving load and earth pressure are considered for the analysis. Self weight of the structure is considered as dead load. The weight of the soil over the bridge, weight of pedestrian pavement surface above ground level and pedestrian load are considered as live load on top slab. The weight of the rails, ballast and sleepers are considered as live load on bottom slab. A train axle load with double headed 25ton loco consists of 12 wheels each having a weight of 245.2kN is considered as moving load on the bottom slab. The axle spacing and wheel loads are considered as per IRS code for “Bridge Rules”. The active earth pressure due to backfill and surcharge is considered on both the side walls. A three dimensional model of UGRP with pinned ends and soil-structure interaction model are developed using STAAD Pro software. Pinned ends are provided at junctions of bottom slab and side wall for the analysis of UGRP without SSI. The springs in the side walls and bottom slab are provided in SSI analysis of UGRP. The stiffness of soil springs are estimated using modulus of sub grade reaction and Newmark’s Beta method for side walls and stiffness of soil springs on the bottom slab is estimated using Winkler beam method. A three dimensional

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analysis is carried out using STAAD-Pro for UGRP without and with SSI for the load combination of DL+LL+EP+ML and the results obtained with and without SSI are compared and presented.

DISCUSSION OF RESULTS
The results obtained from the analysis of UGRP with and without SSI are tabulated in the Table. 1. From the analytical results, it is observed that the bending moments, shear forces and deflections of top slab, bottom slab and side walls are lower in the case of analytical results of UGRP with SSI when compared with results obtained in the UGRP without SSI. The reduction in maximum bending moments and shear forces in bottom slab and side walls is observed due to the effect of spring idealization below the bottom slab.

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<td>-79.06</td>
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<td>684.111</td>
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<td>-124.76</td>
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<td></td>
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CONCLUSION
From the comparison of analytical results of UGRP models with and without SSI, it is observed that the bending moments, shear forces and deflections of side walls, top slab and bottom slabs are observed lesser in the analytical results of UGRP with SSI due to the effect of soil spring idealization. Hence soil-structure interaction analysis shall be performed for UGRP.

Keywords: Underground railway passage, soil springs, Newmark’s Beta method, Winkler Beam method, Soil-structure interaction.


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ABSTRACT
An underground railway passage (UGRP) is the structure which is constructed below the ground surface for the passage of trains for transportation. Generally, UGRP are constructed below the earth surface at several meters of depth. In the recent years, most of the urbanized cities are adopting the intercity UGRP to cater the needs of the people having high population density and to maintain aesthetics of the city. Hence, the design of UGRP involves the evaluation of different environmental loads and analysis of the structure. A three dimensional analysis of the UGRP with soil-structure interaction has been performed for railway passage. The loads considered for the analysis are dead load, live load and earth pressure. A soil-structure interaction (SSI) model is developed in STAAD Pro. The stiffness of soil springs in the side walls is estimated using modulus of the sub-grade reaction of the considered soil strata and Newmark’s distribution. The stiffness of the soil springs for the bottom slab is estimated using Winkler beam method. 3-D analysis of UGRP is performed for the considered loads with and without SSI and compared the results. The results indicate that the B.M’s, S.F’s and deflection in structural elements with SSI are lesser when compared without SSI.

Keywords: Underground railway passage, earth pressure, soil springs, Newmark’s Beta method [1], Winkler’s Beam method [2], soil-structure interaction.


1. INTRODUCTION
UGRP’s are mainly used for the purpose of controlling vehicular traffic and to provide maximum facilities at one place within a nominal ground area. They are primarily used in densely populated cities and where lot of inconvenience occurs due to vehicular traffic to the public. As the whole UGRP completely rests under the ground surface, a model of 3-D UGRP is developed in STAAD Pro to observe the bending moments, shear forces and deflections of structural elements on soil-structure interaction analysis (SSI).

2. BRIEF LITERATURE REVIEW
The soil-structure interaction analysis of an underground passage was performed by many researchers in the recent past. Mohankar and Ronghe (2010) [3] performed two dimensional analysis of an underpass RCC bridge by developing a computer program. Analysis was also done using numerical
methods. The results obtained from the computer program and using numerical methods were compared well. Pidurkar et al. (2012) [4] developed a 2-D model using computer program and performed analysis of an underpass RCC bridge with and without soil-structure interaction. Authors concluded that the results of bending moments obtained from the 2-D analysis of with and without SSI were differed by a percentage variation of about 5.3%, 14% and 12.2% for top, bottom and side slabs. They also concluded that when SSI analysis was performed, there was a decrease in the result of S.F for bottom slab. Vinayak and Swapnil (2013), [5] carried out analysis of 2D underpass RCC Bridge for 3 different cases (i) considering boundary condition as fixed (ii) SSI analysis by assigning springs at bottom surface only, (iii) SSI analysis by assigning springs at bottom and vertical wall members. A 3-D model was developed in computer program and was analyzed for different load combinations by considering dead load, live load, earth pressure, pedestrian load, base pressure and surcharge. A comparison of results was carried out for all the 3 cases. Authors concluded that the bending moment at corner and top slab shear force are lesser in the case iii. Authors also concluded that as the stiffness of the soil increases, the bending moment and shear force decreases. Liu (2012) [6] performed 3-D analysis of underground tunnels by considering soil liquefaction with seismic loading by developing a model using computer program. The tunnel was analyzed under seismic loading assuming that the structure was placed in both saturated dense and loose soils. Author concluded that the model exhibited two different deformation modes due to the effect of two soil layers. It was also accomplished that the maximum stresses were obtained at the dense and loose soil interface.

Based on the literature review, it was observed that the three dimensional analysis under moving rail loads is limited. Hence, the main objective of the study is to perform analysis of UGRP under combined loads of dead load, live load, earth pressure and moving load by developing a three dimensional model with and without SSI.

3. SPECIFICATIONS AND MODELING OF UGRP

An UGRP with two railway tracks is considered with broad gauge [7] is adopted based on the maximum width and height of a train [8]. A side clearance of 2.012m is provided from the side wall to the outer rail having a clear width of 10.4m. The clear height of the passage is considered as 6.4m. The road surface on the ground level above top slab of underground passage is assumed to be used as footbridge only. An expansion joint at a spacing of 60 meters is assumed for the UGRP. The cross sectional details of the considered UGRP are shown in the Fig.1.

![Fig. 1 Cross-section of UGRP](image1)

3.1. Modeling three dimensional UGRP without SSI

A three dimensional model (Fig. 2) without SSI is developed in STAAD Pro by using beam elements.

![Fig. 2 Three Dimensional Model of UGRP](image2)

The side walls, top slab and bottom slab are modeled using beam elements. The side walls, top and bottom slabs are modeled at a spacing of 1m along the longitudinal direction. The side walls are modeled with a breadth and depth of 0.5m. The width and
depth of top and bottom slabs are modeled with 0.6m and 0.5m respectively. The boundary condition is provided with pinned joint at the junction of the bottom slab and side walls.

3.2. Development of Soil-structure interaction model of UGRP

The present UGRP is assumed at a depth of 20m below the ground level. Soil stratum is considered with six different layers. The properties of soil layers are listed in Table 1.

<table>
<thead>
<tr>
<th>Layer No.</th>
<th>Unit wt (kN/m³)</th>
<th>Angle of internal friction (deg)</th>
<th>Depth of layer (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>17.3</td>
<td>35.8</td>
<td>1</td>
</tr>
<tr>
<td>II</td>
<td>17.3</td>
<td>35.8</td>
<td>3.5</td>
</tr>
<tr>
<td>III</td>
<td>17.5</td>
<td>30</td>
<td>3.5</td>
</tr>
<tr>
<td>IV</td>
<td>17.5</td>
<td>30</td>
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</tr>
<tr>
<td>VI</td>
<td>17.5</td>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>VII</td>
<td>17.5</td>
<td>30</td>
<td>7</td>
</tr>
</tbody>
</table>

**Table. 1 Properties of Soil Layers**

The soil-structure interaction is idealized by modeling linear springs along the length of bottom slab and side walls. The spring stiffness for bottom slab is estimated using modulus of sub grade reaction and Winkler’s Beam method [2]. The idealization of spring stiffness for bottom slab using Winkler’s Beam method is as follows.

First spring stiffness,

\[ k_1 = k_s B \left( \frac{L}{2} \right) \tag{1} \]

Intermediate spring stiffness,

\[ k_2 = k_s B \left( \frac{L_1}{2} + \frac{L_{i+1}}{2} \right) \tag{2} \]

Last spring stiffness,

\[ k_3 = k_s B \left( \frac{L}{2} \right) \tag{3} \]

where, \( L \) is the length of the segment.

The length of the segments is done in such a way that the ratio of the segment length to the thickness of the wall \( \left( \frac{L}{a} \right) = 1 \).

The spring stiffness of side wall springs is estimated based on modulus of sub grade reaction \((k_s)\) and Newmark’s distribution. The sub grade reaction for side walls is estimated using Vesic (Bowles, 1974) [1] equation as given below.

\[ k_s = 1.3 \times 10^4 \frac{E_s B^4}{E_p I_p} \left( \frac{E_s}{1 - \mu_s^2} \right) \tag{4} \]

where, \( E_s, E_p \) = modulus of soil and side wall respectively; \( B \) = Thickness of the side wall; \( I_p \) = Moment of inertia of side wall; \( \mu \) = Poisson’s ratio of soil.

The stiffness of springs along the length of side walls is estimated using Newmark’s Distribution as follows.

Stiffness of first spring

\[ k_i = \frac{B L}{24} \left( 7k_s(1) + 10k_s(i) + k_s(i+1) \right) \tag{5} \]

Stiffness of intermediate springs

\[ k_i = \frac{B L}{12} \left( k_s(i-1) + 10k_s(i) + k_s(i+1) \right) \tag{6} \]

Stiffness of last spring

\[ k_n = \frac{B L}{24} \left( 7k_s(n) + 6k_s(n-1) - k_s(n-2) \right) \tag{7} \]

The representation of springs for bottom slab and side walls is shown in the Figs. 3(a) and 3(b) respectively.
4. ASSUMED LOADS

Analysis of UGRP is performed by considering loads such as dead load, live load, earth pressure and moving load. Dead load is considered as self weight of the structure. Weight of the soil over the UGRP, pedestrian pavement surface and pedestrian load is taken as live load on the top slab. The live load on the top slab is estimated by considering the unit weight and depth of the soil. The estimation of live load on top slab is as follows.

Load due to Layer I \(= 17.5 \text{kN/m} \)
Load due to Layer II \(= 60.55 \text{kN/m} \)
Load due to Layer III \(= 61.255 \text{kN/m} \)
Load due to Layer IV \(= 78.755 \text{kN/m} \)
Load due to Layer V \(= 77.855 \text{kN/m} \)
Load due to Layer VI \(= 52.55 \text{kN/m} \)
Pedestrian pavement load \(= 13.704 \text{kN/m} \)
Pedestrian live load \(= 4.8 \text{kN/m} \)

Therefore, total live load due to the soil over UGRP is taken as 366.904\text{kN/m}.

On the bottom slab, a live load consisting weight of the rails [7, 10 and 11], ballast and sleepers are considered.

4.1. Earth Pressure on UGRP

The earth pressure acting on the UGRP is considered as active earth pressure. On both the side walls an active earth pressure due to backfill and surcharge is considered. The active earth pressure is estimated based on the Rankine’s earth pressure theory [2]. The coefficient of active earth pressure is

\[ k_a = \frac{1-\sin(\phi)}{1+\sin(\phi)} \] (8)

where,

\[ \phi = \text{Angle of internal friction} \]

The active earth pressure is estimated using Eq. (9).

\[ P_a = k_a \gamma H \] (9)

where, \( \gamma = \text{Unit weight of soil}; H = \text{Depth of soil fill} \).

4.2. Moving Load

A train axle load [12] with double headed 25ton loco consists of 12 wheels, each having a weight of 245.2\text{kN} is considered as moving load on the bottom slab. The coefficient of dynamic augment and the axle spacing of wheels are considered as per IRS code for “Bridge Rules”. The representation of moving load is shown in Fig. 4. The moving load is considered with two numbers of trains passing through UGRP at a time.

**Fig. 4** Three Dimensional Model of UGRP with Moving Load
The developed models with and without SSI are analyzed for the considered loads and load combination [12] as follows.

\[ DL + LL + EP + ML \]

The elevation and the cross-sectional view of UGRP are shown in Figs. 5(a) and 5(b) respectively.

![Elevation of three dimensional SSI Model](image1)

![Cross-sectional view of UGRP](image2)

### 5. DISCUSSION OF RESULTS

Analysis of UGRP is performed on three dimensional models with and without soil-structure interaction by considering dead, live, earth pressure (surcharge and active) and moving loads of train axles. The results from the analysis of UGRP with and without SSI are tabulated in the Table. 1. From the analysis it is observed that the bending moments, shear forces and deflections of top slab, bottom slab side walls and bottom slab are lower in the case of analytical results of UGRP with SSI when compared with results obtained in the UGRP without SSI. The percentage variations are also tabulated in Table 2. The maximum bending moment of side walls in the SSI analysis of UGRP is observed about 124.76% lesser when compared with UGRP without SSI due to the effect of springs in the side walls. Similar observation is presented with 79% reduction in bottom slab bending moment also, due to the effect of spring idealization below the rail beams. The maximum shear force reduction of 81% is observed in side wall shear force of UGRP SSI analysis due to the effect of soil spring idealization.

### 6. CONCLUSIONS

Three dimensional analysis is performed in the models of UGRP with and without soil-structure interaction considering dead load, live load, earth pressure (surcharge and active) and moving loads of train axles running at a time. The three dimensional model of UGRP is idealized with pinned support only at the junctions of bottom slab and side walls in the analysis of UGRP without SSI whereas SSI model of UGRP is developed by modeling linear springs along the side walls and bottom slabs at equal spacing and maintaining effective length to width of the element ratio equal to 1. The results obtained in the above mentioned approaches are compared and observed that the bending moments, shear forces and deflections of side walls, top slab and bottom slabs are observed lesser in the analytical results of UGRP with SSI. The reduction in bending moments, shear forces and deflections are observed due to the effect of soil spring idealization. Hence soil-structure interaction analysis shall be performed for UGRP.
Table 2 Analytical Results of three dimensional UGRP

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7. REFERENCE

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