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Surface displacements due to tunneling in granular soils in presence and absence of geosynthetic layer under footings

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Abstract. This paper presents the results of numerical modeling studies on the effect of displacements of tunneling in granular soils. Presence of building loads is considered, to find displacement generated at the surface on tunnel. Effect of varying eccentricities of building is simulated, to find influence of building on vertical and horizontal displacement. Studies were carried out in two cases of with and without a geosynthetic layer installed at the bottom of the footing. Results of analysis revealed, the presence of geosynthetic layer under footing, with building placed on centre line, reduced the surface displacements compared to displacement generated without geosynthetic layer. Presence of geosynthetic layer under footing had a dominant effect in reducing displacements in high storey structures. However, when the building was shifted to greater eccentricities from centre line, presence of geosynthetic layer, led to insignificant reduction of displacements on the centre line at the surface.

Keywords: tunneling; geosynthetics; vertical displacement; horizontal displacement

1. Introduction

Tunneling at shallow depths induces subsurface and surface settlements. Magnitude of displacements depends on several factors with predominant factors being strata type, excavation method and overburden depth. Earliest state of art research on tunneling conducted by Peck (1969) indicated a Gaussian settlement profile.

Tunneling in the presence of a building generates different surface profiles. In the past few years most researchers have concentrated their studies on ground movements either by considering the building as an elastic beam, with varying amount of stiffness at different floor levels, without actually considering the actual profile/shape of footings and columns (Potts and Addenbrooke 1997, Franzius 2003). However in the recent years, very few researchers have considered the advance of tunnel by simulating a two storey-building structure consisting of beams, columns and footings (Mroueh and Shahrouer 2003, Son and Cording 2011). Results of their research (Potts and Addenbrooke 1997, Franzius 2003, Mroueh and Shahrour 2003) revealed that the presence of an overlying structure reduced the surface displacements.

Type of strata has a major influence on tunneling induced displacements. Most researchers have concentrated their studies on finding out displacements due to tunneling, which was either in clayey soil strata or in C-Ø soils. On the other hand few researchers have focused their investigations on behavior of tunneling induced ground movements in granular soils. Lee (2009) carried out detailed experimental investigation to predict the subsurface settlements at shallow and deep depths in granular soils and results of lab investigations were found to be in good agreement with results of Finite element modeling. Transparent soil models which simulate behavior of granular soils were also used to investigate the subsurface displacement troughs (Ahmed and Iskander 2011). The measured data was consistent with the field measurements.

In recent years, modifications in properties of soil mass in general or improvement of bearing capacity of soil mass in particular, is brought about by inclusion of geosynthetics at the appropriate location. In buildings, geosynthetics are found to be quite efficient in increasing the bearing capacity of soils, by making surrounding soil mass stiff under footings. Applications of geosynthetics in the civil engineering field are innumerable, with geosynthetic not only acting as a stiffener but also as a base isolator in seismic design of buildings Shivashankar (2013).

Focus of this study is to estimate displacements due to tunneling, in coarse grained strata, subjected to varied building loads and eccentricities, in the presence and absence of geosynthetic layer under footings.

2. Problem definition and details about numerical modelling

The material model considered for the strata is an elasto-plastic model with Mohr-Coloumb failure criteria. Diameter of the tunnel was 6.1 m with lining thickness of 0.25 m. A constant depth of overburden of 8m was considered. A linear-elastic constitutive model is assigned for the tunnel liner and building. Artificial boundaries permitting

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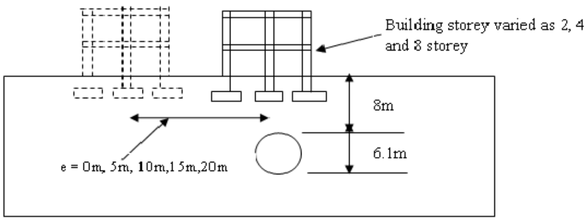

Fig. 1 Location of building with respect to tunnel

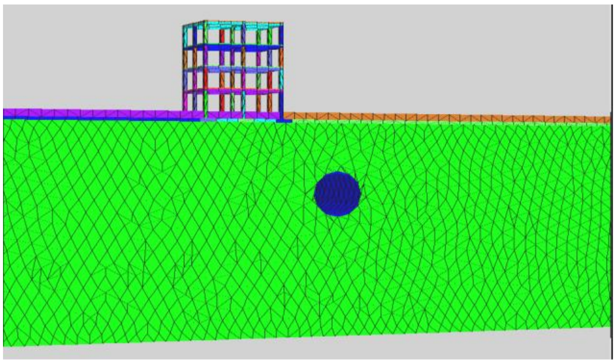

Fig. 2 Meshed model with building placed at 10 m from centre line

movement along the vertical direction was applied at the side boundaries and bottom boundary was fixed. To reduce the effect of artificial boundaries, a distance of 4D was provided (where 'D' is the diameter of tunnel) at the sides in the transverse direction and a distance of 17 m was provided from tunnel bottom to the bottom of the model. The entire domain was divided into deformable blocks with each block further discretized into tetrahedrons with predominant geometrical/geological features forming boundaries of different blocks. The average length of each element was 1.5 m. Finer mesh refinement was provided for building with an average element size of 0.5 m.

Three Dimensional Distinct Element code(3DEC) was utilized to study the effect of varying building stories, varied centre line eccentricities on tunneling induced settlement in granular soils. In distinct element codes like 3DEC it is necessary to bring the model to a state of equilibrium and therefore unbalanced forces were reduced by increasing the number of cycles or by making changes in the model properties in the absence of the tunnel. The tunnel is excavated in the absence of the building, for a length of 60 m, the unbalanced forces were reduced and subsequently the change in displacement was noted. Later on the presence of the building with varying storeys and varied centre line distances are modeled and subsequently vertical and horizontal displacements were measured. Change in displacement was compared to the case of displacement prior to the application of building loads, namely, change in displacement is compared with displacement generated at greenfield conditions.

2.1 Details of the building

A framed building without brick-infill walls was considered for the analysis. Slightly oversized beams and columns are provided to facilitate ease in modeling. Columns are of size 0.35 m × 0.45 m with an axial stiffness of 128MN. Slab was assigned a thickness of 0.15 m. Beams have cross-sectional dimension of 0.3 m×0.35 m with axial stiffness of 85.8MN and bending stiffness 0.876MN-m^2. The footings are of dimensions 2 m×2 m with a thickness of 0.5m (Fig. 1). To further stiffen the strata under footings, a sand layer of 10 cm thickness sandwiched between two geosynthetic layers was provided under each footing and an angle of friction of 20°(μ=0.36) was assigned between the soil and geosynthetic. A distance of 4 m was assigned from the centre line of one footing to the other, both in the transverse as well as longitudinal direction. Bearing pressure exerted by each footing was approximately 24.6 kN/m^2, 49 kN/m^2 and 98.549 kN/m^2 for 2, 4 and 8 storey building respectively. The centre line of the building was varied, with respect to the centre line of the tunnel, in the transverse direction. Centre line distance of the building was varied as e = 0 m, 5 m,10 m,15 m and 20 m. Number of stories of the building was varied as 2, 4 and 8 storey. A meshed model of both the tunnel and building is shown in Fig. 2.

Table 1 Properties assigned to strata

Density (kN/m^3)	Bulk modulus (Pa)	Rigidity modulus (Pa)	Angle of internal friction
20	3.3e^8	1.1e^8	32°

2.2 Details of simulation/parametric study

The numerical model, material models and details assigned to the tunnel are explained in Section 2.0. In this parametric study changes were incorporated with and without a geosynthetic layer under footing. A parametric study was carried out involving various geometrical variables in single layer of granular soil of moderate density with and without a geosynthetic layer under it. An uniform layer of strata was taken into consideration, with granular soil of density 20 kN/m^3 and zero cohesion. Earth pressure coefficient '*Ko*' of 0.5 was taken throughout the analysis. The changes in displacement was compared to the displacement under Greenfield conditions. The properties assigned to the strata are in Table 1.

3. Analysis of displacement with and without geosynthetic layer under footing

In this section horizontal and vertical displacement generated at the surface and at the footings is described and analysed. Response of soil mass at the surface is studied for both the cases of with and without a geosynthetic layer at the bottom of footing.

3.1 Analysis in granular soil with geosynthetic layer

Effect of tunneling in uniform layer of strata, with a geosynthetic layer at the bottom of footings, is analyzed. The change in vertical displacement with varied building storey and building eccentricity with respect to the centre line of tunnel were assessed.

3.1.1 Effect of varying building storey on vertical displacement

The building storey taken into consideration was 2, 4 and 8 storeys. The change in displacement upon excavation, without the presence of building was -10.37 mm at the tunnel surface (green field conditions) (Fig. 3). Inclusion of a building reduced the displacements at the surface as compared to the case without building loads. In the case of a single layer of strata, upon increasing the building load, the displacements reduced. The displacement reduced by 6.26%, 10.6 % and 16.97% respectively in 2 storey, 4 storey and 8 storied building respectively. The main reason for reduction in displacement is that loose soil surrounding the footing stiffens upon inclusion of building weight and as a result overall displacement will reduce. Presence of geosynthetic layer further reduces displacement. With an increase in building load and *Ko* value of 0.5, greater magnitude of displacement was transferred to the sides of the tunnel and therefore reduces displacements at the crown. Greater the number of stories greater will be the transfer of stress on either sides of the tunnel and thus fewer displacement will be noticed at the crown and surface in medium dense granular soils. The reduction in vertical movements is in agreement with studies carried by Mroueh and Shahrour (2003), Franzius (2003), Potts and Addenbrooke (1997).

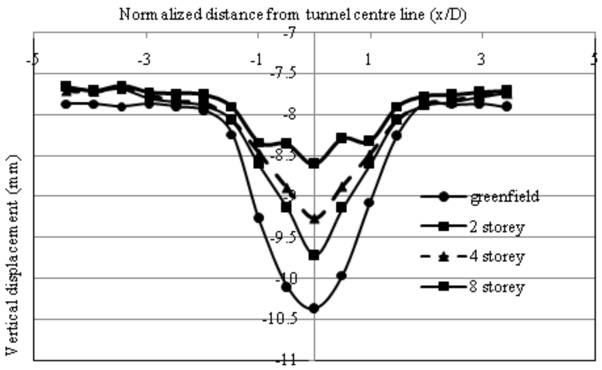

Fig. 3 Displacements on surface with building placed on centre line of the tunnel

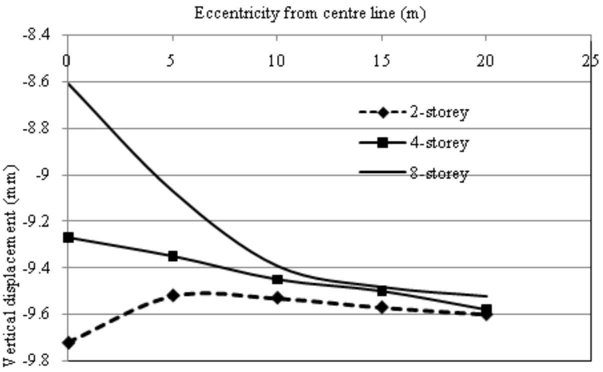

Fig. 4 Displacements on surface with 2, 4, 8-storey building placed at varying eccentricities from centre line

Table 2 Vertical displacement on the centre line due to varying building eccentricities (mm)

	gf *	e *=0 m	e=5 m	e=10 m	e=15 m	e=20 m
2 storey	-10.37	-9.72	-9.52	-9.53	-9.57	-9.6
4 storey	-10.37	-9.27	-9.35	-9.45	-9.50	-9.58
8 storey	-10.37	-8.61	-9.07	-9.39	-9.48	-9.52

*gf: under Greenfield condition, e: eccentricity

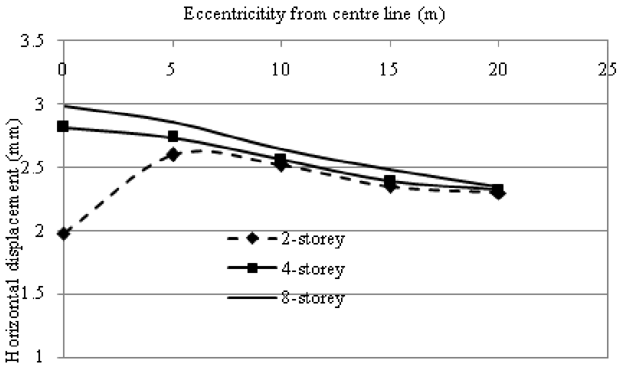

Fig. 5 Horizontal displacement along depth with varying building eccentricity and storey

Table 3 Horizontal displacements at the -3.1 m (10 m depth) from centre line due to varying building eccentricities

	gf *	e *=0 m	e=5 m	e=10 m	e=15 m	e=20 m
2 storey	1.85	1.98	2.6	2.52	2.35	2.3
4 storey	1.85	2.82	2.74	2.56	2.39	2.32
8 storey	1.85	2.99	2.86	2.64	2.48	2.35

*gf: under Greenfield condition, e: eccentricity

3.1.2 Effect of varied eccentricities on vertical displacement

Effect of varied eccentricities on displacements is studied for all the three building stories. The eccentricities were varied on the left side of the centre line by 0 m, 5 m, 10 m, 15 m and 20 m eccentricity. As the building eccentricity was increased, the displacements at the centre line on the surface increased and thus displacement matched the transverse displacement profile created by the case without a building (Fig. 4, Table 2). Even though there is an overall reduction in displacements due to inclusion of building weight, displacements at the footing were of lesser magnitude compared to other points in the transverse direction. Detailed studies on displacement generated under footings are explained in Section 3.3.

3.1.3 Effect of varying building storey and eccentricity on horizontal displacements

The horizontal movements in the vicinity of the tunnel increases with increase in storey. However for a given storey, displacements towards the tunnel opening reduced as the building moved away from the centre line. Horizontal displacement at an offset distance of 3.1 m on the left side of the centre line (springing level) was 1.98 mm, 2.6 mm, 2.52 mm, 2.35 mm and 2.3 mm when a two storey building

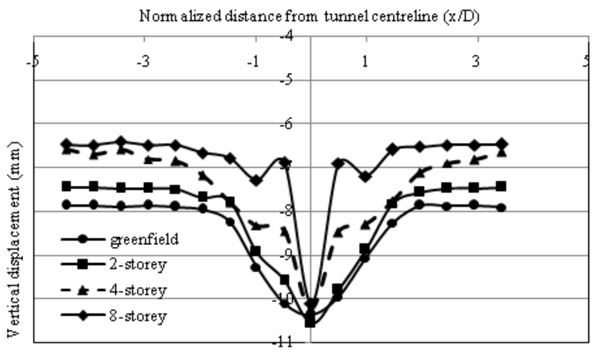

Fig. 6 Displacements on surface with 2, 4, 8-storey building placed on centre line

Table 4 Comparison of vertical displacement on surface (centre line) with varying eccentricity (mm)

	gf *	e *=0 m	e=5 m	e=10 m	e=15 m	e=20 m
2 storey(with gst)	-10.37	-9.72	-9.53	-9.52	-9.57	-9.6
2 storey	-10.37	-10.56	-9.22	-8.66	-8.63	-8.52
4 storey(with gst)	-10.37	-9.27	-9.35	-9.45	-9.50	-9.58
4 storey	-10.37	-10.22	-9.19	-8.37	-8.32	-8.29
8 storey(with gst)	-10.37	-8.61	-9.07	-9.39	-9.48	-9.52
8 storey	-10.37	-10.11	-8.01	-7.58	-7.42	-7.39

*gf: under Greenfield condition, e: eccentricity

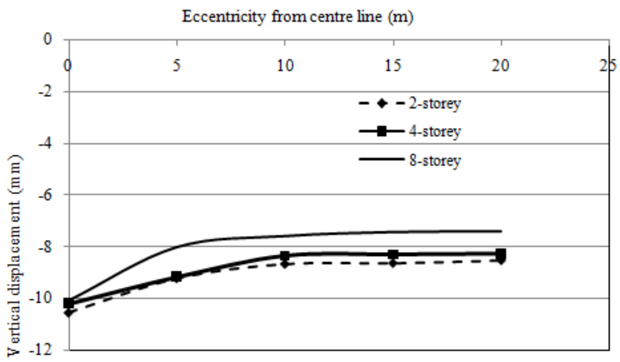

Fig. 7 Displacements on surface with 2, 4, 8-storey building placed at varying eccentricities from centre line

Table 5 Vertical displacement on the centre line due to varying building eccentricities (mm)

	gf *	e *=0 m	e=5 m	e=10 m	e=15 m	e=20 m
2 storey	-10.37	-10.56	-9.22	-8.66	-8.63	-8.52
4 storey	-10.37	-10.22	-9.19	-8.37	-8.32	-8.29
8 storey	-10.37	-10.11	-8.01	-7.58	-7.42	-7.39

*gf: under Greenfield condition, e: eccentricity

was placed at 0 m, 5 m(0.819D), 10 m(1.63D), 15 m(2.45D) and 20 m (3.27D)(where 'D' is the diameter of the tunnel). Horizontal displacements increased by 42.4% when a 4 storey building was placed on the centre line, compared to displacement generated due to a 2 storey building. Thus, horizontal displacement of 2.82 mm, 2.74 mm, 2.56 mm, 2.39 mm and 2.32 mm occurred when the building eccentricities were varied from 0 m to 20 m. Placing of an 8 storeyed building at zero eccentricity resulted in 51% increase in horizontal displacements at the springing level, compared to a 2 storey building. The transfer of displacements to sides of tunnel due to low rise buildings was less as compared to high rise buildings. When the horizontal displacements at the springing level was high, it resulted in lower vertical displacements at surface and hence high rise buildings in less dense strata reduced the vertical displacements at the crown, and subsequently at the surface. For a given building storey, the reduction in horizontal displacements, as the building moved away from the centre line, is in concurrence with the results of Franzius (2003) (Fig. 5, Table 3).

3.2 Results of analysis in granular soil without geosynthetics

In this section changes in the form of displacements were assessed, in the absence of a geosynthetic layer at the bottom of the footing. The change in vertical displacement with varied building storey and building eccentricity with respect to the centre line of tunnel were assessed.

3.2.1 Effect of varying building storey on vertical displacement

Analysis of tunnels in granular soil without geosynthetics, indicated that displacement in transverse direction, increased the displacement on the surface at centre line of the tunnel. Displacement generated at surface without geosynthetics was -10.56 mm, -10.22 mm, -10.11 mm respectively for 2, 4 and 8 storied building, and with the geosynthetic layer, the values were -9.72 mm, -9.27 mm and -8.61 mm respectively for the 2, 4 and 8 storied building loads placed on centre line. At other points, along the transverse direction especially under footings, displacements were higher than those generated in the condition of model with geosynthetic layer (Fig. 6). However, upon inclusion of a geosynthetic layer and varying the eccentricities of the building with the tunnel centre line, significant reduction of displacements at the centre line is not noticed (Table 4).

3.2.2 Effect of varied eccentricities on vertical displacement

Effect of varied eccentricities on displacements is studied for all the three building stories. The eccentricities were varied on the left side of the centre line by 0 m, 5 m, 10 m, 15 m and 20 m eccentricity. As the eccentricity of the building increased, the displacements at the centre line on the surface reduced (Fig. 7, Table 5). Even though there is an overall reduction in displacements due to inclusion of building weight, displacements at the footing were of greater magnitude compared to other points in the transverse direction. Section 3.3 describes the vertical displacement generated under footings.

3.2.3 Effect of varying building storey and eccentricity on horizontal displacements

Considering the absence of geosynthetic layer, horizontal movements in the vicinity of the tunnel increased

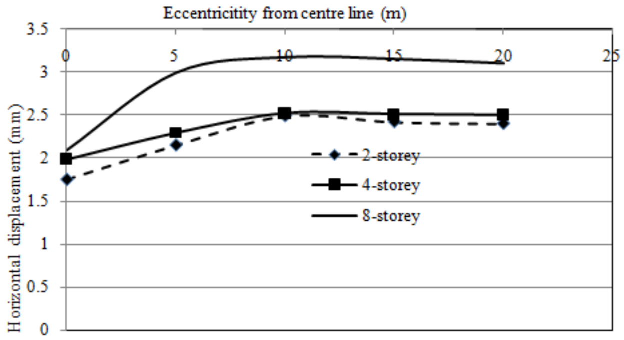

Fig. 8 Displacements on surface with 2, 4, 8-storey building placed at varying eccentricities from centre line

Table 6 Horizontal displacements at the -3.1 m (10 m depth) from centre line due to varying building eccentricities

	gf *	e *=0 m	e=5 m	e=10 m	e=15 m	e=20 m
2 storey	1.85	1.75	2.15	2.49	2.42	2.4
4 storey	1.85	1.99	2.3	2.53	2.52	2.51
8 storey	1.85	2.09	2.99	3.17	3.15	3.1

*gf: under Greenfield condition, e: eccentricity

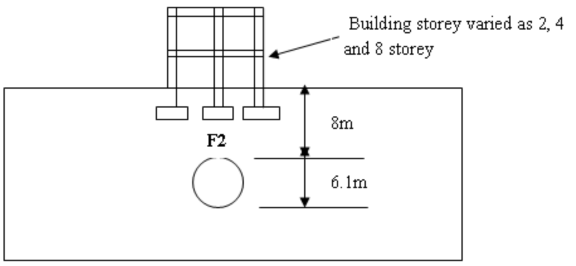

Fig. 9 Location of footing 'F2'

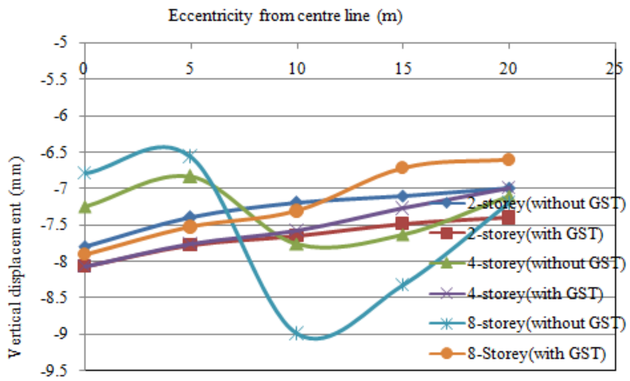

Fig. 10 Displacement under footing with varying building eccentricity and storeys

with increase in storey. However for a given storey displacements towards the tunnel opening reduced as the building moved away from the centre line. Horizontal displacement at an offset distance of 3.1 m on the left side of the centre line (springing level) was 1.75 mm, 2.15 mm, 2.49 mm, 2.42 mm and 2.4 mm when a two storey building was placed at 0 m, 5 m (0.819D), 10 m (1.63D), 15 m (2.45D) and 20 m (3.27D) from centre line. Horizontal displacements increased by 13.7% when a 4 storey building was placed on the centre line, compared to displacement generated due to a 2 storey building. Thus, for a four storied building, horizontal displacement of 1.99 mm, 2.3 mm, 2.53 mm, 2.52 mm and 2.50 mm occurred when the building eccentricities were varied from 0m to 20 m. Placing of 8 storied building at zero eccentricity resulted in 19.42% increase in horizontal displacements at the springing level, compared to a 2 storey building (Fig. 8, Table 6).

3.3 Effect of tunneling on displacements under footings

Displacement developed under footings, depends predominantly on building loads/storey and the soil-tunnel-footing interaction. Presence of geosynthetic layer was studied under footings. The footing under consideration is the middle footing 'F2' as shown in Fig. 9. For a 2-storey structure the presence of the geosynthetic layer under footing led to least reduction of vertical displacement as compared to Greenfield conditions. Further, presence of geosynthetic layer in short storey structures led to insignificant change in displacements as those generated in absence of geosynthetic layer.

In a 4 and 8-storey structure, with building placed at 0 m and 5 m eccentricity from centre line, presence of geosynthetic layer under footing, increased the vertical displacements as compared to 2 storey building. However placing the building at eccentricity of 10 m, 15 m and 20 m, from the centre line, reduced the displacements under footing the main reason being that in a 4 and 8-storey structure or in high storey, the creation of an opening does not lead to direct flow of material towards the opening, which is mainly caused due to strengthening of soil surrounding the footing, thus building which is tallest and which is the farthest from the centre line had the least magnitude of displacement under footings (Fig. 10).

4. Conclusions

Effect of tunnelling in medium dense granular soils was studied in the paper. Analysis of presence and absence of geosynthetic layer under footing of buildings with varied stories and varied eccentricity from the tunnel centre line has led to the following conclusions**.**

• Inclusion of a building, with a geosynthetic layer under footings, reduced the overall displacements as compared to the case without building loads. This is in agreement with results by Mroueh and Shahrour (2003), Franzius (2003), Potts and Addenbrooke (1997). Thus in medium dense soils, upon increasing the building load the vertical displacements at surface reduced.

• As the eccentricity of the building was varied, the vertical displacements at the centre line, on the surface, kept on increasing and the displacement matched the transverse displacement profile created by the case without building. Even though there is an overall reduction of displacements due to inclusion of building weight, displacements at the footing were of lesser magnitude compared to other points in the transverse direction.

• Horizontal displacements towards the tunnel opening reduced as the building moved away from the centre line. The transfer of displacements to sides of tunnel in case of low rise buildings was less as compared to high rise buildings. When the horizontal displacements at the springing level was high, it resulted in lower vertical displacements at the tunnel crown and hence high rise buildings in such strata reduced the vertical displacements at the crown and subsequently the surface.

• Presence of geosynthetic layer under footings and with building placed at larger eccentricities from centre line, had a significant effect in reducing displacements under footings of high storey structures and led to insignificant reduction of displacements on the centre line at the surface.

• Greater magnitude of displacements was observed under footings, without geosynthetic layer, compared to footings with geosynthetic layer. Even though there is an overall reduction in displacements due to inclusion of building weight, displacements at the footing were of greater magnitude compared to other points in the transverse direction.

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