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Settlement of Existing Structure Due to Construction of a Tunnel in Layered Soil

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Abstract. Metro construction in congested urban areas often involve the excavation of new tunnels. Tunnel construction induce the ground settlement above and the prediction of greenfield settlement is well established for homogeneous soil condition and can be estimated using semi-empirical or numerical modeling. This paper investigates the influence of ground surface settlement caused by tunnel construction in layered soil on existing structure using numerical modeling. The numerical modeling has been done by keeping the soil condition similar to actual scenario with multi layered soil like clay, silt and sand. The numerical method is validated by comparing with the field settlement values. The study illustrates the results for two varying parameters such as the center-to-center distance between tunnel and loading of structure. The results show that the effect of tunnelling on the foundation lies within two times the tunnel diameter from the center line of the tunnel and the displacement beneath the foundation increases with increasing the surcharge.

Keywords: Settlement, Tunneling, PLAXIS 3D.

1 Introduction

Rapid growth in public transport demand can lead to excavation of new tunnels which may passes through densely populated area. Stress relief and over-excavation during tunnelling create movement inside the soil, leading to greenfield settlement which is studied by many researchers [1-3]. The word "greenfield" refers to a tunnelling scenario with no surface or subterranean structures.

Many researchers applied three-dimensional analysis to investigate the influence of tunnelling on existing structures and ground settlement [4-7]. To assess ground settlement, empirical and semi-empirical studies have been conducted in clay and sand [8]. Field measurements are used to investigate the effect of tunnelling by TBM on bridge piles and existing structures [9]. The ground settlement is examined using a 2D analysis, which reveals that the primary influencing parameter is the elastic parameter of the soil [10]. The study is based on various assumptions. According to frame structure finite element modelling, the existence of structure can decrease differential settlement and horizontal ground displacement compared to greenfield condition [11]. To evaluate the influence of tunnelling on existing structures, a 3D analysis was carried out using PLAXIS 3D(2018) by varying pressure on footing from 100 kPa to 300 kPa and position of footing like foundation center at tunnel center, edges of footing at tunnel center, edges at 1D (‘D’ Diameter of Tunnel) from tunnel center, edges 2D from tunnel center and edges at 3D from tunnel center.

2 Input parameters for the numerical analysis

The sub-surface parameters from SPT data were obtained from site and using existing established correlations. The water table was observed at a depth of 20 m below ground level and same has been considered in the analysis. The soil was modelled using the hardening soil model which is an advance model for simulation, in which soil stiffness is described accurately by using three different input stiffnesses: the triaxial stiffness E_{50}, the triaxial unloading stiffness E_{ur} and the oedometer loading stiffness E_{oed}. Details of sub-soil properties considered in the numerical analysis is given in Table 1.

Table 1: Sub-Surface Properties of Hardening Soil Model.[12]

Property	Fill	$Sand_1$	$Sand_2$	$Clay_1$	$Clay_2$	$Clay_3$	$Sand_3$	Silt
Layer Thickness, m	0 - 2	2 - 5.5	5.5 -7.5	7.5 - 9	9 - 15	15 - 17.5	17.5 - 21	21 - 50
$na(\frac{N}{3})$	16.0	15.7	16.4	17.0	17.2	16.8	17.0	17.0
$a(\frac{N}{3})$	18.2	17.8	18.7	19.6	19.9	20.0	20.0	20.50
n	0.61	0.68	0.6	0.57	0.51	0.6	0.55	0.60
$_{50}(\frac{N}{2})$	26540	66640	71460	3135	3588	2788	49640	44780
$(\frac{N}{2})$	26540	66640	71460	2508	2870	2230	49640	44780
$(\frac{N}{2})$	79630	199900	214400	27080	29770	15550	148900	134300
Power, m	0.67	0.67	0.67	1.0	1.0	1.0	0.67	0.67
$'(\frac{N}{2})$	1.0	2.0	1.0	199	236	176	3.0	1.0
$'(°)$	28	30.8	32.4	-	-	-	34.3	34.3
$_0^{nc}$	0.5305	0.4880	0.4642	1.0	*1.0*	1.0	0.4365	0.4365

* $_{na}$ =unsaturated unit weight, $_{a}$ = Saturated unit weight, $_{n}$ = Void ratio, ($_{50}$, , , Power, m, ^{nc})= Stiffness parameter, (' $_{0}$, ')= Strength Parameter.

Table 2: Material properties of TBM and lining (data from [13]).

Parameter	**TBM**	**Lining**
Material weight, kN/m^3	76	25
Young's modulus, kPa	210×10^6	27×10^6
Poisson's ratio	0	0.15

Table 2 lists the parameters of the TBM and the lining used in the numerical study. The Earth Pressure Balance System (EPBS) was used to build the tunnel. The tunnel's external and internal diameters are 6.3m and 5.8m, respectively. Each segment is 1.4 m long.

3 Finite Element Model

As shown in Figure 1, the finite element model has a dimension of 50mx70mx50m (L×B×H). To reduce the computational only one half of the tunnel was considered in the model. The dimensions have been set to eliminate boundary effects. The TBM was made up of 9 segments with a total length of 12.6m. The tapered section was given a consistent contraction of 0.5 %. The tunnel crown is 11.7 m deep. The numerical simulation is done in the same way as it is done in the field, with each step in the advancement of TBM is 1.4m. Detailed stepwise numerical simulation procedure is provided in [12] . The face pressure and grout pressure were 70kPa and 300 kPa which is the same as in field. For existing structure, the calculated load is applied to a plate that is held 2 m below the ground and the lateral position is varied to evaluate the behavior. The size of the foundation was considered as 10mx10m.

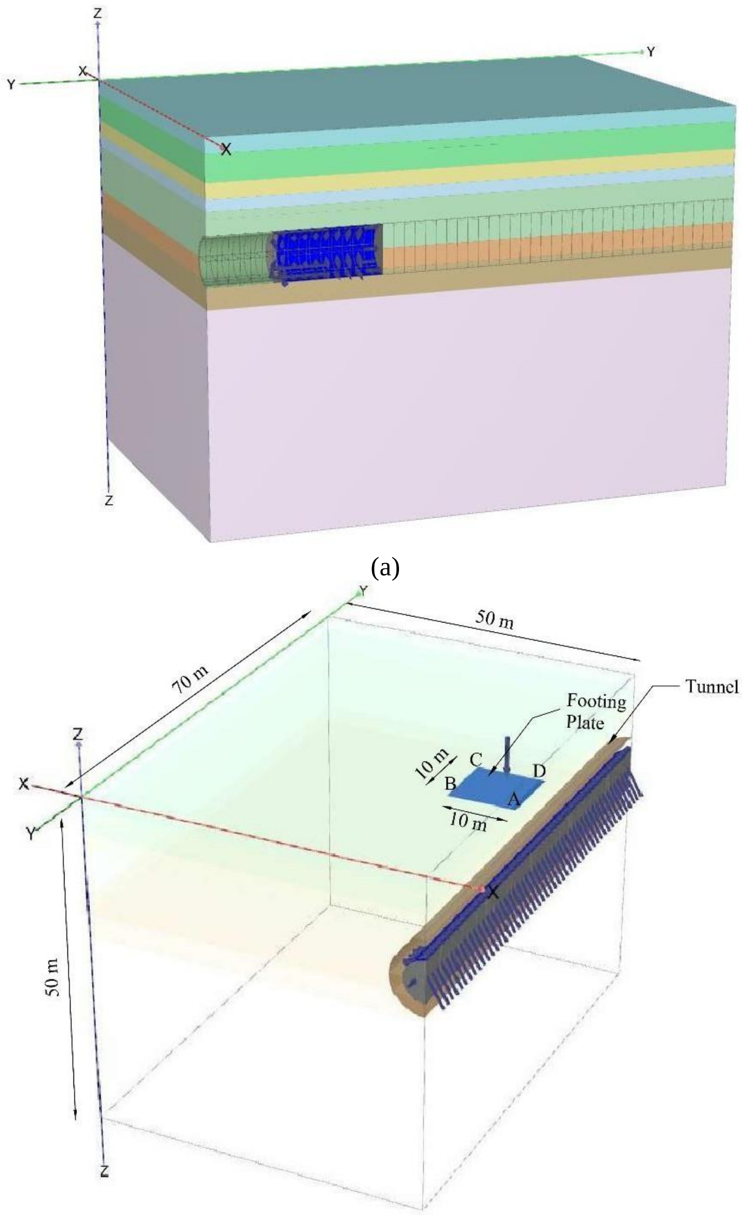

Figure 1: Numerical model for assessing the evolution of Settlement of footing on ground.(a) Soil Layers and (b) Foundation of Structure

In assessing the evolution of displacement owing to tunnel construction, four points A, B, C, and D (Fig. 1) are taken into account. The TBM face was initially positioned at a distance of -2D (‘D’ diameter of tunnel) from the point A of footing, and the tunnel's construction stages were continued until the tunnel face moved to a distance of 5.2D from the D point of footing. The data is considered at 0.5D intervals in transverse direction to examine the displacement at ground owing to existing load. Apart from that, the displacement is measured at the center of the footing and at the center of the tunnel on the ground for every 0.5D advancement of the TBM.

4 Results and discussion

Deformation due to the Tunnel-Foundation interaction is studied by varying the distance of foundation with respect to tunnel centre axis and foundation pressure.

4.1 Foundation Settlement

When the TBM face is at 3.43D to 6.54D from footing plate Point 'A', maximum settlement occurs on the footing plate. As seen in Fig. 2, when the footing moves away from the tunnel center, the displacement decreases and the two cases of “tunnel center at footing center” and “edges of footing at tunnel center” gave almost identical results. In all the cases considered the maximum settlement on the footing is observed at point D.

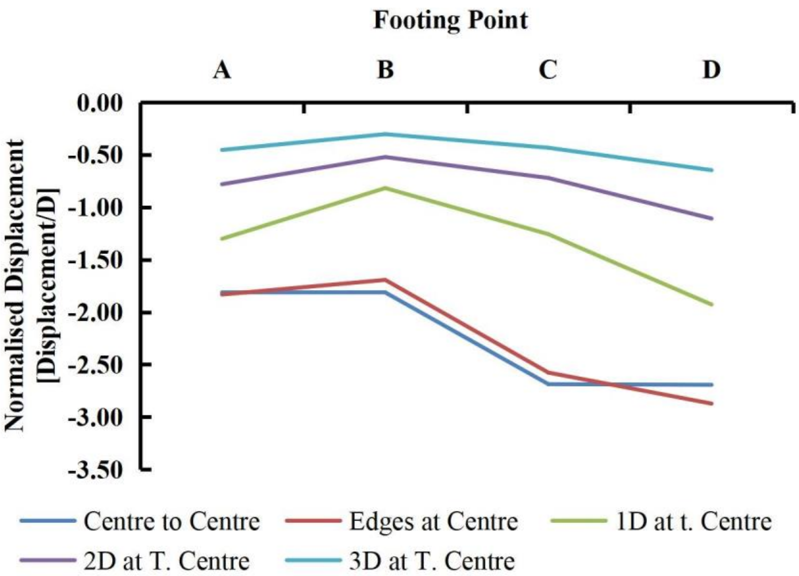

Figure 2: Settlement of Existing Footing.

As shown in Fig 3, increasing the pressure on the foundation from 100kPa to 300kPa causes the displacement to increase, and the case where the "center of footing plate is located at tunnel center" shows more displacement than the other cases. As can be seen from the graph, the highest settlement of footing plate occurs at 300kPa Pressure. From [11] study it can be observed that by increasing a number of storey the settlement will be increasing at the edges of footing which is similar to the present study.

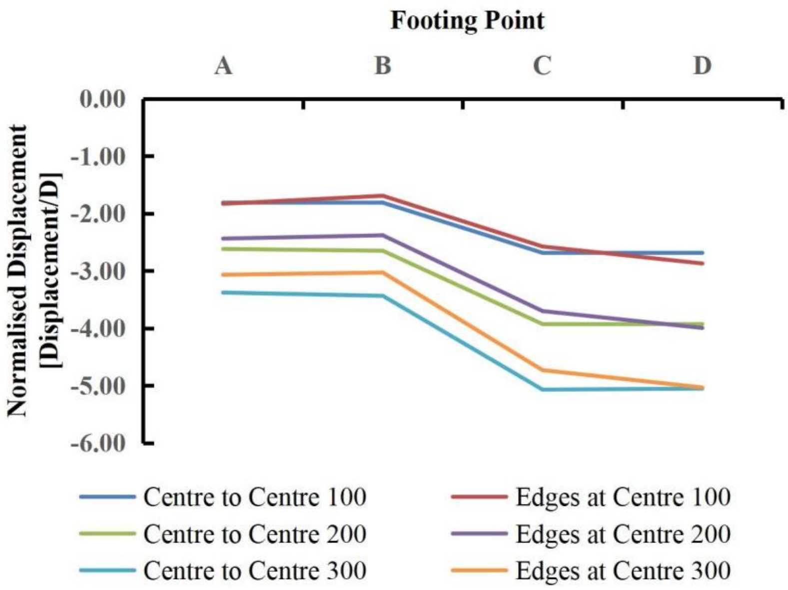

Figure 3: Settlement of Existing Structure at Different Pressure.

4.2 Transverse Settlement

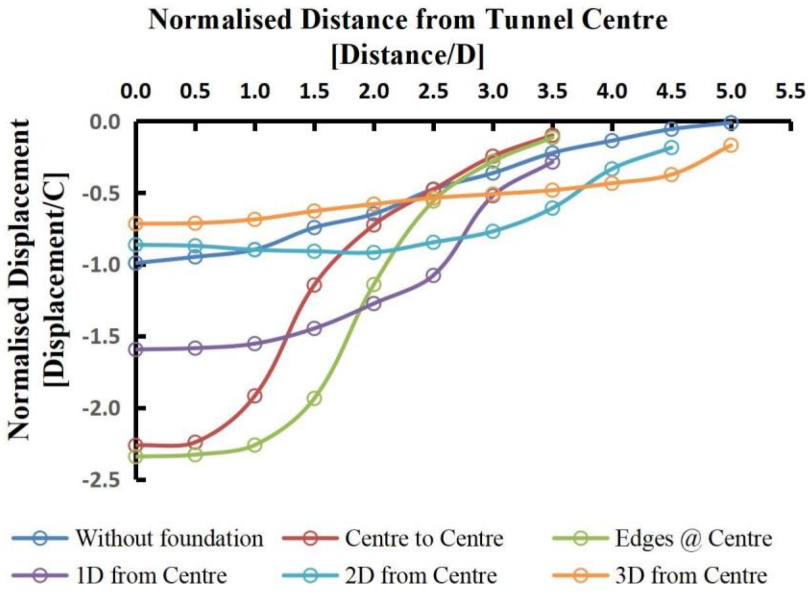

Figure 4: Settlement in Transverse Direction from Centre line of Footing.

Fig. 4 compares ground settlement in transverse direction from the mid line of the footing plate for various footing positions. At every 0.5D distance, the displacement data is taken into account. As can be seen in the graph, the maximum displacement is for two positions of footing plate, namely when the footing center is exactly above the tunnel center and when the edges of the footing plate are above the tunnel center, When the footing plate is placed at 2D away from the tunnel center, the displacement is nearly equal to greenfield settlement at the tunnel center. The displacement is reduced when the footing plate is 3D from the tunnel centre, the influence on ground settlement is up to 2D.

It can be inferred from Fig. 5, that as the surcharge increases the maximum settlement (S_{max}) Increases and it is more pronounced when the foundation lies very close to the tunnel centre-line. Trough width (I_x) was plotted against the surcharge, a narrower trough is obtained when footing is placed closer to tunnel centre axis and it becomes broader as the distance of foundation increases. It can also be noted that as the surcharge increases beyond 200 kPa the effect on I_x is minimal.

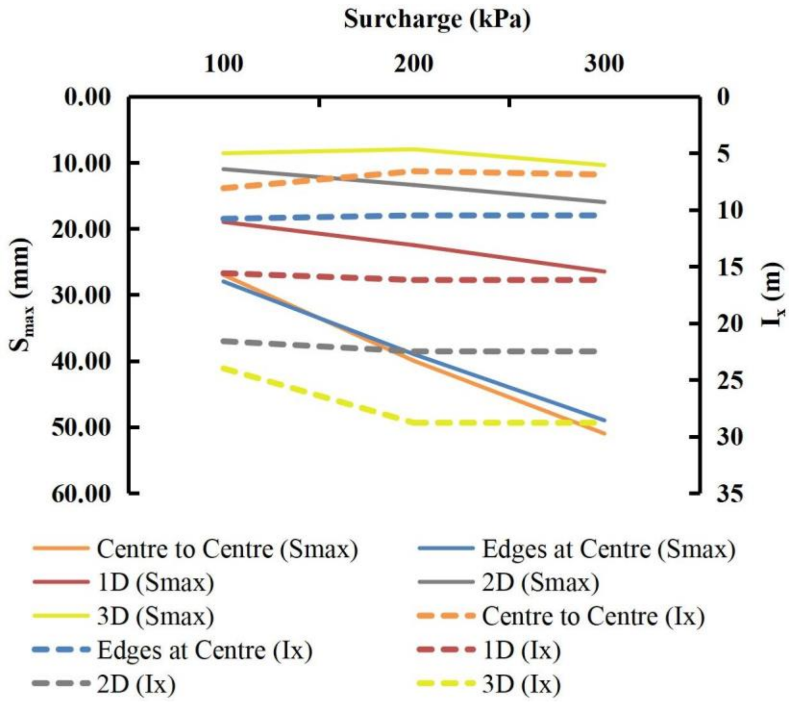

Figure 5: Maximum Settlement and Trough Width for Different Location of Footing.

4.3 Longitudinal Settlement

As can be observed in Fig. 6, as the face of the TBM approaches the foundation settlement increases linearly and reaches maximum when it crosses the point D. It can be seen that when the footing center is exactly above the tunnel center and the footing edges are exactly above the tunnel center, the result shows the highest displacement when compared to other footing positions. We can also say that when the footing is placed 1D from the tunnel center, there is more displacement than greenfield displacement, so the effect of footing pressure on displacement is up to 2D from the tunnel center. From study [11 and 13] it has been seen that the settlement is affected by the presence of existing structure,.

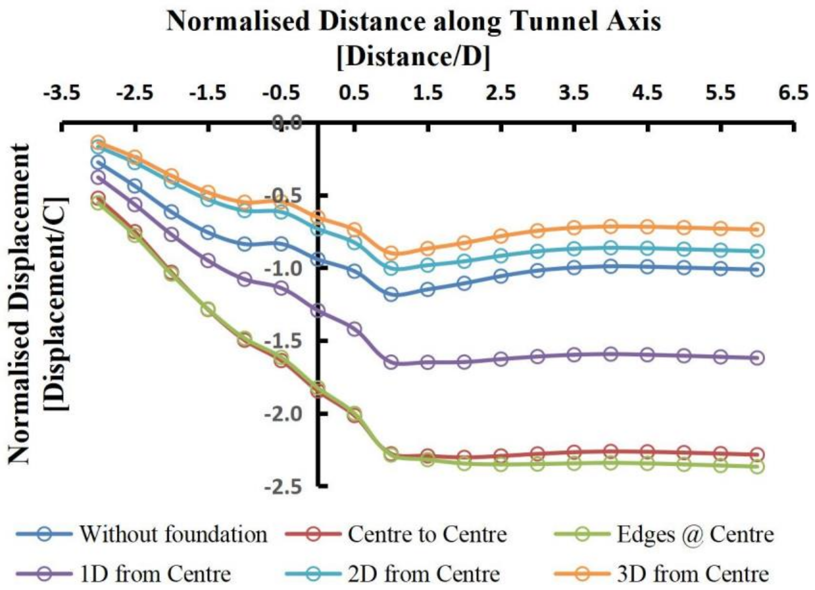

Figure 6: Settlement of Footing when TBM is moving for 100KPa Pressure.

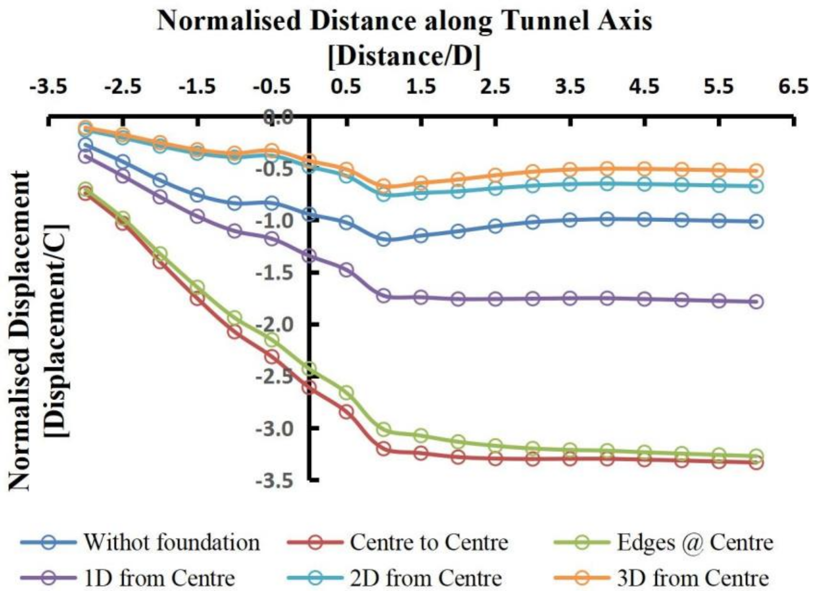

Figure 7: Settlement of Footing when TBM is moving for 200KPa Pressure.

When the pressure on the footing is increased, the effect on displacement remains the same (up to 2D from the tunnel center), but the displacement rate increases (Fig. 7).

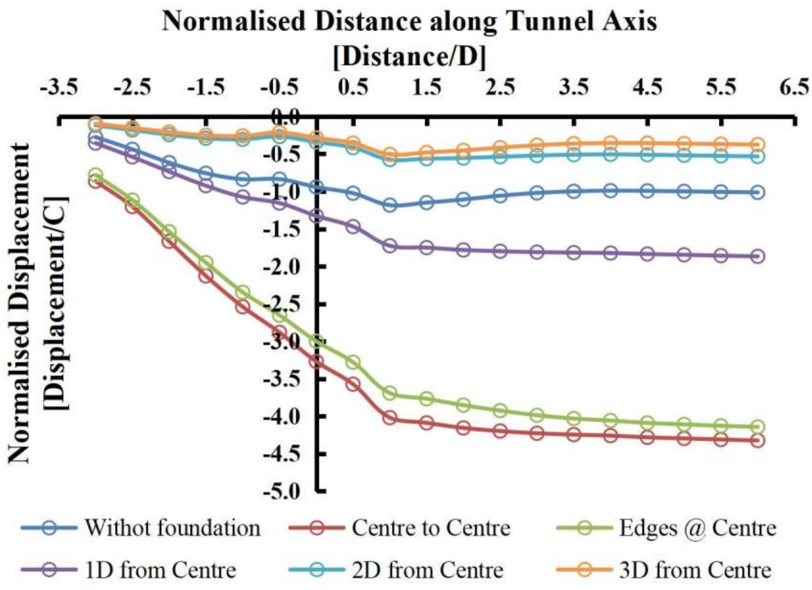

Figure 8: Settlement of Footing when TBM is moving for 300KPa Pressure.

When pressure increased to 300 kPa the displacement will be more compare to other to cases but for this pressure also it is clear from Fig 8 that the effect of footing on displacement on ground is up to 2D from Tunnel Centre.

4.4 Volume Loss.

Volume Loss is Calculated by [14] and the same mathematical formula is used, which is given below.

$$= {}^{2} \left\{ - \frac{-}{{}^{2} + (- {}^{2})} + (3 - 4) \frac{+}{{}^{2} + (+ {}^{2})} - \frac{2[{}^{2} - + ({}^{2}] [{}^{2} +)}{+ {}^{2}]^{2} ( )} \right\} \times \frac{4 + {}^{2}}{4^{2}} - \left\{ \left[\frac{3.12^{2}}{(+ \tan)^{2}} + \frac{0.69^{2}}{{}^{2}} \right] \right\}$$

Where *g*=gap parameter, *R*=radius of the tunnel, *H*=depth of the tunnel from the ground surface, v=soil Poisson's ratio, and = angle of the influence zone of ground settlement.

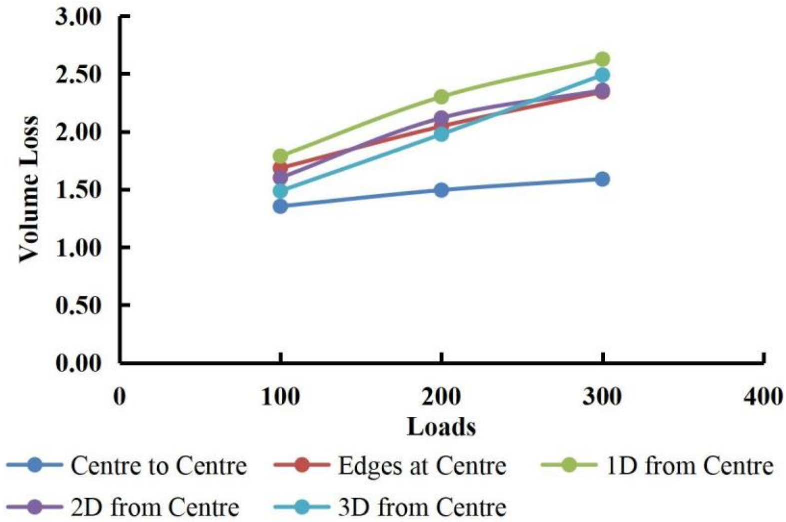

Fig. 9. Volume Loss on Ground at Centre of Footing for Different Pressure on Footing.

From Fig.9 when footing is placed 2m deep from ground it can be observed that volume loss is increasing by increasing the pressure on footing and the data shows that volume loss is maximum when the footing placed at 1D from center of tunnel and after that when footing move away from center of tunnel the volume loss start decreasing. Reason for such a behaviour is because the angle of influence zone increasing but the settlement in transverse direction decreases due to that the gap parameter decreases.

5 Conclusion

To understand the influence of shield tunneling by tunnel boring machine on existing structures in layered Soil, a numerical 3D analysis was carried out. The following are some of the inferences that may be drawn from the analysis results:

1. The maximum settlement observed at the footing point "D" irrespective of Footing Location.
2. Maximum settlement observed above tunnel centre is increases by increasing the pressure on footing and trough width remain almost similar.
3. As the TBM advances, the settlement increases, reaching its maximum when it is at 1D from the mid-line of the footing along tunnel axis. Thereafter, the settlement remains nearly the same, and the results are consistent even when the distance between the tunnel center and footing is increased beyond 2D in transverse direction.
4. The volume loss on the ground is increased by increasing the pressure on the footing. It is also stated that it is increased by increasing the distance of the existing structure from the tunnel center up to certain limit and after that its

start decreasing, with the greatest results obtained when the structure is at one time the diameter of the tunnel from the tunnel center.

When a structure is located up to 2 times the diameter of the tunnel from the tunnel center, the above-mentioned effect can be observed.

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