Study on the Effect of Surface Subsidence Due to Tunneling Under Various Loading Conditions

Somu S. Krishna · R. D. Lokhande

Received: 18 March 2021 / Accepted: 7 July 2021 / Published online: 12 July 2021
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2021

Abstract The subsidence caused on the surface due to the construction of subsurface tunnels for various purposes in urban areas is a major concern for both the tunnel and the overlaid buildings. Seeing the importance of study, different models has been created keeping reference of commercial and residential buildings. The amount of surface deformation and the stresses so generated are calculated, which plays a paramount role before construction. These models are analyzed on circular and semicircular tunnels with various loading conditions and varying litho. In this paper, two software’s namely STAAD Pro and Rocscience were used for structural design and analysis respectively. The study gives the basic idea of behavior of these two shapes of tunnels with varying loading condition and strata which shows a path for predicting unforeseeable displacements in real life situations.

Keywords Tunneling · Subsidence · Surface displacements · Stresses

1 Introduction

Underground Tunnels are majorly used for transportation or passage of water, sewerage, and utilities. Due to the exponential growth of population in urban areas, there is a lot of space constraint, so the other way left is to go with sub surface. But because of the skyscrapers in cities, if the tunnels are constructed beneath it, huge stress is created around the tunnel. Due to this Stress, there may be a loss of ground volume and due to uneven displacement on the surface, building gets cracked and even may be collapsed. So, before the construction of tunnels, displacements and stresses around the tunnel are to be calculated. This calculation involves soil properties, loading condition, depth of the tunnel and many other factors.

There are three methods for the calculation of ground displacements like empirical method, analytical method, and numerical method. The empirical method involves simple calculations like ground volume loss and its displacements. The empirical method is best suited if the tunnel conditions are known well. Analytical method is limited only to circular tunnels in homogeneous soil conditions. Numerical methods such as FEM, FDM can be used for different shapes of tunnels under heterogeneous soil conditions and is capable to consider soil-structure interaction, nonlinear behavior of soils and construction methods.
This paper mainly focuses on the study of surface displacements in urban areas due to different shapes of tunnel namely circular and semicircular under various loading conditions and varying litho. For this displacement calculation, Rocscience Phase 2 which works on FEM is used.

2 Background

A parametric study was conducted to predict the surface displacement behavior for varying anisotropy ratios, tunnel properties and rock mass dimensions (El 2001). A detailed analysis of the interaction between tunneling in soft soils and adjacent structures were performed using three-dimensional Finite element method (Mroueh and Shahrour 2003). A detailed analysis was undertaken to study the impact of construction of urban tunnels on adjacent pile foundations. The analysis is carried out using an elastoplastic three-dimensional finite element modelling (Yoo and Kim 2008). A study on the surface settlement due to the construction of a shield tunnel in soft clay in Shanghai was performed by some scholars (Lu and Liu 2009). Some scholars performed a case study on the underground structure settlement risk due to tunneling (Yasrobi and Salehi 2011). Analytical, empirical and numerical solutions on the shape of settlement trough caused by tunneling in cohesive ground is investigated by a group of scholars. The width of settlement trough was obtained through finite element method (Fattah et al. 2011). A study was performed on the settlement analysis by carrying out 2D and 3D modeling of tunnel construction according to finite element method. The analysis of ground settlement profiles obtained during simulation of the small depth open face tunnel excavation in clayey-marly terrain are then presented (Maraš-Dragojević 2012). Some scholars carried out in situ measurement of surface settlements due to tunnel construction and then the tunnel was modeled using the finite difference software FLAC-3D (Mahdi and Shariatmandari 2013). Evaluation of the heading confinement pressure effect on ground settlement for EPB TBM was performed using full 3D numerical analysis (Haghi et al. 2013). A numerical modelling on surface displacements on tunneling under buildings were analyzed using 3DEC software (Rebello et al. 2014). Some scholars investigated the land subsidence deformation caused by urban shallow buried tunnel construction. The paper also carries out the comparison analysis of the field measurement of the land subsidence (Wang et al. 2014). A numerical analysis of shallow tunnels in soft ground using PLAXIS 2D was also performed (Shabna and Sanker 2016). A series of study were undertaken to predict and analyze the surface settlement due to shield tunneling for Xi’an Metro (Zhu and Li 2016). A new technology for surface settlement prediction for Saint-petersburg Metro Escalator Tunnels excavated using earth pressure balance tunnel-boring machines were developed (Novozhenin and Vystrichil 2016). Some scholars have analyzed the ground deformation caused by shield tunnel construction combining an elastic half-space model and stochastic medium theory. They developed a model describing the interaction between soil and an EPB shield used in tunnels based on the classical elastic theory of Mindlin. This model was then applied to two running tunnels and the sensitivity of the ground deformation to the calculation parameters was also discussed (Shi et al. 2017). A detailed review on long term tunnel behavior and ground movements after tunneling in clayey soils were performed particularly focusing on ground surface movements and tunnel lining deformation in the interest of engineering concerns (Soga et al. 2017). A numerical analysis of surface subsidence in asymmetric parallel highway tunnels were performed (Ratan et al. 2017).

3 Calculation of Loads

For the structural design, STAAD Pro software has been used which analyses in limit state method as it is designed for ultimate loads and serviceability is also considered. To relate this paper with live life conditions, a five- storied residential building and a ten-Storied commercial building are preferred as the models for analysis. A load combination of dead load, live load, wind load and earthquake load are considered. These models are constructed using STAAD Pro software and the vertical forces on the footing are calculated. To give the uniform design load, the vertical forces on each column are divided by the area of the footing. The column section with maximum loading on footing is used in the final models.
3.1 Five-Storied Residential building

To understand the impact caused by various loading condition, a five storied residential building is considered so that it can relate to live life condition. The line diagram of a residential building is shown in the Fig. 1. The column section with node 3-10-14-18-22 is taken for the analysis which is presented in Fig. 2. The loading conditions at the nodes where analysis is done is represented in the Table 1.

3.2 Ten-Storied Commercial Building

To understand the impact caused by various loading condition, a ten storied commercial building is considered so that it can relate to live life condition. The line diagram of the commercial building is shown in Fig. 3. The column section with node 3-6-9-13-17-21 is taken for the analysis which is shown in Fig. 4. The loading conditions at the nodes where analysis is done for commercial building is represented in Table 2.

4 Loading Conditions

The ground displacements increase as the load applied on the center line of tunnel increases and vice versa. For this, six different types of loading conditions as shown in Fig. 5 are considered for the analysis, the detailed are as follows:

4.1 No Loading

In this no load is applied on the tunnel and analyzed for the surface displacements.

4.2 Residential Structure Away from Tunnel

In this condition, the load of the column strip ends at a distance of radius from the centre line of the tunnel.

4.3 Residential Structure on Top of Tunnel

In this model the load of the column strip is placed above the center line of the tunnel.

4.4 Commercial Structure Away from Tunnel

In this condition the load of the column strip ends at a distance of radius from the centre line of the tunnel.
4.5 Commercial Structure on Top of Tunnel

In this model the load of the column strip is applied above the centre line of the tunnel.

| Column node | Loading (MN) | Area (1.5 m*1.5 m) (m²) | UDL (MN/m²) |
|-------------|--------------|--------------------------|-------------|
| 3           | 2.00817      | 2.25                     | 0.892       |
| 10          | 1.75679      | 0.780                    | 0.780       |
| 14          | 1.24704      | 0.554                    | 0.554       |
| 18          | 1.67032      | 0.742                    | 0.742       |
| 22          | 0.51355      | 0.228                    | 0.228       |

**Fig. 3** Line diagram of a commercial building

**Fig. 4** Line diagram of footing of commercial building with column nodes selected for analysis

4.5 Commercial Structure on Top of Tunnel

In this model the load of the column strip is applied above the centre line of the tunnel.
4.6 Commercial Structure on Top with Tunnel Lining

In this model the load of the column strip is applied above the center line of the tunnel. To reduce the ground displacement, liner around the tunnel is applied and analyzed for the reduction in displacements and compared it with the previous case.

5 Material Properties

In this paper, different types of litho with varying loading conditions on different shapes of the tunnels are analyzed for surface displacements. For this elastic property of soil & rock based on the Mohr Coulomb failure criterion is considered.

The Table 3 below shows the various different litho along with respective properties required for the compilation of the model.

6 Liner Properties

Liner is provided in the last case of commercial structure on the top of tunnel. This is done to compare the reduction in the displacement under similar loading condition without liner. In this paper liner properties are assigned considering the weak strata like sandy gravel and applied on the periphery of the tunnel.

Reinforced concrete liner was used and the properties of it are represented in Tables 4 and 5.

7 Development of Displacement Models

A model of 70 m wide and 40 m height is contrived and a tunnel of radius 5 m is excavated at the center and the soil properties of the strata are assigned. The boundaries of the models are restrained from forces except for vertically downward forces. Load is applied on the surface according to the required condition. Uniform mesh of 3 noded triangles with an approximate of 10,000 mesh elements is chosen. More the mesh elements, accuracy of the displacement is more. Then the model is discretized and mesh is applied. The model is computed and interpreted. From the interpreted model, total surface displacement values are captured. The obtained values are tabulated. The process is repeated with change in soil strata, loading condition and tunnel shape. The ground displacement values are compared with various combinations and are figuratively represented.

7.1 No Loading Condition

7.1.1 Limestone

In no loading condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Limestone as the litho. The surface displacements due to both the shapes of tunnels are as follows:

The surface displacements from Fig. 6 shows, it is about 0.061 mm in (a) and 0.071 mm in (b), from which circular results in slightly lesser ground displacement than semicircular in Limestone litho with no loading condition.

7.1.2 Sandstone

In no loading condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Sandstone as the litho. The surface displacements due to both the shapes of tunnels are as follows:

The surface displacements from Fig. 7 shows, it is about 12.67 mm in (a) and 14.78 mm in (b), from which circular results in lesser ground displacement than semicircular in Sandstone litho with no loading condition.
than semicircular in Sandstone litho with no loading condition.

Fig. 5 Circular tunnel with different loading conditions
7.2 Residential Structure Away from the Top of the Tunnel

7.2.1 Limestone

In residential away condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Limestone as the litho. The surface displacements due to both the shapes of tunnels are as follows:

The surface displacements from Fig. 8 shows, it is about 0.231 mm in (a) and 0.203 mm in (b), from which semicircular results slightly lesser ground displacement than circular in Limestone litho with residential away loading condition.

7.2.2 Sandstone

In residential away condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Sandstone as the litho. The surface displacements due to both the shapes of tunnels are as follows:

The surface displacements from Fig. 9 shows that it is about 46.82 mm in (a) and 46.57 mm in (b), from which circular and semicircular results approximately same surface displacements in Sandstone litho with residential away loading condition.

Table 3 Properties of different soil strata

| S. No | Strata       | Material properties                  |
|-------|--------------|--------------------------------------|
|       |              | Unit weight (MN/m³)                  |
|       |              | Poisson’s ratio                      |
|       |              | Young’s modulus (MPa)                |
|       |              | Tensile strength (MPa)               |
|       |              | Cohesion (MPa)                       |
|       |              | Friction angle (degree)              |
| 1     | Sandy Gravel | 0.02059                              |
|       |              | 0.25026                              |
|       |              | 40.0083                               |
|       |              | 0                                     |
|       |              | 0.001                                 |
|       |              | 35                                    |
| 2     | Limestone    | 0.02648                              |
|       |              | 0.2906                               |
|       |              | 28,393.4                              |
|       |              | 1.58                                  |
|       |              | 6.72                                  |
|       |              | 42                                    |
| 3     | Sandstone    | 0.027                                |
|       |              | 0.30                                 |
|       |              | 140                                   |
|       |              | 3.25                                  |
|       |              | 3.00                                  |
|       |              | 32                                    |
| 4     | Shale        | 0.027                                |
|       |              | 0.30                                 |
|       |              | 150                                   |
|       |              | 1.22                                  |
|       |              | 8.04                                  |
|       |              | 14.4                                  |
| 5     | Marble       | 0.02711                              |
|       |              | 0.35                                 |
|       |              | 70,000                                |
|       |              | 1.8                                   |
|       |              | 25.3                                  |
|       |              | 21.2                                  |
| 6     | Granite      | 0.0264                               |
|       |              | 0.20                                 |
|       |              | 45,000                                |
|       |              | 11.7                                  |
|       |              | 55.1                                  |
|       |              | 51                                    |
| 7     | Basalt       | 0.02768                              |
|       |              | 0.17                                 |
|       |              | 60,000                                |
|       |              | 13.1                                  |
|       |              | 66.2                                  |
|       |              | 31                                    |
| 8     | Quartzite    | 0.02612                              |
|       |              | 0.23                                 |
|       |              | 75,000                                |
|       |              | 11                                    |
|       |              | 70.6                                  |
|       |              | 48                                    |

Table 4 Liner concrete properties

| Concrete |
|----------|
| S. No    | Properties               | Values    |
| 1        | Thickness (m)            | 0.300     |
| 2        | Young’s modulus (MPa)    | 26,713.10 |
| 3        | Poisson’s ratio          | 0.150     |
| 4        | Compressive strength (MPa)| 25,000   |
| 5        | Tensile strength (MPa)   | 3.000     |
| 6        | Unit weight (MN/m³)      | 0.024     |

Table 5 Liner reinforcement properties

| Reinforcement |
|---------------|
| S. No         | Properties               | Values    |
| 1             | Spacing (m)              | 0.6       |
| 2             | Section depth (m)        | 0.254     |
| 3             | Area (m²)                | 0.0004    |
| 4             | Moment of Inertia (m⁴)   | 6.458e⁻⁰⁰⁶|
| 5             | Young’s Modulus (MPa)    | 200,000   |
| 6             | Poisson’s ratio          | 0.25      |
| 7             | Compressive strength (MPa)| 415      |
| 8             | Tensile strength (MPa)   | 415       |
| 9             | Weight (kg/m)            | 3.112     |

*M25 grade precast concrete and Fe 415 grade steel of 15.875 mm diameter are used as liner reinforcement*
7.3 Residential Structure on Top of the Tunnel

7.3.1 Limestone

In residential top condition, the overburden is considered to be 20 m in both circular and semicircular tunnel with Limestone as the litho. The surface displacements due to both the shapes of tunnels are as follows:

The surface displacements from Fig. 10 shows that it is about 0.257 mm in (a) and 0.262 mm in (b), from which circular results slightly lesser ground displacement than semicircular in Limestone litho with residential top condition.

7.3.2 Sandstone

In residential top condition, the overburden is considered to be 20 meters in both the circular and
semicircular tunnel with Sandstone as the litho. The surface displacements due to both the shapes of tunnels are as follows:

The surface displacements from Fig. 11 shows that it is about 52.23 mm in (a) and 53.05 mm in (b), from which circular results in lesser ground displacement than semicircular in Sandstone litho with residential top loading condition. Commercial structure away from the top of tunnel.

7.3.3 Limestone

In commercial away condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Limestone as the litho. The surface displacements due to both the shapes of tunnels are as follows:

The surface displacements from Fig. 12 shows that it is about 2.783 mm in (a) and 2.727 mm in (b), from which semicircular results in lesser ground displacement than semicircular in Limestone litho with residential top loading condition.
displacement than circular in Limestone litho with commercial away loading condition.

7.3.4 Sandstone

In commercial away condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Sandstone as the litho. The surface displacements due to both the shapes of tunnels are as follows:

The surface displacements from Fig. 13 shows that it is about 558.9 mm in (a) and 547.72 mm in (b), from which semicircular results in lesser ground displacement than circular in Sandstone litho with commercial away loading condition.

7.4 Commercial Structure on Top of the Tunnel

7.4.1 Limestone

In commercial top condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Limestone as the litho. The surface displacements due to both the shapes of tunnels are as follows:

The surface displacements from Fig. 14 shows that it is about 3.060 mm in (a) and 2.952 mm in (b), from which semicircular results in lesser ground displacement than circular in Limestone litho with commercial top loading condition.

7.4.2 Sandstone

In commercial top condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Sandstone as the litho. The surface displacements due to both the shapes of tunnels are as follows:

The surface displacements from Fig. 15 shows that it is about 615.23 mm in (a) and 592.65 mm in (b), from which semicircular results in lesser ground displacement than circular in Sandstone litho with commercial top condition.
7.5 Commercial Structure on Top of the Tunnel with Lining

7.5.1 Limestone

In commercial top with lining condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Limestone as the litho. The surface displacements due to both the shapes of tunnels are as follows:

The surface displacements from Fig. 16 shows that it is about 3.014 mm in (a) and 2.912 mm in (b), from which semicircular results slightly lesser ground displacement than circular in Limestone litho with commercial top with lining condition.

---

**Fig. 14** Surface displacement in Limestone litho with Commercial Top loading condition

**Fig. 15** Surface displacement in Sandstone litho with Commercial Top loading condition

**Fig. 16** Surface displacement in Limestone litho with Commercial Top with lining loading condition
7.5.2 Sandstone

In commercial top with lining condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Sandstone as the litho. The surface displacements due to both the shapes of tunnels are as follows:

The surface displacement from Fig. 17 shows that it is about 515.178 mm in (a) and 526.84 mm in (b), from which circular results in lesser ground displacement than semicircular in Sandstone litho with commercial top with lining condition. Development of Stress Models.

Stress models are developed similar to the displacement models. But after the interpretation we select the mean stress from the tool bar instead of total displacement. Then the models with stress contours are displayed. We capture the required stress values at surface and around tunnel and are tabulated. Comparison of stresses with different conditions is figuratively represented.

7.6 No Loading Condition

7.6.1 Limestone

In no loading condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Limestone as the litho. The stresses developed around the tunnel in both the circular and semicircular tunnels are as follows:

The stresses from Fig. 18 shows that it is about 1.05 MPa in (a) and 1.59 MPa in (b). From the figures, circular results in lesser stress around the tunnel than semicircular in Limestone litho with no loading condition.

7.7 Residential Structure Away From Top of the Tunnel

7.7.1 Limestone

In residential away loading condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Limestone as the litho. The stresses developed around the tunnel in both the circular and semicircular tunnels are as follows:

The stresses from Fig. 20 shows that it is about 1.08 MPa in (a) and 1.71 MPa in (b). From the figures, circular results in lesser stress around the tunnel than semicircular in Limestone litho with residential away loading condition.

7.7.2 Sandstone

In residential away condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Sandstone as the litho. The stresses generated around the tunnel in both circular and semicircular tunnels are as follows:

In no loading condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Sandstone as the litho. The stresses generated around the tunnel in both circular and semicircular tunnels are as follows:

The stresses from Fig. 19 shows that it is about 1.07 MPa in (a) and 1.64 MPa in (b). From the figures, circular results in lesser stress than semicircular in Sandstone litho with no loading condition.
Fig. 18 Max mean stress in Limestone litho with No Loading condition

Fig. 19 Max mean stress in Sandstone litho with No Loading condition

Fig. 20 Max mean stress in Limestone litho with Residential Away loading condition

The stresses from Fig. 21 shows that it is about 1.1 MPa in (a) and 1.76 MPa in (b). From the figures, circular results in lesser stress than semicircular in Sandstone litho with residential away condition.

7.8 Residential Structure on Top of the Tunnel

7.8.1 Limestone

In residential top condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Limestone as the litho. The stresses developed around the tunnel in both the circular and semicircular tunnels are as follows:

The stresses from Fig. 22 shows that it is about 1.07 MPa in (a) and 1.66 MPa in (b). From the figures, circular results in lesser stress around the tunnel than semicircular in Limestone litho with residential top loading condition.

7.8.2 Sandstone

In residential top loading condition, the overburden is considered to be 20 m in both the circular and
The stresses generated around the tunnel in both circular and semicircular tunnels are as follows:

The stresses from Fig. 23 shows that it is about 1.09 MPa in (a) and 1.71 MPa in (b). From the figures, circular results in lesser stress than semicircular in Sandstone litho with residential top condition.

7.9 Commercial Structure Away from Top of the Tunnel

7.9.1 Limestone

In commercial away condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Limestone as the litho. The
stresses developed around the tunnel in both the circular and semicircular tunnels are as follows:

The stresses from Fig. 24 shows that it is about 4.21 MPa in (a) and 5.48 MPa in (b). From the figures, circular results in lesser stress around the tunnel than semicircular in Limestone litho with commercial away loading condition.

7.9.2 Sandstone

In commercial away loading condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Sandstone as the litho. The stresses generated around the tunnel in both circular and semicircular tunnels are as follows:

The stresses from Fig. 25 shows that it is about 4.24 MPa in (a) and 5.59 MPa in (b). From the figures, circular results in lesser stress than semicircular in Sandstone litho with commercial away condition.

7.10 Commercial Structure on Top of the Tunnel

7.10.1 Limestone

In commercial top loading condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Limestone as the litho. The stresses developed around the tunnel in both the circular and semicircular tunnels are as follows:

The stresses from Fig. 26 shows that it is about 3.99 MPa and 4.97 MPa in (b). From the figures, circular results in lesser stress around the tunnel than semicircular in Limestone litho with commercial top loading condition.

7.10.2 Sandstone

In commercial top condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Sandstone as the litho. The stresses generated around the tunnel in both circular and semicircular tunnels are as follows:

The stresses from Fig. 27 shows that it is about 4.03 MPa in (a) and 5.07 MPa in (b). From the figures, circular results in lesser stress than semicircular in Sandstone litho with commercial top condition.

7.11 Commercial Structure on Top of the Tunnel with Lining

7.11.1 Limestone

In commercial top with lining condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Limestone as the litho. The stresses developed around the tunnel in both the circular and semicircular tunnels are as follows:

The stresses from Fig. 28 shows that it is about 3.97 MPa in (a) and 4.73 MPa in (b). From the figures, circular results in lesser stress around the tunnel than semicircular in Limestone litho with commercial top with lining condition.

7.11.2 Sandstone

In commercial top with lining condition, the overburden is considered to be 20 m in both the circular and semicircular tunnel with Sandstone as the litho. The stresses generated around the tunnel in both circular and semicircular tunnels are as follows:

Fig. 24 Max mean stress in Limestone litho with Commercial Away loading condition
The stresses from Fig. 29 shows that it is about 3.79 MPa in (a) and 6.45 MPa in (b). From the figures, circular results in lesser stress than semicircular in Sandstone litho with commercial top with lining condition.

8 Analysis of Displacements and Stress Models

8.1 Sandy Gravel

In sandy gravel strata, from Fig. 30, (a) reflects the surface displacement which is more in commercial away and commercial top condition in case of circular tunnel when contrasted with semicircular. But after lining the tunnel with circular shape results in lesser
surface displacement when compared to semicircular. In residential and no loading condition surface displacement due to semicircular and circular tunnels are identical. The stresses generated is more in case of semicircular tunnel in all loading conditions when compared to circular which is shown in (b). From Fig. 30, when both (a) and (b) are compared, the semicircular even producing more stresses, results in approximately identical surface displacements as circular except in commercial top condition which is a bit lesser than circular.

8.2 Limestone

In Limestone litho, from Fig. 31, (a) shows that there are virtually same surface displacements except in commercial on top and with lining conditions in which circular tunnel results in more surface displacement.
From Fig. 31, (b) reflects that the stresses in commercial away is more than the commercial on top condition and lining condition. The stresses mostly reduced in case of lining when collated with commercial on top in semicircular and in circular tunnel which remains almost constant. The surface displacement in case of residential and no loading condition is very less and almost equal. From Fig. 31, when both (a) and (b) are compared, the semicircular even producing more stresses, results in approximately identical surface displacements as circular except in commercial top & lining condition which is a bit lesser than circular.

8.3 Sandstone

From Fig. 32, (a) shows that the surface displacement in commercial top is more than commercial away but with the provision of lining, the displacement is reduced more in circular collated to semicircular. In residential condition the surface displaces more in case of semicircular followed by circular. From Fig. 32, (b) shows that the stresses are more in semicircular. In lining conditions, semicircular generates more stress than commercial away and on top conditions. Commercial away induces more stresses than on commercial top condition & lining in circular tunnel. When both (a) and (b) from Fig. 32 are compared, semicircular shape results in lesser surface displacements except in lining condition and stresses in generated are more. In other cases, the surface displacements are virtually same in both shapes of tunnels.

8.4 Shale

In case of shale litho, Fig. 33, (a) shows that the surface displacements due to different shape of tunnels follows the same trend as in the Sandstone but with a little lesser value in all the loading conditions. The stresses generated around the tunnel, follows the same trend as in the Sandstone with approximately similar values which is shown in (b) from Fig. 33. The stresses are reduced more in commercial top than in commercial away and increased in lining condition in semicircular tunnel shape. From Fig. 33, (a) shows that in
residential condition, surface displacements due to circular and semicircular tunnels are similar and in commercial conditions surface displacements are slightly varied except in lining condition.

8.5 Marble

In marble strata, from Fig. 34, (a) represents displacements of circular and semicircular tunnels which are approximately similar in all the conditions. The stresses in case of semicircular tunnel are more when compared with circular tunnel, which is shown in (b) from Fig. 34. There is a trivial change in stresses in residential conditions. The stress is reduced in lining condition when collated to commercial away & commercial top in semicircular shape of tunnel and remained constant in circular shape.

8.6 Granite

In case of granite litho, from Fig. 35, the surface displacement with circular and semicircular are almost same in all the conditions as shown in (a) and it follows the same trend as marble. From (b), it is clear that the stresses generated are slightly more in all the loading conditions in case of semicircular tunnel.

8.7 Basalt

The ground displacements and the stresses around the tunnel follows the same trend as in granite and marble litho. In Fig. 36, (a) shows the surface displacements which are slightly varied and is virtually same in all the loading conditions. From Fig. 36, (b) shows the decreasing of stresses slightly in commercial on top and in lining when compared to commercial away. The stresses generated are slightly high in semicircular in all the loading conditions compared to circular.

8.8 Quartzite

Quartzite litho also follows the same trend as in the granite and basalt strata. From Fig. 37, (a) shows negligibly high surface displacements in semicircular
with residential loading and vice versa in commercial and lining conditions. The stresses with semicircular in all loading conditions are slightly more which is shown in (b) from Fig. 37. There is negligible change in stress in both commercial top and lining conditions in circular tunnel. In semicircular, the stress is more in commercial away and reduces in commercial top and lining condition.

9 Conclusion

In the study, the displacement and stresses were analyzed on circular and semicircular tunnels with various loading conditions and varying litho.

1. In sandy gravel, Sandstone & shale strata the displacements due to circular shape tunnel results is showing lesser displacement compared to semicircular in no loading, residential loading
and support condition. In all the other strata, the displacements are almost similar in all the loading conditions.

2. With varying litho, in all the loading conditions, the stresses around the semicircular tunnel are more when collated with circular shape of tunnel.

3. Under same loading condition, tunnel with liner shows reduced surface displacement when compared with tunnel without liner.

Also Circular tunnel is better selection for tunnel design as it generates less stress and displacement compared to semicircular tunnel.

Acknowledgements The authors are thankful to VNIT, Nagpur for providing necessary support and permission to conduct and publish this research work. A special thanks to Aparna Unnikrishnan who helped in editing and other support for this study. The views expressed in this paper are those of the authors and not necessarily of the organization they represent. This paper forms a part of the M Tech of the first author. We hereby declare that this submission is our own work and that to the best of our knowledge and belief. This research work is done pertaining the M Tech degree of the first author.

References

El Tani M (2001) Surface Displacements due to Pressure modifications induced by tunnels. Modern Tunneling Science and Technology, Adachi Et Al, @2001 Swets & Zeitlinger, ISBN 9026518609

Fattah MY, Shlash KT, Salim NM (2011) Settlement trough due to tunneling in cohesive ground. Indian Geotech J 41(2):64–75

Haghi AH, Asef MR, Taheri A, Mohkam M (2013) Evaluation of the heading confinement pressure effect on ground settlement for EPBTBM Using Full 3D numerical analysis. Int J Min Geo-Eng 47:13–32

Lu ZP, Liu GB (2009) Analysis of surface settlement due to the construction of a shield tunnel in soft clay in Shanghai. Geotechnical Aspects of Underground Construction in Soft Ground. Taylor Francis Group, London

Mahdi M, Shariatmadari N (2013) back analysis of tehran metro tunnel construction using FLAC-3D. Int J Civ Environ Eng 7(9):685–689

Maral-Dragojević S (2012) Analysis of ground settlement caused by tunnel construction. GRADEVINAR 64(7):573–581

Mroueh H, Shahrou I (2003) A full 3-D finite element analysis of Tunneling-adjacent structures interaction. Comput Geotech 30(3):245–253

Novozhenin SU, Vystrechil MG (2016) New method of surface settlement prediction for saint- petersburg metro escalator tunnels excavated by EPB TBM. Procedia Eng 150:2266–2271

Ratan D, Singh PK, Kainthola A, Panthee S, Singh TN (2017) Numerical analysis of surface subsidence in asymmetric parallel highway tunnels. J Rock Mech Geotech Eng 9:170–179

Rebello N, Sastry VR, Shivashankar R (2014) Study of surface displacements on tunnelling under Buildings Using 3DEC numerical modelling. Int Sch Res Not 2014:13

Shabna PS, Sankar N (2016) Numerical analysis of shallow tunnels in soft ground using PLAXIS 2D. Int J Sci Eng Res 7(4):978

Shi C, Cao C, Lei M (2017) An analysis of the ground deformation caused by shield tunnel construction combining an elastic half-space model and stochastic medium theory. KSCE J Civ Eng 21(5):1933–1944

Soga K, Laver RG, Li Z (2017) Long-term tunnel behaviour and ground movements after tunnelling in clayey soils. Undergr Space 2(3):149–167

Wang D, Guo X, Jia Y (2014) Analysis of land subsidence deformation caused by urban shallow-buried tunnel construction. Open Civ Eng J 8:219–224

Yasrobi S, Salehi B (2011) Analysis of a tunnel structure subsidence risk a case study from Tehran, Iran. In: International Conference on Tunnelling & Trenchless Technology, Kuala Lumpur

Yoo C, Kim SB (2008) Three-dimensional numerical investigation of multifaced Tunneling in water- bearing soft ground. Can Geotech J 45(10):1467–1486

Zhu C, Li N (2016) Prediction and analysis of surface settlement due to shield tunnelling for Xi’an Metro. Can Geotech J 54(4):529–546

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.