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PERFORMANCE OF SUB-RECTANGULAR TUNNEL UNDER STATIC AND DYNAMIC LOADING

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Abstract. Tunnel is an artificial underground passage built through a hill, road or river. Due to lack of space on the surface, it becomes essential to construct underground tunnels. To select a suitable type of tunnel section and its analysis is one of the important areas in Geotechnical Engineering. Sub-rectangular tunnels are ideal for underground projects such as subway entrance passages, underground pedestrian crossings and so on. However, just a few research have looked into sub-rectangular tunnels so far.

In this paper, the performance of sub-rectangular tunnel under static as well as dynamic loading has been studied and results are compared with the twin-circular and rectangular tunnel in terms of crown settlement of tunnel sections. For this purpose, numerical analyses of different tunnel sections viz., twin-circular, rectangular and sub-rectangular tunnel were carried out using MIDAS GTS NX and by considering different soil conditions prevailing in India. Tunnel sections were analysed by considering varying parameters such as overburden depth from top to the centre of the tunnel and water table under static and dynamic loading. The performance of tunnel sections is then compared. It is found that sub-rectangular tunnel is found to be more effective for different analysis cases.

Keywords: Crown settlement, MIDAS GTS NX 3D, Sub-rectangular tunnel.

1. Introduction

A tunnel is a man-made underground channel, typically built through a hill or beneath a structure, road, or river. There are various sorts of tunnels based on their shapes, such as round, rectangular, horseshoe, oval/egg, and so on. The various shapes are usually related to the construction method and the ground conditions in which they were built. Due to varying soil conditions along the tunnel's length, some tunnels may be constructed utilizing a combination of these types.
A novel type of cross-section called Quasi (sub)-rectangular cross-section has been proposed to combine the advantages of circular shield tunnels and rectangular shield tunnels while avoiding the disadvantages of DOT (Double –O-Tube) tunnels. Sub-rectangular tunnels, with a sub-rectangular cross-section, are particularly well suited to underground engineering projects such as subway entrance passages and pedestrian crossing.

2. Literature Review

A study regarding the behavior of quasi-rectangular section of tunnel has been carried out analytically and experimentally by various researchers. These works are reviewed and presented briefly as below:

N. T. Tien et. al. (2020), to model the shape of the tunnel, the PLAXIS 2D program was used to conduct a numerical study of the sub-rectangular profile. The effect of geotechnical parameters such as lateral pressure coefficient (K0), soil cohesion (c), and Soil Young's modulus (Es) on stresses in the sub-rectangular lining were investigated, with a comparison to circular lining under the same conditions. It was found that the sub-rectangular tunnel was stable. The area of the circular tunnel looked to be 1.25 times greater than that of the sub-rectangular tunnel with the same clearance profile.

D. Du et. al. (2020), using the Hyperstatic Reaction Method (HRM), analytical research was carried out using a twin-lane metro tunnel as an example, and the optimization method of sub-rectangular tunnels in terms of tunnel lining forces was provided. The effect of several parameters on the internal forces and shape of a sub-rectangular tunnel was then explored, including the coefficient of lateral earth pressure at rest K0, Young's modulus Es of soil, tunnel depth C, and surface loads P0. When K0 is less than 1.25, the optimum R3 of a sub-rectangular tunnel decreases as K0 increases. With the increase in Es, the bending moment of the sub-rectangular tunnel decreased.

N. A. Doa et. al. (2020) carried out an analysis for improving the performance of the Hyperstatic Reaction Method (HRM), which is a numerical method, for the case of squared or sub-rectangular tunnels. The influence of the lateral coefficient of earth pressure and the soil's Young's modulus on the structural stresses and deformations caused by the excavation in the tunnel lining was investigated. HRM might be used to evaluate the behaviour of squared or sub-rectangular tunnels, according to the findings.

3. Validation

The validation of model was carried out by comparing results obtained from the numerical model developed in MIDAS GTS 3D with the results of numerical model developed by N. A. Doa et.al. (2020) where the lateral earth pressure coefficient (K0) and the Young’s modulus (E) of soil was taken into consideration. Material parameters used for silty clay soil and tunnel lining used for computation are given in Table 1 and Table 2 respectively.

Table 1: Soil properties used in FEM analysis (N.A. Do et al.)

Parameters	Symbols	Value	Unit
Unit weight	γ	18	kN/m3
Young’s Modulus	E	3.6	MPa
Poisson’s ratio	ν	0.495	---
Internal Friction angle	ϕ	0	degree
Cohesion	Cu	25.6	kPa

Lateral earth pressure co-efficient	K0	0.6	---
Overburden	H	10	m

Table 2: Properties of tunnel lining used in analysis (N.A. Doet al.)

Properties	Symbol	Values	Units
Young’s modulus	Es	35 x 106	kN/m2
Poisson’s ratio	υ	0.15	---
Lining thickness	t	0.5	m

As the results obtained by comparison are in close agreement with each other, the numerical model of sub-rectangular adopted for present study is considered to be validated.

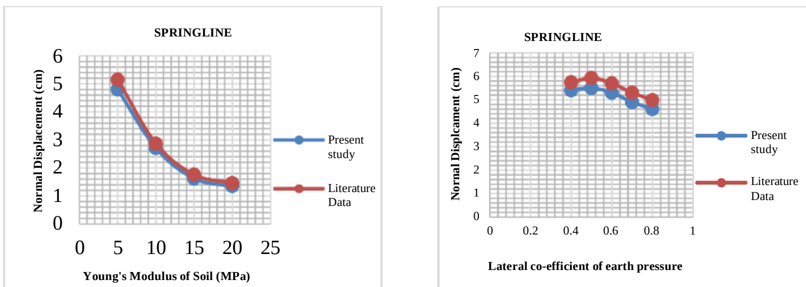


Fig 1: Comparison of results for numerical analysis in silty clay

4. Numerical Analyses

Analysis was carried out for sub-rectangular, rectangular and twin-circular tunnel sections under static and dynamic loading considering different soil conditions prevailing in India. Total element count for each tunnel section and for soil after meshing was around 9000 and 12085 respectively. Tunnel models selected for analysis in present study was ‘Elastic model’. For soil, the model selected for analysis was ‘Mohr-Coulomb’ model. The c/s areas of the tunnels were kept same in all the cases. The soil typical cross sections of different tunnel sections used in the analysis are shown in Figure 2.

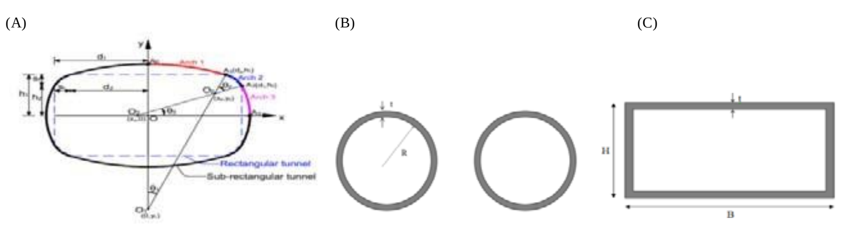


Fig.2. Typical cross section of tunnels: A) Sub-rectangular tunnel; B) Twin-Circular tunnel; C) Rectangular tunnel

Performance of sub-rectangular tunnel (SR) and its comparison with twin-circular (TC) and rectangular tunnel sections (REC) considering soil properties at various sites in India viz., CC23 Delhi Metro, Jaipur Metro Phase 1b, E-W Metro tunnel Kolkata and Mumbai Metro were considered for the analysis. Overburden depths as 1D, 2D, 3D, 5D and 8D from top to the center of tunnel and water table at 1m below ground surface was varied for both static and dynamic loading for all tunnel sections.

5. Geometric Details of Tunnel Sections

The analysis of sub-rectangular tunnel structure is carried out using MIDAS GTS 3D software. The various parameters considered for the study were overburden depth, from top to the centre of the tunnel (C) and water table (hw) below ground level under static and dynamic loading. Table 3 shows various parameters of tunnels considered for the study and their selected values for analysis. Table 4 shows the details of varying parameter for analysis. Table 5 shows the values of horizontal seismic coefficients of various regions used for the dynamic analysis.

Table 3. Details of a parametric tunnel investigation

Sr.no.	Parameters	Values
1	Dimensions for sub-rectangular tunnel	Width of rectangle (B) = 9.34 m Height of rectangle (D) = 5.2 m Arc A_1 = (3.91,2.6) Arc A_2 = (4.67, 1.84) O_1 = (0, -1) O_2 = (2.65, 0.58) O_3= (-1.7, 0) c/s area= 51.03 m^2
2	Dimension of twin-circular tunnel	Radius of the circular tunnel (R)= 2.85m c/s area= 51.03 m^2
3	Dimension of rectangular tunnel	Width of rectangle (B) = 9.63 m Height of rectangle (H) = 5.3 m c/s area= 51.03 m^2

Table 4. Details of varying parameter for sub-rectangular tunnel

Sr. no.	Parameters	Values
1	Tunnel overburden depth (C)	C= 1D, 2D, 3D, 5D, 8D
2	Water table (h_w) from the top	hw= 1 m

Table 5. Horizontal Seismic Coefficients for Different Regions

Sr.No.	Regions	Zone	Horizontal Seismic Coefficients
1	Delhi	IV	0.05
2	Jaipur	II	0.02

3	Kolkata	III	0.04
4	Mumbai	III	0.04

Seven sites were considered for the analysis. Uniformly distributed load (pressure type) of 20 kN/m2 was considered to be applied on the top surface of the soil. Analysis of tunnel sections subjected to dynamic loading was carried out using pseudo-static analysis. The properties of soil and the tunnel lining used for the analysis in MIDAS GTS NX 3D for the present study are given below in Table 6 and 7 respectively.

For the pseudo-static analysis, the horizontal seismic coefficients were considered depending upon the seismic zones. Figure 3 shows the load selection window in MIDAS GTS NX for applying seismic co-efficient for dynamic analysis.

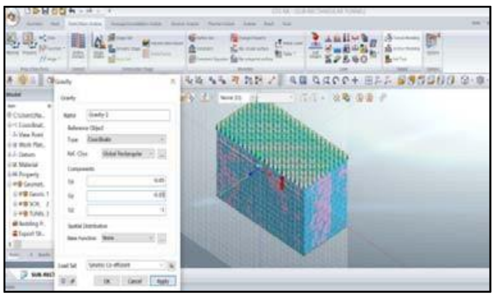


Fig 3. Load Selection Window in MIDAS GTS NX 3D for applying Seismic Co-efficient

Table 6. Properties Assigned to Soil Layer for Analysis

				Soil Properties				
Site		Soil Description	Unit weight	Young's modulus of soil	Poisson ratio	Angle of internal friction	Cohesion	Co-efficient of lateral earth pressure
	Symbols		γ	E_s	υ	Ø	c	K_0
	Unit		kN/m^3	MPa	---	degree	kPa	---
I	CC23 Delhi Metro 3	Soft soil	20	33	0.3	30	10	0.61
II	Jaipur	Sandy silt	19	37	0.4	27	5	0.57
III	E-W Metro tunnel	Clayey silt	18.5	18.6	0.33	25	1	0.5

IV	Kol-kata 1 E-W Metro tunnel	Medium silty clay	18.5	31.5	0.33	31	0	0.5
V	Kol-kata 2 E-W Metro tunnel	Silty clay	18.5	27.5	0.33	29	0	0.5
VI	Kol-kata 3 Mum-bai Metro 1	Silty sand	18	10	0.30	29	5	0.51
VII	Mum-bai Metro 1	Sandy clay	18.5	5	0.35	24	15	0.59

Table 7. Properties assigned to tunnel lining for analysis

Sr. No.	Properties	Symbol	Values	Units
1	Young's modulus	Et	35 x 10^6	kN/m^2
2	Density	ρ	24	kN/m^3
3	Poisson's ratio	υ	0.15	---
4	Lining thickness	t	0.275	M
5	Grade of concrete	----	45	N/mm^2

6. Results and Discussion

After the analysis is completed properly, MIDAS GTS organizes and provides the-post data result for design process A probe result window is shown in Figure 4.

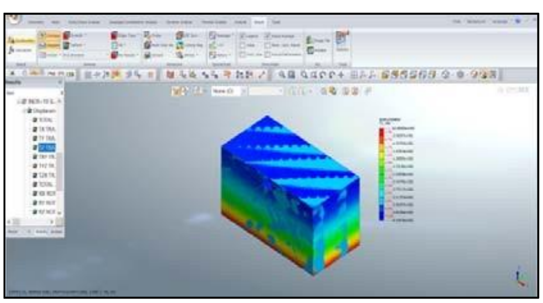


Fig 4: Probe Result Window

Results obtained from analysis of twin-circular tunnel (TC), rectangular tunnel (REC) and sub-rectangular tunnel (SR) under static and dynamic loading are represented in terms of crown settlement as shown in Figure 5 to 10.

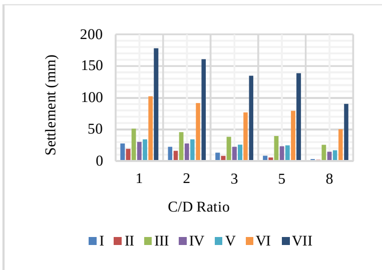


Fig.5. Settlements of twin-circular tunnel subjected to static loading

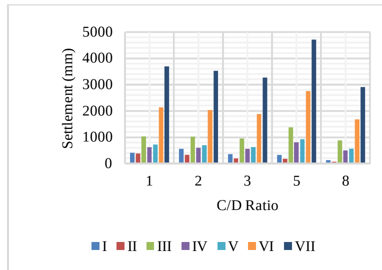


Fig 6. Settlements of twin-circular tunnel subjected to dynamic loading

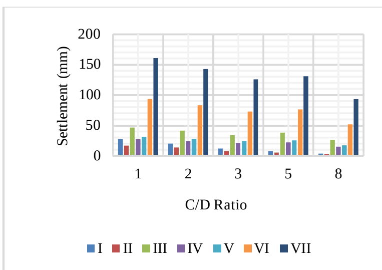


Fig.7. Settlement of rectangular tunnel subjected to static loading

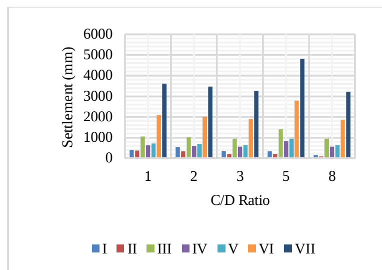


Fig.8. Settlement of retangular tunnel subjected to dynamic loading

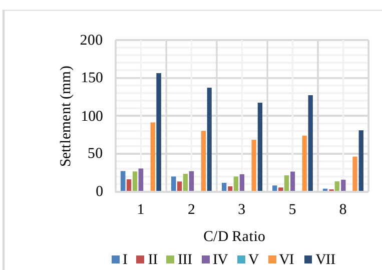


Fig.9. Settlement of rectangular tunnel subjected to static loading

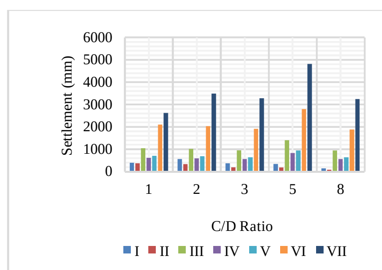


Fig.10. Settlement of retangular tunnel subjected to dynamic loading

From the above results, It has been noted that under static loading, settlement decreases with increase in the C/D ratios. In case of dynamic loading, settlement is found to be decreases with increase in the C/D ratios for all overburden depths except for 5D.

Variations of percentage decrease in settlement of sub-rectangular tunnel (SR) sections as compared to twin circular (TC) and rectangular tunnel section (REC) at various sites with respect to C/D ratio under static and dynamic loading are shown in Figure 11 to 17.

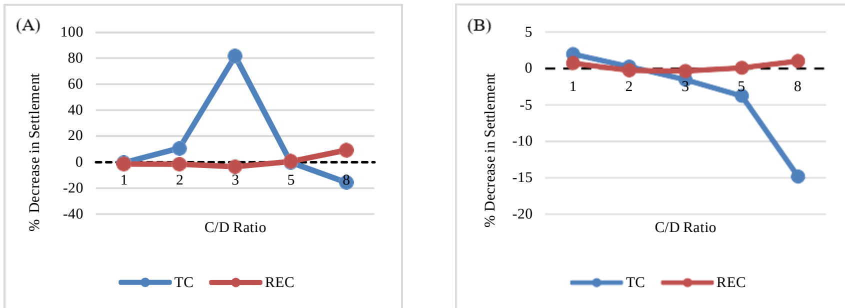


Fig.11. Variation of % decrease in settlement with respect to C/D ratio for site CC23 Delhi Metro 3 for A) Static Loading B) Dynamic Loading

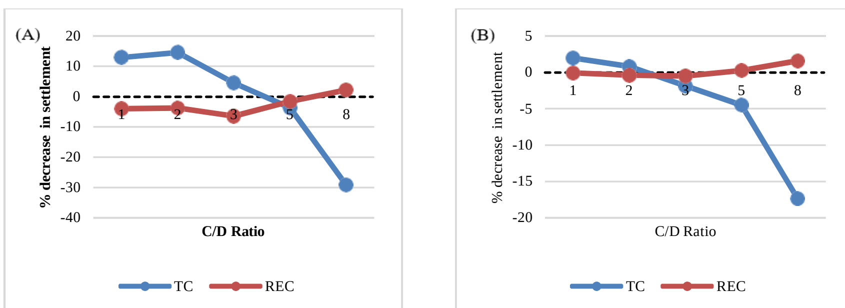


Fig.12. Variation of % decrease in settlement with respect to C/D ratio for site Jaipur Metro phase 1b for A) Static LoadingB)Dynamic Loading

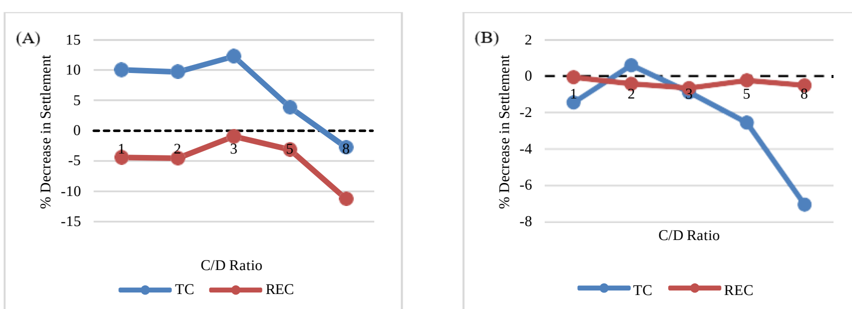


Fig.13. Variation of % decrease in settlement with respect toC/D ratio for site E-W Metro Tunnel Kolkata 1 for A) Static Loading B) Dynamic Loading

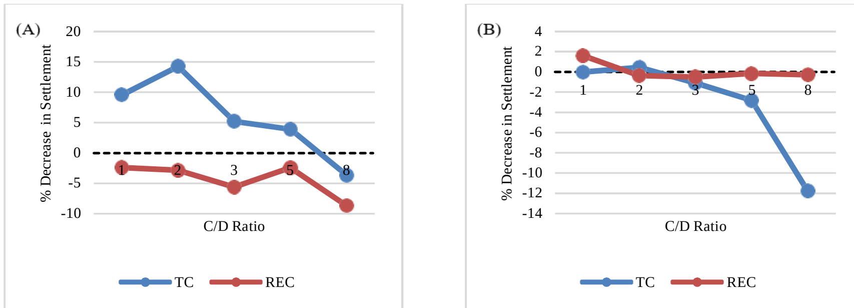


Fig.14. Variation of % decrease in settlement with respect toC/D ratio for site E-W Metro Tunnel Kolkata 2 for A) Static Loading B) Dynamic Loading

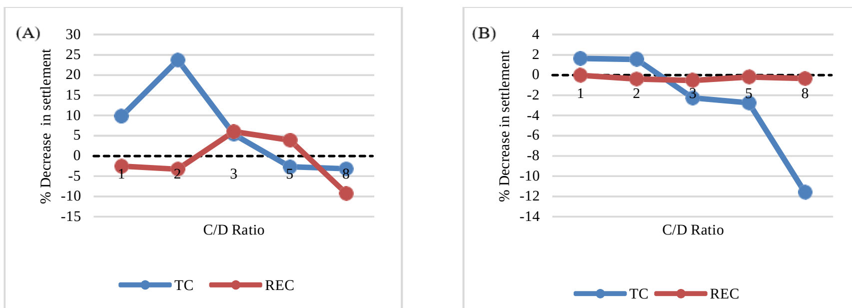


Fig.15. Variation of % decrease in settlement with respect toC/D ratio for site E-W Metro Tunnel Kolkata for A) Static Loading B) Dynamic Loading

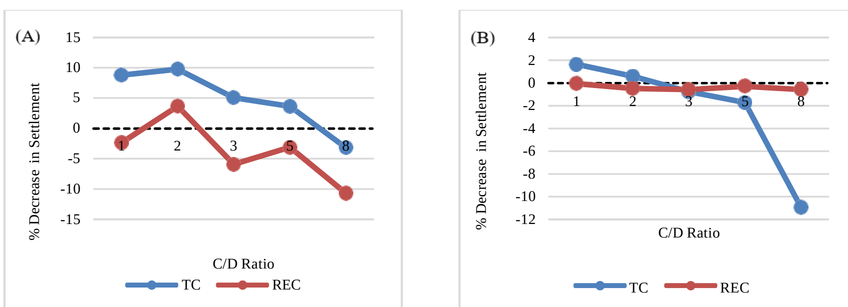
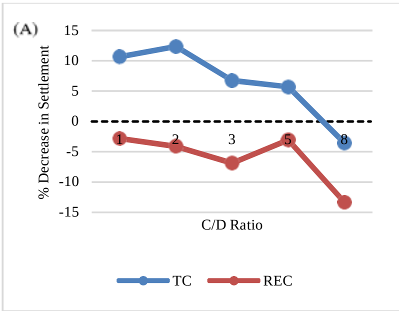


Fig.16. Variation of % decrease in settlement with respect toC/D ratio for site Mumbai metro for A) Static Loading B) Dynamic Loading



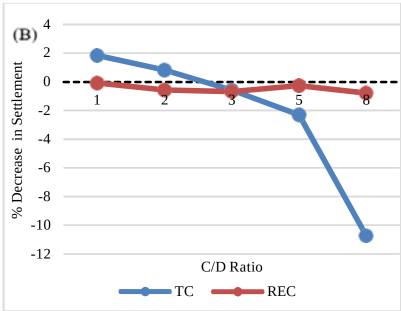


Fig.17. Variation of % decrease in settlement with respect toC/D ratio for site Mumbai metro 2 for A) Static Loading B) Dynamic Loading

The percentage increases in settlements due to presence of water table at 1m below ground surface in case of sub-rectangular tunnel section subjected to static and dynamic loading are shown in Figure 18 and Figure 19 respectively.

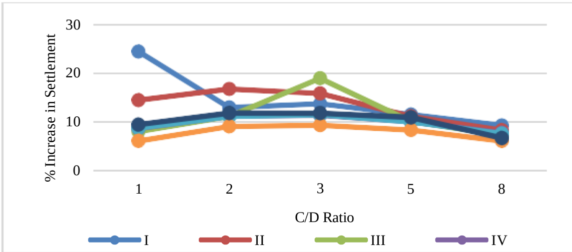


Fig.18. % increase in Settlements of sub-rectangular tunnel section subjected to static loading due to water table

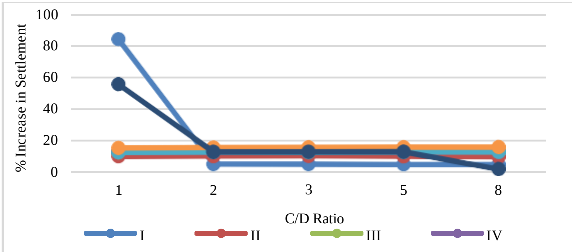


Fig.19. % increase in settlements of sub-rectangular tunnel section subjected to dynamic loading due to water table

7. Conclusions

Numerical analyses of different tunnel sections viz., twin-circular, rectangular, and sub-rectangular tunnel section were carried out using MIDAS GTS NX and by considering different soil conditions prevailing in India. The following broad findings can be taken from the current study which are in the terms of crown settlement:

1. For soft soil, sub-rectangular tunnel is found to be more suitable than circular tunnel for the overburden depths of 3D and D for static and dynamic loading respectively, whereas for overburden depth of 8D, sub-rectangular tunnel is found to be more suitable than rectangular tunnel for static as well as dynamic loading.
2. For sandy silt, sub-rectangular tunnel is found to be more suitable than circular tunnel for overburden depth of 2D and D for static and dynamic loading respectively, whereas for the overburden depth of 8D, sub-rectangular tunnel is found to be more suitable than rectangular tunnel for static as well as dynamic loading.
3. For clayey silt, sub-rectangular tunnel is found to be more suitable than circular tunnel for overburden depth of 3D and 2D for static and dynamic loading respectively.
4. For medium silty clay, sub-rectangular tunnel is found to be more suitable than circular tunnel at overburden depth 2D for static as well as dynamic loading respectively, whereas for the overburden depth of D, sub-rectangular tunnel is found to be more suitable than rectangular tunnel for dynamic loading.
5. For silty clay, sub-rectangular tunnel is found to be more suitable than circular tunnel for overburden depth of 2D and D for static and dynamic loading respectively, whereas for the overburden depth of 3D, sub-rectangular tunnel is found to be more suitable than rectangular tunnel for static loading.
6. For silty sand, sub-rectangular tunnel is found to be more suitable than circular tunnel at overburden depth of 2D and D static and dynamic loading respectively.
7. For sandy clay, sub-rectangular tunnel is found to be more suitable than circular tunnel at overburden depth of 2D for static as well as dynamic loading respectively.
8. For soft soil, % increase in settlement of sub-rectangular tunnel due to presence of water table is found to be more for overburden depth of D, for both static and dynamic loading.
9. For sandy silt, % increase in settlement of sub-rectangular tunnel due to presence of water table is found to be more for the overburden depth of 3D, for both static and dynamic loading.
10. For clayey silt, % increase in settlement of sub-rectangular tunnel due to presence of water table is found to be more for the overburden depth of 3D and 2D for static and dynamic loading respectively.
11. For medium silty clay, % increase in settlement of sub-rectangular tunnel due to presence of water table is found to be more for the overburden depth of 3D and 8D for static and dynamic loading respectively.
12. For silty clay, % increase in settlement of sub-rectangular tunnel due to presence of water table is found to be more for the overburden depth of 3D for static loading and for the overburden depth of 5D and 8D for dynamic loading respectively.
13. For silty sand, % increase in settlement of sub-rectangular tunnel due to presence of water table is found to be more for the overburden depth of 3D and 8D for static and dynamic loading respectively.

14. For sandy clay, % increase in settlement of sub-rectangular tunnel due to presence of water table is found to be more for the overburden depth of 2D and D for static and dynamic loading respectively.

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