Static and Seismic Analysis of Twin Metro Underground Tunnels

Manendra Singh, M. N. Viladkar, and N. K. Samadhiya

Abstract In any metropolitan city, underground structures are key elements of a mass rapid transit system. In situations where metro underground construction is to be undertaken in poor soil strata, it is not possible to excavate a single large diameter tunnel for accommodating the two-way traffic of trains. It becomes therefore essential to have two parallel tunnels aligned either horizontally or vertically. In this paper, an attempt has been made to predict the influence of construction of a second tunnel, aligned either horizontally or vertically, after the construction of the existing first tunnel. The analysis has been carried out for both static and seismic conditions by varying the pillar width between the tunnels. Elasto-plastic finite element analysis has been carried out through Plaxis 2D software for the 1999 Chamoli earthquake of lower Himalaya. The analysis brought forth the fact that vertical stresses at critical points and the forces in RC liners of both horizontally and vertically aligned twin tunnels increase during the earthquake for a pillar width equal to half the diameter of tunnels. These vertical stresses and forces in RC liners have been found to reduce with increase in pillar width in case of vertically aligned twin tunnels, whereas a reverse situation arises in case of horizontally aligned twin tunnels.

Keywords Seismic · Tunnels · Metro

M. Singh
Department of Civil Engineering, National Institute of Technology Hamirpur, Hamirpur 177005, India
e-mail: manendra@nith.ac.in

M. N. Viladkar (✉) · N. K. Samadhiya
Department of Civil Engineering,
Indian Institute of Technology Roorkee, Roorkee 247667, India
e-mail: mnviladkar50@gmail.com

N. K. Samadhiya
e-mail: nksamfce@iitr.ac.in

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1 Introduction

In any metropolitan city, metro underground tunnels and underground rail stations form key components of a Mass Rapid Transit (MRT) system. With the growth in population and the limitation of space in a metro city, there is a growing need to enlarge these transportation networks. In areas which lie in seismic zones, there is always the vulnerability of such underground facilities to seismic loading and it is a very sensitive issue. A large earthquake not only can cause the potential loss of human life but can also damage many other infrastructural facilities. In turn, it can result in considerable economic losses, particularly if the time required to restore the functionality of the network is large. This loss can be reduced if the possible risk and the associated damage can be reduced. For these reasons, it is essential to understand as to how metro underground tunnels suffer damage during earthquakes and how to enhance the service efficiency. A single tunnel provided for both the up and down tracks in a metro underground network usually leads to a very large diameter of the tunnel. Construction of such a large size tunnel may not be always feasible depending of course upon the site-specific conditions. It is therefore usual to provide another tunnel aligned in parallel either horizontally or vertically. In this paper, the influence of construction of a second tunnel after the construction of the existing first tunnel has been investigated by varying the pillar width (clear distance) between the tunnels. Both static and seismic analyses of twin tunnels have been performed. Many authors such as Soliman et al. (1993), Kawata and Ohtsuka (1993), Saitoh et al. (1994), Perri (1995), Yamaguchi et al. (1998), Shahrour and Mroueh (1997), Hu et al. (2003), Chu et al. (2007), Chehade et al. (2008), Chen et al. (2009a, b), Afifipour et al. (2011), Li et al. (2012), Hussein et al. (2012) and Comodromos et al. (2014) have studied the static behavior of twin tunnels. Many authors, namely Kumari et al. (2012, 2013, 2014), Motaal et al. (2013), Sahoo et al. (2013), Shaalan et al. (2014), Azadi et al. (2014), Rahim et al. (2015) and Shirinabadi (2016), also studied the dynamic behavior of twin tunnels.

2 Horizontally Aligned Twin Tunnels

2.1 Twin Tunnel Geometry

As a part of the current investigation, it was decided to consider the behavior of twin tunnels of DMRC which were excavated through alluvium deposits, generally known as Delhi silt. The geometric parameters of twin tunnel section are defined in Table 1. For the present study, the soil mass was treated as homogeneous.

Properties of the soil medium surrounding the tunnel are presented in Table 2. These properties remain unaltered with depth of soil strata. No water table was

Table 1 Geometric details of tunnel (Yadav 2005)

Properties	Values
Diameter of both tunnels, *D*	6.0 m
Overburden depth, *H*	12 m
Support system	Segmental reinforced concrete (RC) liners
Thickness RC liners	0.28 m
Clear distance between tunnels	0.5 D–5.0 D
Elastic modulus of RC liners, E_c	3.16×10^7 kPa
Poisson's ratio of concrete	0.15

Table 2 Properties of soil medium (Yadav 2005)

Properties	Values
Unit weight, γ_{bulk}	18 kN/m^3
Saturated unit weight, γ_{sat}	20 kN/m^3
Cohesion, *c*	0
Friction angle, φ	35°
Dilatational angle, ψ	5°
Poisson's ratio	0.25
Elastic modulus, *E*	25 MPa

encountered during tunnel excavation. Complete geometry of physical model of soil–tunnel system is shown in Fig. 1 along with the locations of various critical points where the response was monitored.

2.2 Numerical Modeling

Two-dimensional plane strain finite element analysis has been carried out for DMRC metro tunnels using Plaxis 2D software. The extent of the model in the two directions, after carrying out sensitivity analysis, has been taken as 180 m × 60 m. Six-noded triangular elements were considered for modeling of soil domain. Segmental RC liners of tunnel were simulated using plate bending elements. The stress–strain behavior of soil was considered as elasto-plastic which follows the Mohr–Coulomb yield criterion. For RC liners, elastic behavior was considered. No-slip (perfect bond between soil and liners) condition has been assumed between the tunnels and the surrounding soil medium. Damping in soil and RC liners of tunnel were taken as 15 and 2%, respectively. Response spectra compatible time history for 1999 Chamoli earthquake of lower Himalaya, as shown in Fig. 2, was preferred for the analysis. For static response, nodes along vertical boundaries of finite element mesh were

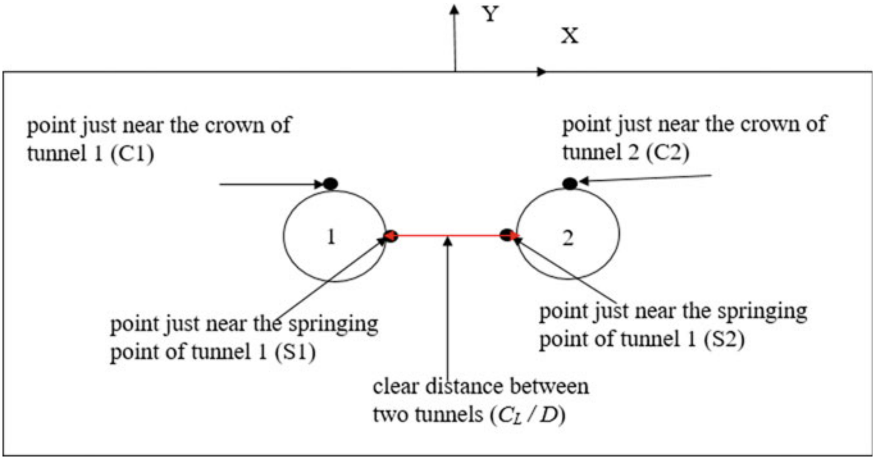

Fig. 1 Layout of geometry of twin tunnels

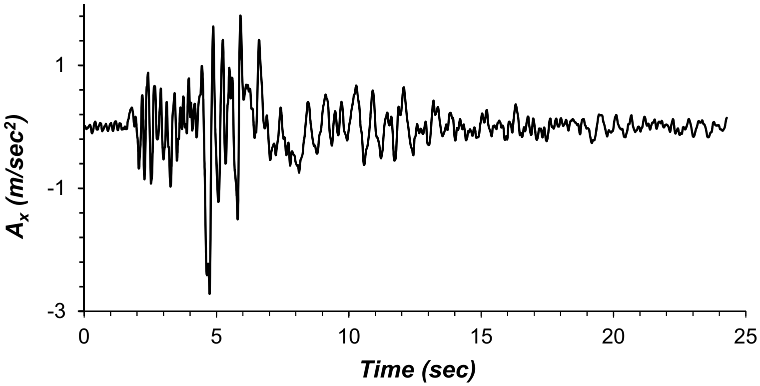

Fig. 2 Response spectra compatible time history of 1999 Chamoli earthquake

restrained in X (horizontal) direction and were free to move in Y (vertical) direction, whereas the bottom boundary was fixed in both directions. For dynamic analysis, viscous absorbent boundary, proposed earlier by Lysmer and Kulhemeyer (1969), was used to represent the displacement condition along both vertical boundaries. Coefficients of absorbent boundary, C_1 and C_2, have been taken as 1 and 0.25, respectively.

2.3 Stages of Calculations

Stage 1: Only initial stresses are generated using K0-procedure. Both the tunnels and other loadings are kept inactive in this phase.
Stage 2: Soil inside tunnel 1 has been removed, and RC liner was applied as the permanent support system. Tunnel 2 is kept inactive in this phase.
Stage 3: Contraction of 3% was applied for simulating the volume loss during the construction of tunnel 1. This completes the construction of tunnel 1. Tunnel 2 is still kept inactive.
Stage: 4: Repeat step 2 for tunnel 2.
Stage 5: Repeat step 3 for tunnel 2. Static analysis of the whole system was first carried out, and the resulting stresses were stored as initial stresses in the whole system. This defines the state of stress surrounding the tunnel before the occurrence of an earthquake.
Stage 6: For dynamic analysis, the boundaries are treated as viscous absorbent boundaries and corresponding constants *a, b* are defined. The time history of earthquake loading is therefore applied along the base of the model, and the seismic analysis is carried out.

2.4 Results and Discussion

Vertical stress concentration around the tunnels and the forces mobilized in RC liners during static and dynamic analysis are presented here. For studying the effect on vertical stress concentration during static and dynamic analysis, four critical points, namely C1 (point just near the crown of tunnel 1), S1 (point just near the springing point of tunnel 1), C2 (point just near the crown of tunnel 2) and S2 (point just near the springing point of tunnel 2), are selected, as shown in Fig. 1.

2.4.1 Static Analysis

Firstly, tunnel 1 has been constructed. Stresses were redistributed after the construction of tunnel 1, and these resulting stresses were stored as initial stresses in the whole system prior to the construction of tunnel.

The aim is to predict the effect of construction of tunnel 2 on tunnel 1 and the surrounding soil. Figure 3 shows the incremental vertical stress after the construction of tunnel 2 for different values of the pillar widths where σ_{s2} is the vertical stress after the construction of tunnel 2 and σ_{s1} is vertical stress after the construction of tunnel 1. It can be seen from Fig. 3 that vertical stress (σ_{s2}) at both critical points of tunnel 1, namely C1 and S1, increases by about 1.7 times σ_{s1} for a pillar width of 0.5 D. It can as well be noticed that vertical stress at points C1 and S1 of tunnel 1 decreases when the pillar width increases from 0.5 D to 3.0 D. Thereafter, it remains constant even if the pillar width is increased to 5.0 times the diameter.

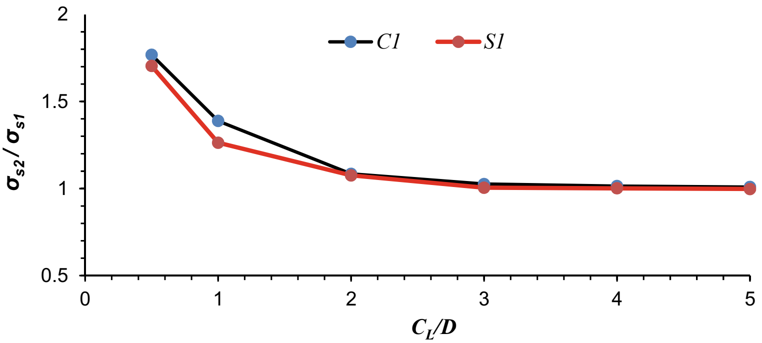

Fig. 3 Increment in vertical stress at different points after construction of tunnel 2

Figure 4 shows the horizontal displacement at ground surface after the construction of tunnels for pillar width of 0.5 D. Maximum horizontal displacement after the construction of first tunnel is of the order of 10 mm. It can be also seen that the maximum horizontal displacement increases to 19 mm after the construction of the second tunnel.

Values of maximum horizontal displacement at the ground surface have been summarized in Table 3 for different pillar widths. It can be noticed that horizontal

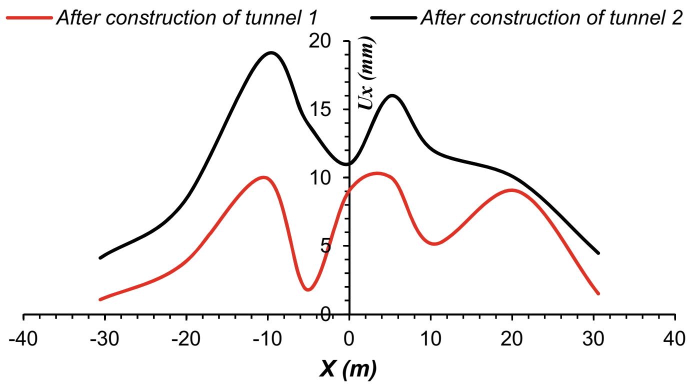

Fig. 4 Horizontal displacement at ground surface after construction of both tunnels ($C_L = 0.5$ D)

Table 3 Displacements at ground surface (0, 0) after construction of tunnel 2

Pillar width, C_L	U_x (mm)	U_y (mm)
0.5	19	44
1.0	16	41
3.0	10	23
5.0	7.5	22

displacement at ground surface reduces with increase in pillar width between the tunnels. Maximum values of horizontal displacement are of order of 19, 16, 10 and 7.5 for pillar widths of 0.5 D, 1.0 D, 3.0 D and 5.0 D, respectively.

The values of vertical displacement at the ground surface (ground subsidence), which occurs after the construction of both tunnels, are presented in Fig. 5. The maximum vertical displacement after the construction of first tunnel was about 25 mm. It can also be seen from Fig. 5 that maximum vertical displacement increases up to 44 mm after the construction of the second tunnel. These values of maximum vertical displacement at ground surface decrease with increase in pillar width as shown in Table 3.

Forces in RC liners after the construction of tunnel 1 are taken as initial condition prior to construction of tunnel 2. Then, percent increase in forces in RC liners of tunnel 1, after the construction of tunnel 2, is presented in Fig. 6.

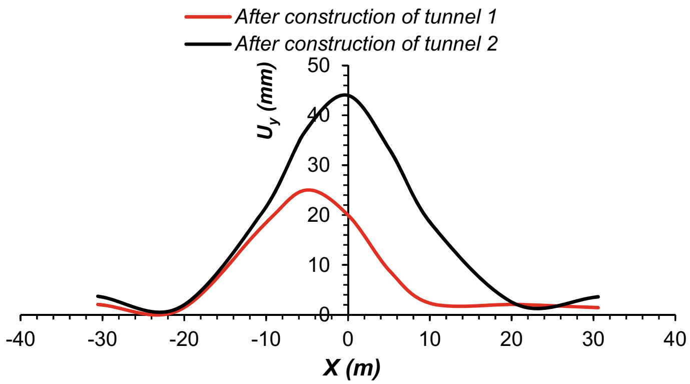

Fig. 5 Vertical displacement at ground surface after construction of both tunnels ($C_L = 0.5$ D)

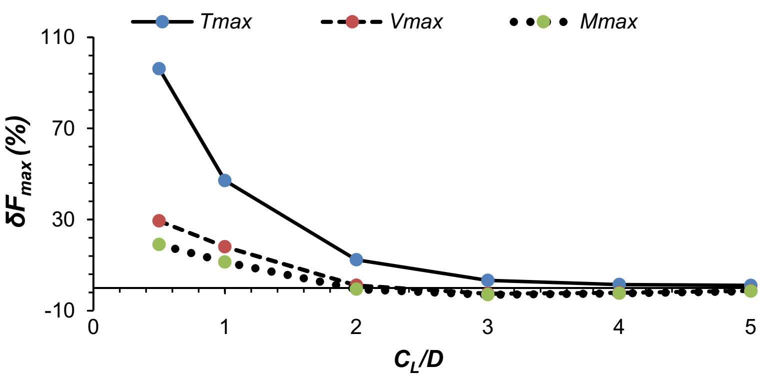

Fig. 6 Percent increase in forces in RC liners of tunnel 1 due to construction of tunnel 2

The maximum forces in RC liners are denoted as axial force, Tmax, shear force, Vmax, and the bending moment, Mmax, respectively. The incremental values of these forces are plotted in Fig. 6 with respect to pillar width. It shows that axial force, shear force and bending moment increase significantly when the pillar width reduces to half the diameter of tunnel. The corresponding increment in axial force, shear force and bending moment is of order of about 96, 29 and 19%, respectively. Forces in RC liners of tunnel 1 were found to reduce significantly as the pillar width between the tunnels increases from half to 3 times the diameter of tunnel. Thereafter, the forces attain almost a constant value.

2.4.2 Seismic Analysis

Stresses are redistributed after the construction of the second tunnel, and these resulting stresses were stored as initial stresses in the whole system prior to applying the earthquake loading. Figure 7 shows the increase in vertical stress at different points of both the tunnels during the earthquake. In Fig. 7, σ_{s2} is the vertical stress at different points of both tunnels after the construction of tunnel 2, and σ_{eqm} is the maximum vertical stress during the earthquake. It is seen that vertical stress during earthquake increases at all points with increasing pillar width and that it is maximum at the crown points of both tunnels.

Then, percentage increment in forces in RC liners of tunnel 1 and tunnel 2 during the earthquake was estimated and their variation with respect to size of pillar width is presented in Figs. 8 and 9, respectively.

Both the figures suggest that increment in shear force and bending moment in the liners during the earthquake is practically independent of the pillar width. The increment in axial force in the liners of tunnel 1 increases significantly from about 28% for pillar width equal to 0.5D to almost 141% for pillar width equal to 3D and subsequently remains practically constant (Fig. 8). Figure 9 shows similar trend during earthquake for shear force and bending moment in the liners of tunnel 2.

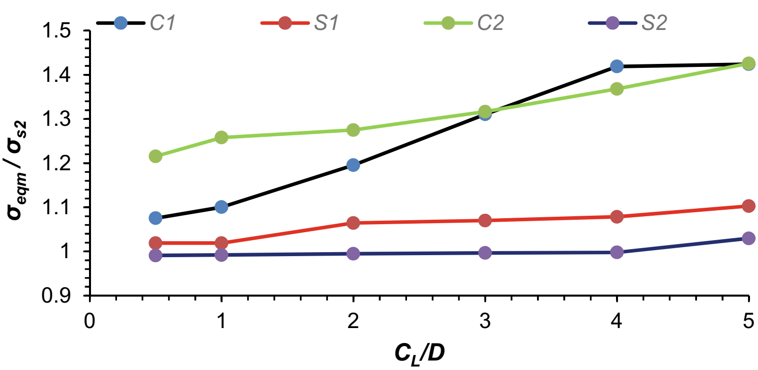

Fig. 7 Increase in vertical stress at different points during the earthquake

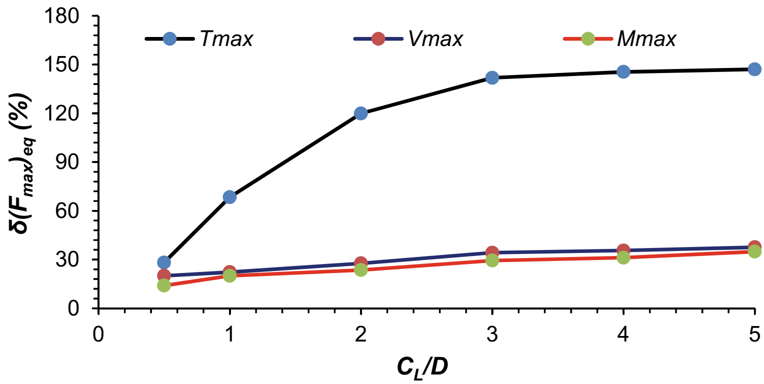

Fig. 8 Percent increase of forces in RC liners of tunnel 1 during earthquake

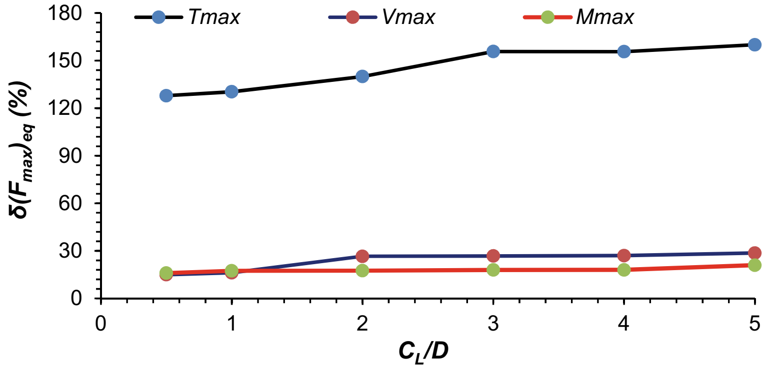

Fig. 9 Percent increase of forces in RC liners of tunnel 2 during earthquake

However, incremental axial force in liners increases from 127% for a pillar width of 0.5 D to about 151% for a pillar width of 3D and thereafter it remains constant.

3 Vertically Aligned Twin Tunnels

In this section, the case of vertically aligned twin tunnels is considered for analysis. The layout of twin tunnels is shown in Fig. 10. It is treated that lower tunnel 2 is first constructed and then the upper tunnel 1 is constructed. The depth of overburden above the upper tunnel 1 is two times its diameter. All other properties were kept the same as in case of horizontal twin tunnels, except the position of the tunnels. For studying the vertical stress concentration and forces in RC liners during static and seismic analysis and also for studying the influence of varying pillar width, six

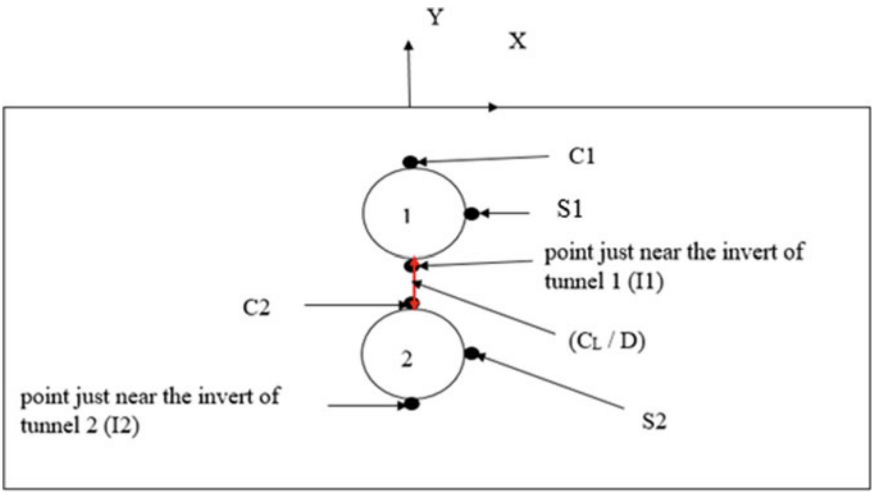

Fig. 10 Layout of geometry of vertical twin tunnels (not to scale)

critical points, namely C1 (point just at the crown of tunnel 1), I1 (point at the invert of tunnel 1), S1 (point just at the springing point of tunnel 1), C2 (point at the crown of tunnel 2), I2 (point at the invert of tunnel 2) and S2 (point at the springing point of tunnel 2), have been chosen, as shown in Fig. 10. Results of static and seismic analysis are presented in the following subsections.

3.1 Static Analysis

Figure 11 shows the change in vertical stress concentration at critical points of lower tunnel 2 after the construction of upper tunnel 1 for different pillar widths. σ_{s2} is the vertical stress after the construction of lower tunnel, whereas σ_{s1} is the vertical stress after the construction of upper tunnel. It can be seen from Fig. 11 that vertical stress concentration factor (σ_{s1}) at all critical points of lower tunnel 2, namely C2, I2 and S2, was found to be 0.52, 0.88 and 0.87 times that of σ_{s2}, respectively, for a pillar width of 0.5 D. This is due to the fact that soil mass surrounding tunnel 2 has entered into plastic state. The minimum concentration factor is at the periphery of the tunnel only. This vertical stress concentration around lower tunnel was found to reduce with increasing pillar width between the tunnels till finally at a pillar width of five times the diameter, the stress concentration factor at all points, C2, I2 and S2, attains a value of unity indicating an all-round elastic state in soil mass.

Figure 12 shows the horizontal displacement at ground surface after the construction of the both tunnels for a pillar width of 0.5 times the diameter of tunnel. Maximum horizontal displacement after the construction of lower tunnel 2 is of order

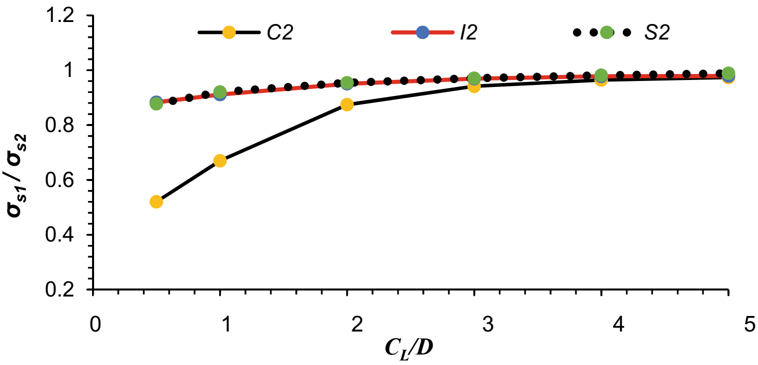

Fig. 11 Change in vertical stress at different points around lower tunnel (2) after construction of upper tunnel (1)

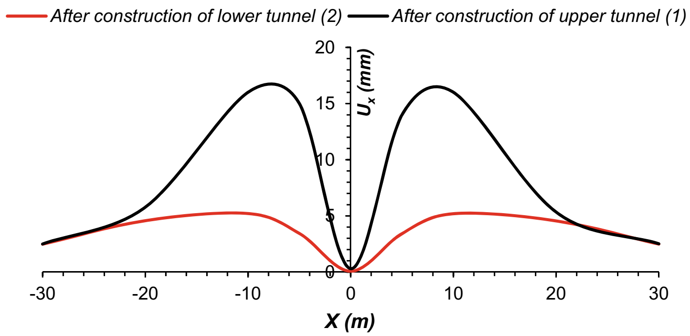

Fig. 12 Horizontal displacement at ground surface after the construction of both tunnels (C_L = 0.5 D)

of 5.21 mm. From Fig. 12, it is also clear that maximum horizontal displacement increases to more than 16 mm after the construction of the upper tunnel 1.

The effect of increasing the pillar width on horizontal displacement at ground surface has been shown in Fig. 13. It can be noticed that horizontal displacement at ground surface reduces with increasing pillar width between the tunnels due to reduction in stress concentration around the tunnels. Maximum values of horizontal displacement are, respectively, of the order of 16, 15, 13 and 12 mm corresponding to pillar widths of 0.5 D, 1.0 D, 2.0 D and 5.0 D.

The profile of vertical displacement, which occurs at ground surface after the construction of tunnels, is shown in Fig. 14 for a pillar width of 0.5 D. It has been found that maximum vertical displacement after the construction of lower tunnel 2 was maximum above the tunnel with a value of 14 mm. This maximum vertical displacement was found to increase up to 39 mm after the construction of the upper tunnel 1.

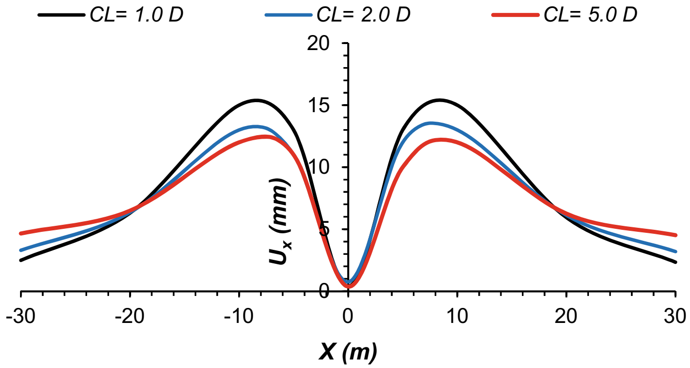

Fig. 13 Horizontal displacement at ground surface for different pillar widths after construction of both tunnels

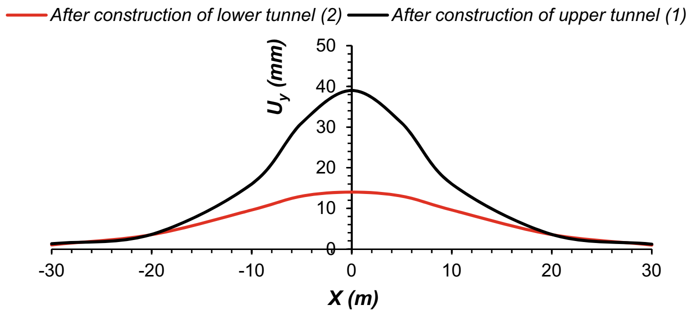

Fig. 14 Vertical displacement profile at ground surface after the construction of both tunnels ($C_L = 0.5\ D$)

Maximum vertical displacement at ground surface was found to be almost similar for all values of pillar width except for pillar width of 0.5 D as is obvious in Fig. 15.

Then, percentage changes in forces in RC liners of lower tunnel 2, due to construction of upper tunnel 1, are presented in Fig. 16. Negative sign along y-axis of Fig. 16 suggests that forces in RC liners of lower tunnel actually reduce significantly after the construction of the upper tunnel.

It can be seen that axial force, shear force and bending moment in lower tunnel 2 reduce significantly after the construction of upper tunnel 1, by about 19.94, 46.87 and 53.12%, respectively, for a pillar width of 0.5 times the diameter of tunnel. This percentage reduction further reduces significantly with increasing pillar width from 0.5 times to 3 times the diameter of tunnel, and thereafter becomes almost constant at a pillar width of about 5.0 times of diameter of tunnel.

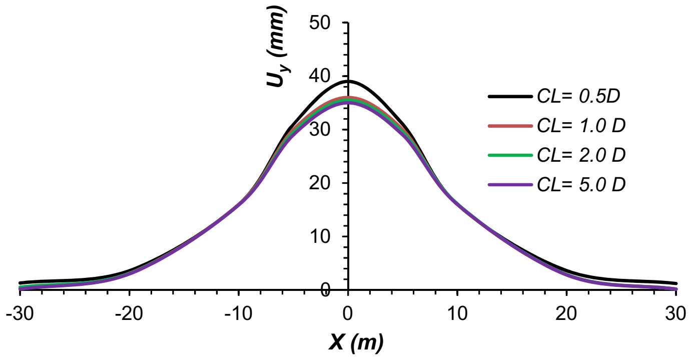

Fig. 15 Vertical displacement profile at ground surface after construction of both tunnels

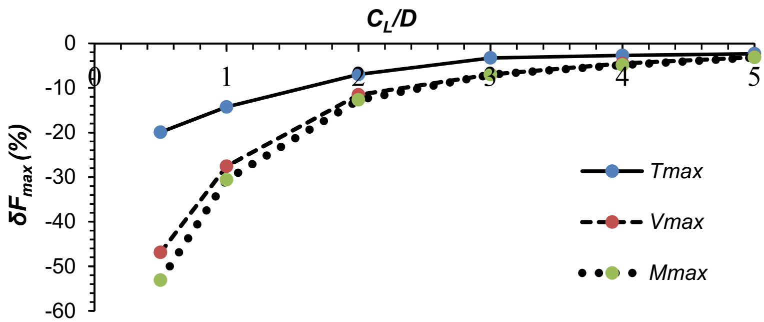

Fig. 16 Percentage change in forces of liners of lower tunnel 2 after construction of upper tunnel 1

3.2 Seismic Analysis

Seismic soil–structure interaction analysis of vertically aligned twin tunnels was also carried out. Figures 17 and 18 show the vertical stress concentration after the Chamoli earthquake for lower tunnel 2 and upper tunnel 1, respectively.

From Figs. 17 and 18, it can be noticed that vertical stress at crown and invert of both the tunnels increase slightly after the earthquake for a pillar width of 0.5 D, and these stresses reduce with increasing pillar width between the tunnels. But the vertical stress at springing points of both the tunnels was found to be almost similar after the earthquake for different values of the pillar width.

Then, percentage increment in liner forces for both the tunnels during the Chamoli earthquake was estimated and these values are presented in Figs. 19 and 20, respectively, for the two tunnels. It can be seen that the forces in the RC liners of both the tunnels increase significantly during the earthquake for pillar width of 0.5 D and these forces then reduce with increasing pillar width between the two tunnels.

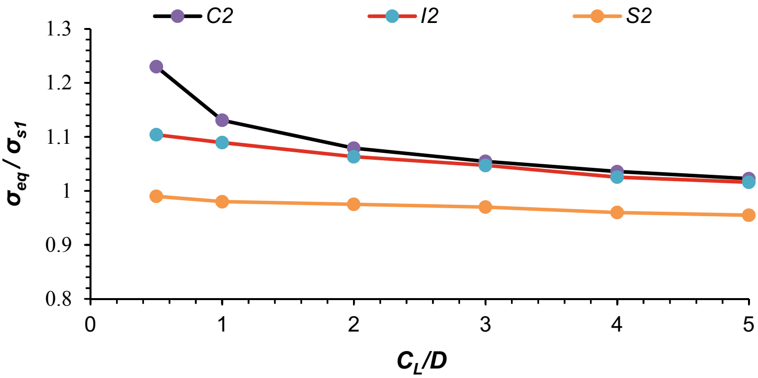

Fig. 17 Change in vertical stress at different points of lower tunnel (2) due to Chamoli earthquake

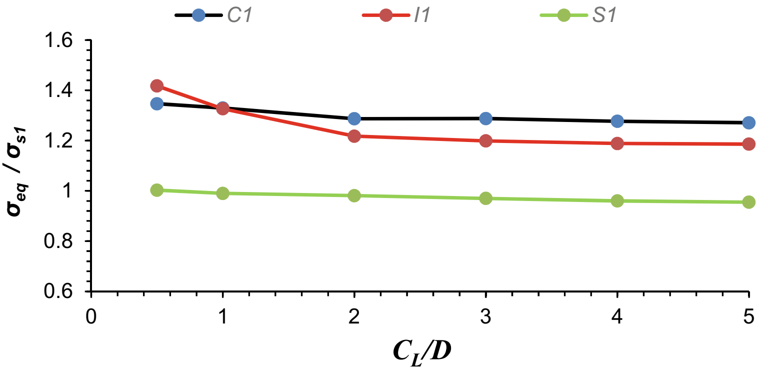

Fig. 18 Increment in vertical stress at different points of upper tunnel (1) due to Chamoli earthquake

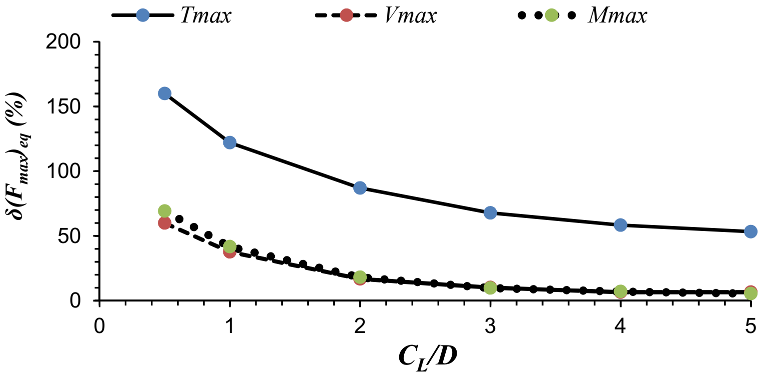

Fig. 19 Percentage increment in liner forces of upper tunnel during Chamoli earthquake

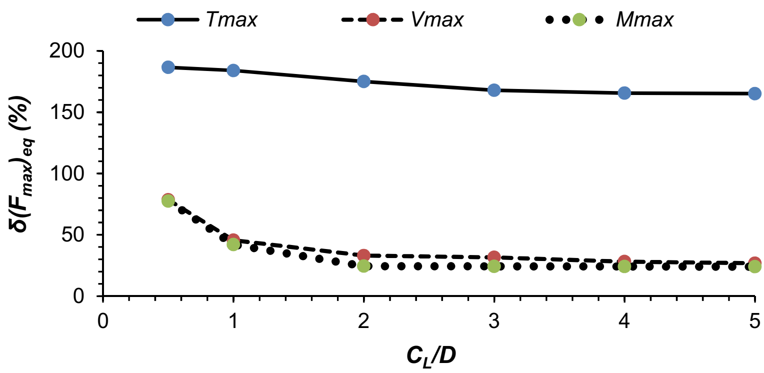

Fig. 20 Percentage increment in liner forces of lower tunnel during earthquake

4 Concluding Remarks

I. Static analysis of horizontally aligned twin tunnels:

(a) After the construction of tunnel 2, vertical stress (σ_{s2}) at both critical points of tunnel 1, namely crown and springing point, increases by about 1.7 times that of σ_{s1} for a pillar width of 0.5 D. It decreases when pillar width reduces from 0.5 D to 3.0 D, and thereafter it becomes constant at a pillar width of five times the diameter.

(b) Axial force, shear force and bending moment in RC liners increase significantly after the construction of tunnel 2, for a pillar width of 0.5 D. Liner forces in tunnel 1 reduce after the construction of tunnel 2 and with the increasing pillar width between the twin tunnels.

II. Seismic analysis of horizontally aligned twin tunnels:

(a) Vertical stresses at critical points of both the tunnels increase during the earthquake, and with increasing pillar width, the earthquake causes an increase in vertical stress in both the tunnels.

(b) Forces in RC liners of both the tunnels increase significantly, and these values increase with increasing pillar width between the twin tunnels.

III. Static analysis of vertically aligned twin tunnels: Vertical stress around the lower tunnel and liner forces in lower tunnel reduce significantly after the construction of upper tunnel and with increasing pillar width between the tunnels.

IV. Seismic analysis of vertically aligned twin tunnels: Vertical stresses at critical points and liner forces in both the tunnels increase during the earthquake for a pillar width of 0.5 D. However, this increment in vertical stress and liner forces shows a decreasing trend with increasing pillar width.

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